A new land dividend:
the opportunity of alternative proteins in Europe

Technical report

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Summary

Europe has set ambitious goals to restore nature, reach net zero and make food systems more sustainable. Whilst vital to food security, these goals all require land, which is already in short supply. In Europe, agricultural land is dominated by meat and dairy production. Without dietary change, these new goals will add to the 40 per cent of Europe's food supply that is already located overseas.[1]

Alternative proteins, such as cultivated meat and products made from plants and precision fermentation, may be key in shifting diets. These products, in the future, could offer the same taste and texture of conventional meat and dairy products, at a cheaper price. Importantly, these alternatives tend to have lower land and carbon footprints than conventional meat and dairy. We estimate alternative proteins could displace between a sixth and two thirds of meat and dairy production by 2050, depending on the success of innovation in driving down price and improving taste, and the support governments offer to scale-up and licence products. This would create a huge land dividend.

We studied what alternative proteins could mean for land use in ten European countries, Denmark, Sweden, Italy, Spain, France, Germany, the United Kingdom (UK), Poland, Romania and the Netherlands, which represent 70 per cent of EU27+UK land area and 80 per cent of EU27+UK emissions.

We found that our ‘high innovation’ scenario, where two thirds of meat and dairy is displaced by alternative proteins, could free up an area the size of France within Europe and see these countries avoid needing land the size of Spain outside their borders. We explored the consequences of using this land dividend to: (1) reduce land use overseas (by which we mean outside each country’s borders)[2]; (2) expand natural habitats; and (3) expand agroecology.

In the main report, we focused on a ‘shared dividends’ scenario that shared the land dividend created by alternative proteins between these three priorities.

Here, we explore that scenario in more depth, provide a full methodology and examine the trade-offs that arise from pursuing this blend of priorities.

With ‘high innovation’ in alternative proteins, we found our ‘shared dividends’ scenario could mean these ten countries become entirely self-sufficient in terms of land use by 2050. The area they would need to feed themselves would be no larger than their own agricultural areas. This would reduce global deforestation pressure and create the space for other countries to reduce emissions and restore nature.

Second, we found that the ten countries studied could collectively almost avoid having to use expensive engineered carbon removal by expanding their

natural habitats to 30 per cent of farmed land, even whilst onshoring and expanding agroecology under the ‘shared dividends’ approach.

The avoided demand for engineered carbon removal would save taxpayers across Europe an estimated €24 billion in 2050 alone.

Third, at the same time, agroecological farmland could expand four times, to a third of farmland.

But these patterns across all ten countries hide important differences on a country-by-country basis and mask the trade-offs inherent in pursuing these three priorities concurrently.

The greatest trade-offs arise in the UK, Germany and Italy which are densely populated countries with high overseas land use. Under the ‘shared dividends’ scenario, ‘high innovation’ in alternative proteins reduces the demand for engineered carbon removal by 42 per cent, but along with overseas land use, engineered carbon removal cannot be avoided under a ‘shared dividends’ approach.

Both overseas land use and engineered carbon removal could be avoided if they were the sole focus, but not at the same time, and not whilst agroecology expands. In contrast, we found that France, Sweden and Romania do not need engineered carbon removal to reach net zero even if diets don’t change.

Unlike the UK, Germany and Italy, provided there is ‘high innovation’ in alternative proteins, France, Sweden and Romania could be entirely self-sufficient for land use even under a ‘shared dividends’ approach.

Denmark and the Netherlands are the countries where alternative proteins create the least opportunity because their land area is small, and production is already highly efficient. High alternative protein uptake does far more to reduce overseas land use than efforts to offshore food production, and demand for engineered carbon removal remains high, regardless of the level of diet change or the priority to free up land.

Finally, in Spain and Poland, both engineered carbon removal and overseas land use can be avoided whilst expanding agroecology, provided there is ‘high innovation’ in alternative proteins; otherwise space for agroecology is traded off against demand for engineered carbon removal.

In all countries, governments will play a crucial role in determining how much meat and dairy is displaced by alternative proteins and whether land really is freed up for other uses.

Without policy change, any land freed up by reduced domestic demand for meat and dairy could see exports increase, leaving taxpayers to bear the environmental costs of other countries' dietary choices.

Governments should seize this opportunity to shape a landscape that mitigates climate change, restores nature, and thereby protects food security for the next generation. At the same time, they would ensure good rural incomes by aligning incentives with the character and quality of the land.

Introduction

Europe has already run out of land but climate mitigation and biodiversity loss demand space to recreate lost carbon and nature rich habitats. [3]

Alternative proteins, which aim to create the same taste and texture of conventional meat and dairy with a range of plant-based, fermentation and cultivation techniques, require far less land than the conventional meat and dairy that they aim to displace and thus could create much needed space.[4] Governments will influence the extent of meat and dairy displaced by alternative proteins. Policy could slow their development, as demonstrated by the recent ban on cultivated meat in Italy, or governments could support the development of new products, and create the conditions to ensure their people benefit from the land dividend alternative proteins create.

Seventy one per cent of agricultural land in Europe is used to produce meat and dairy.[5] As a result of their lower land footprint, alternative proteins present three major opportunities, as follows.

First, by displacing conventional meat and dairy, they reduce the land needed for food production at home and overseas. The space at home then creates the opportunity to onshore some of the remaining overseas production. This makes these countries more self-sufficient, which may be advantageous in an increasingly climate changed, and volatile, world. It also reduces land pressure in other countries, increasing the prospect of ending deforestation and meeting global climate goals.

Second, the space created by alternative proteins allows for the expansion of natural habitats that are home to wild species and store carbon. This is essential to food security which is primarily threatened by climate change and biodiversity loss. It also reduces the costs of environmental degradation paid by taxpayers, including water pollution, air pollution, flooding, and emissions. Without action to reduce emissions and increase the capacity of the land to remove carbon from the atmosphere, in the future, taxpayers will be forced to pay for engineered carbon removal to offset residual emissions. Many countries are looking to bioenergy with carbon capture and storage (BECCS) to deliver negative emissions which is more expensive than semi-natural habitat sinks.[6]

Alternative proteins reduce the demand for BECCS both by displacing livestock production, leaving fewer emissions to be offset, and by creating space to expand carbon storing semi-natural habitats.

Third, the space provided by alternative proteins can facilitate growth of the organic, or agroecological production that the EU has committed to expanding.[7] Without dietary change, expanding organic production, which uses more land to produce the same volume of food, will drive more production overseas, reducing self-sufficiency and increasing pressure on land globally.[8]

Given the EU is committed to ending deforestation, and the nature and climate crises are inherently global, the organic goal cannot be met by pushing more production offshore.[9]

We studied the opportunity alternative proteins create to free up land in ten European countries: Denmark, Sweden, Italy, Spain, France, Germany, the UK, Poland, Romania and the Netherlands. Our model assumed this land would be used to either (1) reduce overseas land use; (2) expand semi-natural habitats; or (3) expand agroecological farming.

Our central scenario presented in the main report, 'shared dividends', spread freed up land across these three priorities. In this technical report, we also present scenarios that took each of these priorities in turn to explore the trade-offs inherent in pursuing all three priorities at once (see appendix, page 29).

For all scenarios, we assessed the resulting demand for land use overseas and carbon removal, and quantified the extent to which agroecology and semi-natural habitats could expand.

Results

Current land use

First, we explored how farmed land in the ten countries studied is presently used, to understand how much land could be freed up by alternative proteins. In every country, more than half of the farmed area is used to produce meat and dairy products. In the colder countries that mainly raise livestock indoors, such as Sweden and Denmark, this land is mostly used to grow feed.

In contrast, the UK is exceptional in how much of its land is pasture grazed by livestock. Despite land use being dominated by gazing animals, the UK still uses more than 20 per cent of its farmed area to grow livestock feed.

All countries use some land for exports. The Netherlands is exceptional in dedicating 68 per cent of its land area to producing exports. By area, France dedicates the most land to producing exports.

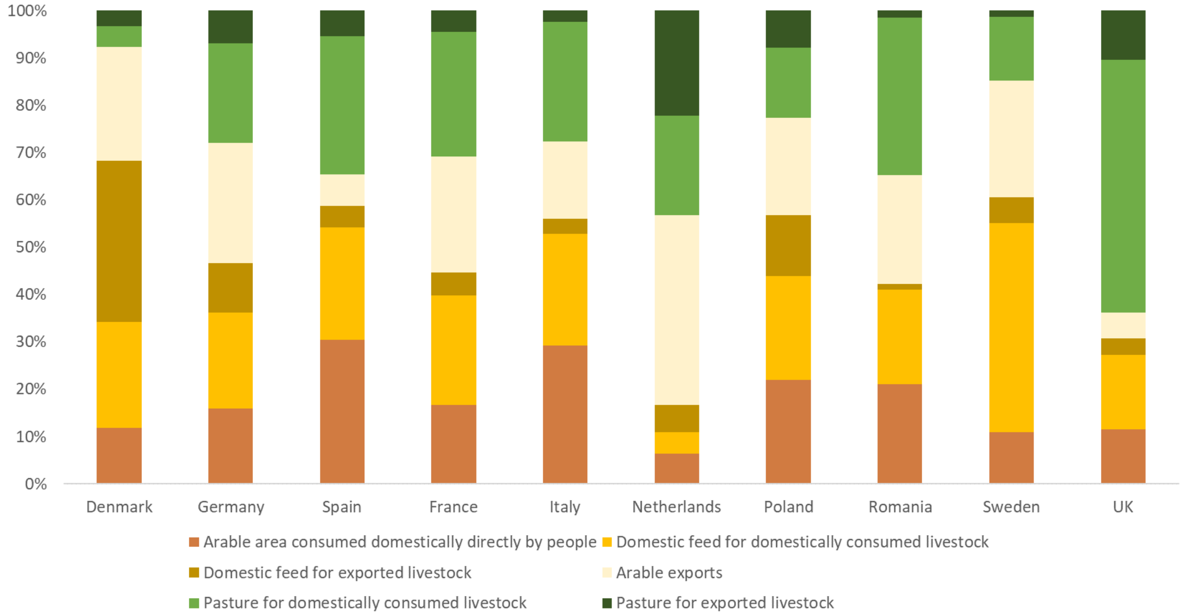


Figure 1. Present use of farmed land in each of the studied countries

In addition to their own agricultural industries, these countries all import food from other countries. The UK, Italy and the Netherlands import food from an area greater than their entire domestic agricultural areas.

France, Denmark, Poland and Romania are the only net exporters of land; all other countries use more land overseas for imports than they use to produce exports.

Taken together, these ten countries import food from an area over twice the size of the land they use to produce exports. Therefore, even if these countries traded all their exports to each other, they would still demand land elsewhere in the world to meet their populations' demands.

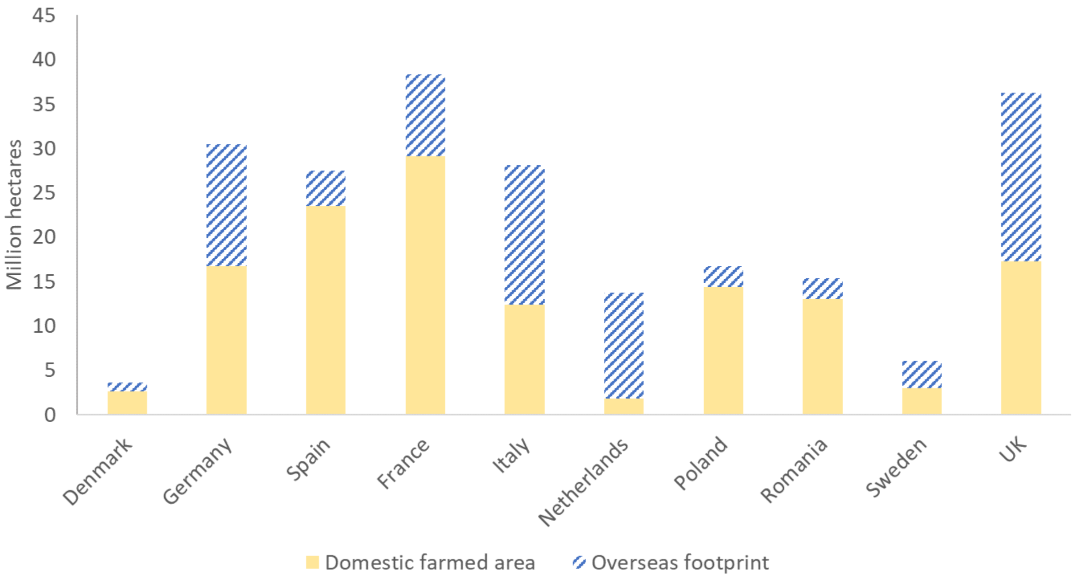


Figure 2. The land presently used for farming within each of the studied countries and the area of land used to produce food they import

Land area freed up by alternative proteins

We designed three scenarios to illustrate the extent to which conventional meat and dairy products could be displaced by alternative proteins and estimate the consequences for land use (see methods, page 18).

Our 'low intervention' scenario assumed that more innovative precision fermentation and cultivated meat alternative protein products fail to reach a competitive price. As a result, only some forms of highly processed meat and dairy, such as ready meals, are replaced by plant based alternative proteins.

Therefore, on average, about a sixth of meat and dairy is assumed to be displaced in this scenario by 2050. Given half of Europeans report having already changed their diets to eat less meat, this represents the lower bound of likely change.[10]

Our 'high innovation' scenario assumed that governments would support the development of the alternative protein industry, such as by funding the infrastructure needed to scale up production, and resourcing their food standards agencies to rapidly, and stringently, approve new products. As a result, there is far greater displacement of dairy, particularly of milk and supermarket cheeses by alternative proteins made through precision fermentation.

In this scenario most processed meat, which accounts for about half of total consumption, is displaced by plant-based products enhanced with compounds made through precision fermentation, and a limited proportion (<20 per cent) of cuts of meat are displaced by cultivated meat. On average, about two thirds of meat and dairy is replaced by alternative proteins in this scenario. Our 'mid ambition' scenario, presented only in the appendix, assumed an intermediate position.

We studied the impacts of these scenarios on land use change, given the difference in area needed to produce alternative proteins vs conventional meat and dairy. In all countries, displacement of meat and dairy by alternative proteins freed up land both at home and in the countries from which they import.

In the 'low intervention' scenario alternative proteins freed up a total 21 per cent of domestic land area by 2050, whilst the 'high innovation' scenario freed up 44 per cent.

Within individual countries, the lowest proportion of land, 30 per cent in the 'high innovation' scenario, is freed up in the Netherlands where most land is used to grow food for exports, which we assumed to be unaffected by domestic diet shifts towards alternative proteins.

The largest proportion of land, 57 per cent, is freed up in the UK. This reflects that the UK uses more of its land for grazing animals than any other country.

In absolute terms, the largest area is freed up in the UK, France and Spain, where livestock tend to live outdoors, whilst far smaller areas were freed up in Sweden and Denmark, where livestock are produced very efficiently indoors.

We found this diet change would free up an even larger area of land used for producing imports, even before any efforts to onshore production. This reflects that these countries predominantly import feed, meat, and dairy. Overall, under the 'high innovation' scenario, 57 per cent of overseas land use was freed up, an area the size of Spain.

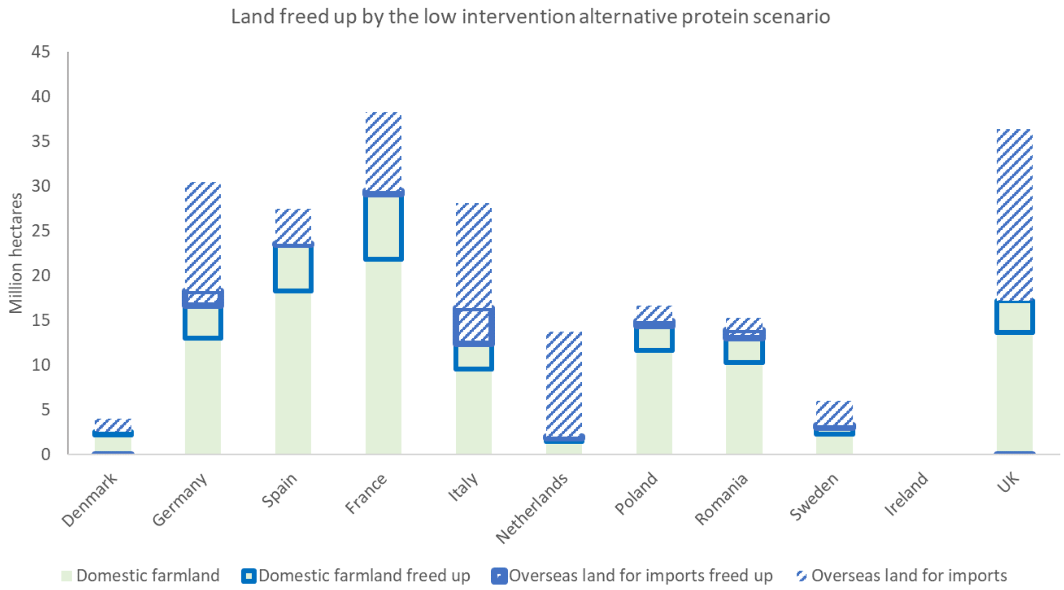


Figure 3. The area of land farmed in each of the studied countries (solid colours) and the area used to produce imports (hashed area) and the amount of that land that is freed up by the 'low intervention' alternative proteins scenario (blue outlined boxes)

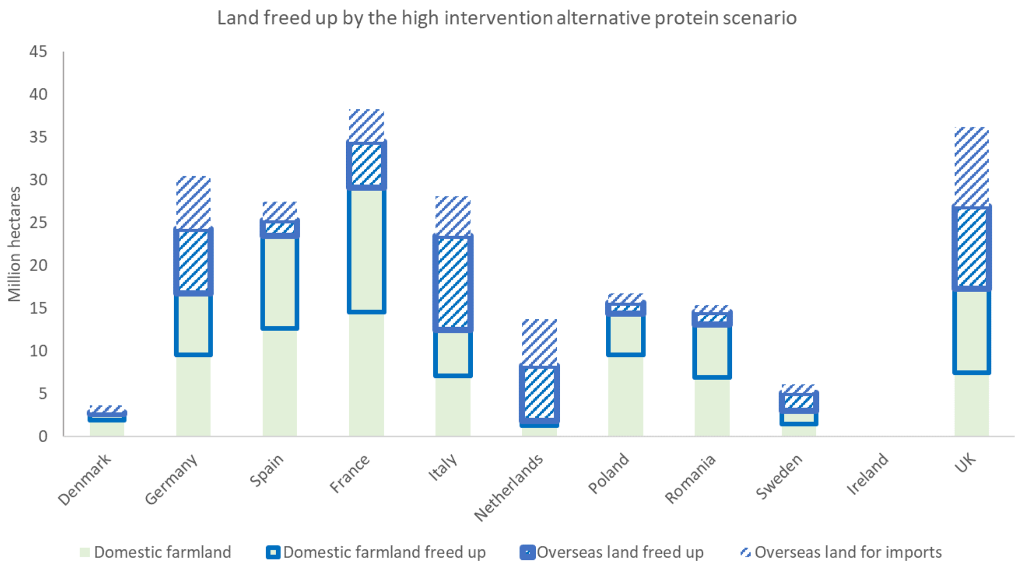


Figure 4. The area of land farmed in each of the studied countries (solid colours) and the area used to produce imports (hashed area) and the amount of that land that is freed up by the 'high innovation' alternative proteins scenario (blue outlined boxes)

Alternative proteins, therefore, create space for governments to direct land towards other uses. We explored using this land to:

1. Avoid demand for engineered carbon removal by expanding habitats that store carbon and create habitats for wild species.
2. Expand agroecological, or organic, farming which reduces yield but increases wildlife on farmed land.
3. Onshore overseas land use to increase self-sufficiency and reduce reliance on, and environmental pressures in, other countries.

In the appendix (page 29) we present the outcomes of using freed up land to deliver only one of these priorities.

Here we present the results of our 'shared dividends' scenario which divided freed up land between these priorities (see Methods, page 18). We present this as a reflection of these countries' priorities rather than as an optimal approach as we did not explore what land allocation led to optimal outcomes, but we explore in the appendix the trade-offs that arise from pursuing all three priorities at the same time.

Continent-wide results

To begin, we present the outcomes of the 'shared dividends' scenario across all ten countries combined.

We evaluated the 'shared dividends' scenario under the 'low intervention' and 'high innovation' alternative protein scenarios according to the resulting: (1)

overseas land use; (2) demand for engineered carbon removal to reach net zero and (3) the area of agroecological farmland.

1. Overseas land use under 'shared dividends'

We found that our 'high innovation' scenario, which sees about two thirds of meat and dairy consumption displaced by alternative proteins, could see the ten countries collectively become self-sufficient in terms of land use (Figure 5, page 12).

The area of land needed to produce imported food, due to alternative proteins freeing up both land overseas and space to bring more production onshore, would fall 75 per cent by 2050, meaning a larger area would be used across those ten countries to produce food for export (assuming the same quantity of exports as today).

This means these countries could trade amongst each other to meet their needs, without demanding any land outside Europe. In reality, demand for produce that cannot be grown year-round in the European climate will see Europe continue to import food from overseas, but alternative proteins would, unlike today, see these countries collectively make a net contribution to feeding the world in terms of land use, rather than being a net drain on global food resources. In the Appendix (page 29), we show that this is a far greater level of food security than could be achieved without diet change, even if onshoring food production is the only priority for freed up land (Figure A 1, page 30).

Under our 'low intervention' alternative protein scenario, overseas land use in 2050 would only be 15 per cent lower than today meaning these countries collectively continue to net import land (Figure 5). Under this scenario, together they would use approximately twice as much land for imports than exports. This is not an improvement on today, meaning without more ambitious alternative protein uptake Europe could continue to hamper other countries' efforts to end deforestation, protect biodiversity and get to net zero.

2. Demand for engineered carbon removal under 'shared dividends'

Alternative proteins substantially reduce demand for engineered carbon removal to reach net zero.

Our 'high innovation' scenario sees demand for engineered carbon removal, across all ten countries combined, fall to 27MtCO_2e per year by 2050 (Figure 5, page 12), assuming countries with excess negative emissions trade them to other countries (without this, demand for engineered carbon removal would be 144MtCO_2e per year). To put that in context, the UK government estimates 52-58MtCO_2e per year will be needed in the UK alone by 2050.[11]

Alternative proteins reduce demand for engineered carbon removal in two key ways. First, they have a lower carbon footprint than conventional meat and dairy, so there are fewer emissions to be offset. Second, they create space for the expansion of habitats that are a non-engineered form of carbon removal.

Demand for engineered carbon removal remains substantial under our 'low intervention' scenario where only a sixth of meat and dairy is displaced by alternative proteins: we estimate 243MtCO_2e per year by 2050 would need to be removed by engineered approaches (Figure 5, page 12). Should this be delivered with bioenergy with carbon capture and storage (BECCS) technology, as planned at the UK's Drax plant in North Yorkshire, that uses imported wood pellets, Europe would demand five times the global wood pellet supply.[12]

This fleet of BECCS plants would generate energy significantly larger than Germany and Poland's combined coal power fleets, at great expense.[13] In the UK, bioenergy is already guaranteed a price 32 per cent above offshore wind, and this price would need to rise further to fund capture and storage of carbon.[14]

Alternative proteins, therefore, are key to reducing the taxpayer cost of this expensive infrastructure and drive more of the available investment into carbon removal to the rural communities of the land sector rather than to a small number of carbon removal businesses.

In the appendix, we explore the outcomes of focusing all the land freed up on expanding agroecology (Figure A 1, page 30). We found this would result in greater demand for engineered carbon removal of 274MtCO_2e per year by 2050 even with 'high innovation' in alternative proteins (assuming countries trade excess negative emissions).

3. Space for semi-natural habitats and agroecology under 'shared dividends'

Given countries do not want to reduce their present level of self-sufficiency, the expansion of lower yielding agroecological farmland needs diet change to avoid pushing production offshore. Our 'shared dividends' scenario that assumes 'high innovation' in alternative proteins sees the current agroecological area quadruple by 2050 (Figure 5, page 12). At the same time, overseas land use falls. If there is only 'low intervention' around alternative proteins, our 'shared dividends' approach still allows the agroecological area to double.

At the same time, our 'shared dividends' scenario allows vast expansion of semi-natural habitats. With 'high innovation' in alternative proteins, more than a quarter of the presently farmed domestic area is released for semi-natural habitat creation under a 'shared dividends' approach (Figure 5, page 12). This would allow these countries to meet the Nature Restoration Law requirement to create and restore Annex I habitats.[15]

Under the 'low intervention' scenario, only 13 per cent of the farmed area becomes semi-natural habitat, which would not allow space to restore and create Annex I habitats in all countries.

Further analysis is needed on whether either scenario allows sufficient recovery of wild species to meet the goals set out in the Kunming-Montreal Global Biodiversity Framework.

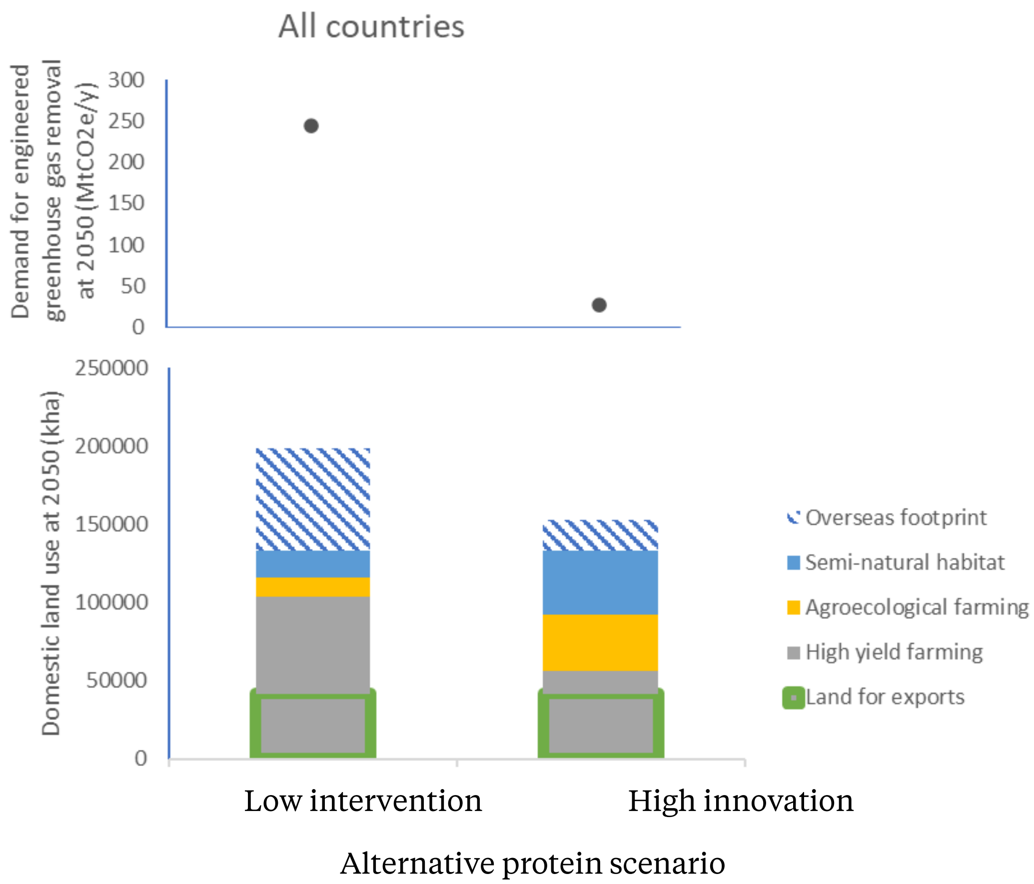


Figure 5. Outcomes of the 'low intervention' and 'high innovation' alternative protein scenarios combined across all countries in terms of domestic land use, overseas land use and demand for greenhouse gas removal

This analysis covers 70 per cent of EU27+UK land and 80 per cent of EU27+UK emissions, so is broadly representative of Europe as a whole. However, looking at results collectively masks differences between these countries. Below, we explore the countries that remain importers of land use, which become net exporters, and which can entirely avoid land use overseas.

Country level results under 'shared dividends'

Group 1: Net zero exporters

France, Sweden and Romania do not struggle to reach net zero. The vast size of existing land-based sinks offer all the capacity needed to offset residual emissions at 2050, even with 'low intervention' around alternative proteins (Figure 6, page 13).

Higher uptake of alternative proteins increases the space available to further expand these sinks, raising the potential for these countries to trade negative emissions with others that would otherwise require engineered removals to get to net zero.

Trade-offs between expanding agroecology, onshoring and expanding natural habitats are lower in these countries compared to others. They can avoid engineered carbon removal whilst becoming net exporters of land use and expanding their agroecological area to at least a third of farmed land (Figure 6, page 13).

High innovation in alternative proteins offers the huge opportunity for France and Romania to become entirely self-sufficient, but Sweden would need to choose between becoming entirely self-sufficient and expanding agroecology.

These are the only countries that could focus solely on using their freed up land to expand their agroecological area whilst not needing engineered carbon removal to achieve net zero, though they would forgo the opportunity to become substantially more net negative in carbon (Figure A 2, page 32).

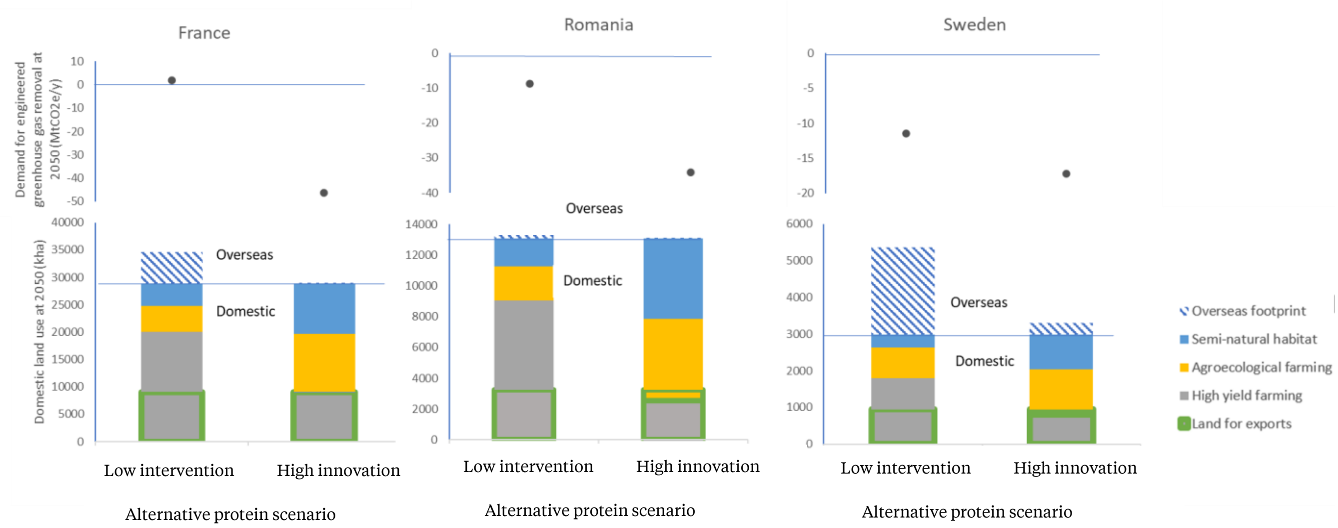


Figure 6. Outcomes of the 'low intervention' and 'high innovation' alternative protein scenarios in France, Romania and Sweden in terms of domestic land use, overseas land use and demand for greenhouse gas removal

Group 2: Countries that remain dependent on overseas land

In contrast, regardless of the amount of meat and dairy displaced by alternative proteins, the UK, Italy and Germany continue to need engineered carbon removal to reach net zero and land overseas to feed their populations (Figure 7, page 15).

Although it is not eliminated, alternative proteins do substantially reduce demand for land overseas. Under our 'shared dividends' approach, overseas land use would fall by at least 75 per cent with 'high innovation' in alternative proteins leaving these countries using more land for exports than imports. As a result, the level of food self-sufficiency would rise by a third in the UK, nearly 50 per cent in Germany and over 80 per cent in Italy (Table A 1, page 38).

With 'low intervention' around alternative proteins, self-sufficiency would show a negligible increase in the UK and a below 20 per cent increase in Germany and Italy (Table A 1, page 38).

Taken together, these countries would still need 2.7 times more land overseas than they use to produce exports. Indeed, our analysis suggests that, in these countries, securing high displacement of meat and dairy by alternative proteins has greater potential to cut overseas land use than focusing solely on expanding agricultural production at home (fFigure A 3, page 34).

Though Germany and the UK would remain dependent on engineered carbon removal, a high level of alternative protein uptake more than halves demand for engineered removals, compared to the 'low intervention' scenario. Demand falls relatively less in Italy, where 'high innovation' requires only 26 per cent less engineered carbon removal than the 'low intervention' scenario.

Whilst there is little space for agroecological farming with only 'low intervention' on alternative proteins, the 'high innovation' scenario allows agroecology to expand in each country to between 31-43 per cent of currently farmed land.

Our additional analyses, that vary what freed up land is used for, found that there are substantial trade-offs in these countries between our three priorities (page 29).

These countries could become substantial net exporters of food or avoid needing engineered carbon removal entirely, but not while expanding the area of agroecological farmland (Figure A 3, page 34).

Equally, expanding agroecology retains high demand for engineered carbon removal, even with 'high innovation' in alternative proteins, though overseas land use does still fall substantially.

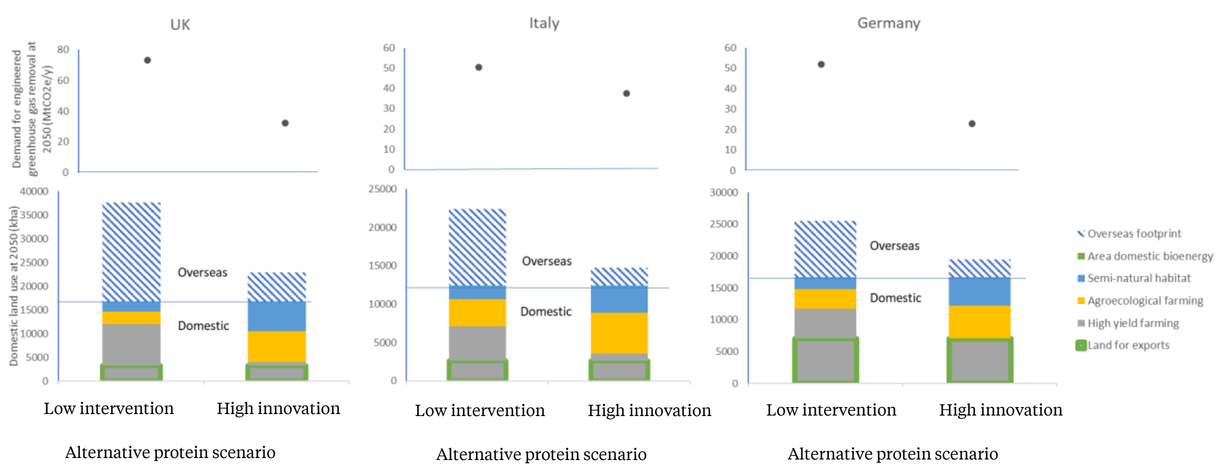


Figure 7. Outcomes of the 'low intervention' and 'high innovation' alternative protein scenarios in the UK, Italy and Germany in terms of domestic land use, overseas land use and demand for greenhouse gas removal

Group 3: Self-sufficient for food, but need high levels of alternative proteins to avoid engineered carbon removal

Like the first group, under our 'shared dividends' approach, Poland and Spain will be net exporters of land in 2050 regardless of the level of diet change (Figure 8, page 16). This reflects that they are much more self-sufficient today than the countries in the previous set: 85-86 per cent of the land used to produce food they eat or export is located within their borders, compared to just 47 per cent in the UK (Table A 1, page 38).

This greater self-sufficiency is enabled by a combination of these countries having lower population densities and greater appetite for pork and chicken, which require less land than the beef and lamb eaten in greater quantities in the UK, Germany and Italy.

With 'high innovation' in alternative proteins, Poland and Spain can maintain exports at present levels whilst avoid needing any land in other countries to feed their own population and expanding agroecology to 24 per cent of farmland in Poland and 38 per cent of farmland in Spain (fFigure 8, page 16).

At the same time, they can offset their whole economies' emissions using their natural sinks; engineered carbon removal is only needed if there is low innovation around alternative proteins or if land freed up by alternative proteins is used solely to expand agroecology, and not expand natural sinks (Figure A 4, page 35).

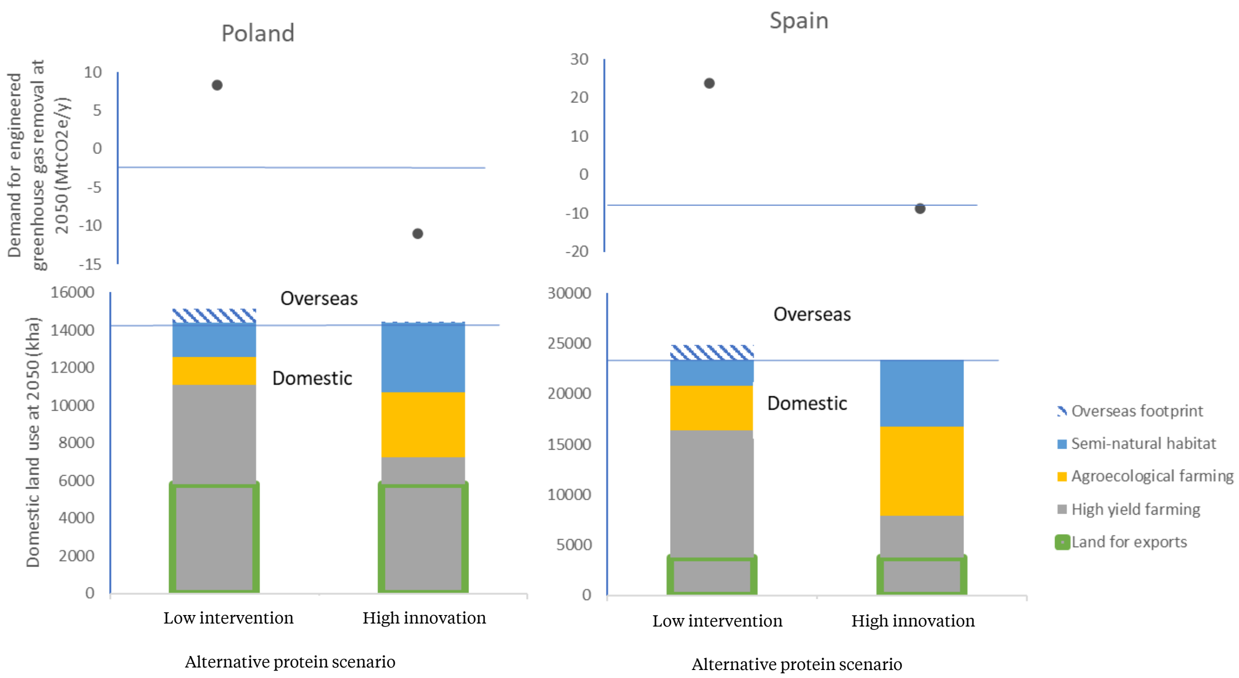


Figure 8. Outcomes of the 'low intervention' and 'high innovation' alternative protein scenarios in Poland and Spain in terms of domestic land use, overseas land use and demand for greenhouse gas removal

Group 4: Small, export-dominated countries where alternative proteins present limited opportunity

Denmark and the Netherlands are the smallest of the studied countries. Here, even 'high innovation' in alternative proteins does not free up much land, partly because so much is used for export. Consequently, these countries have little space to onshore food production that is currently imported, though the lower demand for meat and dairy from 'high innovation' in alternative proteins would halve the area needed for imports (fFigure 9, page 17).

Land sinks created on freed up land under our 'shared dividends' approach are relatively small, and so demand for engineered carbon removal hardly falls even under the 'high innovation' scenario.

The Netherlands uses most of its land to produce exports; rethinking land use for exports, and not alternative proteins, presents the greater opportunity to free up land. Given the limited opportunity available, our 'shared dividends' performs little better than any other scenario, though it does limit the expansion of agroecology in return for little reduction in overseas land use or engineered carbon removal (Figure A 5, page 37).

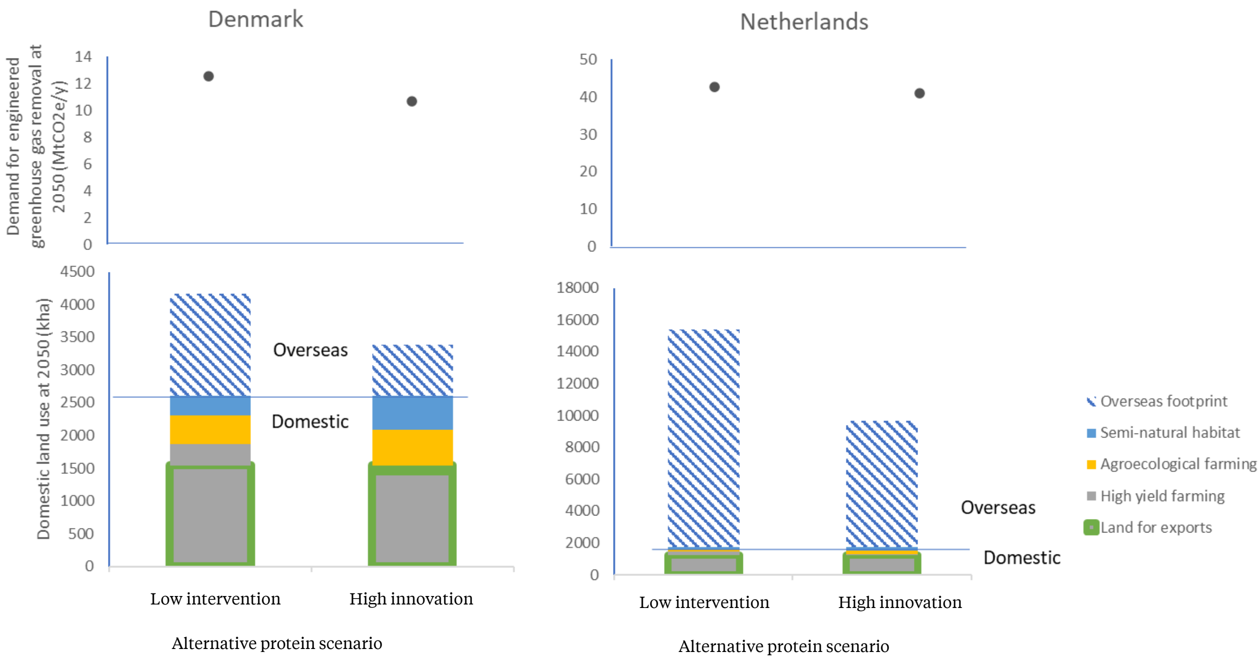


Figure 9. Outcomes of the 'low intervention' and 'high innovation' alternative protein scenarios in Denmark and the Netherlands in terms of domestic land use, overseas land use and demand for greenhouse gas removal

Energy demand of alternative proteins

We estimated the energy needed to produce the alternative proteins in our 'high innovation' scenario was in the region of 300-700TWh, which would require 0.1-0.2 per cent of the countries' combined land area for solar panels or 0.3-0.4 per cent of the combined countries' land areas for onshore wind turbines.

Conclusions

Reducing the consumption of meat and dairy creates a huge opportunity for Europe to restore nature and achieve net zero without offshoring demand for either food or helping to achieve negative emissions.

We found the greater the displacement of meat and dairy by alternative proteins, the larger the opportunity for Europe to increase its self-sufficiency whilst addressing the climate and nature crises.

However, policy is needed to ensure a reduction in meat and dairy consumption does free up land. Without incentives to direct land to other uses, European countries could simply use it to increase exports.

But, with intentional policy, increasing the consumption of alternative proteins offers Europe the opportunity to increase self-sufficiency and reduce the taxpayer costs of net zero. Under a 'shared dividends' approach, where freed up land is divided between agroecology, onshoring food production and expanding natural carbon sinks, alternative proteins enable nearly no demand for engineered carbon removal to reach net zero by 2050. Natural habitats are far cheaper forms of carbon removal and investing in their expansion would see public money flow through rural areas to farmers, land managers and the surrounding communities, rather to the pockets of a handful of big carbon removal businesses.

We found our 'shared dividends' scenario allowed agroecological farming to quadruple in area without offshoring food production which could have net negative environmental impacts and inhibit other countries from meeting their own food, climate and nature goals. But, without diet change, or if freed up land is only used to expand agroecology, space for agroecology squanders the opportunity to increase self-sufficiency by bringing more production onshore or reduce demand for engineered carbon removal.

This demonstrates the importance of securing a thriving alternative protein market to meet targets set in Europe to expand organic production.

While we did not study the impacts of this change to land use on nature, a wide array of species would benefit both from the expansion of on-farm habitats under agroecological farming, and the creation of semi-natural habitat on about a quarter of currently farmed land.

Taken together, our study shows that alternative proteins can dramatically increase self-sufficiency, reduce dependence on overseas land, boost nature and allow farmers to benefit from the investment in carbon removal at far lower taxpayer cost than if engineered solutions are needed at vast scale.

Methods

A. Alternative proteins: possible uptake, land use and emissions footprint

First, we established the volume of currently consumed meat and dairy products that could be displaced by alternative proteins by 2050. We considered three scenarios.

In the 'low intervention' scenario, we assumed innovation fails to deliver cost competitive cultivated meat products, or many fermentation products. With only plant-based alternative proteins on the market, we assumed only some highly processed forms of meat and dairy would be displaced by alternative proteins, such as those in ready meals.

In our scenarios, we used data of the proportion of meat and dairy consumed in the UK that is in processed vs non-processed forms to estimate the proportion of total consumption that would be displaced, given our assumptions (see Table A 1, page 38, and Table A 2, page 43).[16]

In extrapolating this to the other nine countries, we used country-specific data on the overall volume of chicken, pork, lamb, beef, eggs and dairy consumed, but we applied the UK-based proportion of how much of this was processed. Though, at present, consumption of processed food may be lower elsewhere than in the UK, all countries are eating increasingly more processed food, and so it may even be conservative to assume that, in 2050, all countries would eat the same proportion of processed vs unprocessed meat and dairy that the UK does today.[17]

In our 'mid ambition' scenario, we assumed that innovation, supported by policy, enables precision fermentation to become cost competitive. As a result, more than half of current dairy consumption is displaced (see Appendix, page 29).

In this scenario, cultivated meat was assumed not to become cost competitive, so displacement is again limited to processed forms of meat products, though a relatively greater proportion of them are displaced partly due to precision fermentation producing proteins, such as the Heme protein in the Impossible burger, that enhance the taste of plant-based foods. Overall, about 40 per cent of meat, the vast majority processed, is replaced with alternative proteins in this scenario.

The high ambition scenario assumed that cultivated meat also becomes cost competitive. As a result, most processed products are replaced by alternative proteins and a limited portion, approximately 20 per cent, of unprocessed cuts of meat are also displaced. We assumed precision fermentation can displace an even broader array of dairy products, including most milk and mass produced cheese, resulting in approximately 85 per cent of dairy and two thirds of meat consumption being displaced.

A final no diet change scenario assumed no further displacement of meat and dairy by alternative proteins beyond present. (See Appendix, page 29, for full details of all scenarios).

Next, we established the land required to produce alternative proteins, and the associated emissions, according to the best available estimates in published literature (Table 1, page 19). These estimates refer to land use and emissions per unit product, rather than per unit protein. So as not to ignore the non-protein elements of these foods, at times we made assumptions about the nutritional content of the food and the footprints associated with the non-protein components (see references in Table 1, page 19, for full details).

Table 1. The land use and emissions footprints of alternative proteins assumed in this study

	Land use (hectares per tonne product)	Land use source	Emissions (tonnes carbon dioxide per tonne product)	Emissions source
Cultivated Meat	0.25	[18]Sinke et al, 2023	2.8	[19]Sinke et al, 2023
Plant based meat	0.13	[20]Smetana et al, 2015	0.46	[21]Detzel et al, 2022
Precision fermentation egg	0.065	[22]Jarvio et al, 2021	1.8	[23]Jarvio et al, 2021
Precision fermentation dairy	0.0099	[24]Silman et al, 2019	0.065	[25]Behm et al, 2022

B. Conventional meat and dairy: land use and emissions

Land use

Having estimated the area that alternative proteins required, we estimated the area of land currently occupied by the meat and dairy they would replace.

To start, we extracted the volume by weight of chicken, pork, beef, lamb, dairy and eggs produced in each country from FAOstat. From this, we separated out the exported quantity (less re-exports), again according to FAOstat.

This was important as we assumed our diet change scenarios only apply to domestic consumption. Therefore, we assumed our alternative protein scenarios would not change the exported quantity of meat and dairy, though the land area required would change due to yield increases and waste reductions (see next section).

Next, we established how much land is used in each country for these exported and domestically consumed meat and dairy products.

From Eurostat, we extracted the area of pasture and the area dedicated to crops (cereals, pulses, potatoes, sugar beet, fodder crops, industrial crops, vegetables, seeds, fallow, energy crops, permanent crops and other crops) in each country. Some of these crops are not edible or are fed to people rather than livestock. We assumed livestock are fed fodder crops, sugar beet, pulses and cereals and used existing estimates to establish the proportion of these crops fed to livestock in each country, and applied those proportions to estimate the land area associated with feed crops.[26] In addition to crops grown within the country's borders, livestock are often fed crops imported from overseas. Estimating the quantity of imported crops fed to livestock requires some assumptions since the databases report only the tonnes of each product, and not whether it is fed to livestock.

Therefore, we assumed the same proportion of imported crops are fed to livestock as for domestic crops, and converted this to land area using de Ruiter, et al, (2016) who estimated the footprint of crops imported to Europe at 0.11ha/t and to the UK at 0.22ha/t.[27] This allowed calculation of the area of feed and pasture used to produce the meat and dairy consumed in each country and exported from the country, including feed land overseas.

Separately, we estimated the land footprint of imported livestock products using the mean global land footprints identified for beef, chicken, pork, lamb, eggs and dairy by Poore and Nemecek (2018).[28]

Dividing that land area between chicken, pork, beef, lamb, eggs and dairy

Our previously detailed scenarios see alternative proteins displace different proportions of chicken, for example, vs pork consumption. Therefore, we had to break down our estimate of the total land used to produce livestock products by chicken, pork, beef, lamb, eggs and dairy.

We took estimates of the units of dairy cattle, beef cattle, pigs, poultry and sheep from Eurostat, but no database provided the area of pasture occupied by each livestock type. So we took the average pasture use footprints estimated during research for the National Food Strategy in the UK and assumed that the relative differences between livestock types remained constant across all countries, but we adjusted the absolute values such that the total estimated area of pasture matched the total pasture area in each country.[29]

Next, we estimated the area of feed land used by each livestock type using the land use footprints (for pasture and feed combined) in Poore & Nemecek (2018) as a starting point.[30]

This paper did not give country specific land use footprints, but it did present 5^{th}, 10^{th}, mean, median, 90^{th} and 95^{th} percentiles of land use per unit of edible product for each livestock type globally.

First, we adjusted these to land use per tonne deadweight to align with our other production figures. Then, based on the estimates of used pasture and the overall production by weight of these products, given the land area available, we matched each country to the percentile of land use efficiency values that most closely matched the overall land take in each country, given the tonnes produced.

Then we assumed that the relative land uses for chicken, pork, beef, lamb, eggs and dairy remained true to that percentile whilst correcting the absolute land use values such that the resulting land take from the known volume of production matched that observed at the country scale.

As a result, there is some uncertainty in our allocation of land use across each category; error will have arisen where countries are exceptionally efficient in one type of meat, but not another. However, given our scenarios displace relatively similar (though not identical) proportions of each type of livestock product, this error is unlikely to be substantial.

This gave us the area of arable land and pasture used to produce chicken, pork, beef, lamb, eggs and dairy in each country. We used this to estimate the land freed up by alternative proteins, given their land use, assuming the quantity of alternative protein production that displaces conventional meat and dairy is matched per unit protein. Looking to 2050, we also assumed the following factors affect the area of land freed up:

1. Yield growth

We assumed modest yield growth in the region of ten per cent for arable crops, and 15 per cent for livestock, according to research done for the National Food Strategy.[31]

2. Reductions in waste

All EU countries, and the UK, have committed to halve household food waste by 2030, and reduce it 60 per cent by 2040, compared to 2007 levels.[32]

The UK is more transparent in its reporting of food waste than other EU countries. Therefore, in estimating the land freed up by reducing household food waste, we assumed the same proportion of food (measured in tonnes) is currently wasted in other countries as in the UK.[33] We assumed foods are wasted in proportion to the quantities they are produced in so land use declined in proportion to the reduction in wasted food.

3. Population change

We used Statista to estimate the population change expected in each country up to 2050.[34] We assumed the agricultural area needed to feed the population would change in proportion to population growth, and so would fall if the population reduces and rise if it increases, with exports remaining constant. If the space needed to feed a growing population is not available domestically, we assumed it would be met with increased imports.

4. Housing

Where populations are not set to increase, we assumed no net change in the land area needed for housing. In the countries expecting population growth, we assumed some currently farmed land would be needed to supply housing. We based these calculations on the UK Committee on Climate Change's estimate that 430,000 hectares of agricultural land will be needed to meet the approximately ten million more people that will live in the UK by 2050.[35]

We assumed other countries would supply housing to meet their increased populations according to this same ratio of land area for housing to additional people.

C. Estimating the emissions from agriculture and land use

Since net zero targets only apply to domestic emissions, and not those associated with imports, we only estimated the agriculture and land use emissions within each country, and not their imports. In doing so, we assumed emissions from agriculture and land use will change between now and 2050 in three key ways:

1. We assumed emissions of conventional meat and dairy are replaced by those of alternative proteins according to our displacement scenarios. We assumed alternative proteins to have the emissions footprints listed in Table 1 (page 19).

   We estimated the emissions from chicken, beef, lamb, pork, dairy and eggs production for each country separately. To do so, we used estimates from Eurostat of the emissions from enteric fermentation of cows/pigs/lamb/other, manure management of cows/pigs/lamb/other, managed soils, burning of residues, liming, fertiliser, rice and other.

   For enteric fermentation and manure management, in the absence of better information, we assumed 'other' referred to poultry. We attributed emissions to beef vs dairy cows based on relative herd sizes from Eurostat but assumed that emissions from a dairy cow are 50 per cent higher than a beef cow, following the approximate difference in weight.

   We similarly attributed emissions to egg layers vs broilers based on relative stock sizes in each country according to Eurostat. We assumed that managed soils (which we assumed not to include emissions from peat, which are reported elsewhere), burning of residues, liming, fertiliser and other were all associated with crop production, rather than livestock products (at worst, this underestimates the emissions footprints of livestock). Given some of these crops are fed to livestock, we attributed the emissions associated with crop production to each livestock type based on the area used to grow crops fed to livestock as a proportion of total crop area in each country (see previous section).

   We assumed the remaining emissions from crop production were not attributable to livestock products, and therefore would not be changed by alternative proteins.

   We summed the emissions associated with enteric fermentation, manure management and feed to estimate the total emissions associated with beef, chicken, lamb, pork, eggs and dairy. Given our focus on territorial emissions, these estimates do not include the emissions associated with imported feed, nor the emissions associated with production of livestock products overseas.

We did a final correction to account for the difference between Eurostat's estimate of the total emissions from agriculture and those reported by each country in their economy-wide net zero plans (see 'Projecting land use and emissions to 2050', page 24). To do so, we assumed the relative proportions of emissions between our crop and livestock types were accurate, and adjusted the absolute values so that the aggregate total matched the emissions from agriculture reported in the economy-wide net zero plans.

We did this to avoid inconsistencies within the model, assuming that the agriculture and land use emissions reported as part of the economy-wide net zero plans are more accurate than the estimates on Statista. We assumed the emissions from each livestock type would fall in proportion to displacement by alternative proteins, and instead emissions from alternative proteins would occur as per the values in Table 1, page 19.

2. We assumed some level of decarbonisation across agriculture each year. We followed the decarbonisation for the sector set out in the UK Committee on Climate Change's balanced net zero pathway which assumed that emissions from agriculture in the UK will fall 17 per cent between now and 2050, excluding the emissions avoided by diet change[36].

   We assumed this proportional change would occur linearly in all the studied countries. In addition, we assumed that reductions in waste would avoid emissions.

   Given we assume that waste reduction would occur across all foods in the proportions they are presently eaten in, we assumed that emissions from agriculture generally would fall according to the proportion of food that is no longer wasted, as set out in the previous section.

3. We accounted for the changes in emissions associated with changes land use, including the restoration of peat and creation of semi-natural habitats, that occurred in our scenarios (see 'Allocating freed up land', page 25).

D. Projecting land use and emissions to 2050

This gave us a baseline model to understand future land use and emissions from agriculture in each year between now and 2050, with the ability to displace meat and dairy consumption with alternative proteins. We bounded this model in each country's commitment to reach net zero by 2050. To do this, we assumed that all parts of the economy besides agriculture and land use would decarbonise according to each country's published plans.[37]

We then estimated the emissions arising from agriculture and land use, given how the freed up land was reallocated in our model (see 'Allocating freed up land' page 25), and estimated residual emissions. Some countries were net negative at this point, but others were not. Therefore, we assumed any residual emissions would be offset by engineered forms of carbon removal.

We assumed this engineered carbon removal would be bioenergy with carbon capture and storage (BECCS), given this is the technology most European countries are presently looking towards. The level of carbon removal, if any, that can be delivered by BECCS is the subject of much debate.[38] Whether or not it can deliver genuine removals, it comes at a much greater taxpayer cost, and delivers less nature benefit (or even nature cost), compared to habitat creation.[39]

For the purpose of this illustrative work, we assumed that BECCS would deliver genuine removals. We assumed the demand for BECCS would first be met by waste products from each country's own managed forests. We extracted the area of managed forest in each country from FAOstat. We assumed that one tonne of carbon removal requires 0.1 hectares of managed forest land.[40]

We assumed any demand that could not be delivered by waste forests products in that country would be met with imported forest products using the same ratio of land to carbon removal.

E. Allocating freed up land

The demand for BECCS is driven, in part, by how the land freed up by alternative proteins is used. When land is freed up by alternative proteins, we assumed that land could be used to either: (1) expand agroecology; (2) reduce overseas impacts; or (3) expand semi-natural habitats to reduce demand for engineered carbon removal. These decisions have implications for greenhouse gas emissions, overseas land use and demand for engineered carbon removal.

1. Expanding agroecology

We assumed that agroecological farmland yields less than conventional farmed land, so more land is needed to produce the same quantity of food.

We assumed that converting to organic today would reduce the produced food energy by 40 per cent.[41] However, for crop production, we assumed significant potential for innovation over time to close this gap such that, compared to conventional farming, organic crops yields would increase linearly to yield only ten per cent less food energy per unit area in 2050.[42]

Such yield gains are not expected for grazing lands, where low densities are a major characteristic of agroecological farming. As a result, much more pasture is needed per unit of livestock under agroecological vs conventional farming, and we do not assume the area per product declines over time.[43]

We assumed that the per unit area emissions from agroecological farming are lower than conventional. We used Smith, et al (2019) to estimate emissions per unit area of cropland and pasture: organic land typically sequesters an additional 0.26tCO_2e/ha per year compared to conventional production. [44]

2. Reduce overseas footprint

Land freed up by alternative proteins could be used to onshore production currently imported to each country. We assumed the same land would be required to produce that food onshore as overseas; this leads to some error as yields would be expected to vary but correction was beyond the scope of this work. We considered pasture and arable overseas land separately and only allowed either to be onshored when that land type was available domestically. We explored the potential for energy crops to reduce demand for overseas forest products for BECCS in the scenario that aimed to minimise overseas impacts (see Appendix, page 29).[45]

3. Expand semi-natural habitats to reduce demand for engineered carbon removal

If not used to expand agroecology or reduce land use overseas, we assumed spare land would be used to expand semi-natural habitats.

Of the land available for semi-natural habitats, we assumed 43 per cent was used to expand woodlands, 35 per cent was used to restore peatlands and 20 per cent was used to create grassy habitats such as heathlands, scrublands and species-rich grasslands. This follows the relative split of habitat types the National Food Strategy assumed would be established on land released from farming in the UK; we assumed this was applicable to the other studied countries, but further research should be conducted to understand the suitability of land for these habitats. [46]

We assumed these habitats did not produce food, though a very low level of meat may arise from the grazing animals needed to maintain some of these habitats, and some level of food production may be possible on restored peat.

We estimated the carbon sequestration this habitat creation and restoration would deliver in each year to 2050.

For woodlands, we assumed sequestration according to the Woodland Carbon Code of yield class six, planted, thinned woodland.[47] For restored peatlands, we took the present emissions associated with farmed peatlands according to FAOstat, and assumed they would fall to 3.7tCO_2e/ha per year.[48] We assumed grassy habitats would sequester at 2.2tCO_2e/ha per year.[49] We assumed all current farming related emissions on this land would be avoided.

F. Limits within the model

In scenarios that allow all overseas production to be brought onshore, our model does not allow continued expansion of farming, even if land is available. This would effectively increase exports, which we held constant for simplicity.

In addition, we do not allow food produced onshore today to move overseas, though we did allow population growth and demand for biomass for BECCS to drive production overseas where it could not fit into the country; at times this means the share of the country's total land take for food and biomass that is located overseas increases in the future.

G. Overall

The resulting model estimates how much land is freed up each year to 2050 given population growth, reductions in waste, yield growth and the displacement of meat and dairy by alternative proteins.

The model is flexible in whether freed up land is allocated to (1) expand agroecology; (2) onshore overseas production; or (3) expand semi-natural habitats.

We assessed the whole economy emissions, including those from the agriculture and land use resulting from decisions of how to use freed up land, and assumed any outstanding demand for carbon removal would be met using BECCS.

We ran scenarios that (1) maximised space for agroecology; (2) minimised overseas land use and (3) minimised demand for engineered carbon removal by expanding semi-natural habitats, as well as the 'shared dividends' scenario on which our report focuses, which intends to evenly split freed up land between these priorities.

However, limits within the model often prevent an even split of land between these priorities. Most notably, because arable production cannot be onshored onto domestic pasture, there are times when spare pasture can only be used to expand semi-natural habitats or agroecology, leading to relatively less freed up land being dedicated to onshoring.

Furthermore, under the 'shared dividends' approach, we sought to match the area of semi-natural habitat to the overall area of agroecology. It required relatively less land to deliver the same area of agroecology as the area of semi-natural habitat since only enough land must be given to make up the yield penalty vs conventional farmland.

For these reasons, it was rare than the 'shared dividends' scenario led to an even split of land across the three priorities.

H. Estimating the energy use of alternative proteins in the 'high innovation scenario'

We estimated an upper and lower bound of the energy demand created by the 'high innovation' alternative protein scenario. In the upper bound scenario, we took estimates from the literature of energy demand of 160MJ/kg for cultivated meat, 32MJ/kg for plant based and 68MJ/kg for precision fermentation alternative proteins.[50] We treated dairy separately, using an estimate of 6MJ/kg.[51] Using the main model, we knew the tonnes of alternative proteins being consumed in the 'high innovation' scenario in each country and multiplied this by per unit product energy demand to find the total energy demand across all ten countries.

However, not all this demand will be additional if alternative proteins displace conventional meat and dairy, as we have assumed. To obtain a lower bound estimate, therefore, we offset the energy requirement of conventional meat and dairy products that alternative proteins will displace.[52]

We estimated the land area that would be required to deliver that energy demand with either onshore wind turbines or solar panels. To estimate the area that would be required for onshore wind turbines, we assumed a load factor of 0.26 and a mean power density of 19.8MW/km^2. To estimate the area required for solar panels, we assumed a load factor of 0.10 and a mean power density of 80MW/km^2. [53]

Appendix

In our report we presented the 'shared dividends' scenario which splits the land freed up by alternative proteins between (1) expanding agroecology, (2) onshoring and (3) minimising engineered carbon removal by expanding carbon-storing semi-natural habits.

Here, we present the supplementary analyses that prioritised each of those aims in turn. This exposed the trade-offs made in treating these three priorities equally.

A. Methods for additional scenario analysis

We ran these optimisations on a country-by-country basis using the following set of rules for each scenario.

In scenario (1), we allowed agroecology to expand ahead of onshoring or creating semi-natural habitats. If this led to overproduction, we allowed onshoring, with that food being produced domestically with agroecology. If there was still overproduction of food after all production was onshored, we allowed expansion of semi-natural habitats. Any residual emissions were offset with engineered carbon removal.

In scenario (2), which sought to avoid demand for overseas land, we used land freed up by alternative proteins to onshore either food production or negative emissions, depending on which most reduced demand for overseas land. We allowed negative emissions to be delivered either by energy crops or by expanding semi-natural habitats, depending on which best reduced overseas land use. We allowed agroecology to expand if all production had been onshored and there was no demand for engineered carbon removal.

In scenario (3), which sought to minimise engineered carbon removal, we first used land freed up by alternative proteins to restore farmed peat and create semi-natural habitats that store carbon. Provided it did not create demand for engineered carbon removal, we allowed onshoring of production from overseas since this would avoid the country creating demand for engineered carbon removal elsewhere.

B. Results of additional scenario analysis

All countries

Considering all countries together, unsurprisingly, we found that focusing on any one of these priorities delivered a better outcome for that priority than the 'shared dividends' approach.

The highest trade-offs appear between agroecology and carbon removal: prioritising agroecological expansion on freed up land generally sustains high demand for engineered carbon removal.

Even with 'high innovation' in alternative proteins, nearly 274MtCO_2e per year must be removed with BECCS by 2050 if all land is used to expand agroecology; the 'shared dividends' approach saw demand fall to 27MtCO_2e per year.

Alternatively, demand for engineered carbon removal could be more than halved if semi-natural habitat expansion is prioritised on all freed up land, compared to the 'shared dividends' approach. But even with 'high innovation' on alternative proteins, this leaves no space for agroecological farming to expand and overseas land use is 54 per cent higher (though this is still a near two thirds reduction on today and countries would be net exporters of land use).

The 'shared dividends' scenario performs relatively well in terms of overseas land use, compared to the scenario that prioritises this; overseas land use is only reduced 27 per cent further when onshoring is the priority.

Importantly, 'high innovation' in alternative proteins allows countries to become more self-sufficient regardless of how the land dividend is spent. Even focusing only on bringing production onshore cannot deliver the self-sufficiency achievable with 'high innovation' in alternative proteins.

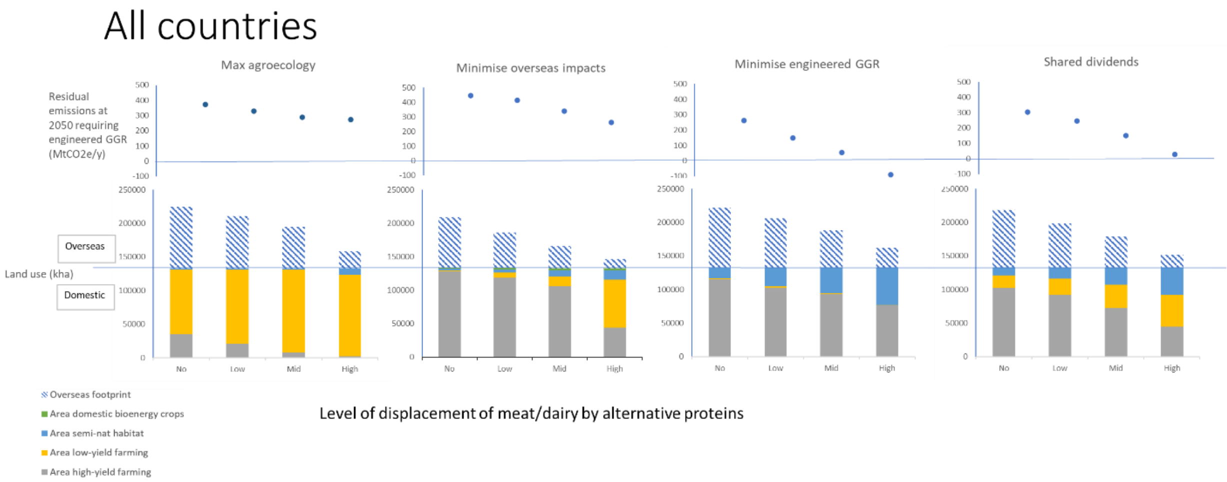


Figure A 1. Outcomes across all countries combined in terms of domestic land use, overseas land use and demand for greenhouse gas removal of four approaches to spending the land dividend (where freed up land is either used to solely (1) maximise agroecology, (2) minimise overseas impacts, (3) minimise engineered carbon removal, or (4) spread across these three priorities) created by four levels of alternative protein uptake (none, 'low intervention', 'mid ambition', and 'high innovation')

Considering all countries together masks patterns that arise in each country across these four scenarios which can be categorised into four groups, as follows:

Group 1: 'Shared dividends' involves limited trade-offs

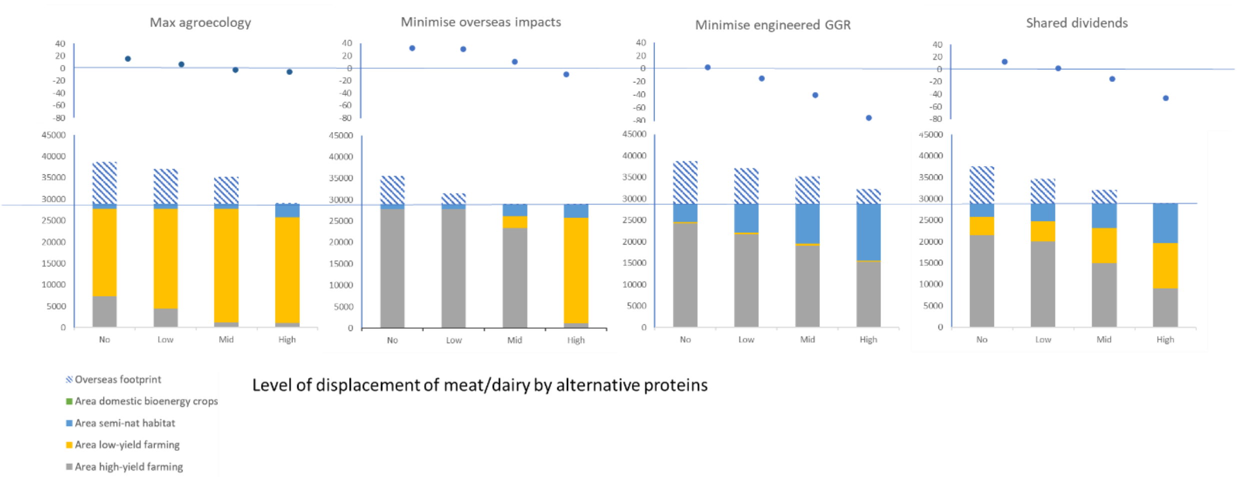
France, Sweden and Romania tend to reach net zero without alternative proteins or engineered carbon removal. Trade-offs between the 'shared dividends' scenario and the scenarios that optimise for a single priority are less severe compared to most other countries.

Provided there is at least 'low intervention' to support alternative proteins, they all avoid engineered carbon removal under 'shared dividends'.

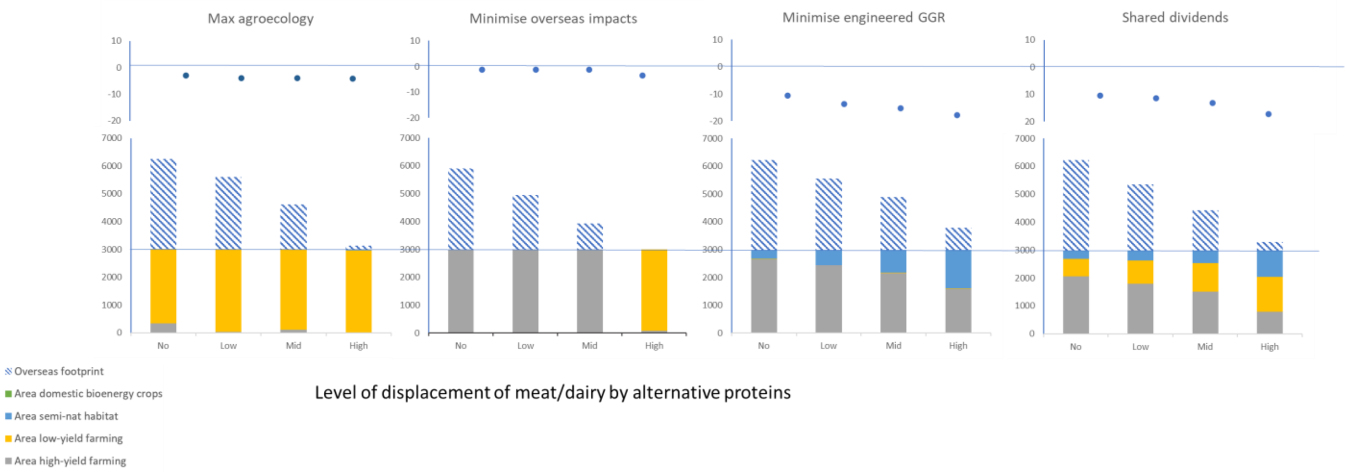
Overseas land use tends to fall close to zero with 'high innovation' in alternative proteins across all scenarios, showing that alternative proteins can substantially reduce overseas land use even without efforts to onshore.

Should these countries decide to focus on becoming substantially net negative, space for semi-natural habitat expansion competes for space with agroecology.

France



Sweden



Romania

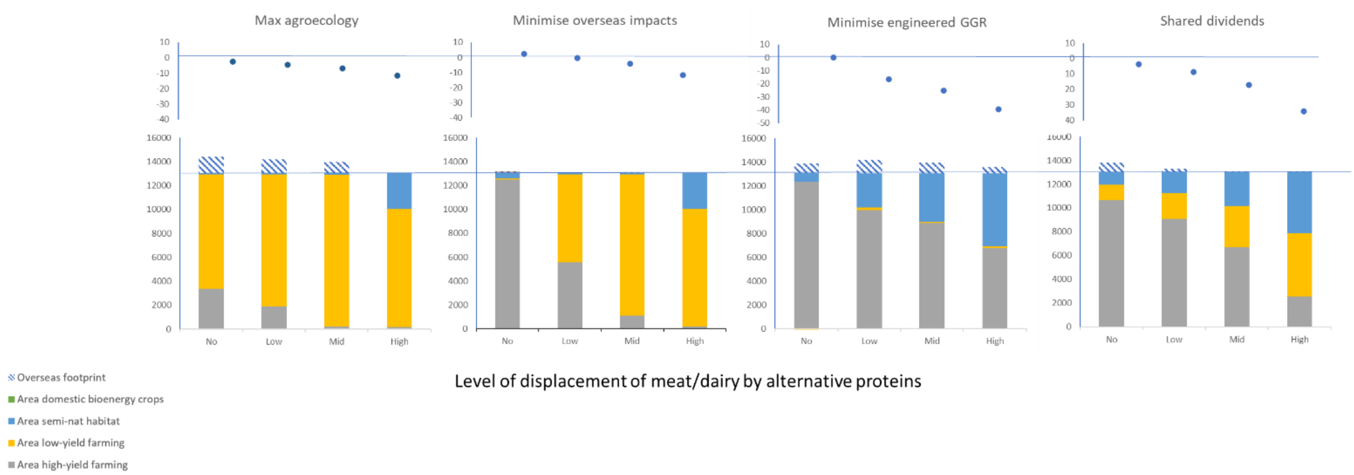


Figure A 2. Outcomes across France, Sweden and Romania in terms of domestic land use, overseas land use and demand for greenhouse gas removal of four approaches to spending the land dividend (where freed up land is either used to solely (1) maximise agroecology, (2) minimise overseas impacts, (3) minimise engineered carbon removal, or (4) spread across these three priorities) created by four levels of alternative protein uptake (none, 'low intervention', 'mid ambition', and 'high innovation')

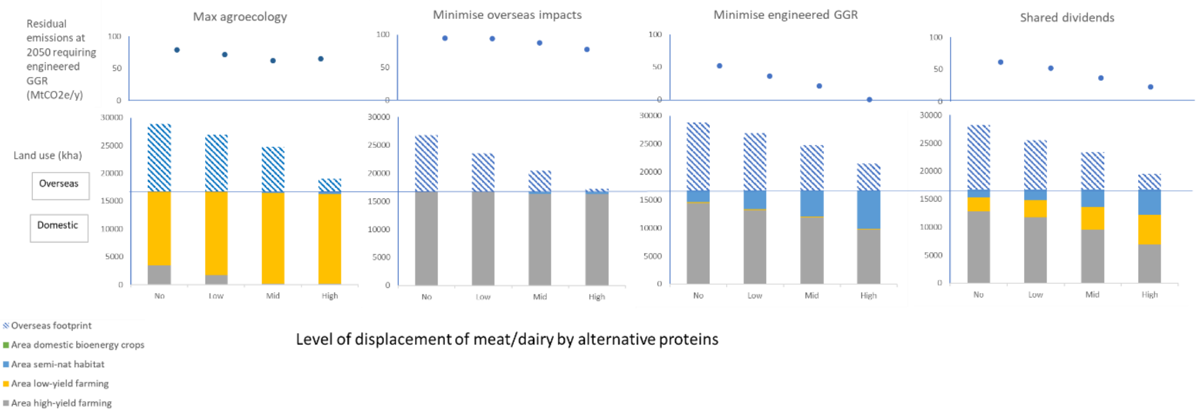
Group 2: High trade-offs; 'shared dividends' is the only way to progress on all fronts

Trade-offs between the three priorities are greatest in Germany, the UK and Italy. Focusing on any one priority results in poor outcomes for the other two priorities. For example, focusing only on expanding agroecology could see most land farmed agroecologically in these countries even with 'low intervention' around alternative proteins, but demand for engineered carbon removal would stay much higher than under 'shared dividends'.

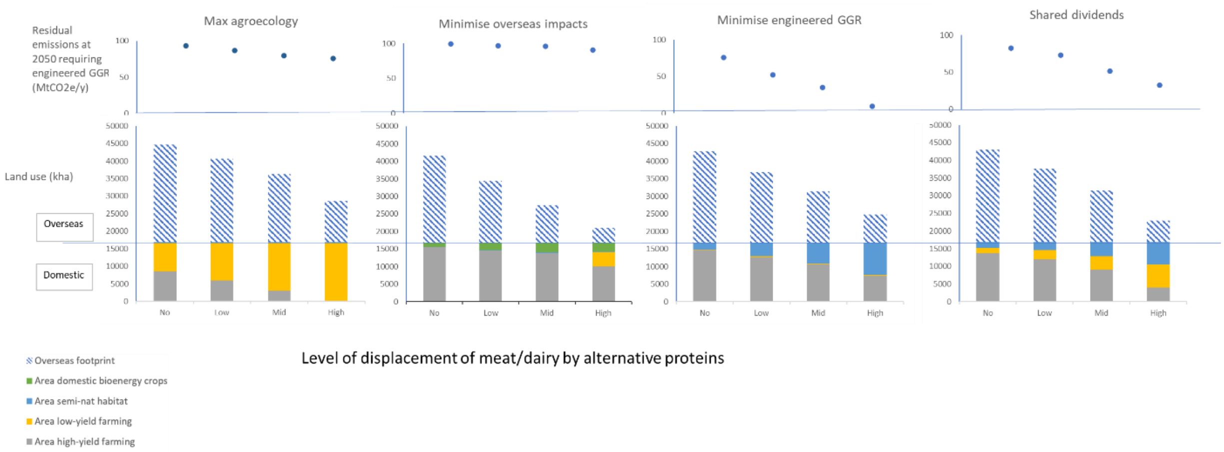
Similarly, Germany and Italy could avoid needing to use land overseas entirely, but demand for engineered carbon removal would again stay high. 'Shared dividends' does allow substantial reduction in demand for engineered carbon removal whilst expanding agroecology and reducing overseas land use.

'Shared dividends' retains some demand for engineered carbon removal which could be avoided by focusing all land on expanding carbon sequestering semi-natural habitats. In this case, Germany and the UK could avoid needing engineered carbon removal entirely, of which they required 23MtCO_2e per year and 32MtCO_2e per year respectively with the 'high innovation', 'shared dividends' approach.

Germany



UK



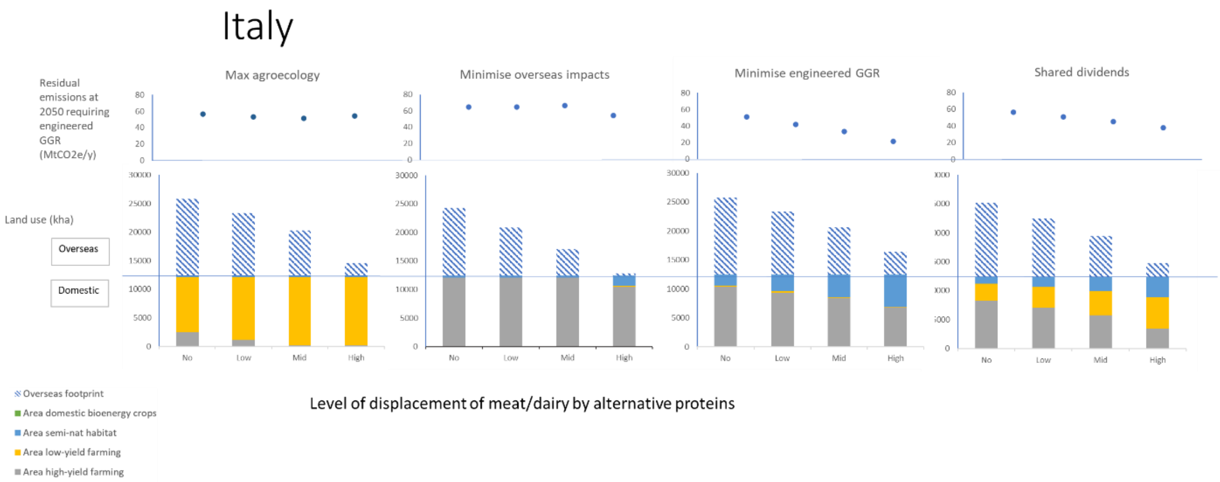


Figure A 3. Outcomes across the UK, Germany and Italy in terms of domestic land use, overseas land use and demand for greenhouse gas removal of four approaches to spending the land dividend (where land is either used to solely (1) maximise agroecology, (2) minimise overseas impacts, (3) minimise engineered carbon removal, or (4) spread across these three priorities) created by four levels of alternative protein uptake (none, 'low intervention', 'mid ambition', and 'high innovation')

Group 3: 'Shared dividends' can avoid overseas land use and engineered carbon removal, but limits the expansion of agroecological farming

Poland and Spain use much less land overseas today, compared to the preceding group, so overseas land use can be eliminated, even under 'shared dividends' provided there is 'mid ambition' to 'high innovation' in alternative proteins.

Similarly, engineered carbon removal is nearly avoided in a 'shared dividends' scenario, provided there is 'mid ambition' to 'high innovation' in alternative proteins.

Generally, the trade-offs are lower than in the previous group. The main trade-off comes in terms of space for agroecology which is much more limited in 'shared dividends'.

Focusing only on expanding agroecology could allow for much greater expansion even with little uptake of alternative proteins, but this creates demand for engineered carbon removal even with 'mid ambition' to 'high innovation' in alternative proteins which is avoided in a 'shared dividends' scenario.

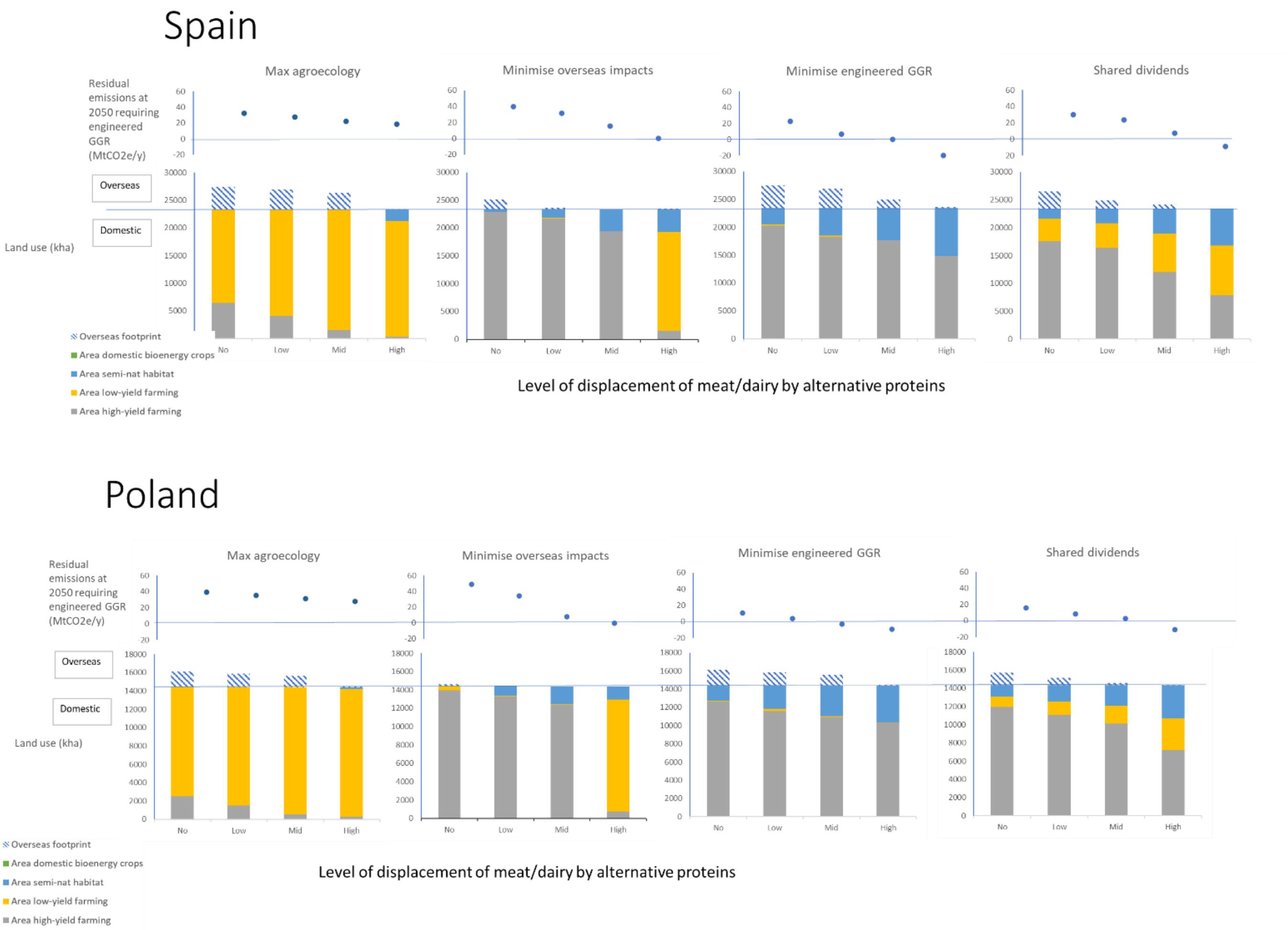


Figure A 4. Outcomes across Spain and Poland in terms of domestic land use, overseas land use and demand for greenhouse gas removal of four approaches to spending the land dividend (where land is either used to solely (1) maximise agroecology, (2) minimise overseas impacts, (3) minimise engineered carbon removal, or (4) spread across these three priorities) created by four levels of alternative protein uptake (none, 'low intervention', 'mid ambition', and 'high innovation')

Group 4: The 'shared dividends' scenario limits agroecological farming's expansion in exchange for little reduction in overseas land use or engineered carbon removal

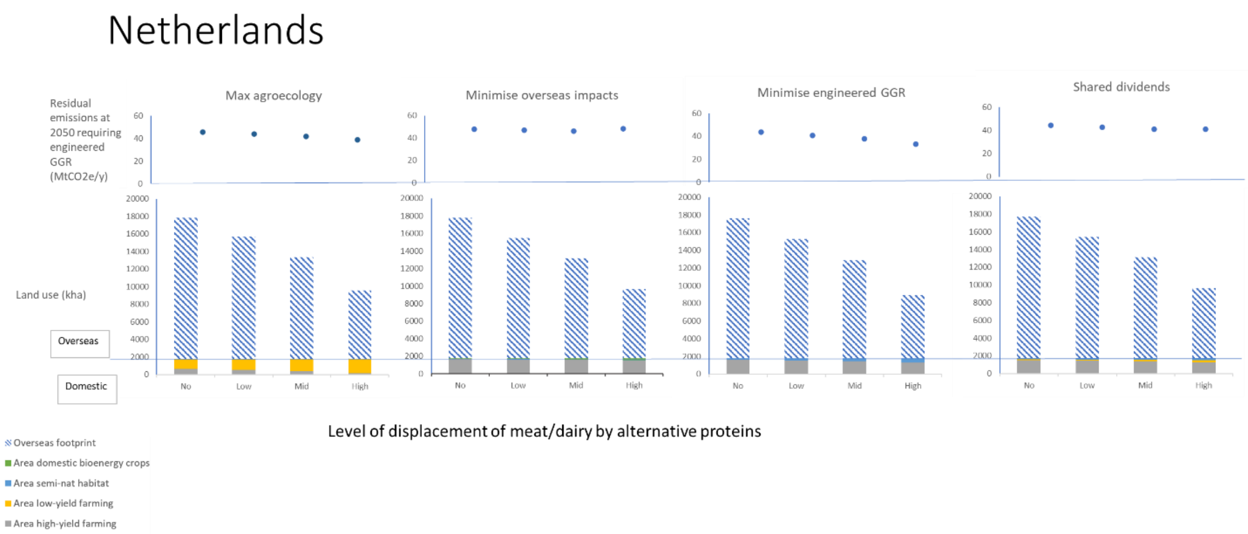
The Netherlands and Denmark are small countries and even high levels of alternative protein uptake would result in little reduction in demand for engineered carbon removal, even if all freed up land is focused on creating natural carbon sinks.

Indeed, our 'shared dividends' scenario does not perform much worse than either the scenario that prioritises avoiding engineered carbon removal or the scenario that prioritises demand for land overseas; as before, overseas land use is brought down much more by higher uptake of alternative proteins, rather than efforts to onshore to these small countries.

Some overseas land use remains, partly because it grows feed which is imported and fed to livestock which are later exported from these countries, and we assumed exports remain constant.

The ‘shared dividends’ scenario limits the expansion of agroecological farming which could expand to all farmland, should its expansion be the sole focus on freed up land. Expanding agroecology in this way does result in some increased demand for overseas land and greenhouse gas removal, compared to other countries but, because these countries mainly use arable land, and the yield penalties we have assumed are greater on pasture than arable land, these trade-offs are less severe compared to other countries.

We assumed that expanding agroecology would not mean arable land becomes pasture to replace nitrogen from chemical fertiliser with manure. If agroecology requires significant conversion of arable land to pasture, so that grazing animals provide nitrogen for crops, then far less agroecological expansion would be possible without reducing production.



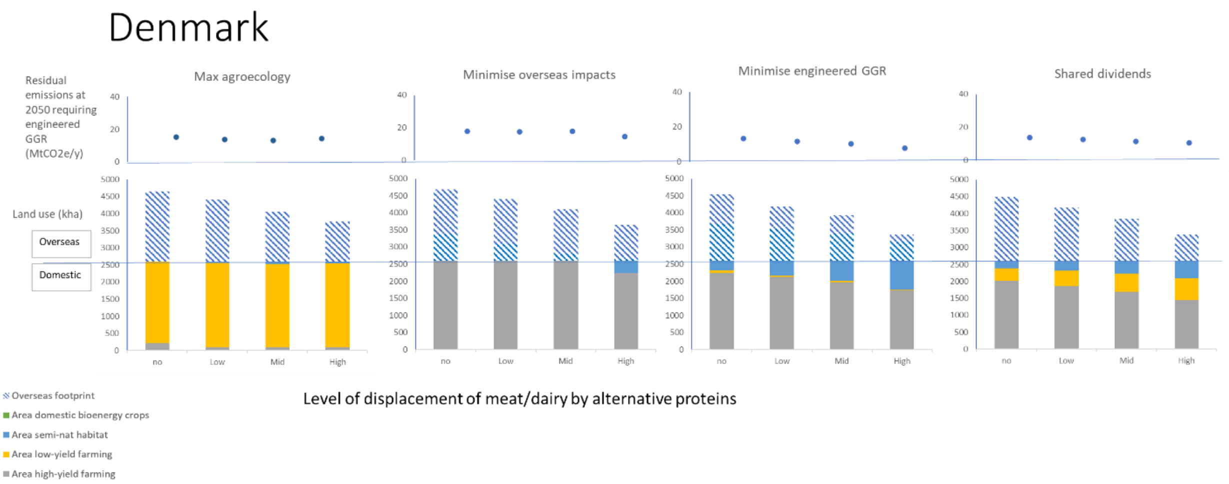


Figure A 5. Outcomes across the Netherlands and Denmark in terms of domestic land use, overseas land use and demand for greenhouse gas removal of four approaches to spending the land dividend (where land is either used to solely (1) maximise agroecology, (2) minimise overseas impacts, (3) minimise engineered carbon removal, or (4) spread across these three priorities) created by four levels of alternative protein uptake (none, ‘low intervention’, ‘mid ambition’, and ‘high innovation’)

C. Additional methods for alternative protein displacement scenarios

Our approach to alternative protein displacement was based on an assessment of where products are likely to mimic the flavour and texture of existing livestock products. Based on conversations with industry, we assessed that more processed meat and dairy products are more likely to be displaced by plant-based and precision fermentation derived alternative proteins, with cultivated meat being able to partly displace complex cuts of meat.

To assess the extent that conventional meat and dairy are displaced, we used the following sources to identify how much of each type of meat and dairy is eaten in processed and other forms (Table A 1, page 38). We assumed consumption at home is representative of overall consumption and, therefore, that the minority of meat and dairy that is consumed outside of the home does not contribute to these assessments. This is UK data, but we assumed other European countries would show the patterns of consumption by 2050 of the UK today; this follows general trends towards more processed foods being eaten across Europe.[54]

Table A 1. The proportion of beef, lamb, chicken, eggs and dairy that is eaten in various forms in the UK, and our grouping of products into categories which we expected to respond similarly to alternative protein displacement ('Treat like?')

UK meat consumption

		Proportion of consumed	Treat like?
Beef	Steaks	0.079938509	Steak
	Roasting	0.058416603	Steak
	Mince	0.240584166	Processed
	Stewing	0.035357417	Processed
	Burgers + grills	0.126825519	Processed
	Sliced cooked meats	0.04765565	Processed
	Marinades	0.011529593	Processed

	Ready to cook	0.003074558	Processed
	Sous vide	0.011529593	Processed
	Other - ready meals and "other beef products"	0.385088394	Ready meal
	Total	1.00	
	Source	[GB household beef purchases | AHDB]()	
Lamb	Steaks	0.06	Steak
	Leg roasting	0.32	Steak
	Shoulder roasting	0.05	Steak
	Chops	0.08	Steak
	Mince	0.08	Processed
	Stewing	0.02	Processed
	Diced/cubed	0.03	Processed
	Burgers + grills	0.05	Processed
	Marinades	0.02	Processed
	Ready to cook	0.01	Processed

	Sous vide	0.04	Processed
	Other - ready meals and "other lamb products"	0.25	Ready meal
	Total	1.00	
	Source	[GB household lamb purchases | AHDB]()	
Pork	Steaks	0.039590126	Steak
	Roasting	0.045645086	Steak
	Chops	0.013507219	Cant replace
	Mince	0.016301816	Processed
	Belly	0.013041453	Cant replace
	Pork ribs	0.005123428	Cant replace
	Burgers + grills	0.005123428	Processed
	Sausages	0.186306474	Processed
	Bacon	0.158826269	Processed
	Gammon	0.048905449	Processed
	Sliced cooked meats	0.177922683	Processed
	Marinades	0.014904518	Processed

	Ready to cook	0.00605496	Processed
	Sous vide	0.013507219	Processed
	Other - ready meals and "other pork products"	0.25523987	Ready meal
	Total	1.00	
	Source	https://ahdb.org.uk/pork/consumer-insight-gb-household-pork-purchases	
Chicken			
	Whole birds	0.4	Chicken breast
	Breasts	0.35	Chicken breast
	Dark meat	0.23	Chicken breast
	Ingredient	0.05	Ready meal
	Total	1.00	
	Source	Looking ahead at UK poultry trends: A retail update - Poultry World	
Eggs	Shell eggs - retail	0.66	Shell eggs
	Egg products - eggs processed for food manufacture	0.19	Ready meal

Shell eggs - foodservice	0.15	Shell eggs
Total	1.00	
Source	UK Egg Industry Data | Official Egg Info	

Dairy

	Proportion of overall dairy	
Liquid milk	0.42	Milk
Cream	0.02	Cream
cheddar	0.25	Cheese
long life territorial cheese	0.02	Cheese
short life territorial cheese	0.00	Cheese
blue vein cheese	0.01	Cheese
other cheese	0.06	Cheese
Butter	0.03	Cream
Yoghurt	0.03	Cream
Condensed milk	0.02	Milk powder
Milk powder	0.07	Milk powder
Other	0.05	average of above

Waste, stock change etc	0.02	average of above
Total	1.00	
Source	[milkutil-dataset-29jun23.ods (live.com)]	

We made assumptions about the proportion of each product that would be replaced by alternative proteins in 2050 that are plant based, precision fermentation based and cultivated meat (Table A 2 below).

Table A 2. Our assessments of the proportion of each group identified in Table A 1 that would be displaced by plant based, precision fermentation or cultivated meat in the 'low intervention', 'mid ambition' and 'high innovation' scenarios

	Proportion replaced in scenario by stated alternative protein by 2050								
	Low intervention			Mid ambition			High innovation		
	Plant based	Precision fermentation	Cultivated meat	Plant based	Precision fermentation	Cultivated meat	Plant based	Precision fermentation	Cultivated meat
Steak						0.10	0.05	0.05	0.10
Processed	0.20	0.05		0.35	0.15		0.30	0.20	0.30
Ready meal	0.225	0.025		0.45	0.05		0.6	0.1	0.3
Cant replace									
Chicken breast	0.20			0.20	0.05	0.05	0.25	0.05	0.30
Shell eggs		0.10			0.20			0.40	
Milk	0.10	0.20		0.10	0.40			0.90	

Cream	0.05	0.10	0.05	0.20	0.50
Cheese	0.10		0.08	0.32	0.90
Milk powder		0.25		0.50	1.00

D. Additional results from the ‘shared dividends’ scenario

Table A 3. Self-sufficiency in each country under the lower intervention and ‘high innovation’ scenarios at 2050 where self-sufficiency is measured as the proportion of the land used to produce food that is either eaten in, or exported from, that country. The remaining fraction reflects the land required overseas

	Percent of land used to produce the food eaten in, and exported from, the country that is located within its borders rather than overseas		
	Today	Low intervention alternative proteins at 2050	High innovation alternative proteins at 2050
Denmark	71%	74%	90%
Germany	55%	63%	81%
Spain	85%	93%	100%
France	75%	81%	100%
Italy	43%	51%	79%
Netherlands	13%	14%	29%

Poland	86%	94%	100%
Romania	85%	100%	100%
Sweden	50%	50%	87%
UK	47%	48%	64%

[1] Friends of the Earth, 2016, *The true cost of consumption: The EU's land footprint*
[2] The term "overseas" is used throughout to mean land used to grow food in each country that is outside its own borders. It therefore includes food imported from other European countries.
[3] Only 1.4 per cent of land in Europe has been identified as untouched according to A Schnitzler, 2014, 'Towards a new European wilderness: Embracing unmanaged forest growth and the decolonisation of nature', *Landscape and Urban Planning*, vol 126, pp 74-80
[4] S Smetana, A Mathys, A Knoch and V Heinz, 2015, 'Meat alternatives: life cycle assessment of most known meat substitutes', *The International Journal of Life Cycle Assessment*, vol 20, pp 1254-1267; P Sinke, E Swartz, H Sanctorum, C van der Giesen and I Odegard, 2023, 'Ex-ante life cycle assessment of commercial-scale cultivated meat production in 2030', *The International Journal of Life Cycle Assessment*, vol 28, issue 3, pp 234-254
[5]Greenpeace, 2019, 'Feeding the Problem: Dangerous intensification of animal farming in Europe'
[6] L Collas, 2022, 'Briefing: Greenhouse gas removal'
[7] The European Commission's 2021 'Farm to fork' strategy aims for 25 per cent of farmland to be organic by 2030
[8] L Smith, G Kirk, P Jones and A Williams, 2019, 'The greenhouse gas impacts of converting food production in England and Wales to organic methods'. *Nature communications*, vol 10, issue 1, pp 4641
[9] Several commitments to end deforestation have been made (and broken). At COP26 in Glasgow, more than 100 world leaders, including the countries studied here, committed to end and reverse deforestation by 2030
[10] ProVeg International, 2023, *Smart Protein Consumer Survey*
[11] HM Government, 2021, *Net Zero Strategy: Build Back Greener*
[12] Delivering 243MtCO_2e per year would require 30 Drax-style plants to deliver the 8 MtCO_2e per year estimated to be possible, see: Drax, 2023, 'Drax enters formal discussions with UK Government on large-scale power BECCS'. Drax is aiming to burn eight million tonnes of wood pellets by 2030 to deliver these negative emissions according to: Drax, 2023, 'Drax ends half a century of coal fired power generation'. Approximately 47Mt of wood pellets are produced annually, based on: Food and Agriculture Organisation of the United Nations, 2023, *FAOSTAT: forestry production and trade*. So 30 Drax-style plants would require five times the global wood pellet supply.
[13] The capacity of coal power stations in Germany and Poland combined is 68GW according to: Statista, 2023, 'Countries with largest installed capacity of coal power plants worldwide as of July 2022'. Drax generates 2.6GW (see Baringa, 2024, 'The value

of a BECCS at Drax power station'). So 30 Drax plants would generate 78GW, larger than Germany and Poland's combined coal power capacity.
[14] T Harrison and P MacDonald, 2023, 'Drax's BECCS project climbs in cost to the UK public'
[15] The EU Restoration Law requires 90 per cent of the habitats needing restoration to be restored by 2050. The habitats needing restoration are set out in table IV of the 'Impact assessment accompanying the proposal for a Regulation of the European Parliament and of the Council on nature restoration'. We assessed the area this affected by finding 90 per cent of the wetland, grassland and heathland habitat areas listed in this table. We assumed the other habitat types were not farmed land and so excluded them from our calculations.
[16] Full data is available in the appendix
[17] Consumption of processed products in other European countries is not yet as high, but is trending in the same direction as the UK, as can be seen in: Systemiq, 2023, 'Ready-made meals study key insights'
[18] P Sinke, E Swartz, H Sanctorum, C van der Giesen and I Odegard, 2023, 'Ex-ante life cycle assessment of commercial-scale cultivated meat production in 2030', *The International Journal of Life Cycle Assessment*, vol *28*, issue 3, pp 234-254
[19] Ibid
[20] Average of soymeal-based products taken from S Smetana, A Mathys, A Knoch and V Heinz, 2015, 'Meat alternatives: life cycle assessment of most known meat substitutes', *The International Journal of Life Cycle Assessment*, vol 20, pp 1254-1267
[21] We assumed the carbon footprint of a plant-based alternative protein from A Detzel, M Krüger, M Busch, L Blanco-Gutiérrez, C Varela, R Manners, J Bez, and E Zannini, 2022, 'Life cycle assessment of animal-based foods and plant-based protein-rich alternatives: an environmental perspective'. *Journal of the Science of Food and Agriculture*, vol 102, issue 12, pp 5098-5110. We used the 'optimised' scenario, since we assume these footprints out to 2050, in which time there will be considerable innovation. We excluded emissions associated with processing, production and transport since these do not differ substantially between meat and plant-based products (comparison of tofu to all other meats in J Poore, and T Nemecek, 2018, 'Reducing food's environmental impacts through producers and consumers', *Science*, vol 360, issue 6392, pp 987-992, and are accounted for elsewhere in our model.
[22] We assumed that an egg product is 76 per cent water and 13 per cent protein based on S Réhault-Godbert, N Guyot, and Y Nys, 2019, 'The golden egg: nutritional value, bioactivities, and emerging benefits for human health', *Nutrients*, vol 11, issue 3, pp 684. We assumed the land use footprint of the protein component from N Järviö, T Parviainen, N Maljanen, Y Kobayashi, L Kujanpää, D Ercili-Cura, C Landowski, T Ryynänen, E Nordlund and H Tuomisto, 2021, Ovalbumin production using Trichoderma reesei culture and low-carbon energy could mitigate the environmental impacts of chicken-egg-derived ovalbumin', *Nature food*, vol 2, issue 12, pp 1005-1013.

We assumed no land use footprint associated with the water content, and we used the land use footprint of plant based alternative proteins for the remaining 11 per cent of the product to estimate the land use footprint per tonne of an egg equivalent product.
[23] As above, but for carbon footprint
[24] We assumed that dairy products are 87 per cent water, 3.5 per cent protein and 9.5 per cent non-protein solids according to USDA, 2023, 'FoodData Central'. We assumed no land use footprint associated with the water content, used the land use footprint from plant-based alternative proteins for the non-protein solid component and took the land use footprint for the protein component from J Sillman, et al, 2019, 'Bacterial protein for food and feed generated via renewable energy and direct air capture of CO_2: Can it reduce land and water use?' *Global Food Security*, vol 22, pp 25-32
[25] We assumed that dairy products are 87 per cent water, 3.5 per cent protein and 9.5 per cent non-protein solids according to USDA FoodData Central, 2023. We assumed no emissions footprint associated with the water content, used the emissions footprint from plant-based alternative proteins for the non-protein solid component and took the emissions footprint for the protein component from the Germany 'base case' study in K Behm, et al, 2022, 'Comparison of carbon footprint and water scarcity footprint of milk protein produced by cellular agriculture and the dairy industry'. *The International Journal of Life Cycle Assessment*, vol 27, issue 8, pp 1017-1034. This study also considered emissions associated with transport and forgone feed production which we excluded as these are accounted for elsewhere in our study.
[26]Our World In Data, 2023, 'Cereals allocated to food, animal feed and fuel'
[27] H de Ruiter, et al, 2016, 'Global cropland and greenhouse gas impacts of UK food supply are increasingly located overseas'. *Journal of The Royal Society Interface*, vol 13, issue 114, pp 20151001
[28] J Poore and T Nemecek, 2018, 'Reducing food's environmental impacts through producers and consumers', *Science*, vol 360, issue 6392, pp 987-992
[29] Research done for National Food Strategy, 2021, private communication
[30] Ibid
[31] Research done for National Food Strategy, 2021, private communication
[32] European Commission, 2023, 'Food waste reduction targets'
[33] Data on the quantity of food wasted in the UK was taken from Figure 2 of the Office for National Statistics, 2021, 'A review of household behaviour in relation to food waste, recycling, energy use and air travel'
[34] Statista, 2023, 'Total population of the EU member states by country'
[35] Committee on Climate Change, 2020, *Sector summary: Agriculture and land use, land use change and forestry*
[36] Committee on Climate Change, 2020, *The Sixth Carbon Budget*
[37] For most countries, we projected emissions from the non-land parts of the economy according to the plans they had submitted to the European Commission (Spain, Italy, Germany, France, the Netherlands, and Denmark). We could not do this for Sweden, Poland, United Kingdom (Balanced Net Zero Pathway), and so used the sources

linked. No plan had been published for Romania's path to net zero and so we had to assume a decarbonisation pathway according to the average reduction from present emissions seen in other countries.

[38] M Fajardy, et al, 2019, *BECCS deployment: a reality check. Grantham Institute Briefing paper No 28,* Imperial College, London

[39] Green Alliance, 2022, 'Greenhouse gas removals'

[40] Calculated according to the 'sustainable management of semi-managed temperate forest' in F Fraxner, et al, 2003, 'Negative emissions from BioEnergy use, carbon capture and sequestration (BECS) - the case of biomass production by sustainable forest management of semi-natural temperate forests', *Biomass and bioenergy,* vol 24, pp 285-296

[41] L Smith, et al, 2019, 'The greenhouse gas impacts of converting food production in England and Wales to organic methods', *Nature communications*, vol 10, issue 1, pp 4641

[42] National Food Strategy, private communication

[43] Ibid

[44] L Smith, et al, 2019, 'The greenhouse gas impacts of converting food production in England and Wales to organic methods', *Nature communications*, vol 10, issue 1, pp 4641

[45] We took the land required to deliver negative emissions with bioenergy crops as 409km^2/MtCO_2e from P Smith, et al, 2016, 'Biophysical and economic limits to negative CO2 emissions', *Nature climate change*, vol 6, issue 1, pp 42-50

[46] National Food Strategy, 2021, *The Evidence*

[47] Woodland Carbon Code, 2021, 'Carbon Calculation Spreadsheet, Version 2.4'

[48] Emissions associated with rewetted bog extracted from Evans et al, 2023, 'Aligning the Peatland Code with the UK Peatland Inventory', and adjusted to be AR5 rather than AR4 weighted

[49] N Ostle, et al, 2009, 'UK land use and soil carbon sequestration', *Land use policy*, vol *26*, pp S274-S283

[50] Estimates of energy needed for precision fermentation and plant based alternative proteins came from S Smetana, et al, 2015, 'Meat alternatives: life cycle assessment of most known meat substitutes', *The International Journal of Life Cycle Assessment*, vol 20, pp 1254-1267. Estimated energy needed for cultivated meat taken from P Sinke, et al, 2023, 'Ex-ante life cycle assessment of commercial-scale cultivated meat production in 2030', '*The International Journal of Life Cycle Assessment*', vol 28*, issue* 3, pp 234-254

[51] N Järviö, 2021, 'An attributional life cycle assessment of microbial protein production: a case study on using hydrogen-oxidizing bacteria', *Science of the Total Environment*, vol 776, pp 145764.

[52] As for our estimates of the energy demand for cultivated meat, we extracted estimates of the future energy demand of meat and dairy products from P Sinke, et al,

2023, 'Ex-ante life cycle assessment of commercial-scale cultivated meat production in 2030', *The International Journal of Life Cycle Assessment*, vol 28, issue 3, pp 234-254
[53] Mean power density for onshore wind was taken from P Enevoldsen and M Jacobson, 2021, 'Data investigation of installed and output power densities of onshore and offshore wind turbines worldwide', *Energy for Sustainable Development*, vol 60, pp 40-51. Mean power density for solar panels was taken from M Barrett and D Scamman, 2023, 'Net zero emission energy scenarios and land use'. Load factor for solar taken from Statista, 2023, 'Load factor of electricity from solar photovoltaics in the United Kingdom (UK) from 2010 to 2022'. Load factor for onshore wind turbines taken from Statista, 2023, 'Load factor of electricity from onshore and offshore wind in the United Kingdom (UK) from 2010 to 2022'.
[54] Consumption of processed products in other European countries is not yet as high, but is trending in the same direction as the UK, as can be seen in: Systemiq, 2023, 'Ready-made meals study key insights'