# Post-COVID-19 land use options to achieve food security, healthy diets and a sustainable environment.

**A report on the opportunities and constraints of UK food and land management options in terms of production potential and environmental impacts.**

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## Summary

This report presents summary findings of a study looking at how the UK's food production can align to enable development of a food system that better meets requirements for a healthy diet and a sustainable environment. The COVID-19 pandemic has primarily been a demand side shock, with economic assess, particularly for those on low or newly lost incomes, causing food and nutrition security issues, rather than supply side shortages. The pandemic and post-EU exit recoveries present an opportunity to realign the food system with human health needs and sustainable, decarbonised production systems.

To investigate options, we used a set of four post-COVID-19 recovery and post-EU exit plausible future scenarios, developed as part of a wider UKRI funded project 'UK food and nutrition security during and after the COVID-19 pandemic', are used to frame the key drivers that may shape future food demand, production and consumption.

The context is that there is need, given the economic and social pressures brought about the pandemic, diet related health issues, climate change, biodiversity loss and ecosystem degradation, to transform the global food system. The aim of this study is to present information to support informed decision making on how the UK food system can transform to achieve multiple human and environmental health objectives.

The research approach is to first consider the potential for change in the UK agriculture and land use, on the basis that changes in UK food production will be highly dependent on the amounts and types of food imported. Import and export issues are addressed in a series of other reports produced by the 'UK food and nutrition security during and after the COVID-19 pandemic' project funded by the UKRI and ESRC.

**The key findings are:**

- There are sufficient land resources available in the UK to enable food production that aligns with a healthy diet.
- Changes in UK land use and food production to achieve a healthy diet can also reduce the environmental footprint.
- Changes in land use and types of food produced needed for human and environmental health will require substantial changes to the food system in respect of consumer behaviour driving market demand.
- Transformation of food production will have consequences on rural communities, socio-economics and business practices, with both risks and opportunities.

**Scenarios:**

- The scenarios used are not predictive. Instead, their purpose is to explore options that achieve food and nutrition security, positive human diet and environmental benefits, particularly climate change mitigation. This approach enables a range of potential trade-offs to be identified between benefits and dis-benefits.
- It is important not to underestimate the extent of the current health crisis. All four exploratory scenarios envisage a plausible, ongoing public health crisis deep into the coming decade, with large inequalities remaining.
- High levels of income inequality, envisaged as persistent in our scenarios, are assumed to result in negative health outcomes.

- To explore the future, there is a need to recognise Brexit as a plausible confounding factor of negative UK food and nutrition security outcomes post pandemic.

**Food groups and healthy diets:**

- Recommendations exist on the types and proportions of foods and drinks needed for a healthy balanced diet, such as Public Health England's Eatwell Guide, that can be used to identify opportunities for changes in land use and food production.
- Moving from current to the recommended patterns in the Eatwell Guide requires more energy to be derived from carbohydrate and protein, and less from fat. The proportion of simple sugars in consumed carbohydrates should be halved, salt consumption should be reduced, and fibre consumption increased.
- A move to healthier diets is expected to increase the demand for milling wheat, vegetables and fruits, with declines for beef, pig meat, sugar, and milk. If these changes occurred, they would affect the level of UK self-sufficiency for these products.
- The COVID-19 pandemic has led to a "K" response in the consumption of healthier food: some people have healthier diets; many people have had a less healthy diet. For example, about 30-40% reported eating more confectionery, biscuits, and cakes compared to about 15% who had eaten less. Because unhealthy food is typically cheaper than healthy food, financial insecurity leads to less healthy diets.

**Risks and opportunities of aligning food production to demand:**

- To increase production to match demand more closely for those commodities already produced in the UK, while at the same time adjusting to aligned production with diets that are healthier for humans and the environment, will have consequences for land use, farm inputs, and income.
- Overall, moves towards self-sufficiency, healthy diets, and the reduction of GHG emissions favour reduction in meat and dairy, as well as cereals because of a decline in demand for livestock feed. Potatoes and horticultural crops (fruit and veg) would see substantial increases in production.
- The combined impact of these changes would be to reduce the demand for land, both pasture and arable (down by as much as 26%) and reduce nitrogen application by up to 23%. Pesticide input would increase substantially (up to 58%) and the shift in commodities would results in increase in income by as much as a 28%.
- Post-COVID-19 Green Recovery scenarios offer a way forward that tackles climate change and diet related ill-health while also offering greater production efficiency. However, the changes in the livestock and horticulture sector would demand significant structural changes to the UK agri-food system.

**Impacts of agroecological farm practices.**

- Sustainable production of food in the UK requires a transition to agroecological practices where the farmed environment is managed for provision of multiple benefits in terms of both crop production and the environment.
- Agroecological farming is based on functional biodiversity which is utilised for: a) internal system regulation and increased production efficiency which together reduce reliance on agrochemical inputs, and; b) enhancing resilience through functional redundancy, thereby insuring against future shocks and improving yield stability in the long-term.
- The capacity for UK farming to benefit from agroecological practices, in terms of long-term sustainability and resilience to future disruption, depends on the extent to which transition is supported following Brexit and in the aftermath of the covid pandemic.

- A “build back greener” recovery, with incentives for crop diversification, soil health and biodiversity management is most likely to deliver the opportunity to transition to more sustainable agroecological production systems in the UK with the potential to meet demands for a more diverse range of home-grown food products.

**UK capacity for protein self-reliance.**

- The capacity of production of high-protein plant grains, and vegetative material, is high, though not realised in practice due to the availability and affordability of imports, despite the high environmental costs of those imports, and loss or/and non-development. of national capacities.
- Animal and aquaculture feed markets present largest demand for home-grown plant protein. Particularly pig and poultry production, such that only a very small percentage of UK grown plant protein is sold to higher premium more lucrative human food markets – and despite the potential human health and well-being benefits. Also, reduced NHS cost burden.
- There is a lack of national capacities to process high-protein plant material to human food grade. National food security should ensure a bio-regionalised approach, such that functionally equivalent capacities are strategically developed across regions of the UK.
- Home-grown legume-based food systems have the capacity address food and nutrition security matters, and other major society challenges such as climate change and biodiversity loss. This can be achieved without jeopardising productivity with the proper facilitative environment in place.

**New technologies:**

- The infrastructure of Controlled Environment Agriculture / Vertical Farming (CEA/VF) is evolving and improving at a significant rate and largely driven by industry meaning that the outputs have been developed on commercial foundations.
- The energy input conundrum for CEA/VF is capable of being resolved and that better links to (renewable) energy generation and management sectors need to be forged.
- The next step change for CEA/VF food production is likely to be biological as we look to redesign the crops to suit the growing environment as we have done for traditional agriculture.
- At the lower technology readiness level, is the production of laboratory or cell culture-based meat which requires very defined levels of controlled environment.
- Laboratory meat, like crop CEA/VF systems, is attracting significant investment and due to the significant contribution of livestock production to GHG emissions could potentially offer routes to low or net zero meat.
- Other opportunities include insect production for protein, oil etc

## Conclusions:

It is feasible to re-align the UK’s land use for food production to meet the requirements to enable a healthy diet. This study has focussed on the production aspects of food in relation to improved human and environmental health. Clearly there are wider considerations including how consumer behaviour and utilisation changes required can be facilitated, but this study has highlighted that from a production perspective, the UK is capable of providing sufficient nutritious food under a range of plausible future scenarios. Post-COVID-19 recovery measures that facilitate diversification in food types produced using agroecological practices will improve human and environmental health. Further, more widespread adoption of agroecological approaches are likely to have positive benefits for biodiversity and ecosystem functioning. The scale of changes will require substantial adaptation within the food system, with consequences on rural businesses and communities.

Post-COVID-19 Green Recovery scenarios not only offer a way forward that tackles climate change and diet related ill-health but also offer greater production efficiency by increasing the income generated from agricultural commodities while simultaneously reducing the required land area. Structural changes would be significant, with a possible reduction of the livestock sector by up to 66% and an 164% increase in horticulture driving a potential 158% increase in pesticide use, although other inputs (e.g. nitrogen) would decline. However, the increased production efficiency could provide scope for innovations in crop, livestock, and other land use strategies to address negative socio-economic and environmental aspects of agricultural transition.

UK infrastructure for the processing of plant protein to human food grade is lacking. Where it does exist, this is to serve mainly animal food markets. Even the limited quantity of high protein grains destined for human food consumption is exported. There is an urgent need to develop bio-regionalised plant-protein facilities so that an array of equivalent capacities is developed and maintained strategically across the UK. The creation of such a capacity would accommodate the necessary functional redundancy to allow food system resilience in the face of system shocks. Additionally, this would demand that protein import dependency is maintained below a threshold level (to be decided). Also, that storage facilities are also re-established nationally regionalised basis, for high protein-grains, or -isolates.

New technologies for food production are advancing at a rapid pace and have the potential to contribute positively to improve food security. Opportunities exist to provide locally produced food from controlled environment agriculture where sustainable water and renewable energy are available.

## Recommendations

- Further evaluation of the impact of social, economic, and environmental drivers on future consumption patterns is necessary to support a more rigorous assessment of future demand on UK agricultural production.
    - There is need for improved understanding of the consequences of changes in land use and management to meet multiple objectives and how these impact on food businesses and rural communities.
- Opportunities to improve planetary health outcomes through future UK agricultural production strategies should be explored and policies pursued to achieve this, e.g. rebalancing production away from livestock to horticulture sectors.
    - There is need to better understand how changes in land use can be achieved to meet multiple objectives, and where this is best applied in respect of land capability.
- There is need to assess opportunities and barriers associated with a substantial reduction in the requirement for livestock grazing and fodder crops, including the diversification of production systems considering increases in other land uses such woodland creation for carbon benefits.
- Policy development should scope the potential to expand horticulture production, considering agronomic, environmental, and business aspects. Specific consideration should be given to the innovation and uptake of practices (e.g. Integrated Pest Management) to counter existing environmentally damaging intensive practices.

# Contents

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This report is available on the project website:
https://www.hutton.ac.uk/research/projects/covid-19-food-and-nutrition-security

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# Introduction

The COVID-19 pandemic is a public health crisis that has had a substantial impact on all aspects of life and affected everyone, including our food and nutrition security and relationships with food. This report details research assessing the UK food system in respect of the balances between what is required for a healthy diet and what is over- and under produced in the UK and relationships between consumption and demand.

# Background

The pandemic has highlighted both strengths and weaknesses in the global food system. The key strengths can be described as centred on people and their resilience: the ability of food producers and those in the production supply chain to maintain food availability; those in logistics, transport and retail to enable access; and the public in their ability to adapt. In understanding the weaknesses, it must be first recognised that the pre-pandemic food system was fundamentally flawed (Lang 2020, BMJ 2020) and requires substantial realignment with human health and environmental quality needs (Dasgupta 2021, Dimbleby 2021).

This is particularly the case in respect of food and nutrition security, inequalities within society, poor diet and nutrition, and lack of environmental sustainability. There have been calls for radically transforming the global food system to achieve a resilient food system before the pandemic (Poore and Nemecek, 2018, Willett and Rockstrom, 2019, Hawkes, 2020), and during it (Stordalen and Rockström, 2020).

The pandemic has exacerbated the issues of inequalities in food security whilst impacts on sustainability are yet to be determined. Recovery, however, is an opportunity to address food system flaws and to contribute to climate and environmental goals. Our hope is that this report will help inform discussion in a post-pandemic recover and Brexit trade agreement adaptation period about how an equitable, resilient and sustainable food system can be developed.

This is set against a background of an increased understanding of the risks associated with climate change (IPCC 2018, IPCC 2019), the degradation of the natural environment (IPBES 2018, 2019, Dasgupta 2021) and species extinction (Ceballos et al 2020) that have added to our appreciation of the additional threats posed to food and nutrition security by ecosystem service deterioration.

The pandemic situation is a rapidly evolving one, presenting challenges in identifying and using relevant and up to date information. The report aims to capture both the latest information available and that produced since the onset of COVID-19, to capture the overall state of food and nutrition security using www-based literature reviews. The report is an output from the Economic and Social Research Council (ESRC) funded project "UK food and nutrition security during and after the COVID-19 pandemic" (Grant ES/V004433/1).

## Defining Food and Nutrition Security

The UN Food and Agriculture Organisation (FAO) defines food security as '*when all people, at all times, have physical, economic and social access to sufficient, safe and nutritious food to meet their dietary needs and food preferences for an active and healthy life*' (FAO, 2009, p. 1). This definition uses key aspects, referred to as the four pillars (or dimensions) of food security (FAO, 2008):

**Availability:** This includes the supply side of food production, reserve stocks and net trade.

**Access:** The ability of people to access food, separated into:

- Physical: ability to travel, access shops and markets and store food.
- Economic: ability to acquire food by purchase or trade.

**Utilisation:** How the body utilises nutrients, with sufficient energy and nutrient intake being connected with feeding behaviours, preparation practices, diversity of diet and distribution within households.

**Stability:** The stability of the other three pillars, when periods of reduction in them can lead to a deterioration in nutritional status.

For food and nutrition security to be realised, all four pillars must be fulfilled simultaneously. Beyond these pillars, it is also necessary to consider other aspects, including the relationships between diet and health (malnourished or overweight and obesity), and factors that limit or inhibit nutrient uptake. A further set of issues include: the practical, economic and moral dimensions of food waste: over-consumption; and nutritional value loss through conversion of primary production into other food products.

A key concern for food and nutrition security in the UK is the inequalities that the food system causes, and now how the pandemic is accentuating the differentiated impacts between sections of society.

In the context of the current COVID-19 pandemic, a further dimension is the duration of insecurity: whether long-term and / or persistent (chronic insecurity); or short-term and temporary (transitory insecurity). A key concern for this project, of which this report is an initial step, is to better understand whether the pandemic impact is part of a wider development of risk to food security arising from other drivers, particularly climate change, biodiversity loss and ecosystem degradation. The aim of this report is to help better understand risk, which is a function of vulnerability, exposure and threats to the food system and its ability to fulfil the four pillars of food and nutrition security.

## About this report

This report provides information to support debate and decision making on options for changes to food production and land management in the UK with respect to pandemic impacts and in the context of improving environmental sustainability alongside achieving healthy diets. The information is presented within the structure of four plausible future scenarios, developed within the overall ESRC project, through interviews with experts and a scenario planning workshop exercise (Duckett et al 2021).

This report is part of a series focussed on the UK's food and nutrition security. The overall project context is to assess the pandemic impact on food and nutrition security, assess options for alternative approaches to food production in the UK, and subsequently explore what lessons can be learned in respect of addressing other risks, particularly climate change, biodiversity loss, and ecosystem degradation. Further details of the project is available here: COVID-19 Food and nutrition security | The James Hutton Institute.

Other associated reports are:

UK food and nutrition security in a global COVID-19 context: an early stock take (Chatham House)
UK food and nutrition security in a global COVID-19 context: an update (Chatham House)
An overview assessment of the COVID-19 pandemic on the UK food and nutrition security (James Hutton Institute)

## Plausible Scenarios

Full details about the development and content of the four plausible scenarios are available here:

Scenarios for UK Food and Nutrition Security in the wake of the COVID-19 Pandemic

The future is inherently uncertain. However, we can look at both past events and the current situation to identify themes and construct patterns to promote strategic thinking. Scenario Planning utilises abductive reasoning in this way to yield plausible hypothesis. In contrast to deductive or inductive logic, there is no attempt to verify the projections. The plausibility test acts rather to harness human creativity and imagination in making plans that are robust enough and sufficiently flexible to deal with unpredictable developments.

The project has adopted an 'exploratory' scenario development approach, a method often deployed to stimulate creative thinking or to gain insight into the cascading effects of social, economic, and environmental drivers. Scenarios are crafted to form plausible accounts of what the future might look like by considering how known drivers of change will potentially operate over time.

Exploratory scenario planning typically asks a focal question containing a time horizon. We selected the year 2030, a timescale sufficiently distant to get a strategic view looking beyond current operational concerns but staying within policy cycles and avoiding the science fiction associated with distant futures. We asked our scenario planners the following question:

**What will FNS look like in the UK in 2030 given changes to the food system following the emergence of the COVID 19 pandemic?**

Six overarching drivers of change were determined by the research team in a semi-structured interview guide. Drivers of change are forces that will shape the future environment. The six preselected overarching drivers are: Demographics, Economy, Public Health, Institutions & Governance, Technology, Ecology & Climate.

Experts were invited to articulate specific challenges and opportunities in each of the six categories forming key drivers of change for our focal question. We recruited our expert scenario planners, acknowledged Duckett et al (2021), from areas relevant to Food and Nutrition Security including health, agriculture, aquaculture, and food systems. They worked with our bespoke, structured technique to develop four scenarios considering key drivers of change and their plausible impacts on the UK's food and nutrition security. Our 'virtual' process was developed to fully comply with the COVID-19 lockdown measures in force during 2020.

No one knows how or which drivers will influence events given that the future is inherently uncertain, however, scenario planning works by exploring different assumptions about how drivers of change may operate. Contrasting sets of assumptions frame the four following scenarios.

***Scenario 1 : 'UK Recovery First'***

*A national recovery at any cost has been achieved against the backdrop of recessionary pressures. Neither a radical green recovery nor any widespread levelling-up have occurred, resulting in higher food prices, negative Food and Nutrition Security outcomes for those on the lowest incomes and mounting societal unrest.*

***Scenario 2: 'Green UK First'***

*A domestic green recovery has achieved environmental improvements within a less globalised, more inward-looking world. Levelling-up has not been achieved and inequality alongside higher food prices has resulted in negative Food and Nutrition Security outcomes for those on low incomes.*

***Scenario 3: 'Best of British'***

*The UK has responded to greater protectionism by investing in UK agriculture putting quality at the centre but without any effective levelling-up, resulting in negative Food and Nutrition Security outcomes for those on low incomes set against higher quality produce for many others. Innovation and technology have helped the food sector to recover and prosper and there has been continuing consolidation resulting in larger farms and food businesses. Hospitality is radically reshaped around suburban spaces.*

***Scenario 4: Back to Basics***

*Economic recovery has been achieved within this, the most prosperous of our post BREXIT scenarios, featuring a return to globalisation and buoyant international trade. The return to the pre pandemic baseline has been an uphill struggle and neither Green Recovery nor levelling-up have markedly reshaped this unsustainable and unequal future.*

## Implications for UK Food and Nutrition Security

Our four scenarios describe plausible futures for the UK food system with a particular focus on food and nutrition security or FNS as defined by the FAO (see also APLU 2017). The following sections articulates the strategic thinking regarding these four pillars and presents the key ideas that emerged regarding cascading effects within and between scenarios.

## Availability

Underpinning FNS is the basic requirement that sufficient food must exist in the first place. Our exercise identified challenges around greening the food system while simultaneously ensuring the delivery of sufficient food stocks. The restructuring of production systems to reduce greenhouse gases, partly by improving the carbon footprint of livestock, particularly in the uplands, restoring peatland, expanding afforestation, and going hard towards net zero targets, requires a corresponding effort in rebalancing the food system in terms of rewarding environmentally sustainable activities that deliver food. This balancing act already appeared precarious in the face of emergent post-Brexit trade relations. UK agriculture needs to find its way under future arrangements with trading partners new and old, and within a changed labour market. COVID-19 has potentially exacerbated the problem by diverting political energy away from wider health and environmental goals. Allowing climate change mitigation and domestic production support arrangements to slip down the agenda is fraught with danger.

## Access

This pillar of FNS addresses the FAO concern that while food may be produced in sufficient quantities and available for consumption, it cannot deliver food security if it does not reach those who need it. People and food systems require adequate systems and resources to obtain appropriate foods for a nutritious and culturally suitable diet. To this end our scenario planners drew attention to the structural causes underlying people's choices about the food they eat and how marginalised groups lack agency to effect change. Radical recommendations were put forward to combat food poverty and the recent escalation in the use of food banks. Foremost among the ideas to address the root causes of inequality was a proposal to significantly increase the national minimum wage. A more equal society, it was argued, could be constructed with relatively higher wages for the bottom tier of society thereby expanding choices and increasing access to more nutritious diets. It was acknowledged that the issues around high unemployment could not be addressed by in-work benefits but that, under other scenario conditions, FNS could be improved via such measures.

Other key recommendations concerned the need not to underestimate the extent of the health crisis that has been created. In all four scenarios a degree of optimism has been taken towards ending the pandemic through public vaccination. However, all four scenarios envisage an ongoing public health crisis deep into the coming decade. C19 has wrought havoc on medical systems and social care, and left a legacy of problems as each scenario imagines in a subtlety different way.

So-called 'levelling-up', whereby economically deprived areas of the UK are given a boost relative to more advantaged areas, was greeted with general scepticism throughout this exercise. None of the four scenarios foresee imminent structural changes whereby food and nutrition security for the less well-off is improved or levelled-up in the coming decade. Conversely, a widening gap features in all four scenarios. This rather bleak assessment rests upon a shared view that different forms of recovery all face an uphill battle of one sort or another that will militate against an increase social justice *vis a vis* the food system.

## Utilization

Food must be prepared and consumed appropriately based on knowledge of basic nutrition and, food hygiene, alongside practical skills including handling and cooking, and cultural sensitivities. The pandemic has wrought changes upon the utilization of food in areas ranging from lockdown disruption of school meal provision to the severe restrictions on food outlets. Perhaps most alarmingly the use of food banks has grown as more people have been unable to purchase food due to changed economic circumstances. A potentially positive outcome regarding nutrition is that disruptions have led to an increase in home cooking.

Our scenarios variously reimagined the future foodscape as one in which a lower tier of UK society continue to experience food and nutrition insecurity. Positive dietary trends are anticipated, notably continuing flexitarianism in **UK Green Recovery First** and a generational shift in preferences towards local, seasonal, organic, vegetarian, and vegan food in **Best of British**, but in all four scenarios, the less well-off continue to struggle through lack of agency. Various proposals emerged throughout the exercise whereby education, information campaigns and economic incentives could be deployed to nudge or reshape social attitudes to nutrition. Our planners also highlighted food waste throughout the food system and recommended technology investment, specifically around both shelf-life and demand forecasting to improve the utilization of food stocks.

## Stability

For the food system to be a dependable delivery mechanism for public goods in terms of healthy, high quality affordable diets in the face of future shocks it needs to be safeguarded against the vagaries of international trade in a sustainable way. Current fears around declining UK food standards in the wake of a comprehensive new deal with the US are realised in **UK Recovery First** and avoided in **Best of British**. Much discussion centred around land use. **Green Recovery First** showed the potential for environmental gains without a radically improved food scape. Conversely, **Best of British** depicted a future in which more localised, more diversified production and consumption has been achieved within a more protectionist food system, yet without significant environmental gains.

Technological fixes are not viewed as a silver bullet to food and nutrition security. More advanced technological food systems, such as the UK system, face challenges that seem more connected to inequity than to technological shortcomings. Nevertheless, our planners saw technology as a part of the solution provided applications are directed towards appropriate goals, for example, reducing the environmental impact of water usage, increasing the use of renewable energy sources or shortening supply chains.

### Scenarios - Concluding remarks

It is not possible to represent an exhaustive range of future possibilities in a complex socio-technical system such as the UK food system. Unanticipated factors or 'unknown unknowns' will shape the future beyond anyone's ability to foresee. However, what we have been able to do is to creatively use relevant expertise to think through 'what if' scenarios, or synthetic futures, considering plausible assumptions in a limited range of contrasting permutations.

## Over- and under-represented food groups required for healthy diets

**Guidance on a healthy diet**

In March 2016, the UK Government promoted the Eatwell Guide to illustrate the types and proportions of foods and drinks needed for a healthy balanced diet (PHE 2016). The diet recommends an energy input for the "average" person of 9.4 MJ/day; in practice the specific recommendation for an individual will also depend on factors such as gender and age. The Eatwell Guide assumed a range of dietary constraints (Table 1) including the recommendation that less than 5% of food energy should come from sugars, and less than 35% from fats. The importance of Omega-3 essential fatty acids is recognised in the recommendation to include two portions of fish each week.

Table 1. Constraints used to develop daily UK dietary guidelines in the Eatwell Guide (PHE 2016)

| | | Constraint |
|---|---|---|
| Nutrients | Energy | 9.414 MJ/day |
| | Carbohydrates | ≥ 50% of food energy |
| | Free sugars | ≤ 5% of food energy |
| | Fats | ≤ 35% of food energy |
| | Saturated fat | ≤ 11% of food energy |
| | Protein | ≥ 14.5% & ≤ 15.5% of food energy |
| | Salt | ≤ 2.36 g sodium |
| | Fibre | ≥ 30 g |
| Foods | Fruit and vegetables | ≥ 5 portions per day |
| | Fish | ≥ 2 portions (2 * 140 g) per week |
| | Red and processed meat | ≤ 70 g per day |

**Comparison of UK diets with a healthy diet**

UK food consumption is described by the rolling National Diet and Nutrition Survey (NDNS) which interviews a representative sample of about 500 adults and 500 children each year (Bates et al. 2019). Because randomly selected participants in nutrition surveys typically under-report their consumption (e.g., Black et al 1993), the NDNS methodology requires participants to also consume a quantity of water including specific isotopes which are measured using urine samples (NDNS 2020). This analysis indicates that initially reported food consumption by those older than 10 years is typically only 67-72% of the actual consumption, and hence a modification is made to correct the values (Bates et al 2020).

Williams et al (2018) undertook research for Defra on the environmental effects of the UK moving from current rates of food consumption to a diet based on the Eatwell Guide (Table 2). The change to an Eatwell Guide diet resulted in a similar energy consumption of 9.4 MJ/person/day, but more of the energy was derived from carbohydrate (+16%) and protein (+12%), and less from fat (-26%). The proportion of simple sugars in the carbohydrates was halved from 55% to 27%, there was an increase in the consumption of fibre, and a reduction in sodium (as found in salt) consumption from 10.7 g to 3.5 g. The Eatwell diet was designed to also enable an increase in the consumption of minerals and vitamins such as iron, iodine and folate.

Table 2. Assumed baseline consumption of selected dietary nutrients and for an Eatwell Guide scenario as reported by Williams et al (2018). Increases of more than 10% are indicated in green, and decreases of more than 10% are indicated in red

| | Unit | Baseline | Eatwell Guide | Eatwell/ baseline |
|---|---|---|---|---|
| Metabolisable Energy | MJ | 9.3 | 9.4 | 102% |
| Protein | g | 88.8 | 99.5 | 112% |
| Fat | g | 70.1 | 52.1 | 74% |
| Carbohydrate | g | 258 | 299 | 116% |
| Dry matter | g | 453 | 491 | 109% |
| Fraction of simple sugars in carbohydrates | % | 55% | 27% | 50% |
| Non starch polysaccharide (NSP), fibre | g | 14.7 | 22.3 | 152% |
| Cholesterol | g | 3.0 | 2.5 | 86% |
| Sodium | g | 10.7 | 3.5 | 33% |
| Potassium | g | 3.4 | 7.6 | 223% |
| Calcium | g | 1.0 | 1.1 | 120% |
| Iron | mg | 15.0 | 21.7 | 145% |
| Iodine | mg | 170 | 195 | 114% |
| Folate | mg | 0.38 | 0.54 | 141% |

Williams et al (2018) also related the change in diet to changes in food categories (Table 3). The Eatwell diet scenario was designed to comprise a similar proportion of starchy carbohydrates (38%) and fruit and vegetables (39%) as found in the Eatwell Guide. The Eatwell scenario had higher levels of starchy carbohydrates (+100%) and fruit and vegetables (+24%) than the current UK diet. There was a reduction in foods high in fats and sugar (-60%), and the consumption of milk (-5%), and meat, fish, and alternatives (-10%). A decrease in red (-47%) and processed meat (-49%) consumption was partly offset by an increase in the consumption of oily fish (+100%), other white fish (+21%), white meat (+16%), and beans, pulses, nuts and seeds (+28%).

**Recent trends**

Prior to the COVID-19, some of the desired dietary changes were slowly happening in practice. A review of the National Diet and Nutrition Survey over the nine years from 2008-09 to 2016-17 (Bates et al 2019) showed significant reductions in fruit juice consumption, although across all age groups "free sugars" still comprised more than 10% of total energy consumption rather than the recommendation of no more than 5% (SACN 2015). Prior to COVID-19, there were also decreases in red and processed meat, and alcohol consumption. The pre-COVID-19 analysis also highlighted that the intake of minerals and vitamins for some groups was lower than recommended. For example, the survey identified increases in Vitamin A and folate deficiency in girls (11-18 years), increased calcium deficiency in boys and girls, increased iron deficiency in women, and increased iodine deficiency irrespective of gender and age. The pandemic has itself greatly changed behaviours and diet (see associated report 'An overview assessment of the COVID-19 pandemic on the UK food and nutrition security' 2021).

Table 3 Baseline intake of food groups in the national diet (fresh matter consumption) and predicted changes under an Eatwell Guide scenario (Williams et al 2018). Increases of more than 10% are shaded green; decreases of more than 10% are shaded orange.

| **Diet constituents** | **Baseline intake** (g/person/d) | **Eatwell guide scenario** (g/person/d) | Proportional weight* (%) | Proportional change (%) |
|---|---|---|---|---|
| **Starchy carbohydrates** | **234.0** | **492.1** | **38** | **110.3** |
| Pasta, rice and miscellaneous cereals | 82.0 | 133.3 | | 62.6 |
| Bread | 81.9 | 219.2 | | 167.6 |
| Potatoes not cooked in fat | 42.7 | 91.1 | | 113.3 |
| Cereals (breakfast) | 27.5 | 48.8 | | 77.3 |
| **Fruit and vegetables** | **407.3** | **503.4** | **39** | **23.6** |
| Fruit | 101.1 | 120.9 | | 19.6 |
| Fruit juice | 59.5 | 56.4 | | -5.2 |
| Vegetables (not raw) including vegetable dishes | 169.0 | 223.1 | | 32.0 |
| Salad and other raw vegetables | 77.7 | 103.0 | | 32.6 |
| **Meat, fish and alternatives** | **240.8** | **216.0** | **17** | **-10.3** |
| White meat | 58.3 | 67.5 | | 15.7 |
| Red meat | 66.0 | 34.8 | | -47.2 |
| Processed meat | 48.7 | 24.8 | | -49.0 |
| Beans, pulses, nuts and seeds | 14.9 | 19.1 | | 27.9 |
| Eggs and egg dishes | 17.5 | 19.1 | | 8.9 |
| Fish (oily) | 10.0 | 20.0 | | 100.0 |
| White fish and shellfish | 25.4 | 30.7 | | 20.8 |
| **Milk and dairy foods** | **198.8** | **189.7** | **4** | **-4.6** |
| Milk (split according to current intake) | 155.5 | 140.0 | | -10.0 |
| Cheese | 13.9 | 14.1 | | 1.3 |
| Yoghurts and other dairy desserts | 29.4 | 35.6 | | 21.1 |
| **Foods high in fat and/or sugar** | **155.5** | **62.4** | **5** | **-59.9** |
| Potatoes cooked in fat | 41.8 | 21.2 | | -49.3 |
| Buns, cakes, pastries, and fruit pies | 34.0 | 12.0 | | -64.7 |
| Biscuits | 13.4 | 5.4 | | -60.0 |
| Confectionery | 2.8 | 1.0 | | -65.7 |
| Chocolate | 8.5 | 3.3 | | -61.4 |
| Spreads and cooking fat (not butter) | 5.2 | 2.2 | | -56.8 |
| Butter, cream, ice-cream | 25.4 | 9.3 | | -63.4 |
| Sugar (table & soft drinks) and preserves | 24.5 | 8.2 | | -66.6 |
| Total fresh matter (excluding drinks) | **1,236** | **1,286** | | |
| Dry matter intake | 464 | 474 | | |

*Excluding drinks

**Relationship between consumption and UK production**

The third component of the analysis completed by Williams et al (2018) was to predict the effect of a move to an Eatwell diet on the consumption of the main agricultural commodities directly consumed by humans. The move to a healthier diet was predicted to result in a greater demand for milling wheat (+70%), potatoes (+24%), tomatoes (+24%), oranges (+20%), and bananas (+20%). There were substantial declines in the demand for beef (-42%), pig meat (-46%), sugar (-31%), and milk (-30%) (Table 4). Note that the table does not include the production or consumption of cereals associated with animal feed, or the consumption of rice.

Table 4 Total UK consumption of main agricultural commodities for the baseline and Eatwell scenario, compared to current production and hence the level of self-sufficiency assuming no production changes (modified from Williams et al 2018)

| Commodity | Assumed consumption | | | Production | Self-sufficiency | |
|---|---|---|---|---|---|---|
| | Baseline (kt) | Eatwell (kt) | Change | Baseline (kt) | Baseline (%) | Eatwell (%) |
| Milk | 17,706 | 12,394 | -30% | 11,104 | 63 | 90 |
| Wheat (milling) | 7,178 | 12,203 | 70% | 5,360 | 75 | 44 |
| Potatoes | 6,813 | 8,448 | 24% | 5,815 | 85 | 69 |
| Barley (malting) | 1,656 | 1,656 | 0% | 1,656 | 100 | 100 |
| Chicken meat | 1,591 | 1,814 | 14% | 1,330 | 84 | 73 |
| Sugar (cane) | 1,342 | 926 | -31% | 0 | 0 | 0 |
| Tomatoes | 1,309 | 1,623 | 24% | 90 | 7 | 6 |
| Pig meat | 1,301 | 703 | -46% | 730 | 56 | 104 |
| Oranges | 1,280 | 1,536 | 20% | 0 | 0 | 0 |
| Sugar (beet) | 1,268 | 875 | -31% | 1,263 | 100 | 144 |
| Beef | 1,074 | 623 | -42% | 799 | 74 | 128 |
| Bananas | 949 | 1,139 | 20% | 0 | 0 | 0 |
| Grapes | 798 | 982 | 23% | 1 | 0 | 0 |
| Eggs | 732 | 783 | 7% | 655 | 89 | 84 |
| Apples | 712 | 726 | 2% | 233 | 33 | 32 |
| Carrots/turnips | 712 | 940 | 32% | 666 | 94 | 71 |

Several assumptions are needed to derive total UK consumption (Table 4) from national statistics and per capita food consumption (Table 3). The actual relationship also depends on assumed levels of avoidable and unavoidable food waste; for example, the Eatwell scenario assumed that it was possible to decrease avoidable food waste by 90% through regulation and good practice (Williams et al 2018). The resulting analysis (Table 4) shows that domestic agricultural production in the UK is currently sufficient to meet above 80% of the demand for potatoes, malting barley, chicken meat, eggs, and carrots and turnips. Assuming current levels of production, milk and pig meat production would also exceed 80% of UK demand in the Eatwell scenario, and beef production would be in excess of consumption. The UK is totally reliant on imports in terms of oranges, bananas and grapes, and about 50% of its sugar consumption. Overall, Williams et al (2018) reported that the Eatwell diet had a negligible effect on overall self-sufficiency as increased sufficiency in some food categories (e.g. meat, milk) was offset by reduce self-sufficiency in others (e.g. vegetables and fruit).

## Impact of COVID-19

COVID-19 has had range of effects on the UK diet. WRAP (2020) reported that self-reported levels of domestic food waste declined from 24.1% in November 2019 to 13.7-17.5% in April and September 2020. Home consumption of food and drink in England in June 2020 was 17.7% higher than in June 2019 (Public Health England 2020, page 4). It is noted that much of this increase is associated with a decline in food and alcohol consumption in cafes, restaurants, canteens, and pubs. The fact that some of the largest increases relate to alcohol (+27.6%), frozen meat (+19.1%), savoury carbohydrates and snacks (+18.8%) and frozen confectionery (+17.8%) (Public Health England 2020), suggests that COVID-19 has led to unhealthier diets. For a one-year period up to mid-June 2020, the annual increase in calories (+13.7%), and saturated fat (+15%) were greater than the overall increase in volume sales (+11.1%) (Public Health England 2020), although the increase in sugar consumption (+11.5%) was similar. Public Health England (2020, page 21) reports results from a Food Standard Agency and IPSOS MORI poll between May and July 2020 where about 25% of people reported consuming more healthy meals compared to about 10% who were eating less healthy meals. By contrast, about 30-40% reported eating more confectionery, biscuits, and cakes compared to about 15% who had eaten less. Baraniuk (2020) reports that the UK's National Food Strategy review has indicated that children are eating more "junk food and snacks" and "fewer fruits and vegetables" during the COVID-19 lockdown, with the effect greatest in poor households. A key feature of COVID-19 has been the so-called "K" response, with some households having more disposable income. By contrast, Barahjuk (2020) reports on a Ford Foundation study that found that that the level of food insecurity in poor households had almost doubled during the pandemic; with the loss of free-school meals being critical for some. The effect of poor food security, which was already increasing during the 2010s (Power et al 2020), in turn feeds through to lower life-expectancy, and reduced mental health and well-being (Health Foundation 2020). The Health Foundation (2020, page 84) reports that between 2007 and 2017, unhealthy food was typically cheaper than healthy food. Hence financial insecurity leads to less healthy diets.

## Impact of scenarios on over- and under-represented food groups to 2030

Although all of the four scenarios described in Deliverable 3 envisaged an economic recovery, disturbingly none has a strongly positive focus on increasing the health of the UK diet. High levels of income inequality in Scenarios 1 to 3 are assumed to result in negative health outcomes. The most positive effect (Scenario 4) assumes a hard-won return to the pre-COVID baseline.

**Scenario 1** "UK Recovery First"; it assumes a lack of green recovery an economy that has prioritised national recovery at all costs within a global trading environment with greater protectionism, and high levels of income inequality. Any hopes of a radical Green Recovery have been dashed due to austerity measures. A higher level of protectionism may help to maintain consumption of UK products such as milk, beef, and lamb which would be the opposite of that indicated by the Eatwell Guide. The scenario also assumes high inequality in incomes and available free time, and these two factors will counteract increased utilization of fruits and vegetables, which are relatively expensive and have a short shelf-life, particularly in low-income households. There is also a race-to-the bottom around food standards brought on by the drive to rebuild the economy at any cost.

**Scenario 2** "Green UK First". This scenario assumes a similar protectionist agenda as Scenario 1 but with a national focus on green recovery building of a successful COP26. With a green economy focus, there is likely to be increased downward pressure on the consumption of animal products associated with high greenhouse gas emissions, which would generally be helpful in moving diets towards the Eatwell Guide. However, continued inequality in incomes and free time, means that poorer households are unable to afford or prepare healthier diets.

**Scenario 3** "Best of British" includes a strong political drive to maintain high national food standards and animal welfare. Green Recovery is de-emphasised with only modest progress as compared to the previous scenario. This has allowed a move to more "organic" or "agroecological" food production systems and, in an innovation driven recovery there are novel plant-based meat- and milk-substitutes. However, the scenario also assumes no significant levelling-up in relation to Food and Nutrition Security outcomes for the less well-off and income inequality is greater than in other scenarios. Hence whilst those with high income levels may move to healthier diets, the budget constraints of those on low incomes will prevent increased alignment to the Eatwell Guide.

**Scenario 4** "Back to Basics". This is the most 'Business as Usual' scenario with the way out of post pandemic recession envisaged in a return to globalisation and free trade. The sheer difficulty of returning to a pre pandemic baseline in terms of economic prosperity has pushed both Green Recovery and so-called levelling-up to the side-lines. There is also a race-to-the-bottom in terms of food standards for foodstuffs where global competition is fierce. A focus on international trade is likely to positive in terms of reducing the relative cost of fruits (which are largely imported), however a lack of a focus on climate change will reduce one of the drivers that is seeking to reduce meat and milk consumption.

## Risks and opportunities of aligning UK food production to demand

At a national scale, food security, the access to `sufficient, safe, and nutritious food', can be promoted through an agricultural system that maximises the domestic production of commodities needed for a healthy diet in a sustainable way. The UK is not self-sufficient in food, producing only about two-thirds of all food consumed (Defra 2019). To maintain access to food the UK relies on international trade with, for example, imports worth £48 billion in 2019, exposing the country to the volatility of global markets. The impact of this was experienced in 2008 when the increases in commodity prices had a knock-on effect on food prices which rose substantially (Headey and Fan, 2010). Future shocks from extreme weather events, pest and disease outbreaks, human conflict, and disease pandemics, each exacerbated by population growth and climate change, pose further risks to the supply of affordable food, hitting hardest the poorest households which must spend disproportionality more on food than the well-off. The post-pandemic recovery presents an opportunity to redevelop the food system and transition to a resilient sustainable one that is able to provide a healthy and affordable diet (FAO 2020).

Achieving a healthy diet for all is a significant challenge in developed countries and lies at the heart of recent efforts to develop guidelines for healthy diets like the Eatwell Guide, a policy tool used to define government recommendations across the UK on eating healthily and achieving a balanced diet (see Section T4.1). In addition, consideration has been given to establishing diets that are compatible with greater environmental sustainability of the agri-food system. The LiveWell Plate developed by the World Wildlife Fund is an example of this which was formulated by adding environmental criteria to the Eatwell Guide.

These food and nutritional security considerations relate in different ways to the post-COVID-19 **plausible scenarios** described in the linked Plausible Scenarios Report (Duckett 2021) also produced as a part of this COVID-19 food and nutrition security project (see Appendix A: Plausible scenarios for a summary). In scenario 1 'UK Recovery First' we see a move towards greater domestic production driven by protectionist trade policies increasing the price of imported commodities and food. Due to recessionary conditions this is combined with a focus on intensive farming producing cheap, poorer quality food. In scenario 2 'Green UK First' tariffs are again responsible for driving up the price of imports but in this case increasing domestic production is combined with an environmentally progressive agri-food system. However, diets remain poor, particularly for the poorer sector of society that cannot afford healthier imported food products. Scenario 3 'Best of British' anticipates a focus on domestic production but this time with a shift to high quality, healthy and high animal welfare standards produced food. Finally, scenario 4 'Back to Basics' assumes an economic recovery has taken place but there has been no health or environmental dividend. In this scenario, the agri-food system looks like that of today with a heavy reliance on imports but with a reduction in regulations driving down food standards.

Using data on the prevailing patterns of the domestic production and consumption of agricultural commodities, coupled with estimates of changes in dietary patterns aimed at improving human and environmental health, we examine what food and nutritional security might look like for the UK in a post-pandemic recovery if delivered via a more sustainable, healthy, and self-sufficient system.

To assess the consequences of food and nutritional security as set out in the post-COVID-19 scenarios we have calculated the change in agricultural output, land area, and inputs arising from becoming self-sufficient in the production of the UK's principle agricultural commodities. These calculations were made for current (2017-2019) consumption patterns and for alternative patterns of consumption based on UK food-based dietary guidelines, the Eatwell Guide, (Scarborough et al. 2016) and an environmentally targeted (reduced GHG emissions) diet (Reynolds et al. 2019).

Data on the annual production and the supply and use of a range of agricultural commodities were obtained from the Agriculture in the United Kingdom 2019 report (Defra 2019a) and associated data (Defra 2019b, c, d). Total domestic use was not available for most commodities and so it was assumed that the annual new supply is equivalent to domestic use in the longer term, i.e., there is not an accumulation or diminution of stocks (unused commodity) over time. With this assumption it is possible to calculate the under or over supply of each agricultural commodity and so determine the self-sufficiency multiplier, i.e., the proportional change in production needed to match consumption. The production and trade figures vary from year to year; therefore, the self-sufficiency calculations were based on the three-year average of data for 2017 – 2019, smoothing out inter annual variability while still giving estimates indicative of current circumstances.

To estimate the additional impact of changing diet on production, published data on the food group composition of alternative diet scenarios were used. Two **'new diet' scenarios** were considered: full national adoption of the Eatwell Guide (Scarborough et al. 2016); and an environmentally targeted (reduced GHG emissions) diet (Reynolds et al. 2019). For both scenarios, food groups were identified that could be directly related to the agricultural commodities being considered and the consumption under the new diets calculated as a proportion of current consumption. These multipliers were then used to estimate the change in production. For this study it was assumed that the consumption driven changes in production would be in addition to a move to self-sufficiency.

This gives rise to four **production scenarios**: 1) 'Business as Usual', assuming current production levels are maintained for all commodities; 2) 'Self-sufficiency' to meet current consumption levels; 3) 'Eatwell', in which self-sufficiency is combined with consumption based on adoption of the Eatwell Guide; and 4) 'GHGE', in which the UK would be self-sufficient in commodities aligned with an environmentally friendly diet designed to achieve GHG emission targets. It should be noted that these scenarios do not take into account other drivers that are likely to influence the patterns of agricultural production or more complex responses to the self-sufficiency, diet and climate change drivers. For example, the industry goal of increasing malting barley output by 30% (The Scotch Whisky Research Institute, pers. comm.).

To assess the impact of these scenarios, the consequence of changing production patterns on land use, farm inputs, and income were calculated. Assuming methods of production remain unaffected, the appropriate self-sufficiency and diet-change multipliers were applied to the land area associated with the production of each commodity. For crops the land area is reported in the Agriculture in the United Kingdom 2019 report (Defra 2019a). To calculate the impact of changing livestock production on land area it was assumed that temporary grass supported a mix of beef and dairy, permanent grass supported a mix of beef, dairy, and sheep, and rough grazing supported sheep. In these cases, a simple average of the appropriate multipliers was applied to the area of grass under consideration. Estimates of nitrogen application rates (kg/ha) were obtained for each crop from the British survey of fertiliser practice dataset (Defra, 2020) and a mean for the three years 2017 – 2019 calculated in line with the production statistics. Estimates of total pesticide application rates (kg/ha) for each crop were obtained from the Pesticide Usage Surveys (https://secure.fera.defra.gov.uk/pusstats/surveys/index.cfm). These surveys are conducted on a sector-by-sector basis, once every two years. Therefore, averages from the last three years (2017-2019) could not be calculated and instead application rates were based on the most recent survey report. The impact of changes to production on UK agricultural income were based on the estimates of real term income per commodity, averaged over the three years of 2017-2019 (Defra 2019e) and modified using the self-sufficiency and the Eatwell and GHGE diet multipliers. Where possible, differences within commodities were accounted for, for example in the application of nitrogen and pesticides arising from differences in the management of winter and spring crops.

The benefits of pulses as an alternative to meat protein, both in terms of improved diet and environmental impact, are well established. However, although production statistics are available, usage has not been recorded by the UK annual censuses. Furthermore, neither Scarborough et al. (2016) or Reynolds et al. (2019) propose increases in the consumption of pulses, hence they have been omitted from the estimates provided in this study but see the following section 'Baselining the UK capacities for protein self-sufficiency' for further consideration of the impact of scenarios on plant-based protein production.

The UK is currently close to being self-sufficient in cereals with production exceeding consumption for barley and oats and reaching 98% of consumption for wheat. As a result, there is little impact arising from a shift to self-sufficiency. Both the Eatwell and the GHGE scenarios influence demand for cereal according to its uses; there is a substantial reduction in livestock feed as a result of declines in meat consumption but an increase in bread, pasta, and other cereal based foods. These changes in consumption balance each other out so that there is little impact on the production of wheat and oats. However, barley is predominantly used for feed and the production of malt for the brewing industry. While there is a reduction in demand for feed, the demand for malt is either not considered (Eatwell) or remains static (GHGE), however, the combination of current surplus production and reduction in use as feed sees the requirement for barley reducing substantially in all but the 'Business as Usual' production scenario. As a result, production of these three main cereals is predicted to fall by 5% to match consumption under the Business as Usual production scenario and to decrease by 15% under the Eatwell and 10% under the GHGE production scenarios.

The response of the other arable crops under consideration (i.e., oilseed rape, potatoes, and sugar beet) are more variable. Current oilseed rape production falls slightly short of domestic demand while both production of sugar beet (based on figures for refined sugar) and potato is about two-thirds of current demand. The Eatwell and GHGE scenarios anticipate substantial increase in demand for potatoes but reductions in oilseed rape and sugar beet. The most notable change associated with this is the approximate 1.5 to 3-fold increase in potato production, dependent on scenario, which would also create a substantial increase in agricultural inputs (e.g., an additional 40,000 kg of nitrogen, with associated increases in $N_2O$ emissions, and 3,750 kg of pesticide applied nationally) as a consequence of the intensity of potato production methods.

Moves towards self-sufficiency, healthy diets, and the reduction of GHG emissions all favour increases in the consumption and production of fruit and vegetables. Working with combined data covering the most common UK fruit (i.e., apples, pears, raspberries, and strawberries), a six- to twelve-fold rise in demand above 'Business as Usual' is predicted: six-fold to match current consumption (Self-sufficiency scenario), and twelve- or seven-fold to meet the changing dietary requirements of the Eatwell and GHGE production scenarios respectively. The changes in vegetable production (i.e., cabbages, carrots, cauliflowers, calabrese, lettuces, mushrooms, onions, tomatoes) are predicted to be less dramatic but still represent substantial increases.

Except for sheep and dairy, the UK is currently dependent on imports to meet demand for livestock commodities. To achieve self-sufficiency targets based on current consumption would see increases in production of the order of 10% for poultry, and eggs, 20% for beef, while for pig meat an increase of almost 60% would be required. The impact of this on land use is difficult to establish due to the mix of production systems both within and between these commodities. Applying a simple average of the self-sufficiency multipliers for beef, dairy and sheep indicates the demand for improved grass would increase by 314,000 ha (*ca.* 4%) across the UK (Table 5). Alternatively, assuming stocking densities of 1 ha head$^{-1}$ for beef cattle, 0.67 ha head$^{-1}$ for dairy cows, and 0.04 ha head$^{-1}$ for sheep suggests that the predicted changes in the size of the national herds and flocks would require an overall increase in grazing area of 163,000 ha (Table 5).

Table 5. Impact of production scenarios on the UK agricultural sectors.

| Commodity sector | | BAU | Self-sufficiency | Eatwell | GHGE |
|---|---|---|---|---|---|
| Arable [a] | Production (T x $10^3$) | 30208 | 31802 | 37889 | 33680 |
| | Land area (ha x $10^3$) | 3922 | 3918 | 3999 | 3572 |
| | Nitrogen (kg) | 627027 | 633150 | 675632 | 610552 |
| | Pesticide (kg) | 16639 | 17560 | 20718 | 18805 |
| | Income (£ x $10^6$) | 5092 | 5494 | 6377 | 5988 |
| Horticulture [b] | Production (T x $10^3$) | 3251 | 8962 | 16389 | 12076 |
| | Land area (ha x $10^3$) | 151 | 422 | 774 | 568 |
| | Nitrogen (kg) | 10529 | 29142 | 53329 | 39251 |
| | Pesticide (kg) | 1155 | 4113 | 7834 | 5426 |
| | Income (£ x $10^6$) | 2292 | 7632 | 14398 | 10119 |
| Improved grass | Land area (ha x $10^3$) | 7336 | 7650 | 2976 | 2685 |
| | Nitrogen (kg) | 394085 | 410935 | 159877 | 144215 |
| | Pesticide (kg) | 348 | 363 | 141 | 128 |
| Livestock [c] | Production (T x $10^3$) | 19893 | 20102 | 12720 | 6718 |
| | Head | 40526981 | 45386892 | 33891672 | 14978945 |
| | Land area (ha x $10^3$) | 3075 | 3238 | 1377 | 1130 |
| | Income (£ x $10^6$) | 13320 | 14819 | 5800 | 5098 |
| Total | Production (T x $10^3$) | 53352 | 60866 | 66998 | 52474 |
| | Land area (ha x $10^3$) | 11409 | 11990 | 7749 | 6825 |
| | Nitrogen (kg) | 1031641 | 1073227 | 888838 | 794018 |
| | Pesticide (kg) | 18142 | 22036 | 28693 | 24359 |
| | Income (£ x $10^6$) | 20704 | 27945 | 26575 | 21205 |

[a] wheat, barley, oats, oilseed rape, potato, sugar beet; [b] fruit, vegetables; [c] beef, sheep, pig, dairy, poultry, eggs

A reduction in the consumption of meat and dairy products is a strong feature of the recommendations for healthy diets and for reducing the impact of agriculture on climate change. The Committee on Climate Change has recommended a 20% reduction in the consumption of all meat by 2030 (CCC 2020). Even with complete self-sufficiency, the assumptions of the Eatwell and GHGE production scenarios result in a substantial reduction in output for all livestock commodities. Turning again to the potential effect of this on land use and using the multiplier approach to calculate the required grazing area gives an estimate for the reduction in demand for improved grass of about 60%, i.e., 4.4M ha for the Eatwell production scenario and 4.7M ha for the GHGE scenario, while the stocking density approach predicts a reduction of 1.7M ha and 1.9M ha for Eatwell and GHGE production scenarios respectively.

## Impact of scenarios on UK food production

In terms of production, future **plausible scenario** 4 'Back to Basics' is close to the 'Business as Usual' **production scenario** in the UK with a heavy reliance on imports and no shift towards healthier or environmentally friendly consumption patterns. In this case, UK agriculture is dominated by livestock commodities which are responsible for 64% of income of the commodities considered (Table 5) and 72% of utilised agricultural area (UAA) (Table 6), while arable production generates 25% of the income coming from the commodities under consideration and accounts for a similar proportion of UAA. Horticulture (fruit and vegetable production) represents a small part of UK agriculture providing just 11% of income (Table 5) and taking up about 1% of UAA (Table 6). The high value of horticultural crops and the relatively small footprint suggests that the failure to promote the domestic horticultural sector represents a lost economic opportunity of ca. £15,000 per ha, even if demand does not grow beyond its current level. Future plausible scenario 1 'The trouble with tariffs' includes a move to greater domestic production and as such is consistent with the Self-Sufficiency production scenario. The effect of increasing production to be self-sufficient in the commodities considered here is to increase UAA by 4% or 581K ha (Table 4.2.2). This is below the UAA that prevailed between 1984 and 1996 (Defra 2019a) and comprises relatively small changes in area required for arable cropping (<0.1% reduction) and improved grass (4.3% increase) indicating that the UK agricultural system could accommodate the increase in production without the need for structural change. The exception to this could be the increase in the horticultural sector which would see an overall increase of 164% in land area required for fruit and vegetable production combined. In Plausible Scenario 1 'The trouble with tariffs' the increase in agricultural output to achieve self-sufficiency would be pursued through intensification. In this case it is expected that agriculture inputs would increase at least in line with the proportional increases in output. With the increases in arable and horticultural production outlined this would see annual nitrogen application increasing by ~4% from 1,031,641kg to 1,073,227kg and total pesticide application by ~21% from 18,142kg to 22,036kg of active ingredient. The expansion and intensification of agriculture under this scenario would be supported, at least in the short-term, by a 35% increase in income derived from the commodities from £20.7 billion to £27.9 billion annually (Table 5).

Table 6. Current agricultural land use and land use change under three production scenarios (hectares x $10^3$).

| | Current land use[a] | Self-sufficiency | Eatwell | GHGE |
|---|---|---|---|---|
| Utilised agricultural area (UAA)[b] | 17450 | 581 | -3660 | -4584 |
| Arable crops | 4532 | -4 | 77 | -350 |
| Horticultural crops | 165 | 271 | 623 | 417 |
| Total improved grass | 7356 | 314 | -4360 | -4651 |

[a] Current land use estimated as the average land use for 2017-2019 (Defra, 2019a)
[b] UAA includes all arable and horticultural crops, uncropped arable land, common rough grazing, temporary and permanent grassland and land used for outdoor pigs (it excludes woodland and other non-agricultural land).

In calculating the effect of self-sufficiency on UK agricultural production, a narrow definition has been used in which the aim of self-sufficiency is to have domestic production sufficient to meet the UK's demand for those commodities that are already produced in the UK. Greater self-sufficiency could be achieved if, in addition, other imported commodities or goods were replaced by domestic alternatives. The use of soybean for animal feed is a clear example of this with 2.8 million tonnes of soybean and soybean meal being imported to the UK annually, offering an opportunity to reduce dependence on imports by the adoption of an alternative domestic produced protein source. However, the UK imports about 700,000 tonnes of soybean per annum and replacing these using domestically produced field beans would require an additional 1M ha based on a yield of 3.5 t $ha^{-1}$ (3-year average 2017-2019, Defra 2019a) and a crude protein concentration of 8% compared with 36.5% for soybean (U.S. Department of Agriculture, 2019). This alone would push the UAA beyond historical levels (1984-present) and suggest that the efforts to achieve self-sufficiency beyond what is proposed in the 'Self-Sufficiency' production scenario would require structural changes to the UK agriculture.

A further area for consideration, requiring more research, is how alterations in land use in the UK impacts local socioeconomics and socio-cultural considerations, as these potential changes will present challenges to traditions and current infrastructure. Changes in the level of imports will also have impacts on exporting countries and their economies, and hence will relate to trade arrangements between them and the UK.

Like the preceding scenarios, **plausible scenario** 2 'Green UK First' and **plausible scenario** 3 'The Best of British' incorporate increases in self-sufficiency arising from reductions in international trade and a focus on domestic markets. Both include pro-environmental sentiments and assume an environmentally progressive agri-food system. Features that distinguish between these scenarios are difficult to resolve through the broad patterns in commodity production and so both are considered as being generally consistent with the Eatwell and GHGE productions scenarios. Furthermore, although motivated by different drivers the outcome of the Eatwell and GHGE productions scenarios are broadly similar with increases in crop commodities and reductions in meat, dairy and eggs.

Both the Eatwell and GHGE production scenarios and hence the 'Green UK First' and 'Back to Basics' post-COVID plausible scenarios result in a reduction in domestic production and a contraction of agriculture across the country with the changes in commodities under consideration here leading to a reduction in land area required by 21% of the current UAA under the Eatwell production scenario and 26% under the GHGE scenario (Table 6). This is driven by reductions in requirements for all forms of grazing by about two-thirds under the Eatwell scenario and GHGE scenarios. The reduced demand for livestock feed offsets the increases in crop commodities for human consumption so that the production volume and the area of arable cropping are relatively constant under the alternative scenarios (Table 5), while the horticulture sector is predicted to increase substantially under both the Eatwell and GHGE scenarios. The impact of these changes is to see a 14% and 23% reduction in nitrogen for the Eatwell and GHGE production scenarios in turn but an increase in pesticide application of 58 and 34% respectively. Despite the overall reduction in land use, the shift in commodities results in a 28% increase in income under Eatwell scenario when compared with business as usual, with an average income of £2.9K $ha^{-1}$ compared to £1.4K $ha^{-1}$ under BAU. The GHGE production scenario shows a similar pattern with overall income being maintained at BAU levels despite reductions in UAA resulting in a near doubling in the income generated per hectare (Table 5).

The picture arising from these results is that shifting agricultural production in a way that fulfils domestic consumption patterns with reduced dependence on livestock commodities, moving arable output towards human food and away from providing feed for livestock, and increasing the horticultural sector is a practicable proposition. Post-COVID-19 Green Recovery scenarios not only offer a way forward that tackles climate change and diet related ill-health but also offer greater production efficiency and the opportunity to do more with less. For example, the reduction in livestock production offers the possibility to diversify the UK arable and horticultural sectors beyond the simple changes outlined by the Eatwell and GHGE production scenarios. Under these scenarios the reduction in livestock will free up an area of temporary grass suitable for crop production equivalent to approximately 15% of the arable land area or 4-5 times the land area used for horticultural. Making this land available for a combination of legume production (see ' Baselining the UK capacities for protein self-sufficiency'), and further diversification of arable and horticultural crops has the potential to further offset imported commodities such as stock feed, and fruit and vegetables; increase environmental sustainability (see 'Impact of scenarios on agroecological farming'); and to increase productivity and income. This may also help in addressing the increase in pesticide that is predicted under these scenarios, providing scope to change cropping practice such as the adoption of Integrated Pest Management and Agroecological approaches. The reduced demand for permanent grass and rough grazing also provides scope for alternative uses including forestry, woodland expansion, and rewilding. Under the GHGE production scenario demand for permanent grass and rough grazing would fall by more than 7M ha, an order of magnitude more than the area needed over the next ten years to satisfy woodland expansion targets across the UK and so making an even greater contribution to climate change mitigation.

## Baselining the UK capacities for protein self-sufficiency

With respect to sustainable protein production, the COVID-19 pandemic has not led to the realisation of the risk posed by the UKs high-dependency upon imported high-protein grains (mainly in the form of soybean) to serve animal-feed demand, especially to produce pigs and poultry. That is, current (arable) production is mainly targeted to serve feed markets for animal feed producers, and major UK industries such as brewing and distilling. During the C19 pandemic, existing (imported) stored supplies and global trade imports have apparently met demand, and feed shortages were not reported. That is, pre-C19 drivers such a national- and global-yields, mainly of barley and wheat, plus global market-/trade- demands (including the relative value of currencies), have persisted as the major determinant of feed availability and prices and so, the UKs continued high feed-protein import dependency. In this context, the recovering market demand for bovine (pig) production in China has led to increased feed prices in late 2020 (Cook and Hesketh, 2020). Added to this, changes in US energy policy away from fossil fuels, and towards biofuels, may also lead to feed-price inflation. Consider, that while meat consumption in the UK is reducing (Statistica, 2020), global demand for meat and especially high-quality (UK) meat is set to increase (Godfrey et al., 2018) despite current health and environmental costs of its production, and perhaps even because of C19 (Farming UK, 2020), In addition, uncertainties in this market have largely been waylaid by establishment of the BREXIT trade deal with the EU. Based on these trends and with respect to the drivers and impacts of the four C19 impact and recovery scenarios;' (Duckett et al 2021) the effects for the UKs mainly animal feed protein potential is described below, and should be considered with respect to the background information supplied as Supplementary Material 4.3. Further details on the role of proteins in The are provided Appendix B.

### Impact of scenarios on sustainable protein production

**Scenario 1 'UK Recovery First':** Return to maintaining the UKs status in a global food system with high levels of import dependency for key food stuff such as those which are central to good health (fruits, nuts and vegetables), and which may incur high environmental and health costs (feed for animal production and meat consumption, respectively. That is pre-C19 existential issues persist, and these are: climate change, environmental degradation, biodiversity loss, and decline in human health and well-being. UK feed-protein production and consumption patterns would be largely unaltered. While there is increasing consumption of plant-, as opposed to animal-protein among UK consumers, there is no strong driver to ensure that this is home-grown. Even then, the market demand from this human plant-based sector of limited commercial significance compared to the large demand of the feed sectors.

**Scenario 2 'Green UK First':** This scenario is driven by a continuing global pandemic including new variants, and Brexit impacts. Greater UK self-sufficiency could/should also be linked towards great uptake of sustainable and healthy diets, benefiting both environmental- (including biodiversity) and personal-wellbeing. This would be best achieved via greater consumption of home-grown fruits, vegetables, plus plant, farmed-fish, home grown grain legumes (among other non-legume grains) for pigs and poultry, and legume-grass fed ruminants. Realising this potential would require a strategic scale-up of diversified and regionalised production, linked to circular food-economies, and establishment of new downstream, i.e. ex-farmgate, value chain capacities and infrastructure too.

**Scenario 3 'Best of British':** This would entail accepting import dependency, and a greater reliance on global food system to meet UK food and nutrition security - perhaps especially so for products which have high GHG costs, such as meat (or high protein grains, imported from the Americas). That is, this approach could externalise environmental costs. UK agri-food production and processing infrastructure would therefore be focused largely on realising the potential of global export markets – which are currently dominated by trade with specific European countries, though also the USA.

**Scenario 4 'Back to Basics':** Business as normal, though with focus on improved human-health via reduced (red) meat, plus higher veg and fruit consumption etc. This is not achieved primarily from home-grown options. As such, progress on food and Nutrition Security in this scenario may depend upon nudging behaviours towards more-healthy (and perhaps -sustainable) norms. An effective implementation plan under these conditions would entail: education focused initiatives; addressing inequality; targeting the youngest, promoting cultural change; and supporting the most vulnerable.

## Impacts of agroecological farm practices

The COVID-19 pandemic has highlighted the need to build-in resilience to the UK food system for future food security. From around the 1950s, intensification of agriculture led to a steady increase in crop yields to meet food security demands, reaching a peak in the 1990s (Bingham et al 2012). Yields were maximised by targeted, single-issue chemical solutions to resolve specific crop protection and nutritional issues. However, this approach has had serious environmental consequences (Brzozowski and Mazurek 2018): pollution of air through greenhouse gas (GHG) emissions (Edenhofer et al 2014) and of water through leaching and runoff (Silva et al 2019); contamination of soil (Battaglin et al (2018) and loss of soil carbon (Janssens et al 2013), limiting root growth and uptake of water and nutrients (Valentine et al 2012); loss of biodiversity (Marshall et al 2003) and consequent negative effects on ecosystem functions delivered by trophic networks (Sharma et al 2018) and soil organisms (Wolejko et al 2020). Crop yields in the UK peaked in the 1990s and since then have stagnated due, at least in part, to these environmental trends (Ray et al 2020). This raises serious concerns about the impacts of intensification on biodiversity and the long-term sustainability of food production systems (Tilman 1999). Further details on opportunities for agroecology are provided in Appendix C.

Alternative biologically-based systems became popular in response to these issues (Roos et al 2018). These systems reduce the use of synthetic fertilisers and pesticides by substituting renewable alternatives and are often, though not always, (Kremen et al 2012) characterised by enhanced biodiversity (Lichtenberg et al 2017), less nitrogen loss and increased soil carbon (Migliorni et al 2014), leading to more environmentally sustainable production (Leifield 2012). However, biologically-based farm systems which merely replace external inputs of synthetic chemicals with alternative organic products tend to have lower and more variable yields (Lesur-Dumoulin et al 2017), reflecting trade-offs between management for short-term productivity and reduced environmental impact (Hawes et al 2019). Neither chemical- or biologically-based systems are therefore likely to deliver the level of production required to meet food security targets in the long-term (e.g. Connor and Minguez 2012). The SDGs, UNFCC and Biodiversity Convention call for new sustainable solutions to overcome this production-environment trade-off (Burgess et al 2019, Therond et al 2017). This can be achieved through the adoption of sustainable cropping practices based on diversification and regenerative practices which minimise environmental impact and dependence on imported goods, thereby increasing overall system resilience. Regenerative farm systems aim to conserve soil, regenerate damaged land, diversify rotations and, in some cases, integrate perennial cropping (Kerbs and Bach 2018, Pearson 2007).

These systems recognise the importance of biodiversity to production and use a mix of land sparing and sharing approaches at nested spatial scales (Maes et al 2012), resulting in enhanced on-farm biodiversity to generate ecosystem services and the functional redundancy necessary for system resilience in the face of local, regional or global disturbance (Bennett et al 2014, Hawes et al 2021, Supplementary Material 4.4]. Predicted effects of the four COVID scenarios (Duckett et al 2021) on the likelihood of these agroecological practices becoming embedded in mainstream UK agriculture are described below. These scenarios highlight the areas that are likely to impact on the farm scale production of home-grown food and the combined effects of global markets, regulatory systems and local policies on what crops are grown and how they are managed.

## Impact of scenarios on agroecological farming

**Scenario 1 'UK Recovery First':** The declining UK share of the global market following Brexit in this scenario results in an increased pressure on growers for home-grown produce from a wider range of crops than is traditionally grown in the UK. This, together with the recessionary environment puts pressure on farmers to reduce costs to minimise already small financial margins by increasing intensification, prioritising production over environment and resulting in a negative impact on biodiversity and long-term agroecosystem functions. COVID-exacerbated food inequalities and regional food and nutritional insecurity have knock-on effects to local demands for different food products – growers in affluent regions or with access to appropriate food processors/suppliers may be more inclined to diversify their cropping systems and produce higher value goods for healthy diets to those who can afford them, contrasting with those in poorer regions where there is less demand or opportunity.

On-farm environmental standards also drop with the absence EU regulation and new WT agreements could generate less incentive for environmentally and welfare friendly farming practices. However, increased state support for a more resilient domestic sector could mitigate some of the financial pressures on growers and allow some scope for farmers to take on potential risks of growing new crops in support of a more self-sufficient value chain. If incentive schemes included environmental impact, then the drive towards lower environmental standards could mitigate the effect of new trade agreements. Overall, further intensification of farming practices is expected in response to a relaxation of regulations and to minimise immediate financial pressure on farmers. No improvement in economic or environmental sustainability will be seen compared to pre-COVID states, but a change in the composition of crops grown, with a wider range of foods produced at a national scale to meet the demands for future UK self-sufficiency, particularly geared towards high value products for affluent middle classes.

**Scenario 2 'Green UK First':** The effects of economic decline are aggravated by a post Brexit UK trading environment in which tariffs and quotas have led to major rises in food prices. The other major reform of the UK food sector in this scenario is the drive to 'Build Back Greener' with a strong pro-environmental stance maintaining and improving standards as a priority. Declining share of global trade together with internal policies towards greater self-sufficiency result in pressure and incentives for farmers to grow a wider range of crops to meet UK demands, as in scenario 1. However, unlike scenario 1, green economic recovery is supported with greater supply chain sustainability which has a positive feedback to producers resulting in increased security and less risk, therefore better receptiveness of farmers for uptake of crop diversification and environmentally sustainable farming practices.
High food standards and regulatory barriers valuing quality over quantity would drive towards more agroecological practices as an alternative to current intensive agriculture, using alternative products and techniques to replace the use of increasingly restricted chemical inputs.

**Scenario 3 'Best of British':** A political rhetoric of greater self-sufficiency particularly around food provision is translated into net reductions in food imports and a significant rebalancing of the UK food system away from importing and exporting and towards supplying the domestic market with a greater proportion of UK sourced produce. This scenario, as in the previous two, results in a drive towards diversification of home-grown food but also for more agroecological approaches due to political pressure for quality over quantity and higher regulatory barriers restricting the use of chemical inputs. However, food inequality, deep recession and unemployment results in less demand for high value crops despite the shift to environmentally friendly foods. The discrepancy between political pressure for green recovery and ability to pay for high value products encourages advances in farming innovation for improved efficiencies. Overall, the top-down pressure for crop diversification and sustainable farming approaches results in improved UK self-sufficiency and modest agri-environmental improvements, but low financial security due to recession means that these benefits are not necessarily sustainable long term.

**Scenario 4 ''Back to Basics':** A more buoyant trading environment in which the UK is open for business, but growing social inequality combined with deregulation sees competition on price shaping a 'race to the bottom' in terms of food standards. There is neither a strong regulatory mechanism to protect the quality of our food nor is there a Green Recovery driving environmental standards upwards. Laissez-faire trade policy encouraging more exports and imports results in increased vulnerability to global markets, more incentive for monoculture commodity crop production and less incentive for diversification. Deregulation in an open free market, globalisation, economies of scale, international competition and innovation efficiencies shape a UK food system driving intensification of production, monoculture cropping and farm system degradation, and with no incentive for environmentally/welfare friendly farming practices, unchecked carbon footprint exacerbates climate change. Drive towards further intensification and environmental degradation.

The likely consequences to farm scale production arising from differences between drivers across these 4 scenarios fall into two main categories: intensification (scaling from intensive, high input production to agroecological approaches for environmental sustainability) and diversification of output (scaling from monoculture commodity cropping to on-farm diversification for self-sufficiency at a local scale). Scenario 2, "Green UK First", has the best outcome for both environmental impact and a transition to diversification of agricultural systems to produce balanced healthy diets. Scenario 3, "Best of British", also results in a positive win-win, but with the lower economic sustainability and deep recession predicted here, any benefit may not be sustained long-term. Scenario 1 would result in positive outcome for diversification of home grown produce but is less likely to promote and incentivise growers to transition towards more environmentally sustainable practices. Scenario 4

"Back to Basics", represents a lose-lose situation for Food and Nutrition Security with negative consequences for the environment and supply chain resilience. These impacts are summarised in Table 7.

| Scenario | 1. UK Recovery First | 2. Green UK First | 3. Best of British | 4. Back to Basics | weighting for farm scale production system |
|---|---|---|---|---|---|
| international trade | 3 | 3 | 3 | 1 | 4 |
| covid | 3 | 3 | 1 | 3 | 1 |
| green deal | 1 | 3 | 2 | 1 | 4 |
| inequality | 2 | 3 | 1 | 3 | 2 |
| food standards | 2 | 3 | 3 | 1 | 4 |
| labour market | 2 | 3 | 3 | 1 | 1 |
| food values | 2 | 3 | 3 | 1 | 4 |
| food supply chains | 2 | 3 | 3 | 1 | 3 |
| diets | 1 | 1 | 1 | 2 | 2 |
| overall average | 2 | 3 | 2 | 1 | |
| overall average with weighting | **2** | **4** | **3** | **1** | |
| Diversity:Environment | win:lose | win:win | partial win:win | lose:lose | |

**Table 7**. Scores for each driver/scenario combination as described in (Duckett et al 2021) in terms of impact on the farm scale production of food for human consumption. Weightings 1 (low) - 4 (high) are an estimate of the extent to which each driver directly influences crop production. These weightings will vary according to position in the value chain.

## New technologies (protected cropping and vertical farming) and opportunities for rapid up-scaling and effects on land.

The COVID -19 pandemic has been an additional and focussed spur for the development of alternative routes to the industrial production of food and here specifically we deal with controlled environment agriculture (CEA) systems including vertical farming. Definitions of CEA vary but these can best be summarised as a set of technologies and skills that allow for the conditions of growth to be controlled to allow the produce, normally plants/crops but increasingly extending to insects, to be grown with enhanced productivity and often quality compared to traditional methods. We have not applied the scenarios to this section.

CAE has its anecdotal beginning in Romans times during the Roman emperor Tiberius (14 – 37 AD) whose physicians prescribed at least one vegetable a day for the emperor. This was to be the cucumber, a favourite of Tiberius, who apparently "was never without it". To ensure production moveable beds were placed outside on favourable days and inside during inclement weather

(Dalrymple, 1973). The creation of CEA as we know it has its true roots in the 1800's with the development of greenhouses and the ability, through glass and steam, to allow light in, and control and maintain temperatures (Walters et al., 2020).

For crops this has been transformative in terms of productivity. For example, Walters et al (2020), 2020) identify that over the period 1929-2014 the area of protected cropping for crops in the USA was estimated to have grown from 5.2M $m^2$ to 8.7M $m^2$, and sales, adjusted for inflation, of £137M and 800M, respectively. Within that timeline tomato doubled its food print from ~2M $m^2$ to 4M $m^2$. This has largely been mimicked at the UK level. For example, data from the Farm Business Survey 2018/2019 - Horticulture Production in England (Crane et al, 2019) identified that area of glasshouse fruit and protected vegetables increased by 32.5% and 16.2% respectively, since 2010. Also, they identified that protected vegetables include crops grown in both heated and cold glasshouses and polythene tunnels, and account for 23% of total vegetable value in the UK.

Aznar-Sánchez et al (2020) identify in their analysis of global research trends on greenhouse technology that globally ~275MHa are dedicated to irrigated crops and that a growth rate of 1.3% was estimated (Hedley, 2014). Although this accounts for ~23% of farmed land, Fiaz et al (2018) and Wu and Ma (2015) estimated that such crops accounted for 45% of total food production. FAO population growth and food demand estimates for 2050 suggests food production must increase by 70% (Anon, 2009). To achieve this means an increase in amount of farmed land and /or a greater intensification of production upon it (Alexander et al 2015). However, this land expansion scenario comes with the obvious caveats that great amounts of water and nutrients need to be used (Fischer et al, 2007; Velasco-Muñozwt al 2018a,b) and the knock-on effect on loss of natural ecosystems (Aznar-Sánchez, et al 2019).

CEA and vertical farming offer the potential to increase not just produce yield and volume as well as year-round production but also benefits in terms of reduced transportation costs (dependant on the siting of the VF), absolute control of food safety and biosecurity, and substantially reduced inputs with respect to water supply, pesticides, herbicides, and fertilizers (Benke and Tomkins, 2017). In 2018, the UK imported £14 billion worth of fruit and vegetables and over half of that value comes from areas where water is scarcer than in the UK. For example, Spain, where climate change and poor water infrastructure is hampering agriculture's efforts to produce food, exports nearly £2 billion worth of produce to the UK. Notably fruit and vegetable market monitor sites such as Fresh Plaza, noted that the UK's fruit and vegetable imports lagged even further in the first months of the COVID-19 than the equivalent period in 2019. Much of this imported produce can be grown via CEA/VF in the UK. More specifically, O'Sullivan et al (2019) highlighted that the production of 1kg fresh weight of lettuce under field, glasshouse and vertical farm conditions came with ~110-210, 2-20 and ~1L water consumption, respectively. However, the energy use to deliver this (assuming grid energy connection) is 1-20, 60-500 and >1000 MJ (kg fresh weight)$^{-1}$, respectively. Supporting this reduction of water use via targeted and managed production is the data from commercial systems presented by Armanda et al (2019) who identify a water use reduction of 90-97% compared to standard production methods for a range of crops such as rocket lettuce, ice plant mustard leaf etc.

Reduced nutrient use and circularity (reuse) is also a much-lauded aspect of vertical farms (and precision CEA) with the associated benefits in terms of reduced nutrient-derived GHG emissions. Weidner et al (2019) discussed the opportunities for reduced requirements in urban CEA, including vertical farming, and identified the potential for mobilising organic waste valorisation via anaerobic digestion and exploitation of the nutrients in the latter's digestate for crop production. Similarly, the exploitation of nutrient-rich wastewaters from aquaculture systems to fertilise horticulture crops is often raised as a potentially beneficial CEA/VF enterprise (Junge et al, 2017).

Together these CEA/VF benefits add to that of space maximisation and environment control that for lettuce has been identified to yield a multiplier of 10: Barbosa et al (2015) identified that for lettuce, field production yields 3.9 kg/annum whilst equivalent greenhouse production delivers 41 kg. This approach was also considered by Banerjee and Adenaeuer (2014) who undertook a theoretical study, in conjunction with engineers, to design a mixed model vertical farm with a footprint of 0.93 ha, a similar footprint to a city block, with 37 floors, 25 for the purpose of crop production, 3 for aquaculture, and the remaining floors for preparation, sales etc. Withing this model several crops were targeted and using literature yield uplifts the estimated yields of a vertical farm compared to traditional agriculture were calculated and identified significant productivity lifts in tomatoes, peppers etc. Interestingly the uplift in yields in this model system were often significantly below those now seen commercially (Barbosa et al, 2015).

An underpinning driving factor for VF and some aspects of CEA has been the ever-evolving development of lighting sources, invariably light-emitting diodes LEDs (Armanda et al. 2019). The LED equipment can be controlled throughout a growing season to emit a programmed spectrum of light that is optimal for photosynthesis for different types of crops. When coupled with regulation of temperature and humidity, the effects of seasonality can be minimized or eliminated. Investing in efficient LEDs also reduces both lighting and cooling costs as less waste heat should be produced by more efficient systems or the heating is exploited for temperature maintenance diminishing/removing the need for heaters. Indeed Neil Mattson, a professor at Cornell University and a leader in the Greenhouse Lighting and Systems Engineering (GLASE) Consortium, revealed at the first HortiCann Light + Tech conference (2019) that "*CEA isn't (currently) a clear winner over field agriculture for crops like lettuce, but LEDs have helped close the gap in terms of costs, and fields can't meet global food demand*". Notably this statement and accompanying data (see below, Table 8) assumes of grid energy for production. Horticultural LED efficiency is ~50% now and a target for improvement and experiencing swift progress according to the anecdotal Haitz's law (an observation) that states forecasts that every 10 years the amount of light generated by an LED increases by a factor of 20, while the cost per lumen (unit of useful light emitted) falls by a factor of 10. By 2007 these forecasts had not only been achieved but surpassed (Haitz and Tsao, 2011) and continue to progress (Taki and Strassburg, 2019).

Table 8. Environmental footprint and energy costs of lettuce production (USA).

| | Grown and delivered to New York City | | |
|---|---|---|---|
| | Field in California | Greenhouse | Plant factor |
| Cumulative energy demand (MJ/kg) | 18.5 | 23.8 | 42.5 |
| Global warming potential (kg $CO_2$-eq/kg) | 1.29 | 1.33 | 2.72 |
| Water (L/kg) | 201 | 21 | 21 |
| Lighting energy cost ($/kg) | - | 0.46 | 1.36 |

Source: HortiCann Lighting + Tech presentation by Neil Mattson, Cornell University, GLASE.

There are two key factors that need to be addressed to allow CEA and vertical farming to make the next step in terms of productivity and sustainability: these are energy sources and management and the produce itself. CEA and VF are invariably identified as having greater energy demands than field crops although many of the claims are refuted by David Farquhar, chief executive of Scotland-based technology provider Intelligent Growth Solutions who stated in the Financial Times that "There is a lot of BS coming from entrepreneurs, and far too many unsubstantiated claims about energy use, the environmental benefits and quality of crops". Supplemental lighting needs to be powered and as identified by Neil Mattson, vertical farming can be more energy intensive than glasshouse production by the very nature that it can run 24/7/365. However, the technologies for energy sourcing and management are evolving at a significant rate along with national energy priorities. In the UK work is ongoing to look at multiple sources of energy for CEA including renewables (predominantly wind, solar, ground heat and possibly anaerobic digestion [AD]) and ideas are developing around the exploitation of disused mineshaft heat. For the latter some have considered having underground farms (https://www.bbc.co.uk/news/uk-wales-46221656) but more recently discussion with investors and VF companies have seen the development of the concept of exploiting the mineshaft heat by heating cold water pumped though the shaft and then exploiting the heat differential for the various CEA requirements such as heating and conversion to electricity for other systems such as cooling (in VF), mechanisms poser, robot charging etc.

Another concept that CEA has in terms of power use that is becoming increasingly explored, at least for VF, is Demand Side Response (DSR). DSR is an umbrella term for a type of energy service that large-scale industrial and commercial consumers of electricity (such as manufacturers) can use to help keep the grid balanced. As a DSR participant, you decrease or increase your facility's power consumption when you receive signals (requests) to do so, thereby helping the grid to maintain its 50Hz frequency. If done well responders receive revenue for participating in DSR, and the amount received depends on which of the several response services (or 'energy markets') participated in, as well as how quickly the responder assets can respond to signals that come in: the quicker, the better and more lucrative. For CAE and in particular VF this is a very attractive approach as turning off the CEA/VF system demand within 30s for a specified duration, e.g., 5-90mins, makes little difference to plants who need periods of dark and light anyway. This means the crop area can outperform large traditional industries where, for example, welding cannot be stopped instantly or in chemical manufacturing where processes once started need to progress to their safe conclusion. This means that as CEA/VF starts to accrue scale the DSR aspect when mixed with direct off grid renewables energy becomes an entirely different proposition from what it is currently. VF Companies such as Intelligent Growth Solutions, Liberty Produce, Vertical Future and Jones Food Company are among many VF companies exploring this aspect of cost reduction/revenue generation as part of evolving business models.

The other key aspect of CEA/VF only now being addressed is that of the crops themselves. Invariably the crops being grown currently are essentially those that have been grown outdoors and in glasshouses. The development of the full gamut of CEA systems to control heat, humidity, light (intensity, quality and periodicity), inputs (water and nutrients), pests and disease and modulating ambient gas composition mean that optimisation can be a rapid process ultimately limited only by the crops' biology and genetics.

The research to deliver improvements in shelf life, sensory traits and nutritional density is continuing as evidenced by the several Innovate UKRI funded projects (IUK 105141, 49078, 55310, 509898, 511273 etc) but the ability to fully control the environment opens up other avenues to be explored to facility productivity and efficiency gains. Accessing a wider range of germplasm for the CEA/VF systems allows for a broader range of options to be developed for crop nutrition and nutritional density, health beneficial compound and unique sensory profiles (Piovene et al., 2015; Hasan et al., 2017). A deep dive review of this was undertaken recently by Kozai et al (2019) in their book reviewing the area.

The next big steps for crops in CEA/VF will centre on photosynthetic efficiency and crop architecture. Crop productivity is limited by the amount of energy it traps to "fuel the system". Many studies have been undertaken to improve the photosynthetic processes through genetic engineering as an avenue to improve yield potential with some studies achieving yield increases of >40% (see Simkin et al, 2019). Linking these studies at the genetic level to genome biodiversity screening and "big data analyses" should open up the option for breeding routes, rather than engineering biology, to improved photosynthetic efficiency. Indeed, the CEA/VF system also lends itself to accelerating the breeding process through speed breeding, a set of technologies and protocols that significantly shorten generation time and accelerates breeding and research programmes (Watson et al, 2018) and is now being applied to orphan, lesser studied crops (Chiurugwi et al, 2019). Through growth optimisation in CEA/VF systems crops can be cycled through multiple generations, e.g., 6 per annum for cereals, and, if properly aligned with genomic screening with gene targets for breeding improvement, the acceleration to a new variety could be done in a fraction of the time currently taken. The speed breeding approach also sees an alternative use for CEA/VF as a breeding technology that broadens its applicability to crops that will always commercially be grown in the field such as cereals, potatoes, stone fruit, cotton, legumes and oilseed, roots tubers and bananas (Chiurugwi et al, 2019).

Of the crops where the CEA/VF system will be the production routes the speed breeding approach also lends itself to crop architecture manipulation such as reduced root mass and resource allocation. Leaf, fruit, bud distribution and size, and stem/leaf biomass ratio etc would also be targets for manipulation. The combination of CEA/VF with the new generation of genomic breeding tools, such as genotyping, marker-assisted selection allied with high-throughput phenotyping and genomic, is at a very early stage but offers much promise in terms of crop productivity and sustainability gains (Hickey et al 2019).

All of the advances described above identifying the ability of the CEA/VF systems to fully control the crop production environment, including losses to pest and disease, and 24/7/365 production of crops have been accompanied with intense commercial interest and investment.

Prior to the pandemic CEA had been a focus of much development and investment with Savills Research (Anon, 2019) identifying that >£56bn had been invested in agritech since 2012. Within that Savills Research (Anon, 2019) estimate that the vertical farming market was £1.5bn and predicted to grow to £8 billion by 2025. Highlighting the speed at which this market is evolving and progressing, more recent estimations of the market value for vertical farming reveals estimates up to £12.4Bn by 2027 (Anon, 2020).

In many areas where resources and land are limited vertical farming is being viewed as a route to increasing localised food self-sufficiency. For example, Singapore imports over 90% of its food supply and is exposed to the volatilities of the global food market. This has prompted a national effort, spearheaded by the Singapore Food Agency, to increase food sufficiency to 30% by 2030; this must comprise 10% protein and 20% fruit and vegetables. Climate change, and rising sea levels and temperatures, are predicted to result in a global shortage of food, with a significant impact on Singapore's food production. More specifically, the country's innate space and resource constraints make it particularly vulnerable to global trends that impact food supply and safety, including urbanisation, and new business models and food products. This creates significant challenges in terms of developing the infrastructure needed to grow the food. The only viable way to deliver this on the national footprint, at least for fruit and vegetables, is through CEA, with its proven ability to deliver increased productivity (in temporal and per $m^2$ terms), lower resources and operational costs, improved product safety and health management and enhanced nutritional quality of produce.

Similarly, efforts to exploit the potential benefits on CEA/VF are being explored in regions such as North Africa where productive land and water is limited but solar power is not. Indeed, the Abu Dhabi Investment Office, a central government hub supporting businesses, is putting $100 million into four agritech companies, including Madar Farms, the start-up building the indoor tomato farm; Aerofarms, a New Jersey-based vertical farming company that will build a massive new R&D centre; RDI, a start-up developing a new irrigation system that makes it possible to grow plants in sandy soil; and RNZ, a start-up that develops fertilizers that make it possible to grow more food with fewer resources. The investments are the first in a larger $272 million program to support agritech. Furthermore, the Saudi Minister of Environment, Water and Agriculture, Abdulrahman Al Fadley, recently stated that “Vertical farming techniques are one of the main axes of developing agriculture and water conservation,” adding that the Kingdom has allocated 100 million riyals ($26.6 million) for this purpose.

Nations where urbanisation is increasing or already at a significant level are also pursuing CEA/VF as a route to food production and self-sufficiency. China is one of these and needs to deliver solutions to the problems of a population projected to reach 1.5 billion in 2030, agricultural land diminishing at 300km$^2$/annum and cultivated land is currently at 0.08ha/person, which is 40% of the world average. Furthermore, it is projected that 80% of the population will live in cities by 2050, all whilst the agricultural worker demographics increases in age, with new entrants down significantly: 60% of farmers are over 50 years old and young people don't want to farm. To counteract this, the Chinese Academy of Agricultural Sciences (CAAS) started a national project on intelligent plant factory production technology in 2013 supported by the Ministry of Science and Technology. This was followed by the establishment of the Institute of Urban Agriculture in 2018 at Chengdu City, Sichuan Province, supported by CAAS (Kozai et al, 2019). This academic research is matched with commercial activity and in China the vertical farming market is predicted to have a 24.7% CAGR for the period of 2020-2027.

As stated earlier, CEA/VF continues to be a major target for investment in the Western world with Blomberg predicting the vertical farming market value to hit $20 Bn by 2026. Within this the North American market is expected to reach $3Bn by 2025. Announcements of investments in CEA/VF are becoming a regular occurrence such as the $200 million investment by the Vision Fund, overseen by SoftBank Group Corp. chief, Masayoshi Son, into the Silicon Valley VF start-up Plenty.

As identified above CAE/VF attracted significant investment pre-pandemic whilst the COVID-19 pandemic highlighted fragility in the food system and supply chains and thus helped deliver a record year for investment. Nicola Kerslake, CEO of Contain, a fintech platform for indoor agriculture, highlighted this stating that "*The industry raised US$565M in 2020. This figure excludes several notable rounds where the amounts raised were not publicly disclosed*". She went on to add "*New Jersey-based vertical farmer AeroFarms was one of four recipients of funding from the Abu Dhabi Investment Office for its Dubai farm. Elsewhere, at-home kit provider Back to the Roots added a prominent Saudi sustainable ag supporter to its existing investor list for an October 2020 round. Even without these rounds, 2020’s total was up nearly 50% on 2019 and represents a record for the industry, besting 2017’s US$391M*". Interestingly, and more recently, the commercial CEA/VF activity is being realised in the UK with a new four-tower VF being built in north-east Scotland. This is to be an IGS system and purchased by Vertegrow. Other commercial activities include the partnering of Ocado with Marks and Spencer with the latter investing £17million in VF while John Lewis plans to grow salads in store in the future in a partnership with LettUs Grow. The CEA/VF concept is also being explored for social or societal ends with International real estate advisor Savills, working with non-profit organisation Rethink Food, and sponsoring 17 vertical farming tower gardens in state primary schools across the UK.

That CEA/VF is here to stay is no longer in question given the market pull, and the journey now is to deliver profitability and sustainability compared to field or traditional glasshouse cropping. As stated previously, energy and technology improvements are key to profitability and the realisation of Haitz's law, relating to LED performance and cost improvements (Haitz and Tsao, 2011), and the development of alternative energy sources as well as grid based DSR should deliver this.

Attention is now shifting to the sustainability of CEA/VF. In their review of innovations towards mitigation of nitrogen-related greenhouse gases Winiwarter et al (2014) identified the benefits of

CEA/VF in terms of significantly increased productivity footprint, lack of soil use (focussing on inert supports, hydroponics and mineral solutions), multiple crop cycles during a year and no weather-related crop losses. Crucially nutrient recycling delivers a significant reduction in eutrophication of the natural environment and the need for synthetic N fertilizers (assuming production is done at scale). Similarly all the component technologies within the CEA/VF system are attracting significant attention for low carbon production with, for example, glass potentially being replaced in CEA systems by the thermoset polymer Ethylene tetrafluoroethylene (ETFE) which although synthetic has many advantages over glass including: allows UV light to penetrate; long-lasting and fully recyclable; self-cleaning thereby allowing maximum light penetration to plants; stronger than glass and protects crops (and businesses) from catastrophic damage such as hail storms; lightweight, flexible and easily repairable. The system is being rolled out at the experimental level by the AgriTech Innovation Centre for Crop and Health Protection (CHAP).

Al-Chalabi's (2015) study of CAE/VF from a sustainable-cities perspective concluded that vertical farming is feasible in areas that have enough sunlight or, going forward, energy from renewable sources. Interestingly, the study suggested that at that point in time there were a limited number of CEA/VF designs to choose from in order to conduct a technical analysis. The sector has advanced beyond recognition in this respect now.

All these benefits for increased and low impact food production are being taken on board at national levels with multiple countries including Korea, Japan, China, Germany, the United Arab Emirates, China, France, India, Sweden, Singapore, and the United States repeatedly convening to discuss and support vertical farming and identifying it as a technology as integral to the long-term sustainability of their food self-sufficiency and in particular as approaches to feed their cities (Al-Kodmany, 2018; Despommier, 2014)

## New technologies - Conclusion

The tools and technologies to design our own destinies in terms of sustainable food production lie within our grasp. The infrastructure of CEA/VF is evolving and improving at a significant rate and largely driven by industry meaning that the outputs have been developed on commercial foundations. Sustainability is an issue embedded within the sector and both industry and academia agree that the energy input conundrum for CEA/VF is capable of being resolved and that better links to (renewable) energy generation and management sectors need to be forged. The next step change for CEA/VF food production is likely to be biological as we look to redesign the crops to suit the growing environment as we have done for traditional agriculture. Also repurposing the CEA/VF "box" for other uses is staring to gather pace with insect production for protein, oil etc (van Huis and Oonincx, 2017; da Silva Lucas et al, 2020). Similarly, but much more at the lower technology readiness level, is the production of laboratory or cell culture-based meat which requires very defined levels of controlled environment (Bhat et al., 2017; Bryant, 2020). Laboratory meat, like crop CEA/VF systems, is attracting significant investment and due to the significant contribution of livestock production to GHG emissions could potentially offer routes to low or net zero meat.

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## Appendix A: Plausible Scenarios

The full report on the scenario planning is available here: [COVID-19 Food and nutrition security | The James Hutton Institute]

**Scenario 1 'UK Recovery First' .**

A national recovery at any cost has been achieved against the backdrop of recessionary pressures. Neither a radical green recovery nor any widespread levelling-up have occurred, resulting in higher food prices, negative Food and Nutrition Security outcomes for those on the lowest incomes and mounting societal unrest.

**Scenario 2 'Green UK First' .**

A domestic green recovery has achieved environmental improvements within a less globalised, more inward-looking world. Levelling-up has not been achieved and inequality alongside higher food prices has resulted in negative Food and Nutrition Security outcomes for those on low incomes.

**Scenario 3 'Best of British'.**

The UK has responded to greater protectionism by investing in UK agriculture putting quality at the centre but without any effective levelling-up, resulting in negative Food and Nutrition Security outcomes for those on low incomes set against higher quality produce for many others. Innovation and technology have helped the food sector to recover and prosper and there has been continuing consolidation resulting in larger farms and food businesses. Hospitality is radically reshaped around suburban spaces.

**Scenario 4 'Back to Basics'**

Economic recovery has been achieved within this, the most prosperous of our post BREXIT scenarios, featuring a return to globalisation and buoyant international trade. The return to the pre pandemic baseline has been an uphill struggle and neither Green Recovery nor levelling-up have markedly reshaped this unsustainable and unequal future.

The morphological matrix for each Scenario is provided below.

(Note: JiT = Just in Time, referring to the supply chain of produce).

## Scenario 1: 'UK Recovery First'

| **Assumptions** | Plausible positive | | *BAU assumption* | | Plausible negative |
|---|---|---|---|---|---|
| **External Drivers** | | | | | |
| International Trade | Laissez Faire trade policy – growing exports and imports | UK and elsewhere more self-sufficient in food | UK Food Sector returns to pre-COVID levels as international trade rebounds | Laissez Faire trade policy – balance of trade in food significantly shifted to imports | **BREXIT Double Whammy – declining global food trade, declining share for UK** |
| COVID | | | **COVID effects continue to be felt but 2021 vaccine ends new transmissions** | Vaccination stalls, further lockdowns, long COVID and mental health legacy | |
| Climate Emergency/ Green Deal | Green recovery with greater supply-chain-long sustainability | COVID dividend – less air travel, lower consumption in long recession | **Pent-up demand underpins rapid revival of air travel and general consumption** | COVID interruption – recovery and growth higher priority than environment | |
| Inequality | Higher NHS investment | **COVID exacerbated food inequality persists - growing numbers of food insecure** | Pre-COVID food inequality returns, COVID unemployment short-lived | **Fragmented regional FNS outcomes with greater devolution** | Deep COVID recession - up to 5 million unemployed |
| **Internal drivers** | | | | | |
| Food Standards | Higher quality and sustainability standards - higher regulatory barriers | Deregulation in 'open' free market | **No clear policy direction – diverse arrangements between silos and devolved regions** | **Lower UK food standards under WTO and other new trade agreements** | Lower environmental standards under WTO and other new trade agreements |
| Food Sector labour mkt | Higher pay and improved conditions - higher food prices | **Legacy Working-From-Home arrangements and changes to UK hospitality** | Seasonal labour sourced beyond EU – no structural change | Labour saving technological innovation environment | Anti-migrant politics exacerbates labour crisis for domestic food system |
| Food Values (revaluation) | Increased demand for healthy foods – nutrition and provenance increasingly valued | Generational shift to environmentally friendly food | Current food values prevail | **Competition on price shapes UK food system – 'race to the bottom'** | Unchecked carbon footprint of food system exacerbates Climate Emergency |
| Food supply chain structure | Stronger demand supporting local/regional shops, farms, processors | **JiT vulnerability tackled with more state support for a more resilient domestic sector** | Globalisation, JiT, economies of scale and competition continue consolidation story | Innovation – longer shelf life, improved forecasting, lower waste – more consolidation | Long supply chains, high carbon footprint, lack of transparency |

| | | | | | |
|---|---|---|---|---|---|
| Diets | Healthier consumption based on more diverse local food systems | Transition away from red meat – build back healthier boost for horticulture | Short-lived consumption decrease – return to pre COVID base line | Transition away from imports – more UK fish, meat, horticulture | **Widening 2-tier system - food insecure V more affluent consumers** |

## Scenario 2: 'Green UK First'

| **Assumptions** | Plausible positive | | *BAU assumption* | | Plausible negative |
|---|---|---|---|---|---|
| **External Drivers** | | | | | |
| International Trade | Laissez Faire trade policy – growing exports and imports | **UK and elsewhere more self-sufficient in food** | UK Food Sector returns to pre-COVID levels as international trade rebounds | Laissez Faire trade policy – balance of trade in food significantly shifted to imports | **BREXIT Double Whammy – declining global food trade, declining share for UK** |
| COVID | | | **COVID effects continue to be felt but 2021 vaccine ends new transmissions** | Vaccination stalls, further lockdowns, long COVID and mental health legacy | |
| Climate Emergency/ Green Deal | **Green recovery with greater supply-chain-long sustainability** | COVID dividend – less air travel, lower consumption in long recession | Pent-up demand underpins rapid revival of air travel and general consumption | COVID interruption – recovery and growth higher priority than environment | |
| Inequality | Higher NHS investment | COVID exacerbated food inequality persists - growing numbers of food insecure | **Pre-COVID food inequality returns, COVID unemployment short-lived** | Fragmented regional FNS outcomes with greater devolution | Deep COVID recession - up to 5 million unemployed |
| **Internal drivers** | | | | | |
| Food Standards | **Higher quality and sustainability standards - higher regulatory barriers** | Deregulation in 'open' free market | No clear policy direction – diverse arrangements between silos and devolved regions | Lower UK food standards under WTO and other new trade agreements | Lower environmental standards under WTO and other new trade agreements |
| Food Sector labour mkt | **Higher pay and improved conditions - higher food prices** | **Legacy Working-From-Home arrangements and changes to UK hospitality** | Seasonal labour sourced beyond EU – no structural change | Labour saving technological innovation environment | Anti-migrant politics exacerbates labour crisis for domestic food system |
| Food Values (revaluation) | Increased demand for healthy foods – nutrition and provenance increasingly valued | Generational shift to environmentally friendly food | Current food values prevail | Competition on price shapes UK food system – 'race to the bottom' | Unchecked carbon footprint of food system exacerbates Climate Emergency |
| Food supply chain structure | **Stronger demand supporting local/regional shops, farms, processors** | JiT vulnerability tackled with more state support for a more resilient domestic sector | Globalisation, JiT, economies of scale and competition continue consolidation story | Innovation – longer shelf life, improved forecasting, lower waste – more consolidation | Long supply chains, high carbon footprint, lack of transparency |

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|---|---|---|---|---|---|
| | | | | | |
| Diets | Healthier consumption based on more diverse local food systems | Transition away from red meat – build back healthier boost for horticulture | Short-lived consumption decrease – return to pre COVID base line | **Transition away from imports – more UK fish, meat, horticulture** | **Widening 2-tier system - food insecure V more affluent consumers** |

## Scenario 3: 'Back to Basics'

| **Assumptions** | Plausible positive | | *BAU assumption* | | Plausible negative |
|---|---|---|---|---|---|
| **External Drivers** | | | | | |
| International Trade | **Laissez Faire trade policy – growing exports and imports** | UK and elsewhere more self-sufficient in food | UK Food Sector returns to pre-COVID levels as international trade rebounds | Laissez Faire trade policy – balance of trade in food significantly shifted to imports | BREXIT Double Whammy – declining global food trade, declining share for UK |
| COVID | | | **COVID effects continue to be felt but 2021 vaccine ends new transmissions** | Vaccination stalls, further lockdowns, long COVID and mental health legacy | |
| Climate Emergency/ Green Deal | Green recovery with greater supply-chain-long sustainability | COVID dividend – less air travel, lower consumption in long recession | **Pent-up demand underpins rapid revival of air travel and general consumption** | COVID interruption – recovery and growth higher priority than environment | |
| Inequality | Higher NHS investment | COVID exacerbated food inequality persists - growing numbers of food insecure | **Pre-COVID food inequality returns, COVID unemployment short-lived** | Fragmented regional FNS outcomes with greater devolution | Deep COVID recession - up to 5 million unemployed |
| **Internal drivers** | | | | | |
| Food Standards | Higher quality and sustainability standards - higher regulatory barriers | **Deregulation in 'open' free market** | No clear policy direction – diverse arrangements between silos and devolved regions | Lower UK food standards under WTO and other new trade agreements | Lower environmental standards under WTO and other new trade agreements |
| Food Sector labour mkt | Higher pay and improved conditions - higher food prices | Legacy Working-From-Home arrangements and changes to UK hospitality | **Seasonal labour sourced beyond EU – no structural change** | Labour saving technological innovation environment | Anti-migrant politics exacerbates labour crisis for domestic food system |
| Food Values (revaluation) | Increased demand for healthy foods – nutrition and provenance increasingly valued | Generational shift to environmentally friendly food | Current food values prevail | **Competition on price shapes UK food system – 'race to the bottom'** | **Unchecked carbon footprint of food system exacerbates Climate Emergency** |

| | | | | | |
|---|---|---|---|---|---|
| Food supply chain structure | Stronger demand supporting local/regional shops, farms, processors | JiT vulnerability tackled with more state support for a more resilient domestic sector | **Globalisation, JiT, economies of scale and competition continue consolidation story** | **Innovation – longer shelf life, improved forecasting, lower waste – more consolidation** | Long supply chains, high carbon footprint, lack of transparency |
| Diets | Healthier consumption based on more diverse local food systems | Transition away from red meat – build back healthier boost for horticulture | **Short-lived consumption decrease – return to pre COVID base line** | Transition away from imports – more UK fish, meat, horticulture | Widening 2-tier system - food insecure V more affluent consumers |

## Scenario 4: 'Best of British'

| **Assumptions** | Plausible positive | | *BAU assumption* | | Plausible negative |
|---|---|---|---|---|---|
| **External Drivers** | | | | | |
| International Trade | Laissez Faire trade policy – growing exports and imports | **UK and elsewhere more self-sufficient in food** | UK Food Sector returns to pre-COVID levels as international trade rebounds | Laissez Faire trade policy – balance of trade in food significantly shifted to imports | **BREXIT Double Whammy – declining global food trade, declining share for UK** |
| COVID | | | COVID effects continue to be felt but 2021 vaccine ends new transmissions | **Vaccination stalls, further lockdowns, long COVID and mental health legacy** | |
| Climate Emergency/ Green Deal | Green recovery with greater supply-chain-long sustainability | **COVID dividend – less air travel, lower consumption in long recession** | Pent-up demand underpins rapid revival of air travel and general consumption | COVID interruption – recovery and growth higher priority than environment | |
| Inequality | Higher NHS investment | **COVID exacerbated food inequality persists - growing numbers of food insecure** | Pre-COVID food inequality returns, COVID unemployment short-lived | Fragmented regional FNS outcomes with greater devolution | **Deep COVID recession - up to 5 million unemployed** |
| **Internal drivers** | | | | | |
| Food Standards | **Higher quality and sustainability standards - higher regulatory barriers** | Deregulation in 'open' free market | No clear policy direction – diverse arrangements between silos and devolved regions | Lower UK food standards under WTO and other new trade agreements | Lower environmental standards under WTO and other new trade agreements |
| Food Sector labour mkt | **Higher pay and improved conditions - higher food prices** | **Legacy Working-From-Home arrangements and changes to UK hospitality** | Seasonal labour sourced beyond EU – no structural change | **Labour saving technological innovation environment** | Anti-migrant politics exacerbates labour crisis for domestic food system |

| | | | | | |
|---|---|---|---|---|---|
| Food Values (revaluation) | Increased demand for healthy foods – nutrition and provenance increasingly valued | **Generational shift to environmentally friendly food** | Current food values prevail | Competition on price shapes UK food system – 'race to the bottom' | Unchecked carbon footprint of food system exacerbates Climate Emergency |
| Food supply chain structure | Stronger demand supporting local/regional shops, farms, processors | JiT vulnerability tackled with more state support for a more resilient domestic sector | Globalisation, JiT, economies of scale and competition continue consolidation story | **Innovation – longer shelf life, improved forecasting, lower waste – more consolidation** | Long supply chains, high carbon footprint, lack of transparency |
| Diets | Healthier consumption based on more diverse local food systems | Transition away from red meat – build back healthier boost for horticulture | Short-lived consumption decrease – return to pre COVID base line | **Transition away from imports – more UK fish, meat, horticulture** | **Widening 2-tier system - food insecure V more affluent consumers** |

## Appendix B: COVID-19 and the UKs high-protein-grain import-dependency for animal feed (meat production)

The UK has imported approximately 70% of its high-protein grain requirement for many years. While this dependency seems high, it is around only 10% higher than total food imports to the UK which rests at around 64 % (expressed as the 'self-sufficiency' [production/supply ratio]), and this reflects a consistent year-on-year decline from 78 % (a 14 % self-sufficiency drop) over the past 35 years (DEFRA, 2019).

This level of high-protein grain import dependency is like that of the EU-country average, and the demand is realised in the form of soybean sourced from previously biodiverse rainforest and or-cerrado regions of South America (Barona et al., 2010), though also oil seed meal too. Most of the soybeans imported serve animal feed industries, especially bovine and poultry markets (EC, 2019). That is, even before the impact of C19 high protein import dependency has been tolerated despite the importance of these South American regions ecologically, including their role in helping safely regulate biogeochemical cycles, such as for carbon and water, and potential to mitigate climate change impacts (Berbet and Costa, 2003; Sampaio et al., 2007; Mitchard, 2018; Rajão et al., 2020). Also, this scenario has persisted despite the existence of home-grown high-protein alternatives (De visser et al., 2014)). However, even use of home-grown non-legume alternative protein sources such as European rapeseed leads to high biogenic emissions of carbonaceous GHGs such as $CO_2$, and $N_2O$ (Reijnders et al., 2008).

These scenarios are allied to fact that high protein legume grains account for only 1-4% of the EUs cropped rotations (Watson et al., 2017). In the UK, this range is also evident with the lower level being found in Scotland and a higher level in England (Squire et al., 2019). However, both proportions fall far below the levels desired for grain legume inclusion in cropped rotations (*ca.* 25 %) to help achieve for agroecological functioning of arable systems (Iannetta et al., 2015). Such an exclusion also means that the potential environmental benefits of grain legumes to local biodiversity, soil quality and fertiliser replacement (Nemecek et al., 2008) are also forfeit. To reiterate, even before any potential food security risks posed by COVID-19 there were strong ethical, environmental, and socio-economic drivers to justify sourcing protein from home-grown legumes, and other high-protein non-legume sources.

These drivers have been acknowledged in EC-CAP and going forward the ECs 'plant protein plan' (EC, 2018). Increasing the levels of production for home-grown high protein legume grains has proved recalcitrant historically (Squire et al., 2019), and compounded by a lack of post-harvest processing capacities (e.g. dehulling and protein:starch fractionation and/or enrichment) and processing technology (such as for protein extrusion), since special attention is paid (among animal feed manufacturers and suppliers) to providing sufficient provision of essential amino acids that might otherwise limit production, especially lysine  and. Nevertheless, recent shifts in consumer diets motivated by ethical, environmental and personal health concerns are already driving major shifts in protein markets (Ebert, 2014; Hamann et al., 2019), though whether the socioeconomic and environmental potential of legumes are realised 'at home' remains to be seen. As such, the UKs protein dependency has been disrupted due to the usual volatile global markets, and animal feed prices increasing. Closure and reduction in the services of private (and public) food outlets at home (Choudhury, 2020), appears to have been balanced by increased demand for UK meat exports (Farming UK, 2020). The extra risk posed by C19 could be perceived as an opportunity to re-establish more-sustainable legume-based cropped, food, and feed systems 'at home', as well as achieving a levels of protein import dependency that is low enough to buffer any shock due to feed-price increases or feed import shortage due to volatile global markets.

While the cultivation of grain legumes in the UK is very much dominated by combinable (i.e., dry harvested) peas (*Pisum sativum* L.), and faba beans (*Vicia faba* L.), alternative species are now being grown with increasing frequency, *albeit* still at low very levels nationally. These include the follwoing: soybean (*Glycine max* (L.) Merr.); lupin (*Lupinus*), as sweet- or narrow-leaf lupin (*L. angustifolius* L.), and white lupin (*L. albus* L.); lentil (*Lens culinaris* Medik.); *Phaseolus vulgaris* L. , including common- (e.g., navy) and French-bean types, plus other more-novel forms such as runner bean (*P. coccineus* L.*);* and chickpea (*Cicer arietinum* L.). Diversification of the UK legume grains market towards crops like soybean and lentils is governed by the multiple benefits offered by home-grown animal feed.

However, such diversification is also being motivated by significant shifts in human behaviour, and the high premiums offered by human food markets for commodities such as the lentils and the cultivation of grain legumes for harvest of immature pods as 'high-protein vegetables'. More-novel species such as *Lathyrus sativus* L. (grass pea), are also anticipated to feature in the list of commercially cultivated UK grain legumes, as this species offers types with excellent levels of protein and essential amino acids (e.g., lysine), and resilience to weather stochasticity, as is characterised by the impacts of climate change. There is also growing interest by consumers across the UK in more exotic and highly nutritious species of the Fabaceae (legume family), and one notable example is *Apios americana* Medik. (potato bean), which offers both edible beans and large tubers of high-organoleptic quality - though the tubers (only) are a more-realistic current option for the UK clines. Nevertheless, the species is perennial, and can be harvested non-destructively for continuous food-provision over successive years.

It should also be noted that a considerable proportion of all agricultural holdings in the UK is comprised of rough-, or more-intensively managed, grasslands, and the total 'grass' area accounts for around 69% or 49% of all agricultural holdings in England and Scotland, respectively (Scottish Government, 2020). These grasslands are often populated with legume-grass mixtures, though current mechanism of recording grassland management does demand that the % legume cover be accounted or estimated.

Nevertheless, the legume of choice is usually white clover (*Trifolium repens* L.), though there are many other forage legumes which can be grown in the UK, and some such as lucerne (also known as Alfalfa, *Medicago sativa* L.), may be especially high yielding. As such, the UK like the EU (EC, 2020a, 2020b) is self-sufficient in animal-feed as forage, and in that context the isolation of protein from legume-grass mixtures has emerged as a potentially significant source of feed for all forms of farmed animals (Corona *et al.,* 2018; see also, www.biorefineryglas.eu), and even food for humans. While the acceptance of products made from biorefined legume-grass mixtures still must be tested on consumers in commercial settings, the potential of this approach to increase protein-self-sufficiency in the UK is clear. This source of protein self-sufficiency allows presents the capacity to satisfy critical demand for specific protein qualities, including the provision of essential amino acids such as lysine (Leinonen et al., 2019; Leinonen et al., 2020). Furthermore, the approach may be applied on whole-crops forages - grain-crops harvested before full maturity and processed as silages. Specific crop mixtures such as co-cropped peas and wheat can yield more protein per unit area than equivalent monocrops.

## Appendix C: Further details on agroecology opportunities

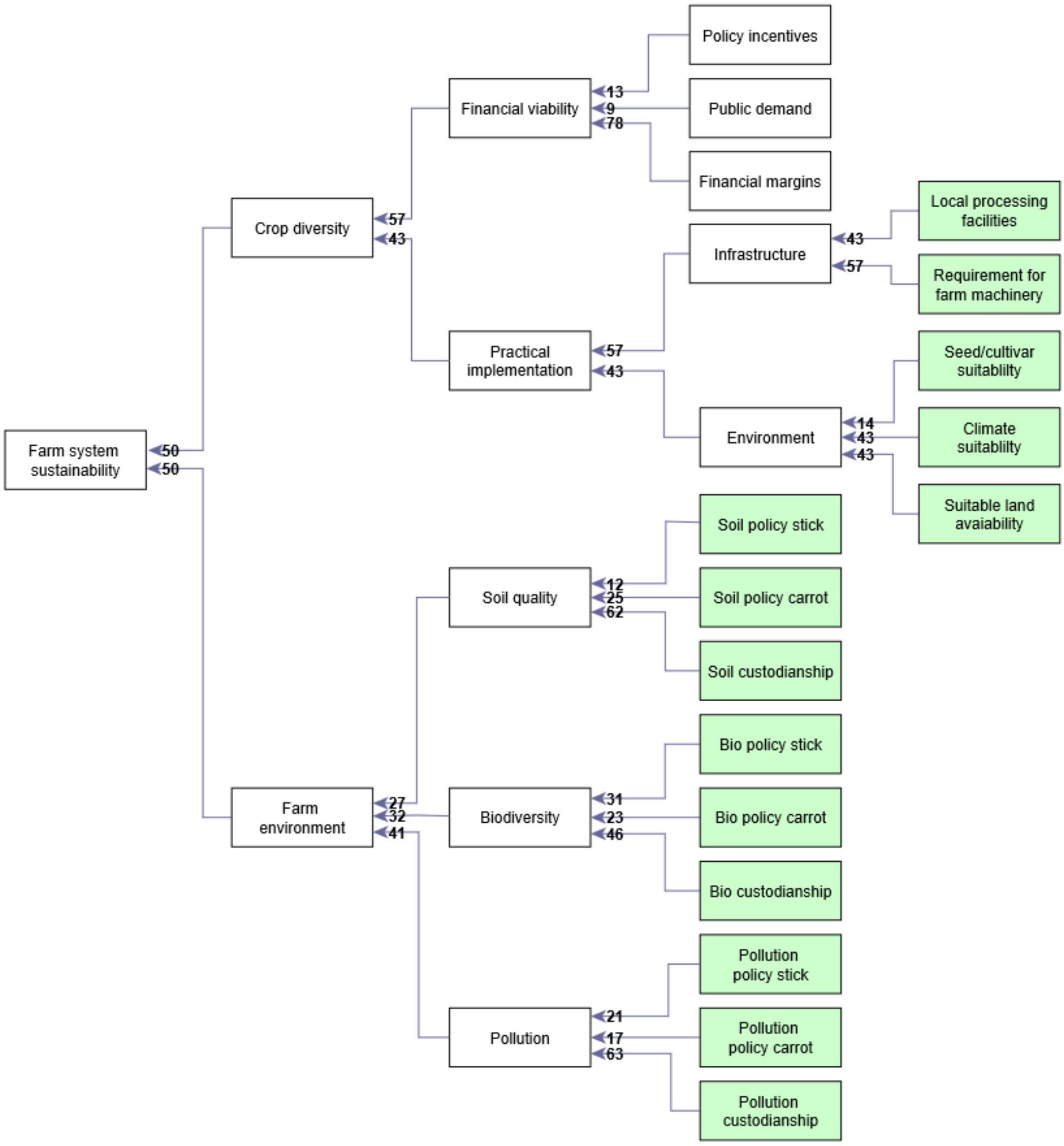
The likely agri-environmental consequences of the combined COVID-19 and Brexit scenarios proposed here relate to the degree of intensification and diversification of farming systems. Intensification scales from high input production in scenarios 1 and 4, to low input agroecological approaches for environmental sustainability in scenarios 2 and 3. In the latter, the goal is to improve the agricultural environment to maintain biodiversity for ecosystem services, to enhance soil quality for plant growth and to reduce pollution by minimising losses to the environment. Diversification ranges from monoculture commodity cropping (scenario 4) to crop diversification for UK self-sufficiency (scenarios 1-3). The spatial scale at which the crop diversification is applied is important. At a national scale, regions of the country could specialise in intensive monoculture production of a particular product, which would potentially meet self-sufficiency but not environmental protection targets (e.g. scenario 1). The smaller the spatial scale that this crop diversification is applied (regions, catchments, farms and even individual fields), the greater the co-benefit to environmental sustainability. Agroecological farming systems aim to increase the range and variety of different crop types grown at a local, on-farm scale to increase resource use efficiency and improve the resilience and reliability of production from the farm. Together, these approaches will result in a more resilient crop production system and therefore a more reliable (lower risk) supply of products to the value chain. Scenario 2, “Inward looking green way out”, has the best outcome for both environmental impact and a transition to diversification of agricultural systems to produce the ingredients necessary for balanced healthy diets. Scenario 3, “Green way out”, also results in a positive win-win, but with the lower economic sustainability and deep recession predicted here, any benefit may not be sustained long-term.

The difficulty with objective evaluations of scenarios such as these is the range of different types of information that must be considered (financial, social, quantitative) and the lack of empirical data to support predictions of future impact. One possible solution is the use of qualitative multicriteria evaluation methods which provide simple methods for assessment of an overall system state using sets of decision rules aggregated across a hierarchical framework. An example of such a tool is a Multi-Attribute Decision Model (MADM) that can combine qualitative and quantitative data in a single modelling framework (Sadok et al 2008). Applying this approach to the sustainability of agricultural systems can be used for iterative improvement towards more sustainable farming practices. Overall sustainability is broken down into several smaller dimensions and these in turn are simplified further into increasingly more quantifiable component parts (Pelzer et al 2012). Aggregating a suite of indicators into a single index in this way provides a more comprehensive holistic assessment of sustainability than assessments based on individual indicators measured in isolation. This approach also allows identification of trade-offs between elements within the system, e.g. where an expected positive effect of a change in management might be offset by a negative impact elsewhere (e.g. Hawes et al 2019).

Here, a simple qualitative, multi-attribute, hierarchical model (Suppl.Fig.1) was constructed using the DEXi software (Bohanec et al 2007) as a prototype to explore possible outcomes of the four scenarios in terms of farm scale environmental sustainability. At the top level, Farm System Sustainability describes the overall impact of each scenario on long-term farm scale agroecosystem sustainability. Scores at this level (categorised as high, medium or low) depend on (a) the diversity of crops grown and (b) the quality of the farm environment at the next level in the hierarchy. The weightings at each level of aggregation can be easily adjusted according to the perceived (expert opinion) or actual (measured) relative impact of each factor on the one above. In this prototype, crop diversity at the second level depends on financial viability of diversification which in turn is influenced by policy incentives, public demand and the likely financial return relative to monocropping of standard commodity crops. Farmer's choice to increase the diversity of crops incorporated into the farm system also depends on barriers to implementation including the availability of processing facilities within a reasonable transport distance, the requirement for specialist equipment for cultivation and harvest, the ease with which seed can be sourced, the match between crop type/cultivar and local soil and weather conditions suitable for growth, and finally, the availability of suitable land on the farm.

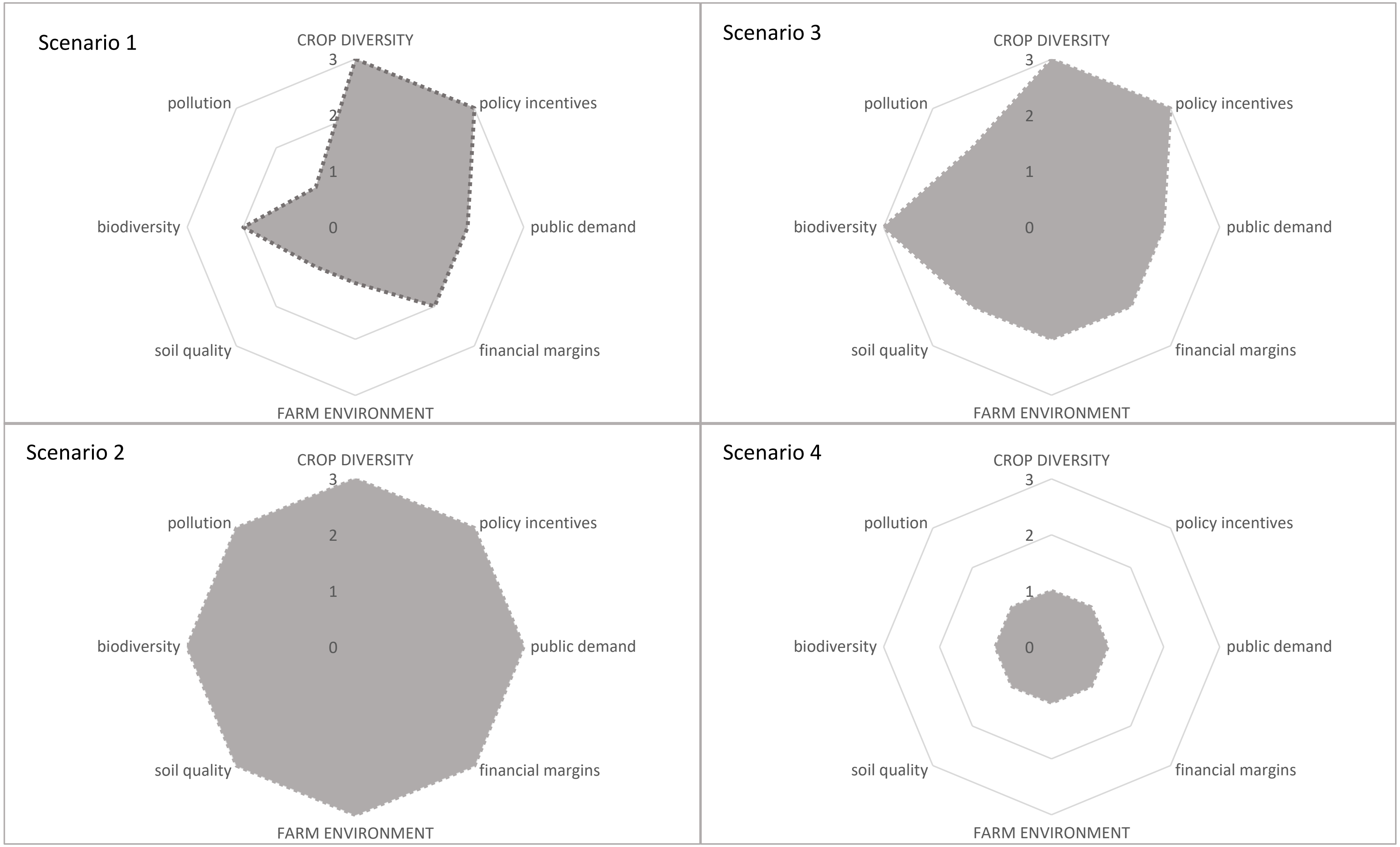
The second branch of the tree describes the farm environmental quality in terms of soil biophysical structure, native farmland biodiversity for ecosystem services and pollution by erosion, run-off, leaching and spray drift. Management to improve each of these factors depends on policy regulation to curb poor practice (labelled as “stick”), incentive schemes to encourage environmentally sound management (“carrot”) and the farmer's own willingness to adopt best practice options (custodianship).

This structure gives 17 input attributes and 10 aggregate attributes through the hierarchial tree, each linked by utility functions which determine the weight of each attribute on the combined, aggregated attribute above. These can be set based on specific case studies or expert opinion and adjusted to reflect the differences between drivers described in each of the four scenarios (Appendix A). Results are illustrated in Suppl.Fig.2. This model has the potential to be developed as a decision support tool for policy makers to assess the likely impact of alternative policy goals and drivers on the sustainability and long-term resilience of food production at the farm level across UK biogeographical regions.




**Supplementary Figure 1.** Hierarchical structure of a prototype Decision Support System for assessing and predicting the impact of global events (COVID, Brexit, etc) on environmental sustainability at the farm scale. Aggregation functions are shown as percentage contribution to the weighting at each level of aggregation (arrows).

**Supplementary Figure 2.** (Next page) Simplified DEXi evaluation of the prototype DSS on each of the four scenarios proposed in Appendix 1 to illustrate the potential utility of this approach in scenario planning/prediction. Shaded area represents scores (1=low, 2=average, 3=high) for each aggregated indicator: larger areas indicate higher scores for more indicators. Level 2 indicators are shown in CAPS (Crop Diversity and Farm Environment). Level 3 and 4 indicators are in lower case: policy incentives, public demand and financial margins aggregate to crop diversity; soil quality, biodiversity and pollution aggregate to farm environment. Scenario 1 scores average (2) overall due to high crop diversity (3) combined with low environmental score (1). Scenario 2 scores high (3) with the best outcome across the board. Scenario 3 also scores med/high (2/3) overall due to a greater proportion of average scores in both crop diversity and farm environment branches. Scenario 3 scores low (1) across the board.



Scenario 1
CROP DIVERSITY
policy incentives
public demand
financial margins
FARM ENVIRONMENT
soil quality
biodiversity
pollution
3
2
1
0
Scenario 3
CROP DIVERSITY
policy incentives
public demand
financial margins
FARM ENVIRONMENT
soil quality
biodiversity
pollution
3
2
1
0
Scenario 2
CROP DIVERSITY
policy incentives
public demand
financial margins
FARM ENVIRONMENT
soil quality
biodiversity
pollution
3
2
1
0
Scenario 4
CROP DIVERSITY
policy incentives
public demand
financial margins
FARM ENVIRONMENT
soil quality
biodiversity
pollution
3
2
1
0

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