The climate impact of alternative proteins

Final 25% Series Paper

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Final 25% series

The Final 25% project at the Oxford Smith School of Enterprise and the Environment aims to identify the landscape of key technological solutions for the final stages of the essential transition to net-zero, and then net-negative, CO_2 emissions.

The underlying premise is that 80% of emission reduction can be achieved by decarbonising electricity generation, transport and heating, and by improving energy efficiency, using technical solutions which are already the focus of significant research and development. The remaining 20% of global emissions are perceived to be difficult to decarbonise and currently lack clear reduction pathways. Research attention must be directed to these emissions sources now, so that necessary technologies and business models can be developed over time.

Net-zero emissions are unlikely to be enough to stabilise planetary temperature below a 1.5°C rise. It is likely that temperatures will overshoot; therefore, in order to limit climate change repercussions, there is a need to go net-negative, by absorbing between 2 and 20 Gt CO_2 per year by 2100 [1]. At the least, this is a further 5% reduction on top of eliminating present-day emissions.

The **Final 25% Series** focuses on the hard-to-abate sectors which form the final 20% of emissions, as well as ways of achieving 5% net-negative CO_2.

A key part of the project is a series of dinners convened in Oxford and London. The Oxford dinners, where selected guests include leading scientists, engineers and technologists, focus on the science and technology research and development needed to reduce emissions and achieve net-negative. The London dinners, where guests include leaders from finance, industry and government, explore how these new ideas can be funded and deployed at scale to make a material contribution.

This report series describes the conclusions of the discussions, offering recommendations based on the insights of experts working closest to these topics. The subjects covered in this ongoing series include nature-based CO_2 sinks, long-term energy storage, the future of cooling, alternatives to fossil carbon for industrial products and processes, bankable carbon capture and storage, and the climate impact of alternative proteins.

Executive summary

The food system is on the brink of a major transition that presents extraordinary challenges and opportunities. New technologies are advancing rapidly. Every year to 2050 there will be well over 60 million new humans to be fed [2]. Food production directly and indirectly accounts for over 26% of greenhouse gas emissions annually (aggregating emissions of different gases using the 100-year Global Warming Potential) [3]. Choices we make in the coming decade will shape our success or failure in feeding the 9 billion people by mid-century, with a nutritionally complete diet, while simultaneously mitigating climate change.

In this context, there is increasing focus on animal products, which account for almost 60% of food-related emissions and 16% of global annual greenhouse gas emissions [3]. Plausible projections suggest the demand for animal products will increase a further 35% by 2050 [4], [5], inevitably leading to an increase in emissions. But such projections do not necessarily come to pass – alternative sources of protein could potentially deliver security of supply within our planetary environmental constraints.

These alternative sources of protein include traditional plant-based proteins (eg tofu, nuts, peas, beans), insects, mycoproteins (eg products made by Quorn), algae (eg spirulina), protein derived from bacteria, and cultured meat [2]. On top of the promise of being affordable, efficient to produce and scalable, these alternative proteins hold two major environmental advantages compared to animal-related products. Firstly, in a world powered by zero-emission energy, production of alternative, zero-emission protein is possible, potentially reducing emissions by 8 Gt CO_2eq per year. Secondly, the land no longer needed for grazing or growing animal feed could be ecologically restored to provide a one-off natural CO_2 sink, offering much-needed greenhouse gas removal services. A substantial 82% of agricultural land is currently used to produce animal-related products [3]. If alternative proteins displaced all animal-related products (clearly a theoretical maximum), the overall potential for the released agricultural land to sequester CO_2 could be 900 Gt CO_2 over 100 years, after which sequestration rates would decrease. Due to the cumulative nature of CO_2, time is of the essence, but changes in human diet may be slow. A quick win could be to replace animal feed with alternative proteins.

Here, we identify four priority research areas to accelerate: (i) bacterial proteins and cultured meat; (ii) novel plant feedstocks for alternative proteins; (iii) analysis of nature-based greenhouse gas removal opportunities to map the potential of agricultural land to provide a sink for CO_2; and (iv) green fertilizer using green ammonia. We highlight three key policy implications. Policy should (i) accelerate the cost declines for alternative proteins; (ii) create environmental services markets to provide alternative incomes for land-owners to ease the transition; and (iii) provide transparent information to the public about alternative proteins, which is likely to aid consumer acceptance.

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1 Introduction: emissions from agriculture

Greenhouse gas (GHG) emissions directly or indirectly related to food make up 26% of global emissions [3] (aggregating emissions of different gases using the 100-year Global Warming Potential), as shown in Figure 1. Of this, animal-related products (meat, fish, dairy, eggs etc) account for almost 60%, representing 8.1 Gt CO_2eq annually. This is almost 16% of global GHG emissions. CO_2eq values must be used with caution because the effect of different greenhouse gases is aggregated; see the note on this in the grey box below. Figure 1 includes land-use change, but does not include the opportunity cost of land, which is discussed in Section 1.3.

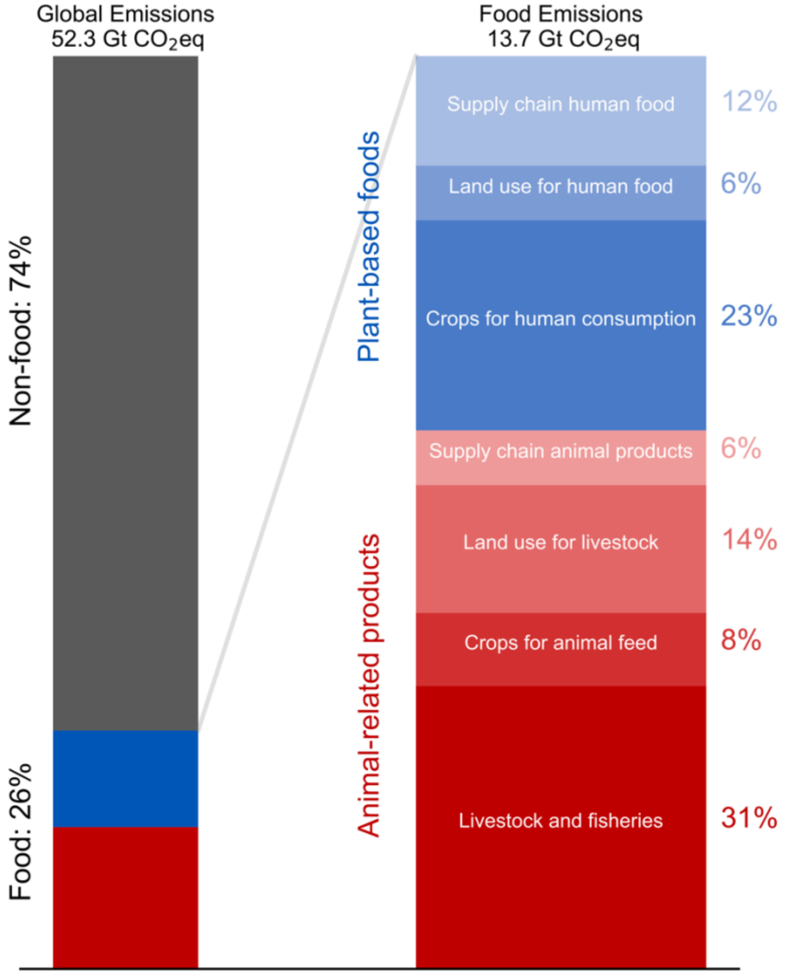

Figure 1 GHG emissions (CO_2eq) from food production. Data from Poore and Nemecek [3] **2018.**

The use of CO_2 equivalent values

CO_2 equivalents (CO_2eq), here calculated using the 100-year Global Warming Potential (GWP100), allow other GHGs, such as methane and nitrous oxide, to be accounted for within one unit. The value considers the global warming potential of each gas over a certain time period. Calculating these values is complicated by the fact that each GHG has different characteristics (ie warming effect and decay rate). This is expanded upon in Section 1.1.

By 2050, global demand for meat is expected to have increased by 35% [4], [5]. This is due to population growth and the fact that demand for meat follows increasing income, which is expected with the growing global middle class. This growth in demand for animal-related products is likely to require further land-use changes which will lead to substantial increases in emissions [6], [7]. Not only are emissions a concern, but with such growth in demand for animal-related products expected, uncertainties over dietary health and food security arise [8], [9], especially in the light of climate change affecting crop production [10]. This raises the question: 'how will we sustainably feed the global population of 2050?'. To understand this challenge better, investigate alternatives and 'provide tools for decision makers to promote healthy and sustainable diets', the Wellcome Trust Project: Livestock, Environment and People (LEAP), was founded at the University of Oxford in 2017 [11]. Research conducted within this project has highlighted the health benefits of reduced consumption of animal-related products, and the alignment of this with climate policy [12], [13]. However, to reduce meat consumption, alternatives will need to be available. In 2019, the World Economic Forum, in conjunction with LEAP researchers, published a white paper highlighting the promise of alternative proteins not only to reduce emissions, but also to transform global nutrition and health [5]. Alternative proteins include traditional high-protein plant-based foods (eg beans, tofu, nuts), insects, mycoproteins, algae, bacterial proteins and cultured meat. This report considers the emission-reduction potential of displacing animal products with alternative proteins.

1.1 Methane and carbon dioxide

It is convention to account for methane as CO_2eq using the 100-year Global Warming Potential. However, methane does not have the same warming affect as CO_2. Methane has a larger warming effect while in the atmosphere, but it decays much faster. So, to stabilise global temperatures, the objective is to reach net-zero CO_2 (although net-negative will likely be necessary), but to maintain (or ideally decrease) the rate of methane emissions [14].

There are many ways of calculating CO_2eq values, so attention must be paid to which method is used – some will decrease the apparent importance of methane, and others will increase it.

This is demonstrated in Figure 2, where three different GWP metrics are used and the resulting difference between the apparent impact of methane is clear.

To avoid uncertainty, there is value in reporting the emissions of different GHGs separately. This allows a deeper analysis of the extent to which emissions must be mitigated or offset (CO_2), compared to stabilised (methane). In this report, despite some misgivings, GWP100 is used in preference to a shorter timeframe. We recognise that there is much debate about the most appropriate timeframe and method to use.

An understanding that CO_2 emissions must reach net-zero and methane emissions must remain constant to stabilise global temperatures will be useful in the next section, where the current sources of emissions are considered.

1.2 Sources of agricultural emissions

Following a study by Poore and Nemecek [3], the emissions from animal-related products and crops for human consumption are split into four sub-categories: emissions from livestock farming and fisheries; emissions from crop production (for either animal feed or human consumption); supply chain emissions; and emissions from land-use changes. They do not include opportunity costs (see Section 1.3).

Livestock farming and fisheries: includes the emissions from rearing animals and the energy necessary to do so; land-use changes are accounted for separately. Ruminants (eg cows, sheep) release methane as they digest food, known as enteric fermentation emissions. Methane is also released from manure. Because of this, it is likely not possible to completely decouple the farming of livestock from all of the associated emissions, specifically methane emissions. Although there are possible pathways to reduce methane emissions from animals (such as changes to diet, supplements that reduce methane emissions [15], breeding out high-methane producers, improving feed-conversion efficiency, and manure management [6], [16]–[19]), this alone is unlikely to be sufficient to stabilise methane emissions given the expected increase in demand [7]. Therefore, production of certain animal-related products will have to plateau or reduce. The energy-related emissions are generally CO_2 and can be addressed by decarbonising electricity, heat and transport.

Crop production: these are dominated by emissions from fertilisers and energy (eg farm machinery). They can be tackled by reducing the use of fertiliser [20]–[22], by manufacturing ‘green’ ammonia (one of the precursors to fertiliser) and by decarbonising energy (electricity, heat and transport).

Supply chain: includes retail, packaging, transport and processing [3]. As such, these emissions are predominantly energy-related and indirect. They can be tackled by transitioning to renewable energy generation, by decarbonising transport and by a move towards sustainable polymers for packaging (as discussed in the accompanying report *Industrial need for carbon in products* [23]).

Land use: these can be considered indirect emissions resulting from land-use change. As discussed in the accompanying report *Nature-based sinks for CO_2 and sources of carbon feedstocks* [24], land-use change can release CO_2 that was previously stored in ecosystems and soils. The emissions associated with land use for livestock are twice as high as the emissions from land use for human food. This is due to the type of lands that are currently being converted for animal feed crops and for grazing (ie deforestation in the tropics [25]), as well as the areas of land needed.

The land-use change emissions reported were calculated based on average historic emissions from land conversion for agriculture. However, in meeting the future demand of animal products, the marginal emissions from land-use conversion will likely be higher than they have been historically. For example, it is probable that, due to strains on current agricultural land, additional demand would be met by deforesting land in the tropics for grazing or growing animal feed such as soya – over 80% of soya produced is used as animal feed [26]. This would incur much higher land-use change emissions in the future, something that must be avoided to stabilise global temperatures.

1.3 The carbon opportunity cost of land

The land-use change emissions discussed so far are those associated with agricultural land currently in use. However, there is an opportunity not only to prevent future land-use change emissions, but also to repurpose conventional agricultural land to provide a natural Greenhouse Gas Removal (GGR) service. This can be referred to as the carbon opportunity cost of land, as discussed in the 2020 Nature Sustainability publication by Hayek et al. [27].

Land has the potential to store carbon. For every hectare of land used for conventional agriculture there is an associated carbon opportunity cost [28], which relates to the carbon that land could store if it were not used for conventional agriculture but instead dedicated to nature-based GGR. For lands which remain in use for agriculture, regenerative agriculture practices should be encouraged to increase the carbon sink potential of the land.

Certain lands are better suited to GGR and therefore the carbon opportunity cost associated with using these lands would be larger than for other lands; deforested lands in tropical regions, for example, have a high carbon opportunity cost. In many instances, the carbon opportunity may not be met automatically by land if it is simply abandoned. Human intervention and stewardship may be required to ecologically restore the land before any benefit can be gleaned from the potential carbon sink.

1.4 Protein-rich foods

Animal-related products are a rich source of protein, an essential part of a healthy human diet. Global protein intake is currently 205 Mt annually, of which ~30% is from animal-related products [29]. As mentioned previously, population growth and an increase in the average consumption per capita due to an expanding global middle class will in all probability increase the demand for animal proteins.

The emissions associated with animal-related products and other protein-rich foods are shown as global average emissions per 100g protein in Figure 2. Carbon opportunity costs of the land are not included, but all other sources mentioned in Section 1.2 are. The contributions from CO_2 and nitrous oxide (N_2O) are indicated separately to those from methane. Methane is converted to a CO_2eq using three different GWP metrics, to demonstrate the significant differences between the methods. The first is the long-term impact using the GWP* method developed by Cain et al. [30], where methane is considered to be 7 times more warming than CO_2. The second is the GWP100 metric, where methane is 34 times more warming than CO_2, over 100 years. The third is the short-term (~20-year) impact of methane using the GWP* metric; methane is considered 112 times more warming than CO_2 over this time period.

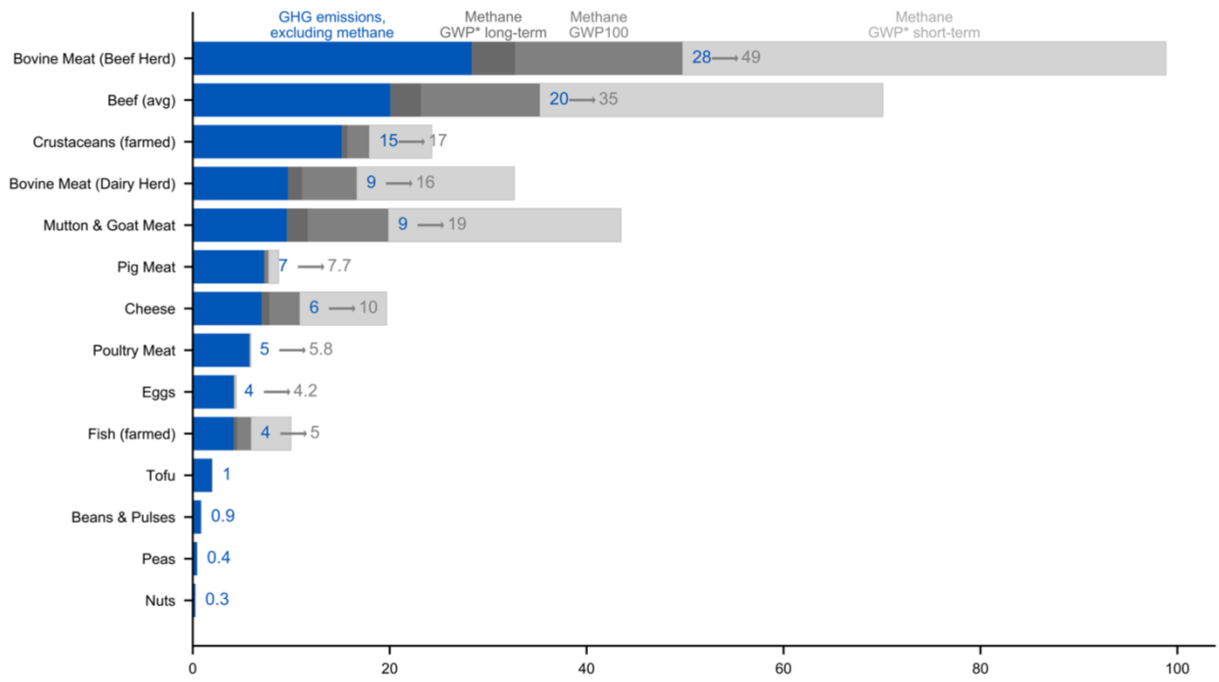

Figure 2 GHG emissions (CO_2eq) from protein-rich foods, per 100g of protein. Data from Poore and Nemecek [3] **2018, interpreted using three different GWP metrics, with methane to CO_2 warming ratios of 7, 34 and 112, respectively.**

Apart from the substantial variation in the apparent impact of methane among the different metrics, the most pronounced conclusion to be drawn from Figure 2 is that (even before addressing supply chain and energy-related emissions) emissions associated with plant-based protein-rich foods (i.e. tofu, beans, peas, nuts) produce are a mere 0.6–4% per unit of protein compared to the emissions associated with beef from a beef herd. In fact, emissions related to products from ruminant animals in general (beef, lamb, goat, cheese) are responsible for some of the highest GHG emissions per 100g of protein. These emissions are dominated by two of the four sub-categories mentioned in Section 1.2. First, livestock farming. Ruminant animals produce more methane than other livestock due to their enteric digestive process. Second, land-use changes. Lands used for grazing and animal feed crops (especially for beef herds) cause significant CO_2 emissions. This is because a substantial proportion of such land has been deforested for this purpose [25], which releases CO_2 into the atmosphere.

1.5 The promise of alternative proteins

From a climate perspective, there is a clear need to reduce CO_2 emissions from agriculture and to limit and reduce methane emissions. Beyond reducing emissions per animal (eg through diet changes and breeding), there are two key approaches to reducing emissions from protein production.

First, a reduction in the land used to cultivate animal feed crops. This exploits the carbon opportunity costs as the land can then be repurposed for nature-based GGR services. This requires cost-competitive alternative animal feed. Replacing purpose-grown animal feed with land-efficient and low-emission alternatives offers a pathway to reducing food-related emissions quickly, without the need for consumers to change their behaviour and diet – such changes take time, something we do not have the luxury of when it comes to climate change. The use of alternative proteins for animal feed also provides an early market, which would allow the products to scale and potentially benefit from cost reductions. Due to the cumulative nature of CO_2 as a GHG, opportunities to reduce emissions quickly are valuable.

Second, reduced consumption of animal-related products, specifically from ruminants (ie beef, lamb, milk, cheese). This would reduce both the land used for animal feed and grazing, and also the enteric methane emissions from ruminants. However, the growing demand for protein will need to be met by some more land-efficient and lower-emission alternative.

Alternative proteins could make the above possible. They are gaining traction as sustainable and affordable alternatives to animal-related proteins. The alternative proteins considered within this report include:

- Plant-based proteins (eg soya, beans, peas and nuts)
- Insects – either whole or as a powder
- Mycoproteins – derived from fungi (eg products made by Quorn)
- Algae – fast-growing aquatic plants (eg spirulina)
- Bacterial proteins – proteins derived from bacteria (eg products made by Solar Foods)
- Cultured meat – in vitro cell culture, meat but not from a slaughtered animal

The potential market for alternative proteins could be significant if demand for protein increases and economies of scale allow the prices of alternative proteins – from traditional and novel technologies – to out-compete the price of meat [31]. On top of being economically acceptable (or preferable), alternative proteins will also need to perform on taste, appeal and suitability to be widely accepted by consumers.

The Smith School of Enterprise and Environment is working with LEAP and stakeholders to identify and capture information relevant to this transition as it plays out. Useful data sets are being collated and data gaps highlighted, and efforts are underway to supplement existing data with new data sets on the emergence of key players and financial flows in the food sectors of the future.

In Section 2, the reduction in land-use requirements and GHG emissions are quantified under the scenarios in which animal feed is displaced or consumption of animal-related products decreased.

2 Land use and emissions from animal-related products

As discussed, animal-related products are responsible for 59% of the food industry's GHG emissions, including all emissions except opportunity cost. In reducing dependence on these food sources, there is scope to reduce the demand for agricultural land (both for grazing and for animal feed), thus decreasing GHG emissions. The availability of alternative, lower-emission sources of protein makes this theoretically possible.

Before animal-related products are replaced with alternatives, Figure 3 considers the upper limit of land use and emissions savings possible under extreme cases in which animal-related products are removed from our diets. Five different cases are considered: current diet; no animal feed; no beef; no beef, lamb or mutton; no beef (including dairy beef), lamb, mutton or dairy (ie cheese and milk); and no animal products. The removed foods are not replaced with protein-rich alternatives until Section 3.3. Instead, Figure 3 is used to provide a baseline on which the possible alternative sources of protein, discussed in Section 3.3, can be added. This report does not delve into the complexities of considering nutritional profiles, and it must be noted that animal-related products contain certain nutrients (vitamins, minerals and fatty acids) which would need to be sourced from elsewhere to maintain a well-balanced diet. Details on nutritional profiles of alternative proteins can be found in the 2018 Nature Sustainability paper by Parodi et al. [32].

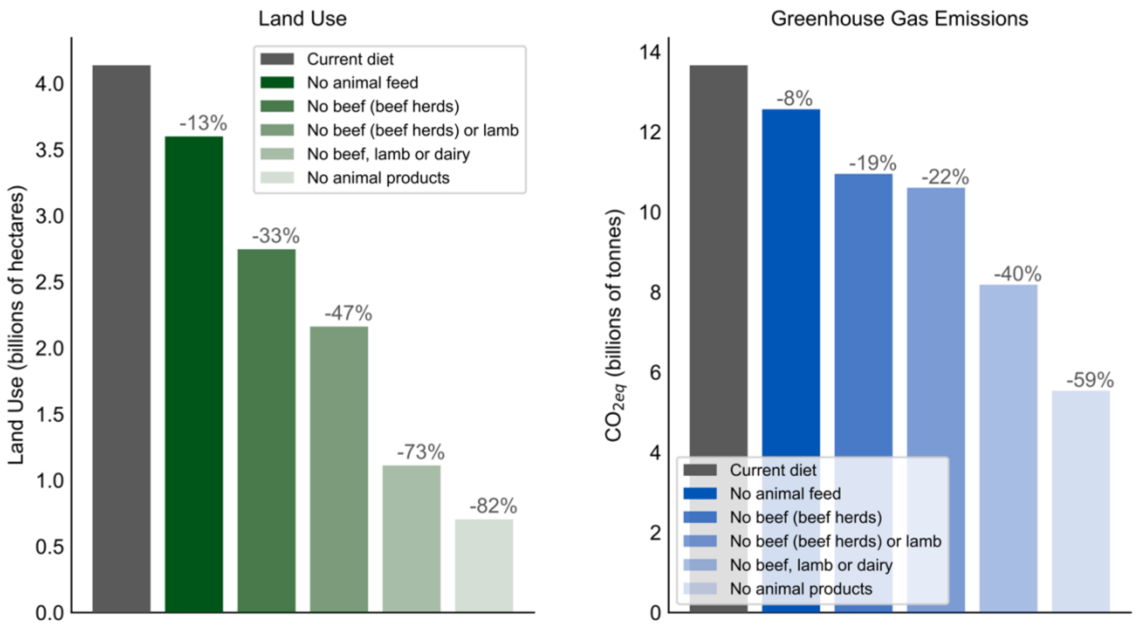

Figure 3 Changes in land use and GHG emissions under extreme cases in which certain groups of animal-related products are no longer consumed. Data from Poore and Nemecek [3]**.**

Figure 3 demonstrates that before considering a replacement protein source, it is possible to release over 80% of agricultural land by no longer consuming animal-related products, negating almost 60% of agricultural emissions. These are of course upper limits, as the animal-related products would need to be replaced with alternative food sources, discussed in Section 3.

The remaining 41% of emissions are dominated by energy-related and fertiliser emissions. The energy-related emissions can be negated by transitioning to renewable electricity resources and decarbonising heat and transport. Fertiliser emissions can be reduced by the use of green ammonia to produce the fertiliser. Additionally, there are farming techniques which require reduced volumes of fertiliser [20]–[22].

On top of the emission reductions detailed above, the land no longer needed for animal feed crops or grazing could be ecologically restored, potentially fulfilling nature-based GGR requirements, which are outlined in the report *Nature-based sinks for CO_2 and sources of carbon feedstocks* [24]. However, there are key political, economic, ecosystem and cultural aspects that must be considered in ecologically restoring land. Developing dedicated policy pathways could assist in addressing these potential barriers.

As mentioned previously, the carbon opportunity cost varies depending on types of land. Schmidinger and Stehfest [33] conducted a study to identify the GGR potential of livestock agricultural lands. The GGR potential (depending on which animal products are removed from the diet) ranges from 20 to 40 kg CO_2/m^2, assuming that the land acts as a carbon sink for 100 years. Nature-based GGR saturates over time and does not continue indefinitely. It must be considered a one-off in any CO_2 sequestration calculations. These values are used to calculate the potential for CO_2 sequestration from restoring agricultural land, shown in Figure 4.

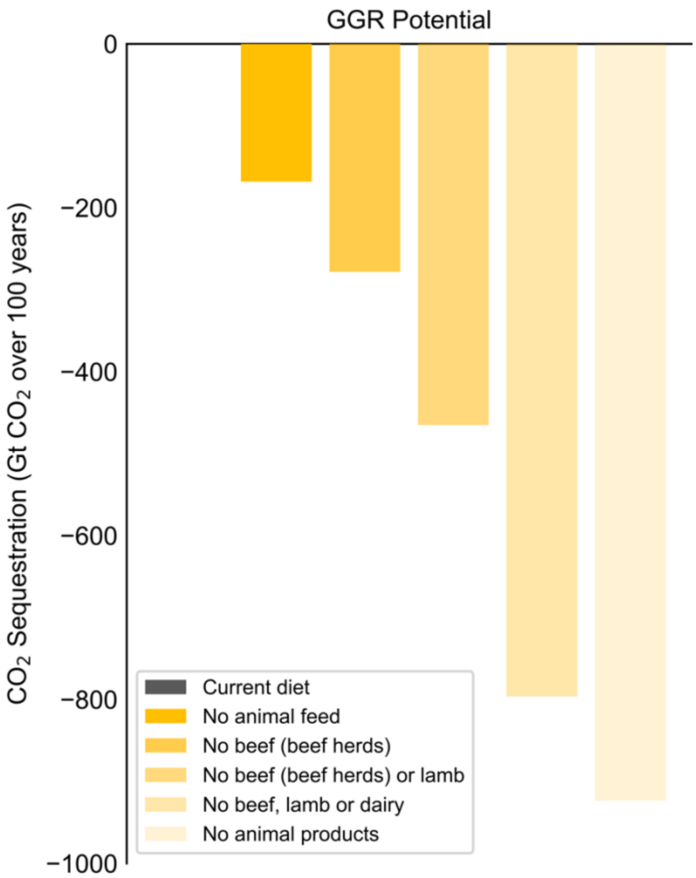

Figure 4 One-off GGR potential of released agricultural land.

The potential of repurposing agricultural land to sequester CO_2 is significant, at just over 900 Gt CO_2 over 100 years, as shown in Figure 4. According to the IPCC, by 2050, globally we will need to sequester between 2 and 20 Gt CO_2 per annum for climate change mitigation purposes, *plus* the equivalent of any CO_2 emissions (eg from industry) [1]. Nature-based GGR is one of the key mechanisms for achieving one-off, large-scale CO_2 sequestration. It is important to emphasise again that GGR from restoring lands saturates. Although initially the quoted values may be achieved, this sequestration rate will decrease and saturate over time [34].

The values shown in Figure 4 are simplistic, using a global average sequestration value for each type of livestock. A more sophisticated analysis identifying lands with high GGR potential would be beneficial in more accurately calculating the global potential of nature-based GGR. This analysis could also assist with locating priority regions where the greatest impact would be felt from replacing agricultural services with nature-based GGR services, as discussed in Section 4.1.3 and the report *Nature-based sinks for CO_2 and sources of carbon feedstocks* [24]. Even when land is identified as having high potential for GGR from restoration, this does not guarantee it can be restored. Local economic, social and biodiversity issues must be considered. Policy pathways will need to be in place to guide decisions regarding land restoration.

However, there will be no point in pursuing the potential of the land for GGR unless there is an alternative food source to replace the agricultural service which that land currently provides.

3 Alternative proteins

In Section 1.5 the six main categories of alternative proteins were identified as: plant-based proteins (such as soya, beans, peas, nuts), insects, mycoproteins, algae, bacterial proteins, and cultured meats. The extent of the emission reductions and CO_2 sequestration achieved will depend on the type of alternative protein and the way in which it is produced, which may be guided by the social and ethical choices of the sector, the financers and the consumers [35].

3.1 The alternative proteins

Each of these sources of protein have different land-use requirements and associated GHG emissions; each have their advantages and challenges. Nutritional values can be found in the paper by Parodi et al. [32]. A brief overview of each source follows.

3.1.1 Plant-based proteins

High-protein plant-based foods include soya, beans, peas and nuts. Impossible Food products [36] and the Beyond Meat range [37] are two examples of meat-free products. Due to their growing popularity, many supermarkets and traditional brands have adopted their own ranges of similar products [38]. Certain plant-based proteins are grown in newly deforested lands; this practice would need to be avoided to minimise future emissions.

3.1.2 Insects

Insects can be farmed for consumption in their entirety or to be used in powder form as flour [39]. A wide variety of plant-based feedstocks can be used, including material that cannot be used for human or vertebrate feed. In some cultures, eating insects has been the norm for centuries [40], with products becoming available more globally [41]–[45].

3.1.3 Mycoprotein

Mycoproteins are a meat replacement derived from fungi. Quorn [46] produces the most well-recognised product in Western markets, with a mycoprotein content of 92%. Wheat or sugar beet can be used as mycoprotein feedstock, but there are alternatives, including gases.

3.1.4 Algae (including seaweed)

Algae are protein-rich aquatic plants. Many different algal varieties exist. Spirulina and chlorella are widely available in powder form. Kelp, which is grown in the sea, is also available. In addition to algae, there are also lemna, or so-called water lentils (for example, duckweed), which are gaining attention as a source of protein. The growth of microalgae can be energy-intensive, shadowing can affect yield, and the structures in which it is grown can be capital-intense, which is why in recent years the focus has tended to be on high-value products [24]. Macroalgae (or seaweed) are able to grow in an uncontrolled environment, but there are challenges associated with its harvesting.

3.1.5 Bacterial protein

Bacterial protein, also known as microbial protein, can have a protein content of over 70%. FeedKind (developed by Calysta) produces feed for fish [47]. SolarFoods [48] is developing a product for human consumption. The process can be energy-intensive. The emissions savings offered by these products will heavily depend on the emissions related to the electricity supply. Costs could fall with the price of electricity [49], and may benefit from economies of scale. The RethinkX report [31] estimates that the cost of bacterial proteins could be 50–80% lower than the cost of the animal-related products they would replace.

3.1.6 Cultured meat

Cultured meat is an in vitro cell culture, ie meat but not from a slaughtered animal. A minimal number of livestock animals may be required to provide necessary stem cells (which can be harvested non-lethally). The growth medium is still being explored. Cultured meat production is energy-intensive, requiring 12 kWh per 100g protein [32]. The first cultured meat burger was manufactured for consumption in 2013 [50], but it is not commercially available at present; therefore, the land-use and emissions values in Figure 5 are speculative. As with bacterial protein, the process is very energy-intensive – emissions savings will depend on the emissions of the electricity supply. Costs could fall with the price of electricity and benefit from economies of scale [5], [31].

3.2 Overview, in a clean-energy world

Rough values for the agricultural land-use requirements and the likely range of GHG emissions (assuming clean energy) are summarised in Figure 5 for the alternative proteins. Poultry is included for comparison.

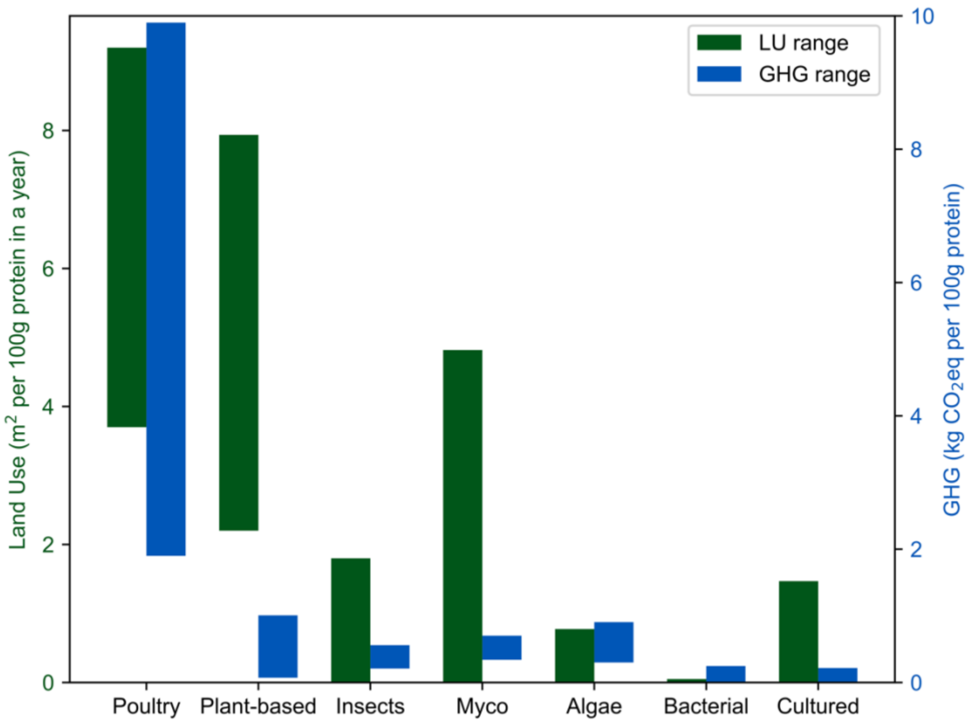

Figure 5 Land use and GHG emissions (assuming net-zero energy-related emissions) for poultry and six alternative proteins. Data derived from references [3], [32], [47], [49]–[57]**.**

Figure 5 shows that the agricultural land-use requirements for alternative proteins can be lower than for the traditional plant-based proteins. Insects require a plant feedstock as a growth medium, but this can be food waste (ie not requiring agricultural land directly). Mycoprotein can use gas or plant feedstock, and therefore has a large land-use range. Algae and bacterial proteins can require negligible land because they do not need plant feedstock. Cultured meat could require a donor herd to provide cells and growth medium [58], [59]; there is still great uncertainty surrounding this, but it could impact land use and emissions considerably.

With the assumption of zero energy-related emissions, the GHG emissions of alternative proteins vary depending on feedstock, growth medium and production process. For plant-based proteins, the range is mainly due to the land-use changes associated with growing crops. The emissions related to algae are due to the use of fertilisers. Fertiliser emissions also form a proportion of the plant feedstock emissions for both mycoproteins and insects. Addressing fertiliser emissions is important for producing sustainable food. This is discussed in Section 4.1.4. Bacterial protein and cultured meat emissions can be negligible if all energy-related emissions are negated, and the cultured meat does not depend on a donor herd. If a donor herd is required, the GHG emissions from cultured meat could benefit from reductions in fertiliser-related emissions and progress to decrease enteric emissions of beef cattle.

3.3 Net GHG emissions reductions if humans consume alternative proteins

Using the average values for land use and GHG emissions for the alternative proteins shown in Figure 5, the net impact of a full conversion in the human diet from animal products to alternative sources of protein can be estimated. A global consumption of 57 million tonnes of protein annually is assumed [29]. Both the annual GHG emissions saving (due to consuming a product which has less land requirements and lower GHG emissions) as well as the one-off CO_2 sink (from repurposing the land for nature-based GGR) are shown in Figure 6. It is important to note that this analysis has limitations because it does not account for nutritional requirements. A simple protein-for-protein trade is considered to give a best-case bound for GHG savings and GGR potential. Research into the global GHG emission reductions that considered nutrition would be valuable.

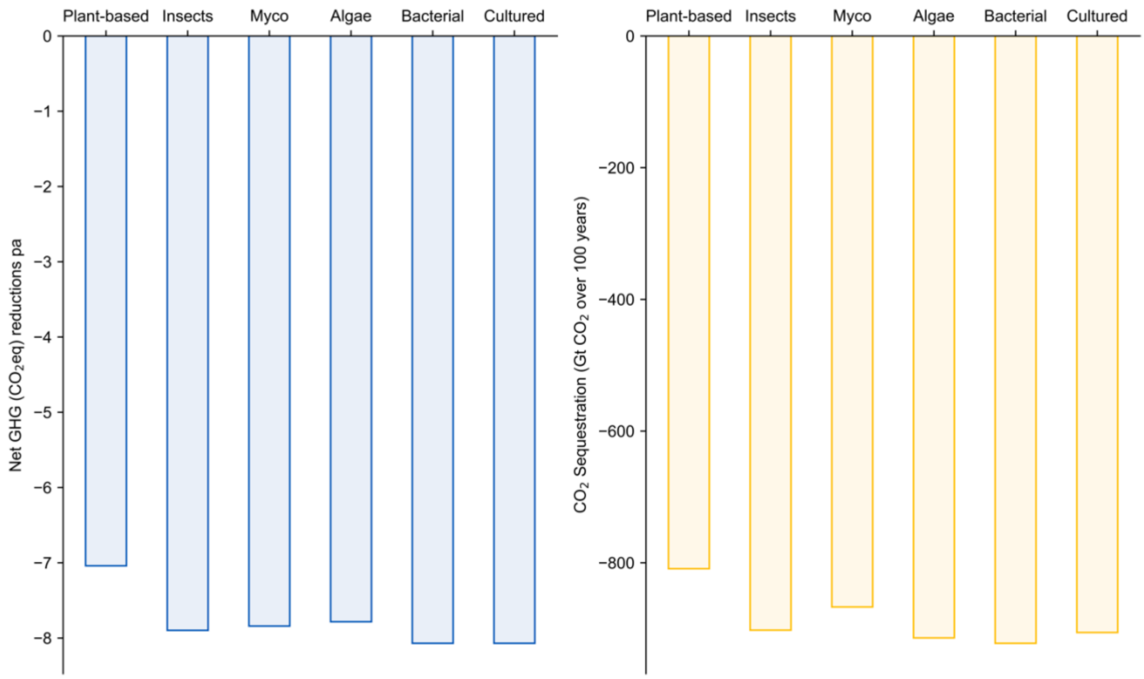

Figure 6 Left: potential reductions in GHG emissions (CO_2eq) annually if humans completely replaced animal-related products with alternative proteins in their diet (assuming net-zero energy-related emissions). Right: CO_2 sequestration potential over a 100-year period if land is repurposed for GGR. Simple protein-for-protein exchange – nutrition not considered.

One point to highlight from Figure 6 is that even transitioning to traditional plant-based proteins results in reduced land use. There is little difference between the GHG emissions impact of consuming the other alternative proteins. This is because the emissions savings from no longer consuming animal-related products dwarf the variation among the alternative proteins.

4 Recommendations for action

Alternative proteins present an attractive substitute for animal-related products. Their smaller land requirements (alleviating land for GGR services) and lower GHG emissions will be ever more important as countries strive to meet their emissions targets. On top of this, the potential for the costs of these alternatives to fall drastically could cause huge disruption to the agricultural industry. This would be positive for some players and negative for others, and we should prepare for it. Low-cost alternative proteins could be game-changing in providing sufficient proteins and other nutrients to satisfy the nutritional needs of the growing global population while reducing food-related emissions and mitigating climate change. To facilitate the adoption of alternative proteins, there is a need for research and development (R&D), as well as supportive policies.

4.1 Priority areas for research and development

There are four areas highlighted for priority research, which will facilitate cost reductions, inform GGR market creation, and enable further reductions in agriculture-related emissions. These are: (i) further research into alternative proteins, particularly bacterial proteins and cultured meat, which are not yet commercial; (ii) investigation of novel plant feedstocks for alternative proteins; (iii) analysis of nature-based GGR potential; and (iv) development of green fertilisers from green ammonia.

4.1.1 Further research into alternative proteins

All alternative proteins are likely to play a role in feeding the future population – they are not mutually exclusive, and pursuit of all options should be actively encouraged. Alternative proteins must become 'normal' in society across food categories and occasions. Bacterial proteins and cultured meat are furthest from market, currently requiring early-stage R&D funding. As such, they may need special attention and public funding in the time-critical race against climate change. Neither are yet commercial, but they both hold significant promise in terms of very low emissions (depending on production processes at scale), low land requirements and low costs (if electricity costs decrease with the use of renewable energy).

4.1.2 Investigation of novel plant feedstocks for alternative proteins

Insects and mycoproteins require a plant feedstock for growth. For mycoproteins, traditional grains and vegetables are currently used (eg wheat, carrot); a broader spectrum of feedstocks are used for insect protein, including by-products from crop production with little or no other value. Ongoing research in the Sahel seeks to identify novel feedstocks for insect protein (at present to produce animal rather than human food). A broad variety of different plant species which can be grown on non-agricultural land that provides few ecosystem services are being investigated (see discussion in the report *Nature-based sinks for CO_2 and sources of carbon feedstocks* [24]).

4.1.3 Analysis of nature-based GGR opportunities

There is uncertainty surrounding the extent to which ex-agricultural land can act as a one-off CO_2 sink if it is repurposed to do so. However, reforestation is known to be a vast and vital component of mitigating climate change [60]–[62], which will require agricultural land within forested regions to be released. The GGR potential of land depends on the natural ecosystem within which the land is located (ie whether it is within a forested region in the tropics), the current use of the land, and whether the land is degraded. The opportunities for nature-based GGR are discussed in the accompanying report, *Nature-based sinks for CO_2 and sources of carbon feedstocks* [24]. This report has highlighted the need for mapping to identify agricultural areas with the greatest potential for GGR if the lands were restored.

4.1.4 Green fertilisers from green ammonia

Throughout this report, fertiliser has been mentioned as one of the key sources of emissions. There is an urgent need to move away from using brown (or grey) ammonia (produced by steam methane reforming of gas) as a fertiliser reagent towards using green ammonia. Scalable techniques for producing green ammonia require R&D, as will be discussed elsewhere in the Final 25% Series.

4.2 Policy

Policy support is necessary in three main areas. First, the acceleration of innovation in alternative proteins. Second, the creation of environmental services markets to support an agricultural transition. Without these there is no economic value associated with GGR services. Finally, policy support is needed to provide transparent information about alternative proteins to facilitate market evolution of alternative proteins through clear narratives and transparency.

4.2.1 Accelerating innovation in alternative proteins

Bacterial proteins and cultured meat might hold vast commercial promise, according to the RethinkX report [31], in which case private investment is likely to flow towards R&D in these areas. However, given the wide range of spillovers and positive externalities (or the avoidance of negatives) associated with these technologies, private sector efforts alone are unlikely to be economically optimal. Further, as highlighted through work at the Smith School of Enterprise and Environment in partnership with LEAP, start-ups in this sector are often capital-intensive, and given the high risks and thus the need for high returns, funding through traditional routes might be challenging. Support from the public purse in the form of conditional grants is likely to be necessary to allow these technologies to reach their full potential in the required timeframe.

4.2.2 Creation of environmental services markets

If costs of cultured meat drop as drastically as predicted by some sources [31], they could out-compete farmed meat and animal-related products and potentially, if consumer adoption follows, reduce demand for these foods. This could cause substantial economic turmoil to an industry that is already heavily subsidised. Policy surrounding jobs and the rural economy will be necessary to ease a shift in production. Governments may wish to consider how they signal upcoming changes in the agricultural sector.

One way of supporting a transition to alternative proteins would be for governments to create environmental services markets, ie for GGR. This would provide an alternative income for owners of agricultural land. Environmental services markets encourage the use of land for CO_2 sequestration and other services, such as those related to biodiversity. GGR is an inevitable requirement for stabilising global temperatures; it will be necessary at a significant scale of 2–20 Gt CO_2eq per annum by 2100 [1]. As GGR is a public good, financing will need to be from the public purse [24]. Capital to pay for environmental services could be repurposed from existing agricultural subsidies. The challenge is that GGR is also a global good; therefore, for it to be effective there must be global markets. The UK can lead the way but will need to work closely with other governments, especially those where land is most valuable for GGR.

4.2.3 Providing transparent information about alternative proteins

Social acceptance and consumer adoption of alternative proteins is a risk to the sector [63] and framing of the emerging foods will be a powerful tool [64], [65]. There is a need for transparent discussion (on the benefits and challenges alike) to build public trust in government, so that citizens know about production processes and are confident they are constantly fully informed and able to make choices based on complete information. Additionally, government messaging will play a key role in framing these foods for the public. Clear narratives are needed to avoid fear of 'frankenfoods', and facilitate acceptance of, and potentially desire for, 'clean' meat. Any advice must be based on scientific evidence to maintain trust in government.

5 Conclusions

Emissions from food account directly and indirectly for over one quarter of GHG emissions annually, when aggregating emissions of different gases using the 100-year Global Warming Potential. To stabilise temperatures, emissions of CO_2 need to decline to net zero, and beyond, and methane emissions need to stabilise, if not fall. Decarbonising energy and developing sustainable fertilisers will help to address emissions from the supply chain and crop production. However, emissions due to land-use change and livestock are more challenging; some of these emissions may be unavoidable. If the consumption of animal-based products grows as anticipated, emissions from livestock and land-use changes would increase rather than decrease. To deliver sufficient food for the growing global population, within our planetary environmental constraints, alternative proteins are required.

Livestock farming accounts not only for 59% of food-related GHG emissions, but also for 82% of agricultural land use. If animal-related products were replaced with more efficient, sustainable, alternative proteins, a dual climate benefit could be realised. Firstly, the associated GHG emissions would be significantly reduced, potentially saving almost 8 Gt CO_2eq per annum. Secondly, the land no longer needed for grazing or to grow animal feed could potentially be ecologically restored to provide a one-off natural CO_2 sink, through much-needed greenhouse gas removal services. The overall potential for the released agricultural land to sequester CO_2 could be up to 900 Gt CO_2 over 100 years.

This transition away from farming livestock is only plausible with the emergence of affordable, scalable and socially accepted alternative proteins. This report focused on six such alternatives: traditional plant-based proteins, insects, mycoproteins, algae, bacterial protein and cultured meats. All of these are considered valuable options to pursue due to their different nutritional profiles and use cases; each has their own specific advantages and challenges, requiring continued critical research.

Research and development into all alternative proteins is necessary because future diets will likely incorporate a combination of these products. Early-stage R&D into bacterial proteins and cultured meat is a priority. These two are furthest from market, yet have the potential to out-compete animal-products and transform the edible protein landscape [31]. Research into novel feedstock crops for alternative proteins and green fertiliser could reduce emissions further and potentially release additional land for greenhouse gas removal. Studies on the potential of ex-agricultural land to provide a sink for CO_2 would enable more accurate quantification of the opportunity, and would help to map the priority regions to re-purpose.

Policy support is needed in three main areas. First, to direct funding to accelerate innovation in alternative protein development, commercialisation and scaling. Second, environmental services markets could be created and expanded to provide alternative incomes for land-owners outside of farming, easing a transition in the agricultural industry. Third, governments can support the provision of transparent information (about both the advantages and challenges of alternative proteins) and clear narratives to ensure public trust in messaging, which may aid consumer acceptance.

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