The Hunger Gap

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A gulf in public understanding prevents us from seeing how and why our food supply is at risk.

By George Monbiot. This is my written submission to the Environmental Audit Committee's inquiry on Environmental Change and Food Security, 3rd March 2023

References are numbered and appended to the bottom of the document.

1. Food security depends on systemic resilience

National food security depends above all other factors on a resilient global food system. Understanding this system is crucial to effective decision-making and the avoidance of crisis.

One of the great deficiencies of our education is that few of us are taught systems theory. Yet everything of material importance to us – the human brain, the human body, human society, ecosystems, the atmosphere, the oceans, the financial system, the food system – is a complex system[1]. The behaviour of these systems, because so few of us study them, repeatedly takes us by surprise.

All complex systems, including the global food system, possess emergent properties. This means that their components, however simple they each might be, behave in non-linear ways when they combine. Through the networks unintentionally created by billions of randomly-distributed decisions, they organise themselves, spontaneously creating order without central control.

Complex systems have thresholds. A system might be secure under some conditions, as its self-organising properties stabilise it. But when conditions change, and it is pushed towards a threshold, these self-organising properties have the opposite effect. Negative feedback loops are replaced by positive feedback loops, which compound the shocks afflicting the network, amplifying chaos[2]. These thresholds can be hard to identify until they have been passed. They are often described as tipping points. Once a system has lost its resilience, a small disturbance can tip it over its critical threshold, at which point it collapses, suddenly and unstoppably.

Once it has collapsed, a system is often subject to hysteresis. This means (in this context) that the system enters a new equilibrium state. Because this new state has its own self-reinforcing properties, that stabilise it, a collapsed system can be difficult or impossible to return to its former state. In general, far more energy is needed to reverse a tipping than was needed to cause it[3]. Tipping a system into a new stable state is like falling off a cliff. Reversing hysteresis is like climbing back up again.

Had the global financial system been allowed to cross its critical threshold in 2008, its collapse would have triggered cascading failure across human society. Only a global bailout amounting to trillions of dollars, at the 11th hour, pushed it back into a safer state. In other words, even before hysteresis occurred, far more energy (or money) was needed to stop the collapse than was needed (via the butterfly's wing of the US subprime crisis) to cause it.

Scientists represent complex systems as a mesh of nodes and links. The nodes are like the knots in an old-fashioned fishing net, while the links are the strands of twine that connect them. If the nodes behave in a variety of ways, and their links to each other are weak, the system is likely to be resilient. If the nodes behave in similar ways and are strongly connected, it is likely to be fragile[4]. This is because the behaviour of similar nodes is likely to synchronise, as they are shaken by the same disruption, while strong links ensure the disruption resonates through the network.

For example, in the approach to the 2008 crisis, the big banks developed similar strategies and similar ways of managing risk, as they pursued the same sources of profit[5]. They became strongly linked to each other (partly through securitisation and derivatives trading) in ways that regulators scarcely understood[6]. When Lehman Brothers failed, it threatened to pull everyone down.

Another important issue is "modularity": to what extent is the system divided into compartments?[7] If different parts of a system have a degree of isolation from each other, the network as a whole is more likely to be resilient, as shocks are less likely to spread[8].

Ideally, the network will contain circuit breakers, like fuses in an electrical system, that prevent the spread of contagious collapse. There should be a backup system, working within or alongside the main network, that operates on entirely different principles[9]. There should be plenty of redundancy (spare capacity) in the system: this acts as a kind of shock absorber.

2. Governments have ignored repeated warnings about rising fragility in the global food system

The global food system – meaning the ways by which we grow, trade, process, pack, distribute, buy and eat our food – has all the characteristics of a complex system. It is subject to stresses similar to those that bore upon the global financial system in the approach to 2008. In other words, it is rapidly losing the six elements of systemic resilience:

– Diversity

– Asynchronicity

– Redundancy

– Modularity

– Circuit Breakers

– Back-Up Systems.

One of the fastest cultural shifts in human history is the convergence towards a "Global Standard Diet"[10]. Originating in rich nations in the 1960s, then spreading rapidly across the rest of the world, one diet has pushed the peculiarities of place and culture out of its path.

While many of us now have access to a much wider range of foods than our grandparents knew, globally our diets have become more alike[11]. In other words, our food is locally more diverse, but globally less diverse[12]. Most of our food comes from a tiny number of species. Just four plants -wheat, rice, maize and soybeans – account for almost 60% of the calories grown by farmers[13].

These crops have concentrated in the regions where their production is most efficient. Only four countries harvest 76% of the maize exported to other nations. Five sell 77% of the rice, and five supply 65% of the wheat[14]. Only three nations grow 86% of the world's soybeans (these soybeans in turn supply three quarters of the world's feed for farm animals)[15].

In just 18 years, the number of trade connections between the exporters and importers of wheat and rice have doubled[16]. Roughly 40% of the world's people now rely on food from other nations[17], and global imports of cereals are likely to double again by 2050[18]. Nations are polarising into super-importers and super-exporters[19].

The result is a system that has become less resilient. There are plenty of warnings in the scientific literature. They show that some nodes (the major exporters) have become bigger and more important, while their links to other nodes (the importers) have become much stronger[20],[21]: these are classic causes of declining resilience[22]. They show that rising trade is removing the compartments that used to exist between national food production systems: in other words, the system is becoming less modular[23]. They show a growing vulnerability to external shocks[24],[25]. They show that these shocks could now proliferate across the entire network, becoming "globally contagious"[26]. But these warnings have been missed or ignored by almost everyone in public life.

The Global Standard Diet creates the Global Standard Farm, and the Global Standard Farm promotes the Global Standard Diet. Farmers worldwide are converging on identical techniques, using the same machinery, the same chemicals and the same varieties of the major crop plants. Since 1900, the world's crops, according to the UN, have lost 75% of their genetic diversity[27]. This genetic narrowing can make crops more susceptible to diseases, such as the Ug99 stem fungus, a virulent pathogen afflicting wheat, that, originating in Uganda, has now swept across Africa and parts of Asia, assisted by global trading networks that sometimes distribute pathogens almost as quickly as they distribute food[28].

As the same herbicides are used to treat the same crops, the same herbicide-resistant superweeds spring up around the world, and now threaten in some places to overwhelm farmers' efforts to control them[29]. Because of the convergence towards identical crops and identical growing techniques, farming's backup systems – different ways of growing food, different ways of selling it – are shutting down.

Farmers everywhere are advised to "close the yield gap", which means maximising the amount of food their crops can produce. This is necessary to feed the world without causing agricultural sprawl, but these gains in efficiency ensure that the redundancy (the spare capacity) within the system declines. Already there are signs that – despite massive investments in research and development – major crops in some places are approaching a "yield plateau": a level beyond which production can no longer rise[30]. Yield plateaus, one study found, have already been reached in around one third of the world's rice and wheat farms[31].

As crops approach their plateaus, returns on effort diminish[32]. Fertilisers have a massive impact on production when yields are low, but every new increment is less effective[33]. Beyond a certain point, the money farmers must invest in improving their yields outweighs any gains they make[34].

These trends have also triggered a classic self-accelerating feedback loop, typical of complex systems. As diets converge, and the farming methods that supply them converge, the biggest players globalise their businesses and destroy their smaller competitors. Corporations that supply the universal seeds, machinery and chemicals enjoy ever greater economies of scale. So do the companies that trade and process the universal farm products. Market power translates into political power: the companies use their wealth to lobby governments and shape trade treaties. They secure wide intellectual property rights (patenting seeds and breeds as well as chemicals and machinery). They gain permission to merge and swallow each other. Their products then achieve even greater dominance[35].

In other words, their growth relies on ripping down circuit breakers, back-up systems and modularity, and streamlining a system whose major nodes are already too big and whose links are already too strong[36]. It's an accelerating cycle that inexorably destabilises the system.

The result is a corporate sector even more concentrated and connected than the financial sector was before the 2008 crash. Four companies – Cargill, Archer Daniels Midland, Bunge and Louis Dreyfus – control, on one estimate[37], 90% of the global grain trade. They are consolidating vertically as well as horizontally, buying into seed, fertiliser, processing, packing, distribution and retail businesses. They continue to snap up their smaller competitors[38].

Another four companies – ChemChina, Corteva, Bayer and BASF – control 66% of the world's agricultural chemicals market[39],[40], while a similar cluster (with BASF replaced by LimaGrain) owns 53% of the global seed market. Some of the mergers that created these giants were designed to integrate seed and chemical businesses, so that the products could be sold as a single package[41]. When farmers purchase a seed and chemical package from these conglomerates, they buy, in effect, a set of decisions about how they will farm. Global standardisation advances every year.

Three corporations – Deere, CNH and Kubota – sell almost half the world's farm machinery[42]. Another four companies control 99% of the global chicken breeding market, and two supply almost all the ducks[43]. Four firms run 75% of the world's corporate abbatoirs and packing plants for beef; four others control 70% of corporate pork slaughter[44]. These firms too are integrating vertically, either buying farms or contracting farmers to supply their meat, under strict and unvarying conditions, often using the standardised feed and other products they supply. Traders take over the feed mills and refineries with which they once did business. Supermarkets dominate and control the growers who sell to them. Fast food chains elbow out independent restaurants.

While mergers and acquisitions have been accelerating in many industries[45], the food sector has consolidated further and faster than most[46]. One reason is that sectors with a high rate of technological change can use their intellectual property – such as patents on genetically engineered seeds – to lock competitors out of the market[47]. In doing so, they accidentally create complex systems of their own, that shift quickly and interact with other systems in ways that are often opaque and unpredictable.

The fragility of the food system is exacerbated by a global shift to just-in-time delivery. Around the world, borders have opened and roads and ports have been upgraded, streamlining the global trade network. Thanks to this neatly integrated system, companies have been able to shed the costs of warehousing and inventories, switching, in effect, from stocks to flows. In good times, this works. But if deliveries are interrupted or there's a sudden surge in demand, shelves can empty suddenly, sometimes with disastrous consequences[48].

The food industry is also becoming more tightly coupled to the financial sector[49]. The same institutional investors crop up throughout the global food system, buying interests in farming, trading, processing and retailing. They too seek integration, ensuring that their market power in one sector reinforces their market power in another[50]. When sectors become mutually dependent, they increase what scientists call the "network density" of a system, making it especially vulnerable to cascading failure. "Hyper-connections" in a network of networks generate "hyper-risks"[51].

Speculation in commodity futures exchanges might once have buffered global markets against risk. By fixing prices for crops before they are harvested, it helped protect both farmers and traders from volatility. But over the years, price speculation has become an end in itself, and is likely now to be a destabilising force. It's hard to find exact figures, but the limited public information suggests that, on the biggest futures exchange in Chicago, every year between 65 and 215 times as much wheat is traded in the US as harvested[52].

One indication suggesting that a complex system might be approaching a tipping point is that it begins to flicker[53],[54]. In other words, its behaviour becomes more volatile[55]: the small, random changes that a system would previously have absorbed are amplified into ever greater shocks. Flickering is what is the global food system now appears to be doing. One paper reports that “the frequency of shocks has increased across all sectors at a global scale” since the 1970s[56].

3. Falling Prices, Rising Hunger

Shock frequency might explain an otherwise inexplicable trend. Until 2014, malnutrition appeared to be heading towards extinction. The number of chronically hungry people was falling steadily, from 811 million in 2005 to 607 million in 2014. The world seemed to be on track towards UN Sustainable Development Goal 2.1: sufficient food for everyone by 2030[57]. But in 2015 the trend began to turn[58]. Hunger has been rising since: to 650 million in 2019, and around 770 million in 2021.

The turning began long before either the Covid-19 pandemic or Russia’s invasion of Ukraine. It was not caused by a shortage of food. Global food production has been rising steadily for more than half a century, comfortably beating population growth. In 1961, there were 2200 kilocalories a day available for every person on Earth. By 2011, this had risen to almost 2900[59]. Crop production as a whole has risen much higher: to 5400 kcal per person per day. But almost half this bounty is lost through feeding the crops to farm animals, using it for other purposes (such as biofuels) and through waste. Even so, in principle, there is more than enough for everyone, if it were affordable and well-distributed. The new hunger appears to be caused by systemic instability.

Take the years 2008 and 2011, which saw, until 2021, the biggest spikes this century in the price of food, accompanied by spikes in hunger. The global wheat price rose by 33% in 2008 and 38% in 2011. But these major shocks had two striking features. Ostensibly, they were triggered by heatwaves and droughts in some food-growing regions in 2007 and 2010. But these disruptions were by no means the most extreme in recent years[60]. Even more remarkably, in both cases the total volume of wheat available in international markets rose: by 5.5% and 3.2% respectively[61]. What appears to have happened is that the impact of small shocks in some growing regions was magnified across the global food system by commodity traders[62],[63]. Major producers then panicked and restricted their exports[64]. The shockwave rolled through the network, becoming bigger as it travelled. It landed almost entirely on the poorest nations, whose imports fell sharply, even as richer countries sustained or raised the amount they bought.

There was a similar story in 2021, when production growth also coincided with a sharp rise in chronic hunger. For example, the global wheat harvest set a new record, in line with its fairly steady rise across the previous decade[65]. Clearly, the pandemic played a major role: logistics chains broke down in places, some countries stopped their exports[66], and some food crops remained unharvested[67]. But these impacts are likely to have been exacerbated by declining systemic resilience.

The most striking feature of the trend is as follows. In 2014, when fewer people were hungry than at any time since, the global food price index stood at 115 points[68]. In 2015, the year when the trend began to turn, it fell to 93, and remained below 100 until the second half of 2020. Only in the past three years has it surged (it rose to almost 160 points in March 2022, but at the time of writing has fallen back to 131). In other words, the downward trend in the incidence of global hunger stopped then went into reverse while the global price of food was falling, a situation many economists would regard as impossible.

Shocks caused by speculative surges, supply chain disruptions, export bans, bottlenecking, environmental crises and other systemic issues scarcely affected rich nations before 2020, and had little impact on the global price of food. But they caused havoc in poor nations with weak currencies, which stand at the end of the queue. Local prices can surge even as global prices remain low.

While our buying power insulated countries like the United Kingdom from shock, at least until 2020, we should all be greatly concerned by the issue these trends reveal: flickering caused by the amplification of shocks across a system that appears to be losing its resilience. National food security depends on global food security. And global food security depends on a resilient food system. Rich nations might be hit later than poor nations by a loss of systemic resilience. But eventually they will be hit nonetheless.

Just as with the banking crisis in 2008, we cannot afford to wait until the system has collapsed to take action, as by then it is too late: hysteresis applies. Governments must work together to reintroduce resilience to the system.

There is, however, a major difference between the food system and the financial system. In 2008, governments were able to bail out the financial system with future money. They cannot bail out the food system with future food.

4. Food nationalism and food security are not the same thing

Even if the UK were able to produce as much food as its people ate, we would not be insulated from global shocks. Unless we were to break not only our trading links but also our financial links with the rest of the world and become as autarchic as North Korea, we would still be affected by the global loss of systemic resilience and, if it is allowed to happen, the collapse of the global food system. If we were to pursue autarchy, we would expose ourselves to a different and more immediate range of threats, losing the environmental buffering that the global food trade permits. At present, a bad harvest at home has little impact on domestic food prices, as long as good harvests have been achieved elsewhere.

Moreover, the pursuit of self-sufficiency in food might depend on a rising dependency on other commodities, such as fertiliser and animal feed. When we see figures for “domestic” production of pigs and poultry, for example, what we are seeing is the throughput volume of US and Brazilian soy and maize.

Similar constraints affect food localism. While there may be strong social and cultural reasons for producing local food for local markets (but, in general, far weaker environmental reasons than are widely assumed), only in a very few parts of the world can such production meet our needs.

A paper in Nature Food sought to discover how many of the world’s people could be fed with staple crops grown within 100 kilometres of where they live[69]. It found that wheat, rice, barley, rye, beans, millet and sorghum grown within this radius could feed only a quarter of the world’s people. Maize and cassava grown within 100km could supply a maximum of 16% of those who need them. The average minimum distance at which the world’s people can be fed is 2,200 kilometres. For those who depend on wheat and similar cereals, it’s 3,800 kilometres. A quarter of the global population that consumes these crops requires food grown at least 5,200 kilometres away.

The reason is that most of the world’s people live in big cities or populous valleys, whose hinterland is too small (and often too dry, too hot or too cold) to feed them. Much of the world’s food is grown in vast, lightly habited lands, such as the Canadian prairies, the US plains, the Russian steppes, Ukrainian chernozem and Brazilian interior, and shipped to tight, densely populated places. As climate breakdown and other disasters are likely to render more places unsuitable for farming, trade distances might need to increase.

Like it or not, we are dependent on the global food system, and our dependency is likely to rise rather than to fall. National food security cannot be achieved without global food security.

This introduces some hard dilemmas. Much of our food has to be grown, for simple mathematical reasons, far from where we live, and shifted in bulk. But long-distance trade and mass production favour transnational corporations and accelerate the homogenisation of the Global Standard Farm. This consolidation makes the food system less resilient, destroys the livelihoods of small farmers and undermines food sovereignty.

These dilemmas are further sharpened by two major trends, bearing upon a global food system that is increasingly fragile: dietary change and escalating environmental shock.

5. Dietary change and environmental shock present existential risks to the global food system

By 2050, the human population of the planet will rise to between 9 and 10 billion. In principle, the world already produces enough food for between 10 and 14 billion[70]. The problem is that an ever smaller proportion of this embarrassment of riches is feeding people directly.

While the human population growth rate has fallen to below 1% a year[71], the growth rate of the livestock population has risen to 2.4% a year[72]. By 2050, to put it in brutal terms, the extra humans on the planet will weigh a little over 100 million tonnes, while, unless the current trend is disrupted, the extra farm animals will weigh 400 million tonnes[73]. The real population crisis is not the growth in human numbers, but the growth in livestock numbers.

This rising pressure is caused by Bennett's Law, which states that the consumption of fat and protein rises with people's incomes[74]. On average, the world's people eat 43 kg of meat per year[75]. In the UK, we eat a little more than our average adult bodyweight: 82 kg.

While in the richest countries, meat consumption has stabilised and in some places declined a little, the rest of the world is catching up. In 50 years, the number of cattle on Earth has risen by around 15%[76], while the number of pigs has doubled, and the number of chickens has increased fivefold[77]. By 2050, according to the UN, world meat consumption is likely to be 120% greater than it was in 2000[78].

These animals must be fed. Already, roughly half the calories farmers grow are used for raising livestock[79]. Much of the growth in feed demand has been met by soya from South America, whose expansion has been devastating to rainforests, wetlands and savannahs. Because we eat so much meat, the UK's diet requires nearly 24 million hectares of land[80]. But we farm only 17.5 million hectares here[81]. In other words, our farmland footprint is 1.4 times the size of our agricultural area. If every nation had the same ratio of consumption to production, feeding the world would require another planet the size of Mercury.

Unless there is a radical change in the way we produce our food, by 2050 the world will need to grow around 50% more grain[82]. This growth in demand raises the pressure on the global food system, reduces redundancy and drives environmental crisis. However, in theory, and assuming nothing else changes, it is just about possible on the land used for farming today. While the rise in yields has slowed, at current rates the harvest of the four major crops (maize, wheat, rice and soya) will, on average, be 50% bigger in 2050 than it is today[83], which happens to match expected demand. But it is unsafe to assume that nothing else will change.

We have an unfortunate tendency, in considering the impacts of global heating, to generalise temperature rises: 2 or 3°C doesn't sound like a major shift. But this 2 or 3° is averaged across the planet. Because the land heats faster than the oceans, and because much of the world's population growth is taking place in some of the Earth's hottest countries, one study estimates that 3°C of global heating above pre-industrial levels translates into an average extra temperature experienced by human beings in 2070 of 7.5°C[84].

Since farming began, humans have concentrated in places with an average annual temperature of around 13°C, which tends to create the best natural conditions for growing crops and raising livestock. Vast numbers have made their homes in this temperature band. But it is about to shift, swiftly and catastrophically. According to the same study, this band will move further towards the poles in the next 50 years than it has done in the past 6000. If people are unable to migrate, one third of the world's population could be confined to places with an average annual temperature of 29°C: in other words, as hot as the hottest parts of the Sahara are today.

How will people farm in these conditions? It might be possible inside an air-conditioned tractor, but the great majority of the world's farmers cannot afford such a thing. For much of the year, a high proportion of the world's smallholders – who are concentrated in the hot parts of the world – will not be able to work. Smallholders (people who farm less than two hectares) produce around one third of humanity's food[85].

But even if corporate farmers with air conditioned tractors took over, could anything be grown? Here too, our perception of the problem has been distorted by the averaging of global temperatures. Most of the published studies look at the impacts of 1.5 or 2 or 4°C of heating on crop production. But if 2 or 4° of average heat means greater temperature increases in some of the major growing regions, the possible impacts might not have been fully captured.

Temperature rises so far have probably caused a small reduction in the yields of major crops[86]. The damage has been lower than some people predicted, partly because crops have been shifted to places that suit them better. For example, even as the planet has heated, wheat fields on average are colder than they were before, because wheat growing has migrated to cooler places[87].

In some cases, yields will improve as temperatures rise by 2°C or even 4°C; in some cases they'll fall. Some papers give the balance as positive[88], some as negative[89],[90],[91]. But there's an urgent need for studies that are better matched to the likely temperature rises in the world's major breadbaskets, which could in some places be higher than 4°C, even if overall heating doesn't exceed 2°C[92].

Moreover, the weight of grain we produce tells us little about how well it might feed us. Even if rising yields can be sustained, experiments and modelling studies show that a combination of higher temperatures and higher concentrations of carbon dioxide in the air will greatly reduce the amount of minerals (such as iron, zinc, calcium and magnesium), protein and B vitamins crops contain[93],[94]. The reason seems to be that plants grow faster in these conditions, and have less time to absorb nutrients[95].

One study estimates that an extra 122 million people could suffer from protein deficiency by 2050 as a result of rising greenhouse gases[96]; another suggests 148 million[97]. Anaemia in poor countries is a major health problem, especially for girls and women; if crops contain less iron, many more will suffer[98]. Zinc deficiency already affects over a billion people: it can cause premature birth, stunting and weakening of the immune system[99]. A further 130 million people could become deficient in folate, one of the B vitamins[100]. Folate deficiencies can be devastating to pregnant women and their foetuses. One paper describes the falling concentrations of protein and minerals in crop plants as “existential threats”[101].

As the planet heats, the number of extreme weather events increases. A study of insurance payouts for maize and soybeans in the US shows that the 1°C of global heating we’ve already experienced has almost doubled the crop losses caused by droughts and heat waves[102]. While there were fewer payouts for frost and deluge, the net effect of extra heat appears to be highly damaging, reducing the food supply and, crucially, causing it to fluctuate more violently.

Worldwide, there are likely to be more cyclones, worse hurricanes, more droughts and more floods[103]. In some regions, moderate weather has given way to a violent cycle of flood and drought[104]: instead of rain bringing farmers relief from droughts, it now drowns their crops. When the waters recede, the drought resumes. Drought, in some regions, brings fire, that destroys homes and crops and kills farm animals. Scientists have discovered an unexpected impact of wildfires: even hundreds of kilometres downwind of a major conflagration, the ozone pollution and aerosols released can damage the health of plants and reduce crop yields[105].

Extreme weather affects not only the production of grain, but also its transport. Around 55% of the cereals and soybeans that are traded internationally are shipped through at least one “chokepoint”: the Panama Canal, the Suez Canal, the Turkish Straits, the Strait of Gibraltar, the Bab-el-Mandeb, the Strait of Hormuz or the Malacca Straits[106]. Some of these chokepoints have already been affected by severe weather. The Turkish Straits have been restricted by high winds and the Panama Canal by drought[107]. In 2021, a sudden gust of wind during a sandstorm helped drive a container ship – the Ever Given – across the Suez Canal, wedging its bow into the bank[108]. It was stuck for six days, during which time several billion dollars’ worth of cargo was delayed, as ships at either end of the canal were unable to pass. If the Ever Given had had to be unloaded to float it off the bank, which would have been necessary if the diggers and tugs had failed to release it, the operation would have taken weeks, and might have caused a serious disruption to food supplies. If this disruption had coincided with the effective closure of the Turkish Straits by Russia’s invasion of Ukraine the following year, the foodchain, for hundreds of millions of people, might have snapped.

One fifth of the world’s wheat exports and one sixth of its maize exports pass out of the Turkish Straits, which are just a kilometre wide at their narrowest point. A quarter of the soybeans and a quarter of the rice traded worldwide pass through the Straits of Malacca, whose bottleneck is a slightly more generous 2.5 kilometres[109]. The Panama Canal, one third of a kilometre across, carries 40% of US maize exports, and half its soybeans. If the canal had to close entirely, many of the ships that would have passed through it would reroute through the Straits of Malacca (crowded at the best of times), causing, in some months, an 80% increase in traffic. As ships stack up in the lanes, waiting to move through, the just-in-time delivery system comes under severe strain[110].

But the least safe of our assumptions is as follows. Farmers all over the world are advised to raise their yields with the help of irrigation. A global study discovered that closing the yield gap worldwide would require 146% more fresh water than is used today[111]. Just one problem: this water does not exist.

Over the past 100 years, humanity's use of water has increased six-fold[112]. Irrigation already consumes around 70% of the water people withdraw from rivers, lakes and aquifers[113]. Because so much water is used for farming, rivers such as the Colorado and the Rio Grande fail to reach the ocean, while lakes like the Aral Sea are shrinking. Irrigation demand is one of the reasons why species living in freshwater are becoming extinct at roughly five times the rate of species that live on land[114].

Already, 4 billion people suffer from water scarcity for at least one month every year[115]. Thirty-three major cities, including São Paulo, Cape Town, Los Angeles and Chennai, are threatened by extreme water stress: during droughts, some of them could lose their supplies altogether[116].

At the same time, crucial water sources are disappearing as a result of global heating. Around one third of the world's irrigated farmland depends on the water running off mountains. As groundwater is overused and demand increases, the importance of mountain water will rise: another blithe assumption is that it will provide around half the world's needs by the middle of the century[117]. But mountains, on average, are heating faster than the rest of the planet's surface[118], and the glaciers and snowpack that supply much of this water are shrinking.

In the world's largest irrigated farming system, along the Indus River, the threat of water wars is as real as the threat of oil wars in the Middle East. Already, 95% of the river's flow is extracted to feed and clothe people in Pakistan, India, China, Afghanistan and, through exports, several other nations[119]. Water stress in this catchment is already intense, especially in Pakistan. Irrigation water is largely supplied by glaciers and snowpack in the Himalayas and the Hindu Kush[120], [121]. By the end of the century, between one third and two thirds of the ice mass in the Hindu Kush and the Himalayas is likely to have disappeared[122]. The volume of water running off them will probably peak around the middle of the century, and then decline[123]. As the economy and the population grow, by 2025 the demand for water here is expected to be 44% greater than the supply. New agricultural, industrial and urban developments are being built on the expectation of water supplies that do not exist.

In the western US and Canada, Central Asia, Chile, Argentina, Turkey, northern Italy and southern Spain, vanishing mountain ice and snow could have devastating impacts on crop production. Snowmelt in temperate regions often arrives just as crops need it most: during the early stages of growth. Farmlands that depend heavily on melting snow produce 10% of the world's irrigated rice, a quarter of the irrigated maize and a third of our irrigated wheat[124].

Climate breakdown is likely, on the whole, to make wet places wetter and dry places drier[125]. Regions that already suffer from water stress, such as the lands surrounding the Mediterranean, southern Africa, eastern Australia and the drier parts of Mexico and Brazil, are drying out, after just 1°C of heating. Another degree, one estimate suggests, would parch 32% of the world's land surface[126]. One paper forecasts that, in the worst case, the proportion of the land used to grow wheat today that suffers from severe droughts will rise from 15% to 60% by the end of the century[127]. Even in the best case – in other words, if countries keep their promises under the Paris Agreement on climate change – the frequency and intensity of droughts in these regions would double by 2070. By the middle of this century, severe droughts could simultaneously afflict an almost continuous belt of land from Portugal to Pakistan.

Altogether, according to a paper in the journal One Earth[128], the impacts of climate breakdown could push one-third of the world's food production out of its "safe climatic space" by the final two decades of this century. "Safe climatic space" means the conditions that allow humans and their activities to persist.

There's a widespread belief that these great threats could be overcome by growing new varieties of crops, resistant to drought and heat stress. But this could be an example of the Adaptation Illusion[129]. Much of the yield gain in major crops that researchers expect under normal conditions will come from new drought- and stress-resistant traits. These, for example, allow crop plants to withstand competition with each other when they are grown closer together, or to be grown at hotter times of the year. In other words, the effect of these new traits might already have been counted. When people claim that, by developing drought- and stress-resistant varieties, crop yields can be maintained in the face of the additional drought and heat caused by climate breakdown, they could be counting the same gains twice.

6. We treat soil like dirt

Even if we manage to address all these crises, our mistreatment of the soil would still pose a major threat to food security. Remarkably, while there are international treaties on telecommunication, civil aviation, investment guarantees, intellectual property, psychotropic substances and doping in sport, there is no global treaty on soil. We seem to be leaving the survival of the ecosystem from which we obtain 99% of our calories[130] to chance.

In the UK, perhaps the greatest threat to our soils is maize farming. Maize is slow to develop in the spring, and often harvested too late to follow with a winter crop. The stubble is widely spaced and sparse. As a result, the soil in these fields tends to be exposed at the times of year when rain and wind are most likely to strip it from the land. It is grown here primarily for two purposes: to feed dairy cattle and to produce biogas[131], a gross perversion of what was sold as a green technology.

Feeding a biogas digester with a capacity of 1 megawatt requires between 20,000 and 25,000 tonnes of maize a year[132]. This means that 450 or 500 hectares of land must be used to grow it. By comparison, wind turbines need one third of a hectare for every megawatt of capacity[133], or 1500 times less land.

One scientific paper reports that the soil structure has been damaged in 75% of fields used for growing maize, sampled in south-west England[134]. Partly because of the loss of carbon as the soil is washed away, biogas made from maize is likely to cause more greenhouse gas emissions than burning fossil methane. An estimate in Germany suggests that in some cases its emissions are comparable to burning coal[135]. Given that maize farming for biogas occupies arable land with a high potential for growing crops for human consumption, and that it can severely damage this potential, stopping such a perverse land use, which is sustained entirely by public subsidies, would enhance our food security.

Soil erosion is generally most severe however in poorer countries. This is partly because many of them are in the hotter regions of the world, where extreme rainfall, cyclones and hurricanes can rip exposed earth from the land, and partly because hungry people are often driven to cultivate steep slopes and other fragile places. One paper finds that erosion rates in the world's poorest nations have risen by 12% in just 11 years[136]. In some countries, mostly in Central America, tropical Africa and South East Asia, over 70% of the arable land is now suffering severe erosion[137]. Already, as a result of drought, soil erosion and the overuse of land, desertification affects one third of the world's people[138]. Soil damage in dry places is one of the reasons why grain yields in sub-Saharan Africa have mostly failed to increase since 1960, even as they have boomed in the rest of the world[139].

Climate breakdown will exacerbate this loss. More intense droughts and storms of wind and rain will rip into soils in North and central Africa, the Arabian Peninsula, West Asia, Peru and Bolivia, even at the lowest levels of expected heating[140]. Under the worst climate scenario, extreme weather would also help denude central and eastern parts of the US and Canada, Mexico, southern Brazil, most of Africa, Europe, India, China and Russia.

While the most obvious vulnerabilities are caused by ploughing and by compaction with heavy machinery, there are subtler impacts that might, in the long term, be extremely damaging. For example, neonicotinoid seed dressings harm a wide range of soil animals[141],[142] and microbes[143],[144]. Soil is a biological structure, created by the organisms that inhabit it. Their destruction leads rapidly to soil degradation.

Another likely threat to soil biology comes from sewage sludge, 87% of which in the UK is sent to farms[145]. The testing rules here have not been updated since 1989. As a result, it's screened for just a handful of contaminants before delivery: heavy metals, fluoride and dangerous bacteria. Since the rules were written, we've discovered that sludge commonly contains a much wider range of toxins, for which no tests are conducted.

The UK Government commissioned a report on this issue, then failed to publish it[146]. It warned that the sewage sludge being spread on farmland contains a cocktail of dangerous substances, including PFASs ("forever chemicals")[147], benzo(a)pyrene (a Class 1 carcinogen), dioxins, furans, PCBs, PAHs and micro-plastics, all of which are persistent and potentially cumulative. Without comprehensive testing, farmers have no idea what they are buying. The Government keeps promising new rules, then postponing them[148]. We could be looking at a severe threat to food safety and security, yet it receives almost no public attention. Government must act quickly to prohibit the spreading of sewage sludge, before large tracts of farmland become unusable, and the damage to ecosystems, from soil to sea, irreversible.

To make matters even worse, microplastics are sometimes spread deliberately on the soil, to make it more friable[149]. Thousands of tonnes of plastic are added to fertilisers, to prevent them from caking[150]; or to delay the release of the nutrients they contain, ensuring that they seep into the soil slowly, matching the demands of the crop. In this case, fertiliser pellets are coated with plastic films – polyurethane, polystyrene, PVC, polyacrylamide and other synthetic polymers[151] ¬– some of which are known to be toxic[152], all of which disintegrate into microplastics. It is almost unbelievable that, in the 21st Century, we deliberately contaminate agricultural soils with persistent and cumulative pollutants.

Experiments show how microplastics cascade through soil food webs[153], poisoning snails[154], springtails[155], mites, ants and nematodes[156], stunting earthworms[157], halving the fertility of potworms[158]. When they decompose into nanoparticles, they can be absorbed by soil fungi[159] and accumulated by plants[160]. We currently have no idea what the consequences of eating contaminated crops might be. Nor do we know what the combined and cumulative effects of the cocktail of toxins spread in sewage sludge might be, either on soil ecology[161] or on our own health.

7. Restoring food security

As some of the examples above suggest, there are some clear and decisive steps the Government could take to enhance food security at the national level. But it is just as important that the UK Government, in conjunction with others, acts at the global level to restore resilience to the global food system. It should be negotiating with other states to reintroduce the six elements of systemic stability: diversity, asynchronicity, redundancy, modularity, circuit breakers and back-up systems.

What does this look like in practice? A crucial strategy is to diversify and decouple the system that has created the Global Standard Farm. Above all else, this means addressing corporate monopolies: the concentration of market power in the hands of a very small number of enterprises. To this end, as in all sectors, anti-trust laws should be strong and intellectual property rights should be weak. In recent years, corporate lobbying has pushed global and national rules and their implementation in the opposite direction. The result is extreme concentration, especially in digital, retail and food and farming, which is often anti-competitive but seldom challenged by governments. This trend undermines security in all systems; the food system is no exception.

We also need to diversify sources of advice and support for food producers. One paper found that the UK, while spending £6 billion of foreign aid across 7 years on conventional farming projects, provided no funds at all for projects whose main focus was the development or promotion of agroecology[162]. In fact, not a penny was spent on organic farming of any kind: it was all directed at agriculture of the sort the private sector already promotes, reinforcing the system's homogeneity and synchronisation. Government funding for research often follows commercial agendas. It should do the opposite, exploring techniques which cannot be monopolised by corporations and used by them to dominate the global food system.

Environmental resilience means farming systems that are simultaneously high-yield and low-impact. One route to developing them is support, especially through research and extension, for high-yield agroecology. High-yield agroecology depends in turn on a much richer knowledge of soil. Just as the spectacular rise in yields over the past century arose from a better understanding of soil chemistry, sustaining those yields without undermining Earth systems will depend on a better understanding of soil biology. But soil remains, in effect, a black box. While nations are spending billions on the Mars Rover Program, to characterise the surface of that planet, we know almost nothing about the surface of our own. Funding for soil science remains extremely sparse.

Governments should encourage not only a diversification of crops but also a diversification of cropping techniques. One promising approach is to support the development and uptake of perennial grain crops, that have great potential to reduce damage to the soil and the need for water and fertiliser. One such crop, a rice variety, has already been fully commercialised, and is now being grown across 15,000 hectares in China[163]. Many more are in development, but most of the work has been left to small non-profits[164]. Not only can perennial crops reduce environmental impacts, but they also diversify, de-synchronise and compartmentalise arable agriculture, enhancing systemic resilience.

There is also great potential to enhance food security by developing alternative protein sources. For the past 12,000 years, we have concentrated on the selection and breeding of multicellular organisms: plants and animals. We have pushed some of these organisms to and even beyond their limits. Yet we have scarcely begun to explore the potential of unicellular species. Precision fermentation – the brewing of particular microorganisms – can generate protein on a tiny fraction of the land area and with a tiny fraction of the water and fertiliser use required by any form of multicellular production[165],[166]. My estimate suggests that all the world's protein could be grown in an area of 420km2[i], which I believe would fit into the committee chair's constituency. (In common with estimates for all other kinds of protein production, this area does not include processing facilities and the requisite energy infrastructure).

Of course, such production should not be concentrated, in the chair's constituency or anywhere else, but distributed as widely as possible. A further great advantage of this approach is that it can be pursued anywhere with an energy source, particularly if the microbial feedstock is hydrogen or methanol. Nations which are entirely reliant on imports from distant places, as they don't possess sufficient fertile land or water for agricultural production, could use precision fermentation greatly to reduce their import dependency, while reintroducing modularity to the system. In principle, every town could have its own microbial breweries, producing protein-rich foods tailored to local demand.

But again, for this to happen, anti-trust laws should be strong and intellectual property laws should be weak. We do not want to replicate the dysfunctions of the existing food system in the new one. Precision fermentation has the potential to create an entirely separate food chain: a backup system that would further enhance systemic resilience.

If alternative protein technologies largely replaced livestock farming and industrial fishing, we could greatly relieve pressure on Earth systems and release very large areas of land and sea for ecological restoration. This could be our last best hope of avoiding environmental catastrophe. A global rewilding on this scale could stop the Sixth Great Extinction in its tracks while simultaneously drawing down much of the carbon dioxide we have released into the atmosphere. It is quite difficult to see how we will get through the century without it.

The major obstacle to the adoption of these technologies is currently regulatory bottlenecking. Novel foods approval in both the European Union and the United Kingdom is slow and cumbersome[167], and further impeded by a lack of institutional capacity[168]. It is essential that all new products be thoroughly safety tested, but without unnecessary and sometimes protectionist delays.

Difficult as it is to resolve, we also need to address the conundrum mentioned in Section 4: how can we continue to rely on long-distance trade and mass production without favouring transnational corporations and accelerating the consolidation of the Global Standard Farm? One possible approach is a revitalised fair trade movement, in which companies buying bulk commodities are pressed to source them from small, productive farmers.

Above all, we need a far better public and political understanding of complex systems. Systems theory should be incorporated into secondary school science teaching, as a foundational tool for understanding the world around us and the means by which we can predict trouble, and intervene to prevent it.

Footnote:

[i] Wet weight protein content of soybeans is roughly 17%. USDA figures show 120m tonnes of soybean harvested in the US/yr-1, so = 20.4mt/protein/yr-1. Total global protein requirement = 146 mt/yr-1.

So US soy provides 14% of global protein. Tomas Linder reports that the equivalent amount of dry bacterial biomass could be produced on a land area of 210km2: https://doi.org/10.3389/fsufs.2019.00032. Protein content of this biomass is roughly 60%, so land area required for protein equivalent to US soy crop is 28% that of equivalent soy biomass = 58.8km2. If that provides 14% of total global requirement, total global protein requirement could be met on 420km2.

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