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THE EFFECT OF INNOVATION IN AGRICULTURE ON THE ENVIRONMENT

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Matt Ridley's books have sold over a million copies, been translated into 31 languages and won several awards. They include *The Red Queen*, *Genome*, *The Rational Optimist* and *The Evolution of Everything*. Matt joined the House of Lords in February 2013 and has served on the science and technology select committee and the artificial intelligence committee. He was founding chairman of the International Centre for Life in Newcastle. He also created the Mind and Matter column in the *Wall Street Journal* in 2010, and was a columnist for *The Times* from 2013 to 2018. Matt won the Free Enterprise Award from the Institute of Economic Affairs in 2014. He is a fellow of the Royal Society of Literature and of the Academy of Medical Sciences, and a foreign honorary member of the American Academy of Arts and Sciences. He owns a farm in Northumberland.

David Hill

David Hill founded The Environment Bank Ltd in 2009 to bring to the UK the concept of biodiversity compensation and net gain from all development. Environment Bank brokers funding from developments to create new, and enhance existing, wildlife habitats at a large scale. He has a strong professional and personal interest in biodiversity conservation and has worked in the planning and development control sector for over 25 years, advising corporates and developers on the environmental impacts of their projects covering minerals and waste management, ports, commercial and residential, energy/renewables, recreation, highways, airports, infrastructure and water. David is a founding non-executive director of the NatureSpace Partnership Ltd providing specific habitat creation and long-term management measures for protected species paid by development. He was a founding member of Natural England, the government's statutory adviser on the natural environment, and its Deputy Chair from 2011 to 2016. David is the Chairman of Plantlife and the Northern Upland Nature Partnership, a Board Trustee of the Esmee Fairbairn Foundation and a Commissioner with the RSA Food Farming and Countryside Commission. He promotes the creation of a 'Restoration Economy' in which the private sector plays a key role alongside the public sector and conservation NGOs to tackle, at a sufficient scale, the critical issue of biodiversity impoverishment in the UK using novel financial mechanisms, an approach that could be deployed internationally.

Summary

- Innovation in farming has led to higher crop yields which, in turn, have allowed more land to be spared from farming than would otherwise have been the case.

- Raising yields further to feed a growing global population will require new technologies to be embraced, including genetic modification, gene silencing and editing, as well as developments in precision farming and robotics.

- EU regulations and its Common Agricultural Policy have hindered innovation in agriculture. Brexit therefore presents a golden opportunity for the UK to look afresh at available technologies. Britain should be at the forefront of encouraging innovation in agriculture, allowing farmers and consumers to reap the economic and environmental benefits.

- Economic incentives can be structured to align such innovation with environmental gain, through concepts such as habitat banking and environmental credits. Innovative policy making can bring rewards to habitat creation, wildlife enhancement and ecological benefits, in a form that is both effective and affordable.

- Whilst many farmers and landowners already deliver some conservation on their land, mechanisms to facilitate greater and larger-scale participation by them will be paramount to restoring biodiversity in the UK.

- In addition to an expansion in sustainable food and farming systems in the coming decades, technological advances provide opportunities to increase efficiencies and provide land for biodiversity restoration.

Introduction

Agriculture is defined in Wikipedia as 'the cultivation and breeding of animals, plants and fungi for food, fibre, biofuel, medicinal plants and other products used to sustain and enhance life'.

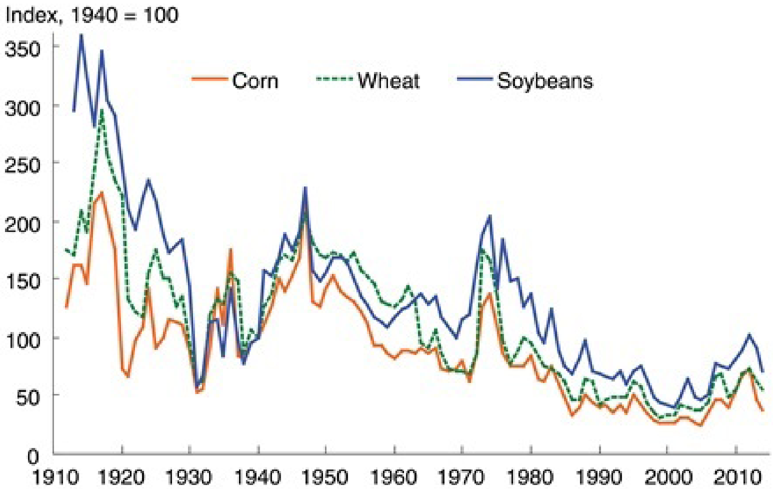
Farming has been continually transformed by innovations ever since it was first invented. These innovations have included genetic changes in crops and animals, implements such as ploughs and seed drills, techniques such as rotation and manuring, and modern technology such as tractors, sprays and computers.

Innovation in agriculture continues at a rapid pace. These two papers examine the innovations currently occurring in farming, and likely to occur in the near future, and explore their implications for British farmers and consumers. Those implications fall into two main categories:

- Economic. The effect of innovation on the competitiveness of British farmers and on rural communities.
- Ecological. The effect of innovation on the environmental impact of farming.

The economic impact of innovation in agriculture must be seen in a global context. Global food prices have fallen over the past 50 years, at the rate of roughly 0.5-1 per cent per year, reflecting the increased productivity of farming worldwide, and despite a doubling of global population (see Figure 1).

Figure 1: Inflation-adjusted corn, wheat and soybean prices, 1912-2014[1]



Britain's agricultural productivity has stagnated in recent years and is well below that of comparable European countries. However, moves are afoot to change this. As a recent report from the Agriculture and Horticulture Development Board (2018) found:

> Investment in agricultural innovation has been bolstered in recent years through the Government's Agri-Tech strategy. Indeed, in 2015, overall investment in agricultural R&D by both public and private sectors in the UK was around £490 million, putting the UK ahead of some of our main competitors in terms of investment as a proportion of agricultural Gross Value Added (GVA).

However, the AHDB report added that 'Public funding of agricultural R&D is still heavily skewed towards blue-sky research, rather than near-market application'.

Innovation often encounters irrational resistance; popular opposition to innovation in food and farming is nothing new. Technologies such as threshing machines encountered organised violence. Margarine was so

1 Source: USDA, Economic Research Service Calculations using data from USDA, National Agricultural Statistics Service and U.S. Department of Labor, Bureau of Labor Statistics.

resented by the dairy industry that spurious health scares about it were widely circulated, resulting in the astonishing fact that more than half of American states had banned margarine altogether by 1940.

The resistance to biotechnology that exploded in the 1990s can be explained partly as a reaction to the BSE (mad cow) epidemic and to a growing distaste for industrialised food production. The lesson of that episode, contrasted with the rapid acceptance of mobile phones around the same time, despite their unknown risks, is that people have to see an individual benefit to them as consumers from a new technology if they are to accept it.

Yet the lesson of history is that these resistance movements may make a lot of noise for a while, but soon fade and are almost always based on irrational arguments and spurious reasoning.

The first paper in this set, by Matt Ridley, explores how British farming could accelerate innovation in order to remain profitable and therefore viable. Innovation will occur anyway, but Britain's imminent departure from the European Union may result in the lowering of external tariffs on food and other agricultural products, thereby exposing British farmers to sharper competition.

In addition, the Common Agricultural Policy, by subsidising existing systems, is generally agreed to have been a disincentive to innovation. Brexit also challenges the dependence of some British farming businesses (especially fruit and vegetable growers) on migrant labour, sharpening the need for adopting robotic innovation.

A key question this paper sets out to answer is whether innovation in agriculture will be good for the environment or bad. By definition, farming uses land and competes with wild ecosystems and wildlife for space, sunlight, water and other resources. Innovation can however allow farming to live alongside abundant wildlife.

The second paper, by David Hill, focuses on whether to incentivise farmers to grow both food and wildlife on the same plot, or on separate plots. It examines how to structure incentives to align farming's progressive innovation with environmental net gain, through concepts such as habitat banking and environmental credits. And it explores the various ways in which innovative policy making can bring rewards to habitat creation, wildlife enhancement and ecological benefits, in a form that is both effective and affordable.

Part 1

Innovation in food production

Matt Ridley

Introduction

The expansion of the human population to over seven billion people was made possible by the cultivation and grazing of increasing amounts of wild land, and the enhancement of yields from land through innovation. As the population expands towards ten billion in the second half of this century, it is innovation, rather than new land, that will have to keep pace. There is relatively little extra land that can be farmed easily or productively.

In medieval times the landscape was required to produce not just food, but fibre for clothing, fuel for heating and material such as wood for construction. It also provided the energy needed to build and run the structures of society, through fodder for people and animals, and through water and wind power.

Gradually all of those products and services, except food and fibre, were decoupled from the landscape. Stone, glass, concrete, coal, oil, gas – and plastic made from oil – were made with materials extracted from comparatively small holes in the ground, rather than being grown organically.

Today the vast majority of agricultural land is devoted to producing only food, though there is a growing movement to return to using the landscape to generate energy, through wood, biofuels, wind, water and solar power.

In the nineteenth century, agricultural output expanded primarily by taking more land from nature and bringing it under the plough and cow: on the prairies, the pampas, the steppes and the outback. In the twentieth century, by contrast, agricultural production expanded mainly by increasing yield per acre.

Innovation achieved this. Four crucial technologies made the most difference:

- The tractor displaced the horse, freeing an extra 20-25 per cent of land for growing human food rather than horse feed (Smil 2000).
- Nitrogen fertiliser, synthesised from molecular nitrogen in the air using energy from fossil fuels, displaced the need to produce manure or legumes from other land, or to import guano.
- New genetic varieties, especially short-strawed wheat and rice, hybrid maize and faster-growing chickens, gave higher yields from the same inputs.
- Organic-chemical (carbon-based) pesticides reduced crop losses to competing weeds and pests.

The price of food

Around the world, labs, foundations, firms and farmers themselves are working on new techniques to improve yields, cut costs, resist pests, survive drought and enhance nutritional content of crops and animals. Even if only a fraction of these initiatives bear fruit, there will be huge changes in farming by 2050.

It is commonly asserted that the world needs to double food production by 2050 to feed a growing population. The most recent analysis, from Penn State University, suggests however that the world will need only '25 percent to 70 percent more crop output in 2050 than was produced in 2014' (Hunter et al. 2017). This implies roughly the same rate of increase as has been seen in recent years, possibly slower.

There is thus reason to believe that food prices will continue to fall in real terms over the next 32 years, as they have done in the past 100, and that land will be released from agriculture throughout the world. Biofuels are the main reason this has not happened till now (Ausubel et al. 2013). A key point is that British farmers cannot expect rising prices to come to their rescue.

The British government should have a strategy for allowing farmers to enhance their competitiveness by increasing yields and cutting costs through innovation. It should also have a strategy for releasing land from farming and returning it to nature. And it should look for, and facilitate investment in, innovations that specifically improve the environment.

Land sparing versus land sharing

For the human race to live alongside rich and diverse wild ecosystems, there are two options: land sharing and land sparing. Land sharing means farming the countryside in such a way that crops and pastures are full of wild species – flowers, insects, birds and mammals. This is roughly the way medieval land-use operated, with fields full of ‘weeds’ and ‘pests’. By definition, such a farming system must have a lower yield per hectare, because some of the sun’s energy is going into the weeds and pests and not into human food. Therefore, the drawback of land sharing is that it requires more land.

Land sparing means growing crops so successfully that less land is needed to feed a given number of people, to the point where some land can be released from agriculture and returned to a state of nature, or ‘rewilded’. A patchwork of productive fields lies alongside a network of nature reserves, or patches and strips of land devoted to wildlife.

Globally, the result of changes in farming practice in the half century between 1960 and 2010 was that roughly 68 per cent less land was needed to produce a given quantity of food (Ausubel et al. 2013). Thus more than twice as many people were fed from a similar area of land. Had yields not increased, pressure on wild lands would have become intolerable – or high food prices and mass starvation would have occurred.

In fact, famine virtually disappeared during this period, except in areas with dysfunctional political regimes. Using the average yields of 1961 to feed 2000’s population of over six billion people, we would have had to graze or cultivate over 80 per cent of the world’s land, instead of about

38 per cent, according to calculations by Goklany (2002), and more than double the area of cropland from 3.7 billion to 7.9 billion acres.

Krausmann et al. (2013) estimate that global ‘human appropriation of net primary production’ (HANPP) is currently about 25 per cent currently. That is, about one-quarter of the world’s green vegetation on land is appropriated by human beings and their domestic animals either as food, fuel or shelter, or through destruction by fire and concrete.

However, they note an improving efficiency of HANPP – feeding more people per quantity of primary production – and conclude that ‘If humans can maintain the past trend lines in efficiency gains, we estimate that HANPP might only grow to 27–29% by 2050’.

Increased productivity of farmland has been crucial to conservation and environmental improvement. For example, if the world stopped using genetically-modified crops that were herbicide tolerant, then an extra 762,000 hectares of land would need to be cultivated. Most of this, 53 per cent, would be new land brought into cropping agriculture for the first time, including 167,000 hectares of deforestation (Brookes et al. 2017).

This ‘land sparing’ is the central concept behind ‘sustainable intensification’, an idea increasingly in vogue among ecologists. On a global scale, there is no question that land sparing is a more practical approach than land sharing. However, on local scales both here and elsewhere in the world, the answer is not quite so simple. A key recent study by Ekroos et al. (2016) pointed out that ‘debate over the relative merits of land sparing or land sharing is partly blurred by the differing spatial scales at which it is suggested that land sparing should be applied’.

The authors, from the University of Lund in Sweden, conclude that land sparing is most effective if it is applied at two or more different scales:

- Within-farm sparing of small patches and corridors of habitat in a mosaic
- Between-regions sparing of larger natural or semi-natural habitats such as forests, heaths and wetlands.

The extent to which innovation in agriculture can contribute to these two patterns will be a key focus of this paper.

One concern is that land sparing with high-productivity farming would have other environmental drawbacks. However, in a recent comprehensive study of the effect of land sparing, led by Cambridge University, but including 17 organisations around the world, Balmford et al. (2018) concluded that more intensive agriculture that uses less land may also produce fewer pollutants, cause less soil loss and consume less water. They found that inorganic nitrogen boosted yields with little to no greenhouse gas 'penalty' and lower water use per tonne of rice. They also found that organic dairy farms caused at least one third more soil loss, and take up twice as much land, as conventional dairy farming for the same amount of milk produced (ibid.). 'These results add to the evidence that sparing natural habitats by using high-yield farming to produce food is the least bad way forward', said Professor Andrew Balmford.

The state and future of British farming

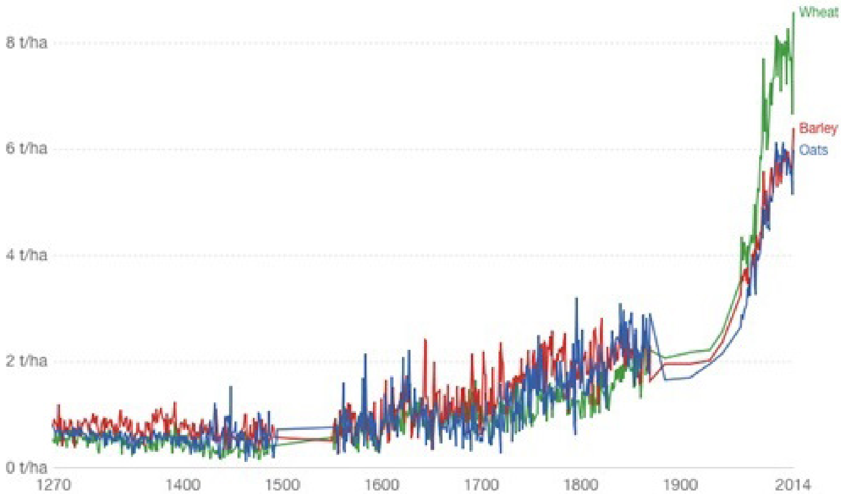
In the fourteenth century, British barley crops at one monastery, Battle Abbey, yielded about three grains per seed sown, of which one had to be held back for next year's sowing, leaving a thin margin of two seeds to provide all the food for the people and animals on the farm (plus the monks or barons who owned the farm and spent their time praying or fighting instead of ploughing). Today, wheat seed sown in a field produces on average about 100 seeds for harvesting, all but one of which can be consumed.[2]

Much of this improvement is recent. Average yields of British wheat crops remained the same, at about 2 tonnes per hectare, between 1885 and 1945. This was probably about double the level of yield generally achieved in the Middle Ages but showed no increasing trend. Over the next half century, however, yields quadrupled to 8 tonnes per hectare before apparently levelling off around the turn of the 21st century (Figure 2).[3] Maize yields in the United States have climbed even higher, roughly fivefold, assisted by genetic modification, and with little sign of levelling off.

2 'Three centuries of English crops yields: 1211-1491', Medieval Crop Yields Database. http://www.cropyields.ac.uk/project.php

3 'UK Wheat Yields 1885-2011', University of Reading. http://www.ecifm.rdg.ac.uk/postwa12.gif

Figure 2: Long-term cereal yields in the United Kingdom, 1270-2014 (tonnes per hectare)[4]



A similar story can be told about meat. Today a chicken reaches the weight at which it will be killed in one-third of the time and after eating one-third of the amount of food compared with a 1950s-variety chicken fed on the same diet. That represents a considerable reduction in waste and in the amount of land devoted to growing feed per chicken. The feed conversion ratio of chickens increases at a rate of about 1-2 per cent a year and could improve faster if the industry was not (rightly) concerned about welfare. Most of that improvement comes from genetics and it shows no sign of reaching a plateau.[5]

4 Source: Our World in Data. https://ourworldindata.org/grapher/long-term-cereal-yields-in-the-united-kingdom

5 'The Genetics of Bigger Chickens', *The Rational Optimist* blog, 22 October 2011. http://www.rationaloptimist.com/blog/the-genetics-of-bigger-chickens/

Biotechnology

Agriculture depends heavily on mechanisms to suppress weeds and pests such as insects, fungi, slugs and nematodes. Ploughing, crop rotation and hand weeding are generally insufficient to achieve this on their own and modern farming relies heavily on chemicals. These include growth regulators as well as herbicides, fungicides and insecticides.

There is good evidence that the risks posed by pesticides are low and declining rapidly. A recent Danish study (Larsson et al. 2017) found that the hazard index posed by pesticide exposure in the diet for a person 'was on level with that of alcohol for a person consuming the equivalent of 1 glass of wine every seventh year'. The toxicity of pesticides has declined by 98 per cent since the 1960s.

However, many in the industry believe that the chemical era in farming may be coming to an end. David Gardner, former chief executive of the Royal Agricultural Society of England, believes that with little new chemistry coming through, and with farmers losing many of the chemicals they already have because of restrictive new regulations and with resistance building up, British farmers are going to need innovative approaches to combating weeds and pests, based on biotechnology and precision robotics.

In 2011, the EU changed to a hazard-based system rather than a risk-based system. The difference is that risk takes into account exposure, whereas hazard measures only whether a chemical is capable of causing harm. This is leading to the banning of many chemicals based on theoretical or experimental demonstrations of harm at unrealistic doses. A report from the Agricultural Industries Confederation (AIC), the Crop Protection Association (CPA) and the National Farmers Union (NFU) in 2014 found that '87 of the 250 active substances currently approved in the UK could be threatened by the cumulative effects of these policies'.

Chemical innovation is harder in Europe than in other competing agricultural regions. This will put EU and UK agriculture at a disadvantage, unless they adopt biotechnology-based approaches, which they have so far been reluctant to do.

All plant breeding has involved genetic change

Hexaploid wheat, derived from multiple crosses between species, with heavy, free-threshing grains, and unable to compete in the wild without human intervention, already existed within a few thousand years of the first domestication of wheat's ancestors around 10,000 years ago.

Accidental mutants and hybrids were selectively chosen and disseminated by prehistoric farmers because of their high yields and easy harvesting. Thus the greatest genetic transformations occurred long before anything resembling civilisation, let alone industrialisation. The view that genetic alteration is a modern, industrial activity is therefore unfounded.

More deliberate selection of varieties continued to improve yields and change varieties throughout the last millennium, aided eventually by the discovery by Gregor Mendel of the principles of genetics. Hybrid maize varieties transformed American farm yields following the discovery in 1908 of heterosis or hybrid vigour. Between 1935 and 1939, Iowa went from growing 10 per cent to 90 per cent hybrid maize, largely abandoning self-fertilised varieties (Pruitt 2016).

The Green Revolution

In the 1960s, the Indian subcontinent was experiencing fast population growth and widespread hunger, including severe famines. Pessimism about the region's future Malthusian fate was widespread (Perry 2018).

Yet by the mid-1970s, India was exporting food, and famine had all but disappeared. This was the Green Revolution, made possible by genetic science and synthetic fertiliser. Its origins lay in Japan at the end of World War II, where an American scientist named Cecil Salmon collected 16 varieties of wheat including one called Norin 10, which grew half as tall as most varieties thanks to a mutation in a gene called Rht1.

In 1952, Norman Borlaug, took some Norin seeds to Mexico. By 1963, 95 per cent of Mexico's wheat was Borlaug's varieties, and the country's wheat harvest was six times what it had been a few years before.[6]

Borlaug's Mexican dwarf wheats transformed yields in India and Pakistan, saving a billion lives and improving economic opportunities for millions. The Green Revolution was also an environmental triumph. Without it, India would have lost its forests and tigers as well as many of its children.

These same dwarfing genes (and the use of growth-regulator chemicals) were crucial to the quadrupling of wheat yields in the UK over the same period.

Radiation-induced mutagenesis

In the 1950s, scientists attempted to speed up the mutation rate in plants by subjecting seeds to gamma rays, X rays or chemical mutagens. This 'mutagenesis' technique produced many new varieties such as Golden Promise, a barley that was especially popular with organic brewers (most of whom are blissfully unaware of its origin in the gamma rays of the Harwell nuclear facility).

Mutagenesis continues to be used today and varieties produced in this way are not subject to any special regulatory hurdles, despite the fact that off-target mutations are undoubtedly far more common than in the technique known as genetic modification. Indeed the European Court of Justice specifically ruled in 2018 that mutagenesis be exempted from tough regulation. Nor have such crops ever been the object of protests by NGOs.

Genetic modification

Genetic engineering of bacteria – the insertion of genes from other species – began in the 1970s. Within a decade, bacteria were producing human insulin for use by diabetics, a form of genetic modification that continues to save lives today.

6 'The Beginning of the Green Revolution', College of Agricultural, Food and Environmental Sciences, University of Minnesota. https://web.archive.org/web/20041227090100/http://www.coafes.umn.edu/The_Beginning_of_the_Green_Revolution.html

Initial opposition to this medical use of genetic modification in countries such as Germany led to the loss of an entire industry to foreign competitors, in this case from Hoechst to Eli Lilly (Nellen 2018).

By the 1990s, it was possible to introduce genes into plants, using bacterial plasmids or gold particles, and genetically modified tomatoes were soon on sale in the United States.

However, Europe rejected this technology almost completely, with popular protests resulting in extremely high regulatory and cost barriers to its deployment, amounting effectively to a ban. Since 2005, Canada has approved 70 different transgenic varieties. The EU approved one, and that took 13 years, by which time it was outdated.

Activists also persuaded many African countries to reject the technology, even in famine relief food. They fought to block for many years the development and testing of a vitamin-enhanced 'golden rice', developed specifically in non-profit institutions as a humanitarian project to alleviate the high mortality and morbidity caused by a reliance on rice for food among very poor people in parts of Asia.

In response, 134 Nobel-prize winners called on Greenpeace to 'cease and desist in its campaign against Golden Rice specifically, and crops and foods improved through biotechnology in general', but this request fell on deaf ears.[7]

By the year 2000, British researchers on GM crops, who had been world leaders in the technology, had mostly shut up shop or moved abroad, as had firms specialising in the commercialisation of such new varieties. Today Europe imports huge quantities of genetically modified crops, mainly soybean and maize from the Americas and cotton from Asia, but grows very little.

Yet the large-scale cultivation of genetically modified crops has continued to increase (see Figure 3) and 189.8 million hectares were grown in 2017, an area of fields 30 times larger than the entire arable agriculture of the United Kingdom (ISAAA 2017).

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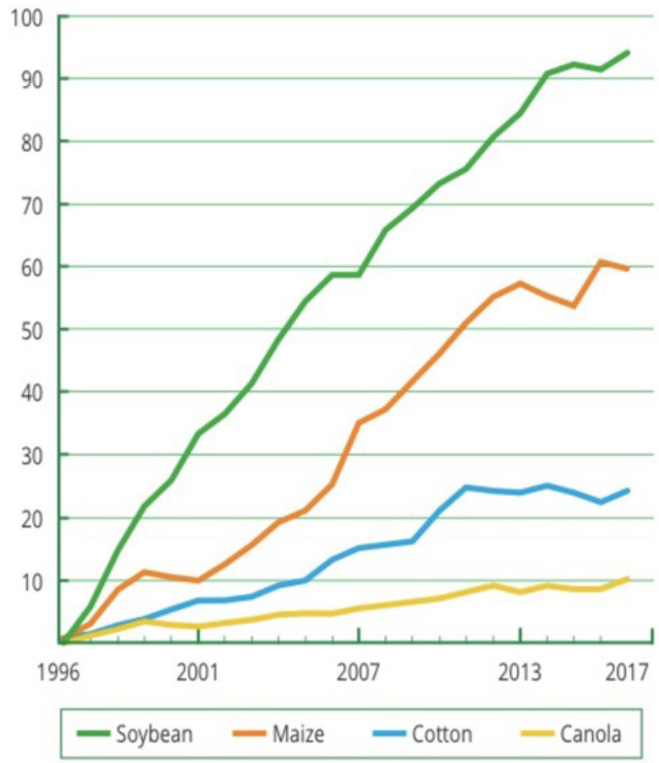
7 'Laureates Letter Supporting Precision Agriculture (GMOs)', Support Precision Agriculture. http://supportprecisionagriculture.org/nobel-laureate-gmo-letter_rjr.html

In 20 years from 1996, such transgenic crops were rapidly adopted in 26 countries, with a value of $18 billion and providing several billion meals. By 2017, 77 per cent of the world's soybean crop, 80 per cent of the world's cotton, 32 per cent of the world's maize and 30 per cent of the world's rapeseed was genetically modified (ibid.).

Figure 3: Global area of biotech crops, 1996-2017, by crop (million hectares)[8]



8 Source: ISAAA (2017).

The American Association for the Advancement of Science stated in 2012:

> The science is quite clear: crop improvement by the modern molecular techniques of biotechnology is safe. Consuming foods containing ingredients derived from GM crops is no riskier than consuming the same foods containing ingredients from crop plants modified by conventional plant improvement techniques.[9]

Environmentally, the evidence is clear that this technology has reduced reliance on chemical pesticides. A meta-analysis published by researchers at Gottingen University in Germany in 2014, brought together all reliable studies done around the world and reached the conclusion that the introduction of genetic modification had reduced pesticide usage by 36.9 per cent on average, while increasing yields by 21.6 per cent and with almost no change in production cost. This remains the most comprehensive and authoritative study to date (Klümper and Qaim 2014).

There is therefore no longer any doubt that the effect of the campaigns against GM crops was to leave British farming more dependent on pesticides and less competitive than it would have been if the UK had adopted GM crops (Brookes and Barfoot 2018; Wesseler and Zilberman 2014).[10]

It is widely believed in political circles in the UK that there is continuing public resistance to genetic modification and therefore perhaps also to the even less risky process of genome editing.

However, evidence from recent years suggests that this is simply not true. 'Days of Action' against GM crops in the UK have recently attracted small crowds of dedicated activists[11] and as *The Observer* says, 'their protest fizzled out – a sign that such activities may be losing their appeal and their momentum'.[12] The days of members of the House of Lords dressed in white boiler suits pulling up GM crop plants for the benefit of television cameras have long passed.

9 Statement by the AAAS board of directors on the labelling of genetically modified food. 20 October 2012. http://www.aaas.org/sites/default/files/AAAS_GM_statement.pdf

10 'Pocket K No. 16: Biotech Crop Highlights in 2017', ISAAA. http://www.isaaa.org/resources/publications/pocketk/16/

11 'The battle over GM: a noisy distraction', *spiked*, 29 May 2012. https://www.spiked-online.com/2012/05/29/the-battle-over-gm-a-noisy-distraction/

12 'There's no choice: we must grow GM crops now', *The Observer*, 16 March 2014. https://www.theguardian.com/commentisfree/2014/mar/16/gm-crops-world-food-famine-starvation

Even NGOs no longer prioritise the issue. As one scientist put it to us, referring to the gradual fading of popular and NGO opposition to genetically modified crops, ‘Unfortunately, the debate died with us in the wrong place’.

Dr Nigel Halford of Rothamsted, in the latest edition (2018) of his book *Genetically Modified Crops*, points out that ‘European farmers are increasingly disadvantaged in a competitive global market, competing with GM crops but unable to use them’.

As Mark Lynas, formerly a campaigner against GM crops, put it in his book *Seeds of Science*:

> The problem isn’t just that almost all of the alarms about GMOs were false. It’s that the anti-GMO campaign has deprived much of the world of a crucial, life-improving technology—and has shown the readiness of many environmentalists to ignore science when it contradicts their prejudices.

Gene silencing

Transgenic genetic modification is now just one of many different genetic and genomic techniques for improving the yield, disease resistance and nutritional quality of crops. Most improvements in the future will use subtler approaches than random mutagenesis or transgenic modification and involve the precise alteration of gene sequences so as to increase or decrease the expression of certain genes, often with the introduction of no ‘foreign’ material (not that DNA is ever foreign, just the particular sequence of its code).

For example, three different techniques for ‘silencing’ genes, so as to suppress undesirable traits, have been developed. All involve the sort of changes that could happen naturally, involve no species-barrier crossings and are extremely precisely targeted with few side effects.

They involve introducing stretches of DNA that interfere with the transcription of the target gene, using complimentary ‘anti-sense’ RNA, co-suppression, or RNA interference.

All three techniques were developed in the UK by Don Grierson at Nottingham University, Wolfgang Schuh at ICI and David Baulcombe at the Sainsbury Laboratory in Norwich.

But in a depressingly familiar pattern they have been more widely employed abroad, for example in extending the shelf-life of tomatoes, because of the de-facto ban on genetic modification in Europe.

Genome editing

A variety of new techniques have more recently emerged to alter the genomes of plants in increasingly precise ways to improve traits of crops. These go under the name of gene editing or genome editing, and they effectively blur the distinction between genetic modification and traditional breeding, as detailed below.

Genome editing techniques include oligonucleotides, meganucleases, zinc-finger nucleases, transcription activator-like effector nucleases (TALENS) and most recently the CRISPR-Cas9 system (see Box 1). All these techniques allow more or less precise cut-and-pastes to be made to DNA sequences to silence, alter, or over-express genes.

The key point here is that the various genetic sequences that determine high yield and good disease resistance often exist within different strains of the same species but cannot easily be brought together by traditional crossing without paying a penalty in terms of other traits. Genome editing solves that problem.

In many cases, there can be a temporary GM step, involving the introduction of transgenic DNA sequences, but, once the mutation has been made, the introduced gene can be removed while the mutation that it made is retained.

Even the GM step can now be eliminated in some cases, with the result that the new variety is in every way a plant of the same species but with a mutation of exactly the same kind that can be made by mutagenesis or natural variation.

An example is a variety of wheat produced by the University of Minnesota and Calyxt, using TALEN, that is resistant to powdery mildew, a fungal pest, and therefore needs less fungicide spray.[13]

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13 'Calyxt Launches U.S. Field Trials with University of Minnesota for Powdery Mildew-Resistant Spring Wheat Variety', Calyxt, Inc., 16 May 2017. http://www.calyxt.com/calyxt-launches-u-s-field-trials-with-university-of-minnesota-for-powdery-mildew-resistant-spring-wheat-variety/

It would be perverse to describe such plants as deserving of extra regulation since they are indistinguishable from plants mutated in ways that do not require such regulation. This is why most countries are now recognising that in principle genome-edited crops could and should be regulated as if produced by conventional breeding, rather than as if transgenically genetically modified. Canada, Brazil, Australia, Argentina and Sweden have followed America down this route. Britain should follow suit immediately.

In 2016 the European Union urged member states to delay a decision on this matter, arguing that a case brought in a French court should be allowed to run its course to the European Court of Justice, and decide the question. This procrastination sent the wrong signal to biotechnologists throughout the continent that there was uncertainty about how quickly and expensively a new variety produced by genome editing could reach the market.

The Advocate General of the European Court of Justice, Michal Bobek, issued an opinion in January 2018 (Case C528/16) that genome edited crops should be given the ‘mutagenesis exemption’, whereby they would be treated by regulators like all conventional varieties.

In July 2018 the court rejected this advice and ruled that genome edited plants must be treated to the same regulation as GMOs, not that applied to mutagenesis crops. The reaction of one Canadian professor was as follows:

> Great news for Canadian & American farmers today! EU based environmental NGOs have politically manipulated their legal system to drive every last cent of ag R&D out of the EU, guaranteeing their farmers will no longer be competitive. Hope all Europeans enjoy their future higher food prices.[14]

The ECJ decision means British farmers will be at a competitive disadvantage so long as the UK remains subject to EU regulations, and that more chemicals will be used here than would have otherwise been the case.

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14 Stuart Smyth, *Twitter*, 25 July 2018. https://twitter.com/stuartsmyth66/status/1022133481441132545

By contrast the United States is moving towards a system that regulates crops according to the trait being selected, rather than the method of selecting, which is widely agreed to make much more sense.[15]

Box 1: CRISPR

In 2012, partly as a result of work in the yoghurt industry on bacterial defences against viruses, various scientists stumbled simultaneously upon a way to use a molecular mechanism in bacteria to edit genomes of plants and animals. Called CRISPR-Cas9, it is the most precise, simple and useful of several genome-editing tools and holds huge promise for the improvement of crops and farm animals.

CRISPR stands for clustered regularly interspersed short palindromic repeats. Specific, repeated DNA sequences of 29 letters are separated by 32-letter spacers with variable sequence that have been 'captured' from viruses. The RNA derived from one such repeat-spacer-repeat sequence then guides an enzyme, Cas9, to destroy the virus.

The system has been adapted to enable it to recognise a particular sequence in a cell and cleave the DNA at that point, allowing the insertion of a different sequence. Thus the deletion and insertion of particular DNA letters can be achieved.

15 'Opinion: Trait-based regulation of GM plants is on the horizon – at last', *Agri-Pulse*, 15 August 2018. https://www.agri-pulse.com/articles/11344-opinion-trait-based-regulation-of-gm-plants-is-on-the-horizon-at-last

Bacterial nitrogen fixation

One promising candidate for a step change in agricultural productivity is bacterial inoculation. Recent work by Professor Ted Cocking at Nottingham University has discovered a new strain of a bacterium (*Gluconacetobacter diazotrophicus*) normally found in sugar cane, pineapple and many other plants.

Gd, as the species is known, can fix nitrogen directly from the air and has been shown to provide 60-80 per cent of the nitrogen needs of some varieties of sugar cane, allowing the crop to be grown sustainably with little or no fertiliser (Dent and Cocking 2017). This new strain, instead of living in the plant's xylem, can live inside cells close to chloroplasts.

Unlike the Rhizobium bacteria that fix nitrogen for legumes, this strain of Gd adapts readily to life inside the roots and shoots of wheat, barley, maize, rice and other crops.

Over 200 trials since 2013 of this 'N-fix' technology, developed by the British company Azotic Ltd, have shown that inoculating such crops with cultures of Gd bacteria leads to higher yields and better protein content, even with lower fertiliser applications.

Early results suggest a one tonne per hectare increase in yields at all levels of synthetic nitrate fertiliser application for seeds coated with this bacterium together with the right enzymes. In this way, N-fix technology promises either a 15 per cent increase in yield for the same fertiliser application, or the same yield for a 50 per cent lower application, with considerable financial saving and reduced pollution or eutrophication caused by nitrate run-off (ibid.).[16]

So far in field trials N-fix is working more consistently with maize and rice than with wheat or barley (where there is inconsistent take-up by separate tillers from the same seed). The latest trials with rice in Thailand and the Philippines in 2018 achieved an average 30 per cent yield increase across four trials amounting to over a tonne per hectare with an average reduction in 50 per cent of fertiliser use.[17]

16 And Dent, D., personal communication.

17 Dent, D., personal communication.

These numbers are huge. If rice, wheat and maize were to experience a 30 per cent increase in yield, with lower costs to farmers and less pollution, there would be dramatic economic and ecological impacts in the form of price falls and land sparing.

N-fix seed dressing will enter grower trials with maize farmers in the US in 2019. It requires no regulatory approval, being a food-grade bacterium found all over the world, but Azotic is seeking Canadian registration, this being the most stringent.

As Dent and Cocking (ibid.) argue:

> Creating new strains of rice, wheat and corn that fix their own nitrogen could achieve in the twenty-first century what the Haber-Bosch breakthrough managed for the twentieth and without the serious environmental drawbacks of industrial ammonia production. Environmentalists should not be scared of this prospect; they should welcome it.

Precision farming and robotics

Modern farm machinery is changing rapidly thanks to the increasing adoption of smart technology. Already it is routine for tractors and combine harvesters to use GPS and satellite guidance to minimise wasted travel within fields, reducing overlap or missing of parts of the crop.

GPS control of combine harvester travel has been estimated to reduce fuel usage by ten per cent. Likewise, the ability to program a sprayer to deliberately turn off, by GPS guidance, when over a certain patch of a field that is dedicated, for example, to habitat for skylarks or lapwings, is already in use.

Slightly more futuristic, but also already occurring in some places, is the use of data derived from mapping with satellites or drones to determine the crop density, plant health, weed density and fertiliser need on a detailed scale, allowing the farmer to decrease or increase applications automatically. This approach is already bringing both cost savings and environmental benefits to farms, albeit mostly at the early-adopter stage.

For example, variable-rate nitrogen application in maize, using normalised difference vegetation index (NDVI) data from a drone, applied by a vehicle steering itself, with row feelers and boom height working from sonar sensors, is actually happening on farms in North America and other places in 2018.

This sort of innovation represents a potential competitive advantage for early adopting countries that adapt their regulations to suit the use of drones and autonomous tractors.

In Europe, the Netherlands has a concentration of this kind of technology, but Britain is well placed thanks to the work of universities such as Harper Adams, a world-renowned robotic pioneer.

Britain also has start-up firms such as Hummingbird Technologies, a company spun out of Imperial College that uses field mapping data to provide services to farmers, and Small Robot Company, in Shropshire, which begins offering digitised robotic services to farmers in commercial trials in 2018. High-tech farming companies such as G's lettuce growers are early adopters of automation.

Most experts believe that within ten years, at least in certain crops, robot tractors, operating autonomously, will be able to plant, manage and harvest crops without drivers in the cab. The Hands-Free Hectare at Harper Adams, grown and harvested in 2017 without human beings present at any stage, is an early demonstration of this possibility.

At the moment such experiments are prohibitively expensive, but once robot tractors are reliable and can be mass-produced there could be significant cost savings. They could operate for longer spells of time each day, for example, including working at night.

Crucially, without the need to carry people and spread those people's wages across one large machine, they could be small, numerous and lightweight, operating in platoons. Lightweight machines cause less soil compaction, resulting in much lower fuel costs in cultivation to break up soil pans.

A key component in this rural robotic revolution is computer vision, which allows detailed pattern recognition software, aided by deep learning algorithms, to be used in robotic agriculture. Robots can already identify common weeds and spot-spray them, rather than spreading herbicide indiscriminately. In the future they might use mechanical weeding or lasers to kill weeds identified in this way.

Whichever of these options becomes most successful, the days of blanket spraying or blanket cultivation just to control patches of weeds may soon be at an end.

Computer vision systems can also identify healthy plants and treat sick plants with fungicide at just the right stage of development. This could enable better disease control through more timely spraying, but it could also help farmers to hold back from spraying when and where it is not necessary, reducing the amount of chemical deployed.

Robots could also pick ripe fruit, an especially laborious task dependent on seasonal labour mostly from Eastern Europe. Reliance on cheap labour from overseas is not sustainable both economically and politically in post-Brexit Britain. In any case, there is little doubt that if the UK does not develop this automated fruit-picking capability, other countries will, and competition will be at our expense.

Taken together these precision-agriculture/robotics changes could be as big as the replacement of the horse by the tractor. A high-wage economy such as the UK should be at the forefront of it. Paradoxically, one of the things holding it back here, according to farming technology experts we spoke to, is the unreliability of broadband and data in the countryside.

Other innovations and trends in farming practice

No-till farming

The growing use of no-till, or minimum-till, farming does, under certain circumstances, allow improved economic and ecological outcomes. No-till means sowing crops directly into unploughed ground.

The prime purpose of ploughing is to bury weeds and provide a bare seedbed into which to sow a crop. In wetter conditions it also helps to break up the ground and create the tilth ideal for seed germination.

The advent of modern machinery, such as discs, and of modern chemicals such as the broad-spectrum herbicide glyphosate, has allowed farmers to dispense with ploughing and move to no-till farming in certain conditions and soil types. This generally improves soil structure and increases biodiversity in and on the soil, including worm numbers.

It also makes soil more free-draining in wet conditions and more moisture-retaining in dry conditions. It reduces soil erosion and run-off into water courses. It reduces carbon dioxide emissions and cuts bills for tractor fuel. On the negative side it tends to produce greater problems with slugs and some fungal pests.

However, in the context of innovation it is worth noting that no-till farming in the UK is the very antithesis of organic farming, which relies heavily on frequent tillage to control weeds without weed killers. No-till is almost wholly dependent on glyphosate (Roundup) herbicide, a cheap and effective weedkiller that is also remarkably safe and non-toxic compared with other farm chemicals.

Campaigners against glyphosate have highlighted its presence in certain foods, but dose for dose, coffee is more carcinogenic than glyphosate. Ben & Jerry's ice cream was recently found to contain glyphosate at a concentration of up to 1.23 parts per billion.[18] At that concentration a person would have to consume more than three tonnes of ice cream a day to reach the level at which any health effect could be measured.

There is a growing campaign to have glyphosate banned. However, this is based solely on a flawed report prepared for the International Agency for Research on Cancer (IARC) with the help of an activist paid by a law firm, and in which (according to *Reuters*) 'in each case, a negative conclusion about glyphosate leading to tumours was either deleted or replaced with a neutral or positive one'.[19]

The IARC report contradicts the findings of the European Food Safety Authority (EFSA) as well the equivalent agencies in America and Australia. On behalf of the EFSA, the German Federal Institute for Risk Assessment looked at more than 3,000 studies and found no evidence of any risk to human beings at realistic doses.[20]

The consensus remains that glyphosate has major environmental advantages and is not harmful to human health if used properly.

Brazil adopted no-till farming on a huge scale following the licensing of herbicide-tolerant soybeans in 2003.[21]

Incidentally, according to DEFRA's Organic Farming Statistics 2016, organic farming is currently in decline. The percentage of land farmed organically in the UK continues to decline and is now 2.9 per cent, down from over 4 per cent in 2008.

18 Letter to *The Guardian* from Sarah Mukherjee of the Crop Protection Association, 11 October 2017. https://cropprotection.org.uk/newsroom/2017/letter-to-the-guardian-glyphosate-in-ben-and-jerrys/

19 'In glyphosate review, WHO cancer agency edited out "non-carcinogenic" findings', *Reuters*, 19 October 2017. https://www.reuters.com/investigates/special-report/who-iarc-glyphosate/

20 'Conclusion on the peer review of the pesticide risk assessment of the active substance glyphosate'. European Food Safety Authority, 12 November 2015. https://efsa.onlinelibrary.wiley.com/doi/abs/10.2903/j.efsa.2015.4302

21 'How a Genetically Modified Soybean Helped Modernize an Economy', *Kellogg Insight*, 4 June 2018. https://insight.kellogg.northwestern.edu/araticle/agricultural-productivity-and-industrialization-in-brazil

Crops for wildlife

Setting land aside from cultivation is not necessarily the best way of providing for biodiversity. But rather than growing weedy and low-yielding crops, it can be more effective to plant crops specifically designed to attract birds, bees, butterflies and weeds.

The shooting industry has long recognised the need to plant ‘game crops’ that retain seed throughout the winter to support finches and buntings as well as game birds and is responsible for much of the food available to seed-eating birds in winter.

Many farmers are now experimenting with strips of land around fields devoted to unharvested cereals and flower crops to support birds and insects in summer as well as winter. Detailed research, especially at the Game and Wildlife Conservation Trust’s Allerton Project farm at Loddington in Leicestershire, is resulting in innovative combinations of wildlife crops, such as sweet fennel and perennial rye. Selecting, breeding or genetically modifying varieties that do not shatter, and so hold their seeds longer into the ‘hungry period’ of early spring is a particular focus (Stoate et al. 2017).

In other words, biotechnology and precision farming can contribute to the management of crops for wildlife as well as for human beings.

Indoor farming

There is increasing interest around the world in indoor, ‘vertical’ farming, in which plants are grown in stacks of hydroponic trays under pink LED lights. The reduced heat output and energy use of LED lighting has made this technology feasible.

In Japan, some salad factories are now producing 30,000 lettuce heads a day by this means. They use some 0.3 per cent of the land that would be needed to grow such lettuces outside (i.e. one acre compared with 300 acres), and they also use less water and fertiliser because of recycling, and no pesticides at all, because the factory is a sterile environment. In energy terms, the increased use of electricity for lighting can be roughly balanced by the lower fuel use for cultivation and transport.[22]

22 ‘World First: Robot-Run Farm To Harvest 30,000 Heads of Lettuce Daily’, *Futurism*, 28 January 2016. https://futurism.com/world-first-robot-run-farm-harvest-30000-heads-lettuce-daily/

For example, tomatoes grown outdoors in a Mediterranean climate use about 60 litres of water per kilogram; in a Dutch greenhouse the figure drops to 17 litres; in an indoor farm to less than five litres (Nederhoff and Stanghellini 2010).

This technology will undoubtedly come to the UK and offers significant benefits for the environment in terms of land sparing, plus a reduction in reliance on imports and chemicals. However, it can only work for fast-growing, high value crops such as salads and herbs, at least at this stage. These occupy relatively small areas of land, so the technology is not likely to be significant in terms of agriculture as a whole over the next decade or two.

Fish, invertebrates and other animals

In the search for efficient means of growing protein, there is likely to be increasing space for the farming of fish (salmon, tilapia), insects (such as black soldier fly), crustaceans (shrimp, crayfish) and molluscs (mussels, oysters), all of which being cold-blooded can convert plants more efficiently into flesh than chickens or pigs.

Finding and formulating plant-based diets for these animals could be a significant innovation, probably requiring lysine-enriched varieties. However, it is unlikely that these will have much effect on land-based agriculture in the UK, or that a new species domestication will come along to transform farming on the scale of the domestication of the cow, sheep or chicken, for example.

The same is true of arable crops. New varieties of wheat, rape, potatoes, beans and barley are more likely to be important than new crops currently unknown in the UK.

Artificial meat and cheese

Experiments to synthesise meat that rivals steak in taste and texture, using stem cells from animals, have been remarkably successful in technical terms, but are a long way from commercial viability.

Meat and dairy substitutes made from plants are a different matter and may well present a commercial challenge to Britain's abundant grass-fed livestock in the coming decades. The Impossible Burger, made in Silicon Valley from ‘a combination of proteins, fats, amino acids and vitamins derived from wheat, the roots of soybean plants, coconuts, potatoes and other plant sources’ is one such example. Another is the growing prevalence of plant milks, made from soya, coconut, rice, macadamia nuts or almonds, as an alternative to cow’s milk.[23]

Conservation management

Most innovation in land management is focused on crops. However, an increasing number of land managers are in the business of managing wild habitats, whether as part of in-farm conservation practices or in terms of land management in nature reserves and semi-wild ecosystems.

This includes the planting of bird and pollinator habitats on farms, bracken control in the uplands, the restoration of blanket bog on heather moorland, the reintroduction of species, and the control of invasive species such as Himalayan balsam, signal crayfish or grey squirrels.

These practices can be improved and transformed by intelligent innovation. For example, techniques of biological control of invasive species have improved dramatically in recent decades.

The identification of pathogens or predators that specifically control alien species in their native habitat, and the introduction of such species to control the aliens when they become invasive elsewhere has in the past led to mistakes that did more harm than good: the introduction of stoats to control rabbits in New Zealand and cane toads to control beetles in Australia both proved disastrous for native fauna.

Since then scientists have been much more careful to select and test any biological control organism to be sure it will not harm native species and will control a non-native one. Successful examples of such introductions include the use of prickly pear moth *Cactoblastis* to control alien cacti in Australia. As one review argued recently (Seastedt 2014):

> The science of finding, testing and releasing herbivores and pathogens to control invasive plant species has achieved a level of maturity and success that argues for continued and expanded use of this program.

23 See, for example: https://impossiblefoods.com

For example in the UK, the Centre for Agriculture and Biosciences International (CABI) is experimenting with psyllids for controlling Japanese knotweed, weevils for water fern and floating pennywort, rust fungus for Himalayan balsam and flies for swamp stonecrop. In each case, the control agent is tested for host specificity to ensure it will not attack native flora before release (CABI 2013).

Other initiatives to control invasive species may involve biotechnology. For example, Giovanna Massei of the National Wildlife Management Group in York is working on the adaptation of hormones delivered through pollen to control fertility in species such as grey squirrel. The aim is to find a way of feeding one species of squirrel in the wild with a hormone that suppresses fertility. This approach could be very useful not only with invasive alien species but with problematic native species, for example, when high badger densities threaten native hedgehog populations.

In short, innovation is needed in the management of wild habitats and species as well as farmed ones.

How key UK crops can be transformed by innovation

Wheat

Wheat is the world's oldest major agricultural crop and is still the world's most widely grown domesticated plant, occupying more hectares than any other crop and supplying roughly 20 per cent of all human calories directly or indirectly. It is also Britain's dominant arable crop by a large margin.

In competition with New Zealand, Britain frequently holds the world record for wheat yield per hectare, reflecting the long days in June and the natural soil moisture that is ideal for wheat plants. In 2015, Northumberland farmer Rod Smith achieved over 16 tonnes per hectare, twice the British average, in one field at Beale. Some parts of the field achieved over 23 tonnes per hectare.[24]

However, average British wheat yields per hectare, having quadrupled in the period 1945-1990, have since remained fairly steady, and wheat missed out on the first pulse of transgenic genetic modification. This partly reflects the immensely complex, hexaploid genome of wheat, whose analysis and study is considerably harder than that of maize. Wheat's genome has been considered the 'Mount Everest' of genome sequencing, with six

24 'Northumberland grower breaks world wheat yield record', *Farmers' Weekly*, 21 September 2015. http://www.fwi.co.uk/arable/northumberland-grower-breaks-world-wheat-yield-record/

copies of each chromosome, a total size five times larger than the human genome and many copies of genes and sequences.[25]

There is, though, no reason to think that wheat will remain in the slow lane of yield change over the coming years. Even at 8 tonnes per hectare, a very small percentage (about 1 per cent) of sunlight is converted to grain. This compares with maize's 4 per cent efficiency. Sugarcane (where the leaves are harvested, rather than the seeds) achieves 8 per cent efficiency.[26] For example, the International Wheat Yield Partnership is currently researching 'How can wheat yield be improved?'[27]

The slow pace of research on wheat also reflects the European rejection of, and subsequent over-regulation of, genetic modification around the turn of the century, which resulted in the cessation of much wheat transgenic research.

This picture is now changing thanks to the completion of the sequencing of the wheat genome in 2017 (with a fully annotated version completed in August 2018), and the advent of doubled-haploid breeding in wheat.

In addition, the development of a new 'speed breeding' protocol is likely to transform the rate at which new varieties can be developed and tested, either with new genetic techniques or with more traditional plant breeding.

Speed breeding, under carefully controlled artificial lighting conditions, can allow up to six generations of wheat to be grown in a year, providing a dramatically faster route from laboratory to market. Where it formerly took five months to go from seed to seed in wheat research, this can now be done in eight weeks or even less. Combined with genome editing, using CRISPR-Cas9 and other technologies, this means that it is now possible to produce and test new varieties of wheat rapidly and cheaply (Watson et al. 2018; IWGSC 2018).

25 'Small group scoops international effort to sequence huge wheat genome', *Nature*, 31 October 2017. https://www.nature.com/news/small-group-scoops-international-effort-to-sequence-huge-wheat-genome-1.22924

26 https://en.wikipedia.org/wiki/Photosynthetic_efficiency

27 'Overview: How Can Wheat Yield Be Improved?', International Wheat Yield Partnership. http://iwyp.org/research-program-overview

A review of wheat genomic research, concentrated in China and the United States, said that ‘we expect the leap in wheat transformation efficiency will lead to a functional genomics research era in wheat’ (Wang et al. 2018).

This presents the UK with both a threat and an opportunity. The threat is that other wheat-growing countries will use these techniques to adopt new varieties that have higher yields, better disease and pest resistance, or superior nutrient content, produced at lower cost, putting British farmers at a disadvantage and exerting downward pressure on world prices.

Researchers in the UK report that Chinese and US researchers are pressing ahead with similar work and that Britain cannot afford to get left behind. For example, in the United States, Calyxt has already developed two new, non-transgenic wheat varieties by gene editing to knock out particular genes. The first variety is resistant to powdery mildew, the second is high in fibre content (Perkowski 2018).

The opportunity for the UK is that as a country with proven ability to grow very heavy wheat crops, and several leading wheat research laboratories, Britain could lead this revolution and improve farm incomes while delivering environmental benefits such as lower reliance on fungicides and insecticides.

For example, thanks to speed breeding and new genomics, researchers at the John Innes Centre in Norwich are able to go back to wild relatives of wheat and find genes for resistance to pests that can be introduced more rapidly and cheaply than before. They have already identified and cloned five fungus-resistance genes and one insect-resistance gene. These breakthroughs could reduce dependence on chemicals, or at least prolong the use of existing ones by slowing the emergence of resistance.

These efforts are part of the UK’s Designing Future Wheat programme which brings together researchers at Rothamsted, the John Innes Centre in Norwich, Nottingham University and other centres.

It was initiated in 2017 to exploit the reading of the wheat genome in the British context to generate new varieties that resist pathogens, and optimise plant development and grains per plant.

Particular emphasis on harvesting the rich genetic diversity found in wild 'landraces' of wheat is already paying dividends. The first positive signs of landrace alleles bringing agronomic advantage were seen in 2016 and 2017.[28]

Potatoes

Potatoes are an important British crop, with 4.7 million tonnes produced annually from 103,000 hectares in 2017 in Great Britain (not including Northern Ireland).

Potatoes have only recently been genetically modified in the United States. The first two varieties of white Russet Birbank potato were released by Simplot in 2017, with resistance to browning and reduced asparagine content (meaning they contain less potentially harmful acrylamide when fried).

However, Simplot has since received approval for the release of potato varieties that are resistant to late blight, *Phytophthora infestans*, the fungus responsible for the Irish potato famine and a persistent enemy for potato farmers, many of whom have to spray their crops on an almost weekly basis, or up to 15 times in a growing season. Organic farmers use copper-based compounds to control blight (though there are few organic potato growers in the UK because of the difficulty of controlling blight), while conventional farmers use synthetic fungicides. Both are toxic to human beings at sufficiently high doses.

It has been estimated that potato farmers in Europe spend almost £400 a hectare spraying for blight, and that they could save £60 million in total if all sprayings were to cease. These savings could be largely passed on to consumers. So the prize of a fungus-resistant variety is great.[29]

Moreover, the potato market is fragmented, globally, with different varieties dominating in different countries. The white Russet Birbank dominates in the USA, yellower varieties in Europe and Maris Piper dominates in only the UK. This 'balkanization' partly reflects agronomic conditions but is also

28 'DFW Breeders Toolkit: Arming the Commercial Breeding Industry with Novel Alleles for the Future', John Innes Centre, 30 November 2017. http://www.wgin.org.uk/information/documents/Stakeholders%20Meetings/SM_30Nov2017/8%20OrfordWGIN-Nov2017final.pdf

29 'Genetically modified potatoes "resist late blight"'. *BBC News*, 17 February 2014. https://www.bbc.co.uk/news/science-environment-26189722

entrenched because of the sunk costs of the firms processing potatoes, which are reluctant to switch to lesser known varieties with different properties.

For the UK to get the advantage of blight-resistant potatoes, it will have to develop its own. It is hard to cross-breed different potato varieties using traditional methods, partly because of their tetraploid genetics and non-selfing habits.

Recent trials of two new disease-resistant varieties of potato in the UK, Netherlands and Ireland, published in May 2018, have shown an astonishing 80-90 per cent reduction in average fungicide applications, without compromising yield. One of these new varieties was produced using conventional breeding. The other used 'cisgenesis', in which genes were transferred, not between species but within species from wild races of the potato plant. This would have taken 40 generations with traditional breeding. Further developments include the switching off (or silencing) of genes to achieve less bruising damage (Kessel et al. 2018).

It is therefore inevitable and welcome that potatoes will soon be grown around the world with much greater resistance to disease, and much less need for fungicide use.[30]

However, to take full advantage of this potato revolution Britain will have to license various forms of non-transgenic genetic modification much more rapidly and simply than is possible at present, including cisgenesis, RNA interference and probably gene editing. Without this, Britain will steadily lose market share to more competitive countries.[31]

30 'Research shows GM potato variety combined with new management techniques can cut fungicide use by up to 90%', *Irish Independent*, 15 May 2018. https://www.independent.ie/business/farming/tillage/research-shows-gm-potato-variety-combined-with-new-management-techniques-can-cut-fungicide-use-by-up-to-90-36909019.html

31 Early success for blight-resistant GM potato trial, *Farmers' Weekly*, 7 November 2017. https://www.fwi.co.uk/arable/potatoes/early-success-blight-resistant-gm-potato-trial

Legumes

Global agriculture tends to produce a surplus of carbohydrate but a dearth of protein. High-protein crops, such as legumes (peas, beans, lentils and other pulses), attract premium prices and are a crucial sector for human food but also for feeding animals.

Britain and Europe are heavily dependent on imported legumes. Globally, 14.5 per cent of arable land is devoted to growing legumes, but in Europe it is only 1.5 per cent. Europe imports 70 per cent of its protein feed, of which 87 per cent of soybean (Watson et al. 2017). The European Union imports the equivalent of its entire population's body weight in soya beans each year.[32]

A generation ago, Britain bred most of the protein-rich peas and beans used in domestic animal feed. Today most of that feed is imported, in the form of genetically modified soybeans, from North and South America.

Legume cultivation in Europe declined from 5.8m hectares in 1961 to 1.8m hectares in 2013. Zanderet al. (2016) suggest that 'an increase in legume cultivation in Europe will help to reduce the European plant protein deficit and could contribute to more environmentally and economically sustainable production patterns'.

A generation ago, British pea or faba bean growers could compete with US or South American soybean growers on world markets; today they often cannot. This is largely because of the genetic modification of soybeans throughout the Americas to resist insects and herbicides, which allows them to be grown with cheaper pest and weed control and higher yields. Legumes are an illustration of how Europe has lost out, both economically and ecologically, by turning its back on genetic modification.

Given that legumes fix nitrogen and thus reduce the need for synthetic fertiliser in succeeding wheat crops, the development of competitive legume varieties for British conditions would have added advantages for soil fertility and biodiversity as well as cost.

32 'The Green G-Nome's Guide to GM Crops & Policies in the EU', *Issuu*, 22 March 2017. https://issuu.com/europabio/docs/pdf_test_pr/24

Pigs

Pigs have been the first farm animals to benefit from gene editing. For example, scientists at the Roslin Institute, near Edinburgh, have edited the genomes of pigs, rendering them immune to a dangerous virus, porcine reproductive and respiratory syndrome. Using CRISPR-Cas9, the Roslin scientists sliced out a short section from this gene in the fertilised egg of a pig. They then grew pigs from these eggs that turned out healthy and entirely normal in every way, including the functioning of the gene, but which denied the virus entry to the cell.

Chickens

Some 70 billion chickens are born and die each year (62 billion broilers, 7 billion layers), making *Gallus gallus* the most numerous bird in the world and the fastest growing source of meat for human consumption. However, relatively few lines of birds are used in most of the broiler industry, leaving the genetic stock impoverished compared with the red junglefowl species as a whole, and rendering the industry vulnerable to disease epidemics.

Genome editing of chickens is now becoming a realistic possibility, thanks to the development of primordial germ cell (PGC) cultures, a technique pioneered partly at the Roslin Institute in Edinburgh. PGCs are cells within embryos that will form the gonads, and which can be extracted and grown in culture while retaining their determinism as reproductive cells. They can then be reintroduced as implants following genetic manipulation.

PGCs promise to open up the possibility of altering DNA sequences, using genome editing and other tools, to incorporate genes from the wider gene pool of chickens around the world, for disease resistance and similar traits, without reducing the food-conversion efficiency of modern breeds (Woodcock 2017).

The UK is a key part of the broiler industry and has world-leading research laboratories. It could play a leading role in developing new disease-resistant varieties of fowl. In addition, food-conversion efficiency gains will continue to contribute to sustainable intensification by reducing the land area needed to produce a given quantity of food – in this case meat.

Bioenergy has significant environmental problems

Significant areas of land in the UK are used for bioenergy. These include firewood and wood pellets from forests; ethanol from wheat; diesel from rape; anaerobic digestion from maize; and short-rotation coppice such as willow and miscanthus grass.

This is a return to the medieval habit of using the landscape to produce energy. During the Middle Ages, plants provided almost all fuel, either as firewood or as fodder for horses or oxen – or indeed as food for human beings. Wind and water were also significant energy sources but less important. Wrigley (2010) calculates that coal overtook firewood as a source of energy in Britain between 1600 and 1650. By 1700-1709 coal accounted for 50 per cent of British energy, in spite of significant growth in every other fuel. Coal was mined from underground, effectively freeing up land for food-agriculture or nature. Britain's forests and woodlands, almost gone by the end of the nineteenth century, were gradually replenished during the twentieth century. Today, after centuries of extracting fossil fuels from underground and replanting trees, there is about twice as much woodland in England as there was in 1900, and about as much as in 1300 (Government Forestry Policy Statement 2013).

However, in recent years, there has been a policy to reverse the trend of taking energy from holes in the ground and towards, once again, using land to grow it instead. In 2009, the EU introduced the Renewable Energy Directive to meet internationally-agreed targets for carbon dioxide emissions. Under the directive, all member states must use increasing amounts of renewable energy so that a collective target of 20 per cent is reached by 2020. The UK's contribution is set at 15 per cent of final energy consumption. Because the 'renewable' category is often not broken down in statistics, it is not generally appreciated that the EU, and particularly the UK, has moved towards this target largely by expanding the burning of biomass, and wood in particular.

Today the UK is burning more wood than coal for the first time in four centuries: 5 per cent of UK energy came from coal in 2017 compared with 6.4 per cent from ‘biomass’ (mostly wood) (BEIS 2018). The rationale for this policy is that while bioenergy may contribute to habitat loss as well as land and biodiversity degradation, it is essential to mitigate the greater evil of higher carbon emissions. Actually, the evidence suggests it exacerbates that problem as well.

In terms of land, wood is a low-density fuel. The late Sir David MacKay, former chief scientist at the UK Department for Energy and Climate Change, calculated that temperate forests can produce firewood at a rate of up to roughly 0.5 watts per square metre (MacKay 2009). A firewood system therefore requires a lot of land. MacKay estimated that the British population consumes around 1.25 watts of total energy per square metre of land. Thus it would take more than twice the entire area of the country to grow enough wood and biofuel to power the UK.

Can this density constraint be changed by innovation? While plant breeding and genetic engineering can improve crop yields, they generally do not do so by increasing photosynthetic efficiency but by redirecting growth to the useful parts of the plant, such as seeds or fruit. Woody bioenergy crops mostly use the whole plant so cannot benefit significantly from these innovations. In addition, trees are slow-growing organisms and improved varieties would take a long time to produce results.

Genetically improved plants, selected for their suitability as bioenergy crops, are under development in various parts of the world. These include low-lignin varieties of poplar trees, reduced cross-linkage between cellulose and lignin in the cell walls of various plants, and grasses with high levels of non-cellulosic glucans. There are advances in genomics, genetic modification and genome editing in bioenergy crops but so far with very few actual results, as a recent survey confirmed (Furtado et al. 2014). Even when better varieties of trees are developed, replacing forests with plantations of varieties more suited to combustion will take decades. It will also probably meet stiff opposition from those who prefer natural and diverse woodland to monocultural plantations.

So, in the present state of science, it is highly unlikely that the productivity of temperate forests could be doubled from 0.5 W/m2 to 1 W/m2. Even if that were to happen, it would still not be possible to meet the UK's energy needs from covering the entire country with plantations.

Since the introduction of the Renewable Energy Directive, the European Union has become the world's largest manufacturer of wood chip and pellets. In spite of this, the industry does not even meet half of the EU's own needs. According to Eurostat, between 2005 and 2015 the EU increased its wood imports by 270 per cent.[33] The biggest user of imported wood and pellets by far is the Drax power plant in North Yorkshire. It has been converting its turbines from coal to wood pellets and is now buying 6.5 million tonnes from EU and non-EU countries. That represents half of total EU wood pellet imports.

Environmental campaigners are increasingly concerned that carbon accounting methods are flawed when it comes to biomass, and that the real-world emissions of burning wood are even greater than those of most, if not all, fossil fuels. As Sterman et al. (2018) recently argued:

> A molecule of CO_2 emitted today has the same impact on radiative forcing whether it comes from coal or biomass. Biofuels can only reduce atmospheric CO_2 over time through post-harvest increases in net primary production (NPP)… Because combustion and processing efficiencies for wood are less than coal, the immediate impact of substituting wood for coal is an increase in atmospheric CO_2 relative to coal. The payback time for this carbon debt ranges from 44–104 years after clearcut, depending on forest type – assuming the land remains forest … Projected growth in wood harvest for bioenergy would increase atmospheric CO_2 for at least a century because new carbon debt continuously exceeds NPP.

Without biomass the EU cannot hope to meet its renewables targets and so it has adopted the Intergovernmental Panel on Climate Change's ruling that biomass is carbon-neutral. This claim can only be supported by omitting emissions when the wood chips or pellets are burned and the emissions in harvesting, transporting and processing wood. The justification for these omissions is that a tree will grow in place of every tree felled.

33 'Wood as a source of energy', *Eurostat*. https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Wood_as_a_source_of_energy

However, that will take decades and the replacement tree will then also be felled if the tag ‘renewable’ is to have any meaning. The emissions are up-front, while the carbon capture is perpetually postponed.

Buchholz and Gunn (2017) estimated that actual stack emissions (the greenhouse gases released when wood is burned) from biomass were more or less the same as coal. But when whole life-cycle emissions – harvesting, processing and transport – are included, then the figures go very much against biomass:

	kgCO2e/MWh	
COAL	1,018	
BIOMASS	2,677	over 40 years
	3,478	over 100 years

According to Dr Anna Stephenson and Sir David Mackay (2014), emissions from using biomass to generate electricity could be as high as 5174kgCO2e/MWh when analysed over a 100-year period. This is over five times as high as coal. In contrast, using the methodology under the EU’s Renewable Energy Directive which does not include emissions at the point of combustion for biomass, the bioenergy industry can claim that its emissions are as low as 200kgCO2e/MWh.

In the case of transport fuels, in the UK bio-energy means diesel from rape and ethanol from wheat. For example, the Ensus plant at Yarm on Teesside consumes a million tonnes of wheat a year to produce ethanol, as well as high-protein cattle feed. The problem with liquid biofuels, as with wood, is that there is not enough land to grow them on in sufficient quantity to make a difference. Sir David MacKay in his 2012 Ted talk illustrated the density problem by calculating that if you were to grow the biofuels for use on a busy single-lane road with cars 80 metres apart travelling at 60 mph, by planting crops alongside the road, then the strip of crops would need to be five miles wide.[34] This is impractical. Furthermore, innovation is unlikely to alter the low density of biofuel energy derived from crops.

34 ‘A reality check on renewables’, *TedXWarwick*, March 2012. https://www.ted.com/talks/david_mackay_a_reality_check_on_renewables?language=en

Some farmers have responded to incentives to install anaerobic digesters (AD) to produce methane from plant material by fermentation. Contrary to what many people think, these are not fuelled mostly by waste, but by crops grown especially for them, usually maize. The result has been an increase in maize cultivation in some parts of the UK.

Anaerobic digesters are common in Germany where more than 9,000 plants had been installed by 2016. These turn crops such as maize or turnips, with a small input from manure, into a mixture of about half carbon dioxide and methane using bacterial fermentation. Miersch (2017) says that energy crops, overwhelmingly maize, are using 2.5 million hectares of land in Germany, an area the size of Sicily.

As with other biomass sources of energy, the true life-cycle carbon cost is not taken into account. Subsidies for AD plants are around 22 cents per kilowatt-hour, almost double the price of electricity, while the reliability of the fermentation process can be poor and difficult to manage. As *The Times* commented in August 2018:

> They were sold as EU-subsidised miracle machines that could convert waste into gas to heat homes, but a string of insolvencies has left lenders and investors questioning the wisdom of anaerobic digestion plants.

In addition to chemical inputs such as fertilisers and pesticides, the growing of large areas of maize leaves ground bare in winter, leading to loss of soil into water courses and nutrient-rich run-off. Digestate leaking from plants has also caused pollution problems.

According to *Clean Energy Wire* (Appunn 2016):

> The most challenging argument against bioenergy in Germany has been the 'maizification' of the landscape. In some parts of the country, there has been strong opposition to increasing cultivation of forage maize as an energy crop for biogas plants … More use of maize has also led to increases in land prices and energy crops encroaching on biodiverse grasslands.

Anaerobic digestion is an innovation with significant environmental problems and a high dependence on subsidy.

Overall, by phasing out subsidies for bio-energy, the UK would see lower greenhouse gas emissions, more land available for food and fodder and greater land sparing for biodiversity conservation.

Conclusions and recommendations

To date, innovation in farming at a global scale has led to higher crop yields which, in turn, have allowed more land to be spared from farming than would otherwise have been the case.

But unless we can embrace biotechnology, genetic modification, gene silencing and editing as well as encouraging developments in precision farming and robotics, then those higher yields, needed for our growing global population, are limited.

Conversely, if the UK, post-Brexit, looked afresh at available technologies and innovations in which Britain already leads the world, then British farmers and consumers, as early adopters, would reap the economic and environmental benefits. These include:

- Better returns on investment
- Lower reliance on subsidy
- Greater ability to compete in world markets
- Lower reliance on chemicals
- Lower use of tillage
- Land sparing for nature
- Growth in R&D
- Job opportunities

Britain should be at the forefront of encouraging innovation in agriculture for environmental as well as economic reasons. As with biotechnology, if we don’t do it, others will.

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Part 2

A new countryside: restoration of biodiversity in the UK[35]

David Hill

35 For a more detailed version of this paper, please see: http://www.environmentbank.com/library.php

Introduction

The two key difficulties that conservation has faced ever since it became 'institutionalised' through the establishment of organisations dedicated to it over a hundred years ago, are access to land and access to finance. Only by resolving these at scale will effective biodiversity conservation be delivered in the UK in the coming decades.

Whilst many farmers and landowners already deliver some conservation on their land, mechanisms to facilitate greater and larger-scale participation by them will be paramount to restoring our biodiversity.

Despite the relatively large membership of voluntary conservation bodies in the UK, we have not valued nature sufficiently to avoid substantial losses in the abundance of species caused by competing land uses. The majority of the losses have been caused by the agricultural sector and habitat specialists have been lost at the expense of generalists such as crows and foxes that have benefitted from man's activities.

The easiest restorative measure, purely from a conservation viewpoint, would be to turn back the clock to a period before 1945, encouraging weedier, spring-sown crops undersown with grasses and legumes, lower cropping density, more hedges and smaller fields, more farm ponds, and mixed farming providing manures to fertilise crop growth.

Given the current parlous state of UK farming economics, in which the average farm is only just viable because of subsidy payments (Defra 2017), one might argue that this could be a sensible option if the above were to be recognised as public goods and paid for through environmental land management contracts rather than subsidy. Indeed some farmers, particularly in the uplands, may decide to pursue a 'managed rewilded' system where stock are used as the tools to deliver landscape and nature conservation (which would be paid for through contracts not subsidy) rather than being the end product in themselves.

The key obstacle to achieving this is that we couldn't provide enough food to feed the population. However, we should certainly modify many farming practices into far more sustainable systems, as advocated by the work of the Sustainable Food Trust, using agroecological processes such as nutrient cycling, biological nitrogen fixation, allelopathy, predation and parasitism, protecting and enriching soils and soil structure, mixed cropping, crop and grass rotations and a substantial reduction in chemical use. Although more land would be needed to produce the same amount of food, such systems result in an integration of biodiversity within the farmed environment and, if delivered at scale, would make a major impact on restoring biodiversity on farmland.

If, on the other hand, future farming embraces technology to improve efficiencies and increase yields from a unit of land area, we need to ensure it does so in such a way that nature and biodiversity are mainstreamed as part of an holistic approach to land use and not seen as an unvalued 'nice to have'.

Perhaps the biggest 'threat' from technology is that it could lead to more land intensification, producing food for cash, squeezing biodiversity out. To avoid this, some form of regulation may need to be put in place.

The technological advances in farming techniques described in the first chapter, alongside the Sustainable Food Trust model (see also Sustainable Food Trust 2017), would:

- Provision habitat 'within' the farmed landscape providing food and cover for the full range of wildlife groups at appropriate times of year (land sharing).
- Facilitate land to be dedicated to other uses such as those connected to the protection, enhancement and management of natural capital such as biodiversity and ecosystem services, at scale (land sparing).

This paper suggests ways in which both land sparing and land sharing can be incentivised to benefit wildlife and natural capital without excessive cost to the taxpayer.

Whilst we can identify the type and scale of opportunities for biodiversity and the countryside, novel approaches to financing the capitalisation and long-term management of this land alongside food production and energy provision will be required which go far beyond the traditional system of grant aid that has supported biodiversity conservation over the past 60 years.

A range of funding mechanisms is outlined which, together, would deliver the ‘Restoration Economy’ whereby within-farm and within-region habitat and landscape-scale restoration interventions deliver economic benefits to a new set of skilled labour in the rural environment where job prospects are currently challenging.

Later in the paper I will detail the extensive problems of habitat and biodiversity loss in the countryside but first I wish to present some innovative solutions that together would comprise the ‘Restoration Economy’ (see Box 2). I shall then outline the state of biodiversity in the UK, biodiversity conservation policy, the need for agriculture to improve its environmental performance, the concepts of land sparing and land sharing, the finances around restoring biodiversity in the UK, interventions for biodiversity in the farmed landscape, and investment mechanisms and vehicles.

Box 2: Mechanisms to lever significant investment into the natural environment – the basis for a 'Restoration Economy'

Vehicle type	Mechanism	Requirement
Environmental land management contracts	Conversion of Pillar 1 CAP funds (c. £3.2 billon per annum) in addition to existing c. £400 million agri-environment payments (Pillar 2) into environmental land management contracts. Farmers would be paid to deliver environmental goods and services (or bid for contracts through reverse auctions), for example by creating and managing long-term wildlife habitat at scale.	Spatially literate, locally relevant, contract based on public payments for public goods/payment by results. 25-year contracts.
Habitat banks	Habitat offsetting whereby individual bespoke offset sites or large-scale habitat banks are established across the country, being spatially literate, and joined to existing areas of habitat, funded by the sale of Conservation Credits to developers in order that development delivers net gains in biodiversity (not just 'no net loss') as required by the NPPF and the 25-Year Environment Plan.	Net gain/biodiversity offsetting to be made mandatory – Local Planning Authorities to be required to process all developments; introduce an OfEnv randomised inspection system on LPAs. Much of the net gain would be provided off-site on farmland.

Vehicle type	Mechanism	Requirement
Environmental credits	Through corporate natural capital accounting in which corporates realise that effective reporting on and understanding of the role of ecosystems and biodiversity gives market advantage (i.e. a Biodiversity Disclosure Initiative). Corporates would 'offset' impacts through their supply chain by purchasing environmental credits with funds being invested in projects that rebuild and restore natural capital assets.	Roll out accounting metrics, create standard, accredit providers, include within the financial reporting mechanism for companies.
Green bonds	Government could create biodiversity bonds in order to capitalise interventions to create, enhance, restore and manage biodiversity in the countryside. Returns could be paid for through recycling Environmental Land Management contract funds using the successor to CAP payments.	Tax incentivisation to attract investors. Create bond(s), create standard, accredit providers.
Impact investments	Projects developed that both enhance and restore biodiversity in association with either land sparing as a result of technological advances in agriculture or land sharing through specific interventions to make farming truly sustainable. Returns on investments could be paid for through recycling Environmental Land Management contracts using the successor to CAP payments.	Tax incentivisation to attract investors. Create standard, accredit providers.

The State of Nature

There is a need for a transformational change in the way we farm and the way we use land if we are to make a serious impact on restoring biodiversity in the UK.

That we have lost so much natural and semi-natural habitat and species abundance in the UK, especially over the past 60 years, is, from an ethical and moral viewpoint, nothing short of catastrophic.

These losses are documented in State of Nature 2016 reports (Hayhow et al. 2016a-d) produced by a consortium of conservation NGOs for England, Wales, Scotland and Northern Ireland separately. The statistics of losses have been well publicised but are summarised for some key groups in Table 1.

Table 1: A brief summary of some of the documented losses to biodiversity[36]

Habitat/species	Loss	Period	Geographic relevance/scale
Lowland meadows	97%	1930's - 1984	UK
Lowland heathland	80%	Since 1800	UK
Coppice woodland	90%	1970 - 1900	UK
Vascular plant species	60%	2013 - 1970	UK
Butterfly species	62%	2013 - 1970	UK
Bird species	49%	2013 - 1970	UK
Farmland birds	56%	2016 - 1970	UK
Woodland birds	23%	2016 - 1970	UK
6168 Red List species	12% at risk of extinction		Britain
63 of 234 bird species	27% Red Listed		England
213 species across all taxa	39% decline in those species considered priority for action		UK
UK Priority Species Indicator	67% decline in abundance, 35% decline in occupancy	Since 1970	UK
Marine vertebrates	34% decline	Since 1970	UK
Marine invertebrates	75% decline	Since 1970	UK

36 For country specific details and for other taxa, see the State of Nature reports (Hayhow et al. 2016a-d) from which the above figures are sourced.

Habitat losses such as 97 per cent of meadows destroyed since World War II, 87 per cent decline in Corn Buntings, 95 per cent decline in Turtle Doves (though conditions on their Sahel wintering grounds and spring hunting have also impacted them (Balmer et al. 2013)) and 97 per cent decline in Tree Sparrows since the 1970s are indicators of a farming system operating in an utterly unsustainable manner (Figure 4). Then when we consider that farming products on average deliver net financial loss to farmers, one wonders why such a state and EU-funded system has been allowed to perpetuate for so long, causing so much damage to the natural environment.

Biodiversity loss is obviously not confined to the UK: the WWF-Zoological Society of London Living Planet Index published in 2016 shows that since 1970 we have lost half the 'big' animals on Earth (Lawton 2018). SOER (2015) provides substantive species and habitat trend data at a European level.

The two principal causes of the massive loss in land-based biodiversity have been:

- The industrialisation and intensification of farming since World War II (land clearance for crops and livestock removed habitats much earlier and created conditions where grassland birds and invertebrates, for example, thrived).
- Built development inclusive of infrastructure such as roads, rail, sea ports, residential and commercial property.

By land area, agriculture has caused by far the greatest losses (according to the annual Corine Land Cover Atlas); built development by contrast occupies c.6 per cent of the land surface of the UK – 9 per cent in England. The majority of the remaining biodiversity in England is now confined to the 30 per cent or so of the land area that is not dominated by arable farming, improved grassland or built development.

Many lowland areas of the UK have effectively become 'green concrete' as far as biodiversity is concerned. And whilst urban ecology has its place, I do not consider housing estates better for biodiversity than the wider countryside – it is how we are managing the countryside that has produced the impoverishment of wildlife there.

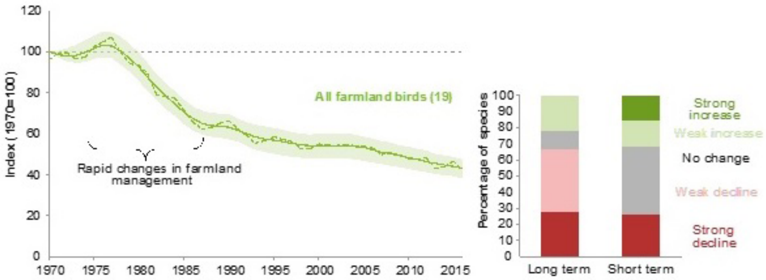
Specific actions to restore biodiversity have been, and continue to be, introduced to target removal of non-native species through reintroductions and translocations, by specific habitat management and restorative measures, and through combatting wildlife crime and unsustainable harvesting.

Some successes have been achieved, principally for single species or specific locations. These include recovery of seabird colonies as a result of predator eradication, water voles through mink removal, otters through river restoration, improvements in water quality and hence fish stocks, habitat restoration for wetland species such as bittern, habitat recreation for invertebrates, habitat measures within agri-environment schemes for Cirl Buntings and Stone Curlews, and reintroduction of Red Kite, White-tailed Eagle and European Beaver.

Ever since the early pioneers of conservation set out to protect areas for nature and the species that inhabit those places, some parts, but certainly not all, of society, have understood our ethical responsibilities to the species with which we share the planet. Many ’get’ the intrinsic value of nature. How we treat the natural environment says much about how we value ourselves. But ethics and intrinsic value alone will not protect existing, nor restore lost, biodiversity in the future.

Our ‘love’ of wildlife to date has not succeeded in averting massive biodiversity loss in the countryside.

Figure 4: Breeding farmland birds in the UK, 1970 to 2016[37]



37 From Hayhow et al. (2017).

Biodiversity conservation policy

Biodiversity conservation policy in the UK focuses largely on the best sites and species. To make a major impact on populations and diversity of species, we need large-scale restoration of ecosystems. These are critical to future generations.

Conservation in the UK is delivered through four spatial levels of policy:

- *EU legislation.* The EU Wild Birds Directive (79/409/EEC) and Habitats Directive (92/43/EEC) are transposed into UK law through the Conservation of Habitats and Species Regulations 2017. These protect the 'best' European sites and species (European Protected Species and those species that comprise the citations on which the European sites are based).
- *Special Protection Areas and Special Areas of Conservation*. There are currently 273 SPAs (covering 3,427,386 hectares) and 658 SACs (covering 4,204,703 hectares of terrestrial habitat, and 10,334,525 hectares offshore) in the UK.
- *Sites of Special Scientific Interest.* These underpin SPAs and SACs in terrestrial sites. There are about 4000 SSSIs across the UK, the majority not EU designated.
- *County Wildlife Sites and Sites of Importance for Nature Conservation* (or some similar nomenclature). These are protected through local authorities' Local Plans.

The level of protection depends where in the hierarchy a site sits. Non-EU SSSI sites and below are protected through local authority planning systems, though the statutory nature conservation advisers (Natural England in the case of England) are consulted on impacts on SSSIs as well as full European sites.

The UK also has a series of Protected Landscapes – National Parks, Areas of Outstanding Natural Beauty, and other heritage-based designations that provide conservation protection.

In theory at least, local authorities have a *duty* to protect biodiversity through the National Planning Policy Framework (NPPF) though they are generally poor at protecting biodiversity under current mechanisms.

The most significant conservation policy development for the wider terrestrial environment in the past decade has been the inclusion of a policy for ‘net gain’, which includes biodiversity offsetting, within both the 25-year Environment Plan (Defra 2018) and the revised National Planning Policy Framework (NPPF, DCLG 2012).

The policy stems from the introduction of biodiversity offsetting (see Defra 2011; Hill 2013) as a mechanism by which development can account for its residual impacts on biodiversity. The government’s Ecosystem Markets Taskforce recommended that biodiversity offsetting become mandatory across the planning system whereby every planning authority would require all developments to offset their impacts on biodiversity before they gained planning permission (EMTF 2013).

The government at that time decided not to make the mechanism mandatory, which resulted in the mechanism failing to scale up across the UK. Only under a mandatory system would sufficient investment be made available to facilitate scale-up and create, enhance and manage large areas of habitat for biodiversity conservation.

The best sites and species are protected through EU Directives and UK Regulations as well as the Wildlife and Countryside Act 1981 (amended) which protects specific groups such as the nests and eggs of all wild birds. But much biodiversity in the wider countryside is not protected.

If offsetting approaches (and other mechanisms for generating investment in the natural environment) were combined with improvements in the environmental performance of farming at scale, we could create the ‘Restoration Economy’ that would transform how the countryside looks and the wildlife it supports.

Agriculture needs to improve its environmental performance

The weeding of crops by hand or tillage is as old as farming itself. From the first use of herbicides to remove ‘weed’ species from crops in the early 1950s through to the deployment of ever more sophisticated chemical concoctions to control species of invertebrate pests and fungi, the removal of habitat and food for farmland biodiversity has been impressively efficient.

Over the past 60 years, physical and mechanical interventions in farming practices have had a substantial negative impact on biodiversity (see Sutherland and Hill 1995). These have included: conversion of semi-natural habitat to farmland; larger fields to accommodate the use of more efficient machinery and the resultant removal of hedgerows; monoculture cropping patterns leading to uniformity of the farmed landscape in preference to mixed farming; winter sowing of cereals in preference to spring cereals undersown with grass and legumes such as clover; loss of soil structure as a result of ploughing; land drainage; artificial fertiliser applications leading to reduced vegetation diversity; increased crop density; early silage-making when ground nesting birds are at a critical stage; ploughing up of hay meadows and sowing with rye grass monocultures, and even harrowing of mole hills during the ground-nesting bird breeding season.

These developments have transformed:

- Diversity of habitat structure, for example, habitat patch size and distance between habitats leading to habitat fragmentation;
- Extent of wetland habitat and soil moisture;
- Extent of woodlands and heathlands;

- Abundance of invertebrate food during the spring and summer breeding season through the application principally of insecticides. Fungicides, though, also have insecticidal properties;
- Extent of arable weeds that harbour invertebrates on which other farmland species depend during the breeding season;
- Amount of nesting, roosting and overwintering habitat for a range of wildlife groups;
- Abundance of weed seeds available over winter on which many bird and mammal species depend.

The result of these transformations has been a major decline in the abundance of a large range of wildlife groups in the farmed environment.

Much of the intensification has been driven by the Common Agricultural Policy and Pillar 1 payments that enabled over-escalation in the deployment of bigger and bigger farm machinery. Increased applications of a wider range of pesticides supported by the chemical industry have also had a massive impact.

To an extent, subsidies also enabled the overuse of chemicals at the expense of adoption of more refined, targeted treatments, a trend that is now under review as farm margins are squeezed because input costs represent such a large proportion of the farming operation.

There is a strong argument that the economic value in farming is not in produce but in the supportive agricultural machinery and chemical industries. Certainly, on average, even the large arable farms are running at a loss in the absence of subsidies (Defra 2017) though the variance around the mean is such that some very efficient farm systems can return a small profit from crops.

The extensive use of pesticides has, however, led to the widespread 'evolution' of resistance of target species of arable plants, fungal diseases and invertebrates to the extent that many of the chemicals in the chemistry set are now no longer viable and alternative methods of cropping are being sought.

Simon Leather, an entomologist at Harper Adams University is quoted in Lawton (2018): 'Pest insects haven't gone down. Aphids don't seem to be showing any downward trend, despite us spending a lot of money trying to control them'.

It is clear that the current system, where public subsidy supports a major loss-making industry, cannot continue. These losses are even greater when externalities are factored in.[38] Subsidies have significantly damaged our biodiversity and cultural heritage and the cost of restoring them, in accordance with the objectives of the 25-Year Environment Plan, will be substantial.

38 See Sustainable Food Trust (2017) and reports by the Natural Capital Committee. https://www.gov.uk/government/groups/natural-capital-committee

Land sharing and land sparing

We should be promoting both approaches based on spatially literate objectives determined by geography, soil type, hydrology, proximity of other semi-natural habitats and marginality of the land for production.

One way to restore biodiversity and natural capital on farmed land would be to reverse these intensifications and interventions. This, though, would be like asking Apple to make their iPhones out of Bakelite. Instead, restoration will need to focus on solutions that can operate at a landscape scale whilst maintaining some level of targeted intensive production that is sustainable and doesn't rely on outdated interventions that exclude habitat and food supplies for biodiversity.

Biodiversity restoration could be achieved either by interventions that increase food and breeding habitat *within* the farmed environment as a result of sustainable food and farming systems (land sharing) or by separating out food production from biodiversity by having specific management actions purely for the 'production' of biodiversity (land sparing otherwise known as sustainable intensification).

Much of the uplands, for example, already hold higher levels of biodiversity than much of the lowlands because they are more difficult to farm and, in the absence of overgrazing by livestock, still provide substantial areas of habitat for iconic species of wildlife. Uplands should therefore be prioritised for habitat and species restoration.

But the lowlands, whilst generally being easier to farm, must also deliver specific ecosystem services and natural capital, including biodiversity. Newly-created and managed sites on land that requires more artificial intervention than other areas to increase food production would yield landscape-scale benefits relatively close to areas of human habitation.

Restoring nature and ecosystems in the UK

Funding needs to be targeted at interventions in the farmed environment that can deliver large-scale significant improvements as quickly as possible.

Prior to the UK government's 25-Year Environment Plan, a number of biodiversity initiatives had been established, but delivery has shown limited success because of a lack of government policy backing, insufficient funding (the conservation NGOs can only do so much) and problems with access to land. These have included initiatives such as Living Landscapes (promoted by the Wildlife Trusts), Futurescapes (RSPB), Wetland Vision (NGO consortium), Important Biodiversity Delivery Areas (Natural England), Nature Improvement Areas (as a consequence of Lawton et al. 2010) and green infrastructure (almost solely targeted at urban areas). These initiatives were designed to expand and de-fragment the existing habitat resource and to help with issues such as resilience of species to climate change impacts at a landscape scale.

The above ambitions have not been realised and they remain aspirational initiatives despite the collective annual income of the 17 largest conservation-orientated NGOs of £979 million, c. £370 million of which is spent on biodiversity in the UK. Added to this sum is government spending of c. £400 million (largely on agri-environment schemes) (NAO 2017).

Lawton et al. (2010) recommended that we needed more, bigger, better and more joined up wildlife sites to combat continuing declines in biodiversity, especially with the additional challenges of climate change. They estimate an additional £600 million per year is needed over and above the current spend on biodiversity by non-governmental organisations and government.

This would help create Ecological Restoration Zones, Nature Improvement Areas and greater protection for non-statutorily designated sites.

An annual spend on UK biodiversity of £700 million is therefore nowhere near enough to provide the restoration at scale needed to move biodiversity from decline and attrition into recovery. Apart from a few single-species initiatives mentioned earlier, biodiversity has continued to be lost at an alarming rate in the UK. However, put into context this spend represents only 0.14 per cent of the UK's annual Gross Domestic Product. This is a very small sum given the recently acknowledged benefits of nature to our health and well-being.[39] And this money has to be very thinly spread across the area of the UK.

If the objectives of the 25-Year Environment Plan are to be met, which includes the restoration of 500,000 hectares of land for ecosystem benefits through a Nature Recovery Network, then new approaches to funding will be required that will need to embrace both public and private sector initiatives.

Since 75 per cent of land in the UK is farmed and since farming intensification has inflicted the greatest impacts on wider-countryside biodiversity, funding needs to be targeted at interventions in the farmed environment that can deliver large-scale significant improvements as quickly as possible.

39 'Health & Wellbeing', Valuing Nature. http://valuing-nature.net/health-wellbeing

Interventions for biodiversity in the farmed landscape

Interventions at three spatial scales offer funding opportunities from environmental land management contracts, habitat banking/habitat offsetting and offsets from corporate natural capital accounting.

A suite of intervention measures is currently deployed to deliver biodiversity conservation on farmland, operating at different spatial scales - for example, 'within-field' or 'whole field within-farm' or landscape scale. Within-field and within-farm options are essentially relatively small-scale actions currently funded by agri-environment scheme payments (grants) made through Pillar 2 of the CAP, amounting to about £400 million per annum (NAO 2017).

The majority of interventions within-fields are concerned with attempting to integrate intensive farming with patches of wildlife habitat. Such schemes include unsprayed margins, beetle banks, bare plots within the crop for breeding skylark, grass and wildflower margins, pollinator strips, and game crops such as quinoa, millet and kale that provide cover and seed food during the winter and an abundance of invertebrates in the spring and summer. Further details of these measures can be obtained from the Game and Wildlife Conservation Trust,[40] the RSPB,[41] Plantlife[42]and Conservation Evidence.[43]

Table 2 illustrates the range of within-field, within-farm and within region/ catchment scale initiatives that are either currently available or that could be developed and funded in order to increase the scale and diversity of

40 www.gwct.org
41 www.rspb.org
42 www.plantlife.org
43 https://www.conservationevidence.com/data/index/?synopsis_id[]=9

opportunities potentially afforded by removal of subsidies and introduction of large and long-term environmental contracts with farmers and landowners. Some of these habitats could also be created and managed through the deployment of habitat banking where Conservation Credits are sold to developers in order for development to deliver net gains in biodiversity (and other natural capital assets and ecosystem services). This is considered in more detail later in this paper.

Restoration can also occur relatively quickly. For example, Table 3 provides data demonstrating that the restoration of farmland birds, for example, can occur within as short a period as five years. Here, the introduction of a new regime for the management of arable and grassland habitat around Abberton Reservoir in Essex, following an extensive development to increase the water-holding capacity of the reservoir, resulted in a major increase in key farmland bird species within five years as evidenced by surveys before the restoration (in 2004; the development took place in 2010 and was completed in 2014) compared to surveys in 2017 at the point at which the newly restored habitats were considered functioning.

Larger, landscape scale, schemes are generally partnership approaches where landowners partner with institutions, government agencies and/or non-governmental nature conservation bodies to leverage necessary funding, usually from a combination of government and EU money paired with other national sources such as Heritage Lottery Fund grants, though securing the latter is increasingly challenging.

Large-scale habitat restoration is currently, in practice, limited to coastal managed realignment where partnerships between landowners and the Environment Agency/Natural England have been established to combat the loss of coastal habitat to climate induced sea level rise, or to whole-estate wilding schemes such as that at the Glenfeshie Estate in Scotland, where the major reduction in grazers (in this case Red Deer) is leading to the restoration of functioning ecosystems, including Caledonian pine forest, over 33,000 hectares. Another example of whole-farm rewilding is the well-known Knepp estate in Sussex (Tree 2017). EU LIFE funding has until now been available for large partnership projects to restore and enhance a range of habitat types and species from sand dune systems, lowland heathlands, upland peatlands and wetland systems.[44]

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44 ‘LIFE Programme’, European Commission. www.ec.europa.eu/environment/life/

Table 2: A range of biodiversity-enhancing habitat creationand management interventions at various scales

Scale	Habitat/type of intervention	Optimal funding
Key		
🔴	Environmental Land Management contract funded by public sector (government).	
🟢	Conservation credits for ‘Habitat Banks’ established on farmland by net gain payments from development.	
🔵	Payments by corporates to offset their supply chain impacts on natural capital after undertaking and reporting on their natural capital accounts.	
Within-field (land sharing)	Unsprayed margins, conservation headlands	🔴
	Grass and wildflower margins and within-field strips	🔴
	Beetle banks	🔴
	Skylark plots, Lapwing plots	🔴
	Pond creation	🔴 🟢 Also Conservation Credits for great-crested newt offsets
	Boundary game crops, cover crops	Farmer funded linked to shooting interests
	Pollinator strips	🔴
	Wild bird seed mixtures	🔴
	Retention of overwinter stubbles	🔴

Scale	Habitat/type of intervention	Optimal funding
Within-farm/ whole field (land sparing)	Hedgerow planting	🔴 🟢
	Increase crop diversity	As part of cropping diversification within the farm business plan
	Wood meadows (Peterken 2017)	🔴 🟢 🔵
	Buffer strips along water courses	🔴 Nutrient and pesticide credits sold to water companies to pay for buffers to be extended significantly in width
	Wetland creation	🟢 🔵
	Manage water levels, ditch management for wildlife	🔴 🟢
	Woodland planting	🔴 🟢 🔵
	Meadow (neutral, acidic or alkaline grassland) restoration and creation	🔴 🟢 🔵
	Set-aside – land left uncropped for 5+ years (now abandoned as policy measure but could be re-instated). 25 year contract for grassland and scrub habitat mosaics.	🔴 🟢
	Delay mowing to after wader breeding season. Substantially reduce silage and haylage making.	Regulatory ban on damaging activity and/or payment through ELM contract on basis of offsetting the deployment of silage making

Scale	**Habitat/type of intervention**	**Optimal funding**
Landscape scale – e.g. whole estates, catchments or farm clusters	Coastal managed realignment	Large scale funding requirement through grant aid, partnerships, successor to EU LIFE funding
	Arable reversion to heathland	🔴 🟢 Heathland habitat banks
	High Nature Value farming in the UK uplands	🔴 Example trial running – agri-environment Payment by Results in Wensleydale[45]
	Peatland restoration in the uplands	🔵
	Wetland systems at catchment scale with associated habitat	🔴 🟢 Potentially through establishment of large across-farm habitat bank involving multiple land owners funded via net gain payments from developments
	Managed rewilding	🔴 🟢 🔵
	Reduce chemical inputs across system – fertilisers, herbicides, insecticides, fungicides, molluscides	🔴
	Reduce tillage – to minimum or no tillage across system	🔴
	Control predatory mammals and birds (legal predator control)	🔴

45 'Results-Based Agri-environment Payment Scheme (RBAPS) pilot study in England', Natural England, 3 March 2017. www.gov.uk/government/publications/results-based-agri-environment-payment-scheme-rbaps-pilot-study-in-england

Table 3: Farmland birds at Abberton Reservoir in Essex[46]

Species	2004 survey	2017 survey	**Units**
Lapwing	0	4	Pairs
Skylark	63	257	Territories
Cetti's warbler	0	21	Territories
Song thrush	14	41	Territories
Nightingale	8	21	Territories
Yellow wagtail	31	55	Territories
Bullfinch	3	8	Territories
Linnet	18	57	Pairs
Yellowhammer	12	43	Territories
Reed bunting	32	84	Territories
Corn bunting	10	34	Territories

46 Derived from Frost (2018). This large-scale management regime, targeted at farmland birds, demonstrates that significant increases can be achieved within a relatively short timeframe. The development began in 2010 and was completed, with the associated 200 hectares of habitat creation, in 2014.

Investing in the natural environment

The ‘Restoration Economy’ would provide the investment necessary to fund the above interventions at scale across the UK to deliver a transformational impact on the countryside, restoring biodiversity to pre-1970 levels.

With the potential for land to be made available for biodiversity conservation and the protection and enhancement of other natural capital assets as a result of major advances in the development of agricultural technology and/or a move towards much more sustainable food and farming systems, there needs to be a robust mechanism for generating financial models that will provide the investment necessary to maximise these opportunities.

There are three broad areas of funding that are considered worthy of development to comprise the ‘Restoration Economy’ (Hill 2018):

Environmental land management contracts: These would use converted Pillar 1 CAP funds (c. £3.2 billion per annum) in addition to existing c. £400 million agri-environment payments (Pillar 2). Farmers would be paid to deliver environmental goods and services, for example by creating and managing long-term wildlife habitat at scale. The mechanism would be delivered via locally relevant, 25-year contracts with farmers and land managers.[47]

47 See example model contracts drawn up by the Country Land and Business Association (CLA 2018).

The CLA have considered four scales of payment/contract:

- A Universal Land Management Contract (LMC) for all farmers and landowners based on broad benefit provision.
- Universal Capital LMC for all farmers and landowners to provide improvements such as woodland creation, infrastructure to reduce pollution and better animal health.
- Enhanced LMC through a competitive application process, to enhance all natural features and maintain those features.
- Landscape Restoration LMC through a competitive process, to create and enhance habitat at a large landscape scale in collaboration with neighbours, in support of the delivery of the Nature Recovery Network.

A number of other organisations have considered the shape of post-Brexit funding for agriculture and the environment. For example, the Game and Wildlife Conservation Trust is promoting three schemes:

- Foundation scheme.
- Universally-accessible scheme with a range of management interventions (outlined in Table 2) for which farmers are paid in accordance with five-year or 25-year land management contracts with five-year break clauses.
- Farmer cluster scheme in which 10-year contracts with five-year break clauses operate at large landscape scales (GWCT 2017).

Other similar approaches are discussed by a number of organisations including Bright Blue (Caldecott et al. 2017), Yorkshire Wildlife Trust (2017) and Aldersgate Group (2017).

The requirements for success are: effective long-term contracts commercially priced to offer core incentivisation to the land manager, simple administration, lack of complexity around compliance, and flexibility, i.e. without rigid rules.

The GWCT (2017) model for delivery suggests that the schemes (presumably meaning outcomes and content of the contracts) should be farmer-led such that the farmer decides on what to do. That is considered inappropriate since there needs to be a formal contracting environment where farmers are either targeted and contracted to deliver specific requirements or the specifications are put out to tender (e.g. via reverse auction).

Farmers would bid to deliver either singly or, at catchment scale, by working in collaboration. This offers the best opportunity of delivering what society requires in order that the environmental performance of farming is improved. Left just to farmers, the easy wins that generate short-term financial gain might be promoted at the expense of long-term value to biodiversity and ecosystem services.

Habitat offsetting: Individual bespoke offset sites or large-scale *habitat banks* are established across the country, being spatially literate, and joined to existing areas of habitat, funded by the sale of conservation credits to developers in order that development delivers net gains in biodiversity (not just 'no net loss') as required by the NPPF and the 25-Year Environment Plan.

In practice, almost all development has an impact on biodiversity and there is compelling evidence that it fails to be retained on-site and what is retained never delivers high quality conservation (Hill 2013). You simply can't integrate wider-countryside biodiversity conservation within a housing estate.

Biodiversity is most effectively delivered by fully offsetting the impacts off-site, preferably using brokers to establish and manage new sites for conservation, funded by the sale of conservation credits to developers (EMTF 2012).

The 25-Year Environment Plan has the objectives of delivering both net gain in biodiversity from development and delivery of a Nature Recovery Network. Habitat banking would bring these two objectives together and turn nature recovery into a reality providing a biodiversity conservation legacy for future generations.

Net gain principles have recently been the subject of detailed consultation and there is now general acceptance across government, local and national conservation NGOs, the professional institute for ecology and environmental management and academia, that development needs to deliver net gain, a key part of which includes biodiversity offsetting. The scale of funding could be in the order of £1.2 billion per year (EMTF 2012; Hill 2013; Hill 2018).

The key requirement for success is a *mandatory* net gain requirement on the part of *all planning authorities* in the UK, in order to provide a consistent, level playing field for developers (EMTF 2013), as well as a standard for accreditation. Only if net gain was made mandatory would the right pricing signals be sent to potential investors for the habitat offsetting and habitat banking market to escalate and deliver the investment into the natural environment that is required alongside LMCs and corporate natural capital accounting offset funds.

Corporate natural capital accounting would provide a third source of funding. Very approximately, estimates of the value of the investment market that could be created for the natural environment through the purchase of environmental credits, as an outcome of corporate natural capital accounting, could be in the order of £3 billion per annum.

The National Audit Office (NAO) and Office for National Statistics (ONS) have been working up metric-based assessments that corporates could deploy in order to quantify, and hence understand, their business reliance upon the assets that nature provides through their supply chains.

Costanza et al. (1997) was one of the first studies to attempt to quantify the value of the world's ecosystem services and natural capital. In 2012, the OECD reported that 40 per cent of global GDP relies entirely on what nature provides (OECD 2012). An updated study (Costanza 2014) has increased the value placed on the contribution made by ecosystem services (including biodiversity and natural capital) to global economic conditions. Work by The Economics of Ecosystems and Biodiversity project[48] has demonstrated the financial and social dependency of our business models on functioning ecosystems and biodiversity. And yet corporates are only just beginning to understand the risk to their businesses of treating natural capital, including biodiversity, as a commodity with zero value. We are failing as a society to value these assets properly and to account for them in our business activities.

That position is changing as corporates realise that effective reporting on, and understanding of, the role of ecosystems and biodiversity gives market advantage. It is likely that investor interest in a company's position and their mitigation of impacts on ecosystems and biodiversity will scale-up substantially in the next decade.

48 www.teebweb.org

Consequently, where impacts are identified, corporates may look to ‘offset’ those impacts by investing in projects that rebuild and restore natural capital assets, through the purchase of environmental credits. Third party investors and landowners are therefore likely to bring forward ecosystem projects that can secure that corporate investment.

For this approach to succeed, the metric-based assessment methodology that can be adopted by corporates must be formally rolled out. Financial reporting regulations are needed that require corporates to report on their impacts on biodiversity (e.g. a Biodiversity Disclosure Initiative). Standards and accreditation will be required to enable a market to be established and to function, a role that could be played by the NAO/ONS.

Conservation credits raised to provide offsetting for development and environmental credits raised to provide a mechanism for corporates to improve their environmental performance, investment standing and reputation, could be traded. Third party investments could be attracted to invest in land management interventions for biodiversity and other natural capital assets if standards were set to enable a market in credits to develop.

The overarching theme, however, is that we need to move beyond grant-based financing of interventions and find new financial levers and models if we are to effect the transformational change in the countryside that is within our grasp.

Investment vehicles

A system of habitat banking, green bonds, environmental credits and impact investments should be developed to fund interventions to restore biodiversity at scale.

There are a range of vehicles and initiatives that would provide the necessary infrastructure to enable investment markets to fund opportunities created through land sharing and land sparing.

Habitat banking

Habitat banking, capitalised by the use of Pillar 1 and 2 funds, net gain (offsetting) funds and corporate natural capital accounting, could create the Nature Recovery Network within approximately three to six years.

Habitat banking provides access to land and finance at a scale unachievable through conventional conservation approaches. It involves the establishment of large areas of land (>40 hectares in the case of the Environment Bank initiative) where habitat is created or enhanced and then managed in accordance with a long-term contract. The resulting increase in biodiversity yields 'conservation credits' that are purchased by developers who are required to offset their impacts.

Habitat banks are the preferred mechanism for delivery of habitat compensation schemes across the world. They work particularly well where the system is supported by public authorities (Carol, Fox and Bayon 2008). Habitat banks have been in place for decades in the USA and Australia creating a fully functioning industry.[49]

49 See: www.ecosystemmarkets.com and www.environmental-finance.com

Environment Bank is pioneering their use in the UK as a cost-effective means by which developers are able to compensate for their impacts on biodiversity and to deliver net gain.

Habitat banking applies most readily to the large amount of development that impacts on sites of low biodiversity value that, until now, have been developed *without any* compensation. Habitat offsetting does not mean, as some try to suggest, that places of moderate or high biodiversity value can be destroyed by development and replaced elsewhere. Opposition to the concept on the basis of misinformation and an unwillingness by some to understand how it would work, has undoubtedly slowed down the pace at which it could have been providing the much-needed investment into the natural environment, where biodiversity decline has already been so significant.

The one million new houses currently in the planning system will provide little value to biodiversity in the wider countryside because developers have not previously been required to account for their individual losses to biodiversity which, in aggregate, are substantial.

I recommend moving rapidly to a system of habitat banking which operates at greater scale than individual bespoke offsets, providing more for biodiversity more cost-effectively and creating the right conditions to attract the required upfront capitalisation investments.

Habitat offsetting and habitat banking help the local authority that has jurisdiction for permitting development to demonstrate their legal compliance with the National Planning Policy Framework (as revised) and helps the developer to achieve permission for a more sustainable development through the statutory planning system.

Conservation credits can be purchased from the bank as required by a multitude of developers, and unit costs are cheaper. Habitat banks can therefore deliver large-scale habitat from a series of both small and large development impacts.

Table 4 identifies costs associated with the creation or restoration and then long-term management of a range of habitat types that could constitute a habitat bank.

Table 4: Typical costs for the creation and long-term management of a range of UK habitat types to attract offset providers (2018 prices).[50]

Habitat	Capital creation costs £/ha	Capital restoration costs £/ha	Annual management costs £/ha
Arable reversion	2500	1500	500
Unimproved grassland	4500	3000	600
Wetland	35000	18000	750
Grazing marsh	10000	3300	450
Saltmarsh	15000	9000	450
Woodland/ scrub	8500	6500	550
Heathland	5000	2000	450
Boundaries, ditches, buffer habitats	10000	4500	700

For habitat offsetting and habitat banking to succeed, the UK government should regulate for net gain to ensure that all local planning authorities routinely require biodiversity impacts on all developments to be assessed and for developments causing impacts to be required to deploy compensation. A central mandate on the need for net gain provides consistency, clarity and certainty across all planning authorities and this will reassure developers that there is a level playing field.

Habitat banks need to be of sufficient size with significant habitat/biodiversity uplift potential. Owners of habitat banks must demonstrate an ability to deliver biodiversity management plans. Brokers have the expertise necessary to identify effective sites.

Habitat offsetting and banking need effective monitoring, reporting and contractual governance to be in place. With tight legal agreements, scheme owners are paid on delivery of conservation commitments.

50 Based on Environment Bank Ecocredit calculator (2018 prices).

The following agreements are deployed by the Environment Bank as an example of how a system can be made to work:

- *Conservation credit purchase agreement* between the broker and the developer purchasing conservation credits.
- *Biodiversity compensation management plan* between the broker and the landowner of the habitat bank (on which the conservation credits are raised).
- *Letter of sale* provided by the broker to the developer.
- *Conservation bank agreement* between the broker and the landowner of the habitat bank.
- *Conservation credit certificate* presented to the developer by the broker on purchase of the credits which in turn is presented to the local authority to demonstrate the discharge of their biodiversity liabilities.

Habitat banks are most useful when upfront funding allows initial habitat bank set-up and on-the-ground habitat creation and management to be established prior to the first sale of conservation credits. This allows for cost efficient conservation credits to be immediately sold to a developer upon demand.

Under a mandatory offset regime, third party investors would put up the capitalisation and long-term management funding structured so as to provide payback over five years, for example, at an attractive interest rate.

Funds generated from the sale of conservation credits within that five-year period would be used to provide a return on the capital and to pay off the investment. Once the credits have been extinguished (and the bank has ‘sold out’) further investments would be used to recycle the funds through the creation of further habitat banks.

In principle, funding from conversion of Pillar 1 and Pillar 2 CAP funds (i.e. funds equivalent in scale) could be used to capitalise habitat banks under a five-year contract with the funds being paid back through the sale of conservation credits over the same time period.

Considerations in establishing this mechanism would include the extent of development in the region and hence the demand for conservation credits. This would take account of the types of habitat that could be created and managed within the habitat bank subject to soils, hydrology and other conditions.

Table 5 analyses the length of time it would take if the equivalent of annual Pillar 1 and Pillar 2 funds were used to fund the Nature Recovery Network as outlined in the 25-Year Environment Plan. This covers 500,000 hectares and includes the detailed costings from the Environment Bank (see Table 4). Such an approach could fund the Nature Recovery Network for a 25-year period under contract, in five and a half years.

Table 5: Assessment of how far the funding could go under a land sparing scenario

		Unit
Cost of creating, enhancing and managing a 40ha habitat bank (neutral grassland-wildflower meadow with structural boundaries)	£1.585	M
Capital and management cost represented as an annual sum per year	£1.58	k/yr/ha
Period over which fund applies	25	Years
Value of fund from Pillar 1 CAP	£3.2	bn/yr
Value of fund from Pillar 2 CAP	£0.4	bn/yr
Value of fund from net gain/offsetting (NG)	£1.2	bn/yr
Assumed value of fund from corporate natural capital accounting (CNCA)	£3.0	bn/yr
Area of land brought into habitat banking – exc. CNCA and NG	90,850	ha/yr
Length of time to deliver the 500,000ha Nature Recovery Network – exc. CNCA and NG	5.5	Years
Area of land brought into habitat banking – inc. CNCA and NG	196,845	Ha
Length of time to deliver the 500,000ha Nature Recovery Network – inc. CNCA and NG	2.5	Years

Green bonds

With appropriate standards and an accreditation system, the range of interventions required to increase biodiversity in the wider countryside could be funded, in part, through the issuance of green bonds.

A green bond is specifically used for climate and environmental projects. These bonds are typically asset-linked and backed by the issuer's balance sheet. They are designated bonds intended to encourage sustainability and to support climate-related or other types of special environmental projects.[51]

Those that fund climate-impact related projects and interventions tend to be referred to as 'climate bonds'. The global green bond market has grown from less than $1 billion in 2007 to nearly $70 billion in 2016,[52] with recent figures for 2017 of $200 billion and an estimated $442.57 billion worth of outstanding green bonds in 2018.

France deploys a bond to fund biodiversity as an asset class (Government of France 2017). The UK government could therefore investigate the creation of environmental bonds in order to capitalise interventions to create, enhance, restore and manage biodiversity in the countryside, with tax incentives for those who invest in the bond.

Environmental credits

Many of the interventions listed in Table 2 would lend themselves to the raising of environmental credits that would be purchased by investors, who would be paid back at attractive rates of interest. If investment in environmental credits were to attract favourable tax incentives, the net investment into the natural environment would be substantial. Trading of credits would be facilitated by implementation of an effective credit standard.

51 'Green Bond', *Investopedia*. https://www.investopedia.com/terms/g/green-bond.asp
52 Ibid.

Impact investing

Impact investments challenge the long-held views that social and environmental issues should be addressed only by philanthropic donations and grants. They are made into companies, organisations, and funds to generate social and environmental impact alongside a financial return. The Global Impact Investment Network reported that 208 survey respondents managed $114 billion in impact assets in 2017, so the market is significant.[53] Investments could be made into projects that both enhance and restore biodiversity in association with either land sparing as a result of technological advances in agriculture or land sharing through interventions to make farming truly sustainable.

Farmers and landowners wishing to offer opportunities for investing into their projects, for example, could aggregate and form a not-for-profit Community Interest Society within their area of operation. There would need to be robust metrics around the environmental credits raised by the interventions when implemented and the outcomes to be delivered by the fund according to a management plan showing milestones and timescales. The impact investment community could implement accreditation of projects to give them clarity, certainty and viability which would provide security to potential investors in terms of risk exposure.[54]

53 See: www.thegiin.org/impact-investing

54 For more details see: https://en.wikipedia.org/wiki/Impact_investing www.triodos.co.uk/en/personal/ethical-investment https://www.investopedia.com/impact-investing/

Conclusion and recommendations

In addition to an expansion in sustainable food and farming systems in the coming decades, technological advances provide opportunities to increase efficiencies and provide land for biodiversity restoration.

Efficiency isn't just about producing food. It also embraces how we produce the other goods and services that land must deliver.

Whichever way farming develops in the next decade, be it through the application of a range of developing technologies or an expansion of sustainable farming methods, or both, it is critical that we address the substantial biodiversity losses of the past.

Despite the sizeable membership and income of the non-governmental nature conservation bodies and the funding provided by government to date, we have failed to avert this massive loss in the habitat in which most declines have been witnessed – the farmed environment. A new farming landscape needs to restore the damage of the past. Opportunities for both land sharing (within-field) and land sparing (whole-field within farm and large areas at landscape and catchment scales) need to be exploited to achieve this as part of the delivery of the 25-Year Environment Plan.

This paper has identified the type and scale of opportunities for biodiversity and the countryside and acknowledges that novel approaches to financing the capitalisation and long-term management of the land alongside food production and energy provision will be required. This will go far beyond the traditional system of grant aid that has supported biodiversity conservation over the past 60 years. The range of funding mechanisms is outlined above. Together, they would deliver the 'Restoration Economy' providing economic benefits to a new set of skilled labour in the rural environment where job prospects are currently challenging.

This paper has also reviewed the state of nature and biodiversity conservation policies in the UK. The most significant policy for the wider terrestrial environment in the past decade being that for ‘net gain’ enshrined within both the 25-Year Environment Plan and the revised National Planning Policy Framework.

The drivers of biodiversity loss, as a result of agricultural intensification caused by changes to farmland structures and reliance on chemical inputs, have been described. Statistics on farming economics show that, in the absence of subsidies, the industry is not financially viable in the UK and it is clear that the current system cannot continue. Public subsidy to support a major loss making industry has destroyed our biodiversity and cultural heritage.

If the objectives of the 25-Year Environment Plan are to be met then new approaches to funding will be required that will need to embrace both public and private sector initiatives. This would include the restoration of 500,000 hectares of land for ecosystem benefits through a Nature Recovery Network.

Since 75 per cent of land in the UK is farmed and since farming intensification has inflicted the greatest impacts on wider-countryside biodiversity, funding needs to be targeted at interventions in the farmed environment that can deliver significant improvements as quickly as possible. A comprehensive range of those interventions is described.

There are three broad areas of funding that should be explored in detail which collectively would comprise the ‘Restoration Economy’:

- Conversion of Pillar 1 and 2 CAP funds (c. £3.6 billion per annum) into environmental land management contracts. Farmers would be paid to deliver environmental goods and services, for example, by creating and managing long-term wildlife habitat at scale.
- Habitat offsetting (c. £1.2 billion per annum) whereby individual bespoke offset sites or preferably large-scale habitat banks are used to restore biodiversity on farmland across the country, being spatially literate and joined to existing areas of habitat, funded by the sale of Conservation Credits to developers in order that development delivers net gains in biodiversity (not just ‘no net loss’).

- Corporate natural capital accounting and offsetting of impacts on natural capital where corporates realise that effective reporting on and understanding of the role of ecosystems and biodiversity in their supply chains and taking measures to offset them (through the purchase of environmental credits used to restore ecosystems) gives market advantage and increased investment attractiveness.

Biodiversity restoration requires substantially more money than is currently available. I suggest four investment vehicles and approaches (in addition to government environmental land management contracts post-Brexit) that would provide the necessary funding:

- Habitat Banks where conservation credits raised on land through biodiversity interventions are sold to developers in order for them to deliver net gain.
- Green Bonds issued to raise capital to deliver projects on sustainable agriculture and the protection of aquatic and terrestrial ecosystems. Government could create biodiversity bonds in order to capitalise interventions to create, enhance, restore and manage biodiversity in the countryside. Returns could be paid for through Environmental Land Management contract funds using the successor to CAP payments.
- Environmental credits purchased by corporates through natural capital accounting in order to increase market advantage.
- Impact investments into projects that both enhance and restore biodiversity in association with either land sparing or land sharing through interventions to make farming truly sustainable. Again, returns could be paid for through Environmental Land Management contract funds using the successor to CAP payments.

The following recommendations are made:

- Mandate biodiversity offsetting/net gain so that all planning authorities deliver their biodiversity duties by requiring all development to deliver net gain, involving off-site habitat creation and management, much of which would be on farmland. Once mandated rather than voluntary, a market for conservation credits, raised through the creation of habitat according to legally secured contracts, will develop and scale-up across the UK.
- Government to provide an accreditation mechanism for offset sites (delivered by brokers), with emphasis on habitat banks.

- Create biodiversity (Green) bonds underpinned by post-CAP payment funds, making these funds go further.
- Expedite the roll out of corporate natural capital accounting metrics and include a requirement for corporates to report on their natural capital impacts with a mechanism for environmental credits to be purchased to offset those impacts. Environmental credits could be raised by brokers. Ensure a standard for environmental credits and an accreditation mechanism so that credit values are retained on the company's balance sheet and could be traded by the corporate as biodiversity values increase on the sites from which the credits are originally raised.
- Investigate the appropriate mechanism for attracting impact investing into the restoration of damaging operations caused by farming.
- Investigate how the tax system could be used to incentivise investors in the purchase of conservation credits, environmental credits and impact investments.

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