EATING AWAY AT CLIMATE CHANGE WITH NEGATIVE EMISSIONS

Repurposing UK agricultural land to meet climate goals

Helen Harwatt, PhD* and
Matthew N Hayek, PhD*

11 April 2019

*Animal Law & Policy Program

Harvard Law School

hharwatt@law.harvard.edu
mhayek@law.harvard.edu

EXECUTIVE SUMMARY

The United Kingdom (UK) is not on track to meet its legally binding commitment to reducing greenhouse gas (GHG) emissions by 80% by 2050 under the UK Climate Change Act, and even further reductions would be required to align with the 1.5°C aspiration of the Paris Agreement. The GHG budget most consistent with limiting warming to 1.5°C would allow the UK around 12 years of emissions at current levels. Hence, if UK emissions do not decrease from current levels, they will be consistent with temperatures beyond 1.5°C of warming in just 12 years' time. Radical action, far beyond that currently planned, is required to reduce GHGs steeply and rapidly in line with the Paris Agreement.

Limiting warming to 1.5°C above pre-industrial temperatures with little or no overshoot requires carbon dioxide removal (CDR) from the atmosphere. The most readily deployable CDR option at scale in the UK is the restoration of its native forests. Reforestation could provide the CDR needed to help meet the UK's current climate change commitments, and beyond that, to staying within the 1.5°C budget. Animal agriculture is the biggest land user in the UK. Due to its relatively low food output to land use ratio, animal agriculture currently occupies 48% of all UK land.

We estimate the CDR potential of returning UK land currently used for animal agriculture to forest cover in two scenarios. Our first scenario maximises CDR by restoring land currently under pasture and cropland used to produce farmed animal feed to forest. Our second scenario trades off some CDR in order to keep all current cropland in production, allowing for the repurposing of animal feed cropland for increased and diversified fruit and vegetable production for human consumption, therefore maximising food self-sufficiency for the UK. The remaining cropland in both scenarios is sufficient to provide more than the recommended protein and calories for each person in the UK. In scenario 2, reforesting land currently devoted to pasture results in CDR of 3,236 million tonnes CO_2, equal to offsetting 9 years of current UK CO_2 emissions. In scenario 1, extending reforestation to include animal feed croplands increases the CDR to 4,472 million tonnes CO_2, offsetting 12 years of current UK CO_2 emissions. In relation to the 1.5°C budget, CDR extends the permissible budget by 75% to 103%, for scenarios 2 and 1 respectively, up to 2050.

Restoring agricultural land currently used for farmed animals back to native forest would contribute substantially to aligning UK GHGs with the Paris Agreement, and provide new opportunities for alternative protein production, fruit and vegetable provisions, and enhanced food security. Reforestation would transform the UK landscape, providing additional benefits including habitats for the reintroduction of wildlife. The multitude of potential benefits provides opportunities for joining up policy across climate change mitigation, agriculture, food, public health and rewilding.

Creating a Paris-compliant food system is essential - carbon dioxide removal from restoring a portion of agricultural land to forest must be included in the UK's revised contributions to meeting the Paris Agreement, together with implementation of comprehensive policy measures to enable this shift and optimise for climate, ecosystem and human health benefits.

Climate change is one of the most severe issues for public health and the natural environment - requiring strong and immediate action. Current levels of warming, around 1°C above pre-industrial levels, have already adversely impacted natural and human systems[1]. The Paris Agreement is a landmark global treaty with a goal of limiting average global temperature rise to well below 2°C above pre-industrial levels, and ideally no more than 1.5°C this century[2]. However, instead of focusing on timeframe, full attention must be given to the greenhouse gas (GHG) budget consistent with limiting global temperature rise to the Paris goal. At current emissions levels, the GHG budget consistent with limiting global temperature rise to 1.5°C will be depleted in around 12 years[1]. For regions such as the United Kingdom (UK), which have historically higher per capita emissions, this timeframe could be much less than 12 years if the emissions budget is allocated on the basis of equity, i.e. allowing a larger proportion of the budget for regions with historically lower per capita emissions.

The adverse impacts at 1.5°C of warming on terrestrial, freshwater and coastal ecosystems are higher than present warming levels, but less severe compared to those expected at 2°C. Limiting warming to 1.5°C, compared with 2°C, could reduce the number of people both exposed to climate-related risks and susceptible to poverty by up to several hundred million people globally by 2050[1]. Adverse impacts are greater if temperature overshoots 1.5°C before returning to 1.5°C this century, compared to no overshoot[1]. Hence, limiting warming to 1.5°C with no overshoot best aligns with the precautionary principle and equity component of the Paris Agreement – in comparison to 2°C[2,3]. To limit or avoid temperature rise overshooting 1.5°C, global carbon dioxide (CO_2) emissions must decline by about 45% from 2010 levels by 2030 and reach net zero by around 2050. This would require radical and unprecedented transitions and deep emissions reductions from all sectors, with a wide range of mitigation options[1].

Current commitments to the Paris Agreement fall short of the reductions required – far surpassing even the least ambitious goal of keeping warming below 2°C[4]. Revising national commitments to align with the Paris goals is crucial. Given the scale of the reductions needed, to limit warming to 1.5°C with limited or no temperature overshoot requires more than emissions reductions – the removal of CO_2 from the atmosphere is essential, at a rate of 100–1000 billion tonnes (Gt) CO_2 this century. It is important to note that Carbon Dioxide Removal (CDR) is not an alternative action to strong and immediate GHG reduction – it is an additional requirement[1]. The CDR options available for deployment (forestation and soil carbon sequestration) should be implemented immediately to help avoid temperature rise overshooting the Paris goals[5].

The main options being explored for CDR are Bioenergy Carbon Capture and Storage (BECCS), reforestation, biochar and soil microbes[4]. In some cases, there are serious issues to overcome before these negative emissions technologies can be deployed at scale. For example, BECCS requires large amounts of land and fertilizer for feed crop production, and the capture component is unproven at scale[6]. The most readily deployable option at scale in the UK in terms of technological feasibility is carbon removal via vegetation growth[5]. This also requires large areas of land and thus elicits legitimate concerns regarding competition with food production[5]. Hence in this report, we seek to provide the first exploration of the potential for CDR in the UK from repurposing a proportion of agricultural lands, and the impact this might have on food production for human needs.

Agriculture is the biggest land user globally[7], with animal agriculture occupying the majority (83%) of this in exchange for 18% of calories and 37% of protein delivered to the food system for global consumption[8]. Since 1960, animal agriculture has caused 65% of land use change globally[9], to grow feed crops for farmed animals, and to house farmed animals (in pasture and feedlots), at the expense of native forest, grasslands or savannah[10]. Given the large land occupation, large contribution to the removal of natural carbon sinks, and relatively low food output to land use ratio for animal agriculture[8,11], we focus our analysis on the CDR potential of returning UK land currently used for animal agriculture to forest cover, the climax vegetation in the UK[12].

The UK Government, and many other national governments, are preparing their revised Nationally Determined Contributions (NDCs) to meeting the Paris Agreement, to submit in 2020. These revisions must make substantially higher commitments compared to previous pledges, in order to avoid temperature rise beyond the Paris range[4]. Radical action, far beyond that currently planned, is required across all sectors - including agriculture. Fundamental change to current agricultural land use to increase CDR is crucial to meeting the Paris agreement. Incremental change is insufficient[13]. A recent report commissioned by the UK Department for Business, Energy and Industrial Strategy advised that the UK Government pursue ramp-up of forestation, habitat restoration and soil carbon sequestration across large areas of land in the UK[5]. At the time of writing our report, the UK Committee on Climate Change (CCC) (an independent, statutory body established under the Climate Change Act 2008) is preparing advice to the UK Government on the options for reconfiguring land use to meet emissions targets. Our analysis is intended to assist with demonstrating the potential of such natural climate solutions, focusing on repurposing a portion of UK agricultural land for climate change mitigation needs. The level of GHG reductions required and the urgent need for action rule out any business as usual (BAU) scenario, for any sector. Hence, we model deep transformations to UK agriculture without any consideration or attempt to maintain BAU.

AIMS OF THE REPORT

Our analysis serves two lines of enquiry. Firstly, to address agricultural GHGs, which are currently on track to use a substantial part of the GHG budget. For example, by 2030 GHGs from animal agriculture alone will use almost half of the GHG budget consistent with limiting warming to 1.5°C, and over a third of the 2°C GHG budget[14]. Secondly, we explore the possibility of converting land currently used for animal agriculture from a net positive source to a net negative GHG sink, and hence the wider role of reconfiguring land use for the purpose of tackling climate change. We assess two options for creating a lower carbon agriculture sector while improving food self-sufficiency in the UK.

2. UK EMISSIONS IN THE 1.5°C CONTEXT

The UK currently contributes 1% to global CO_2 emissions[a] (taking into account only emissions produced within British territory). The latest assessment from the Intergovernmental Panel on Climate Change (IPCC), identified a global budget of 420 Gt of CO_2 as the most certain (66% chance) scenario for limiting warming to 1.5°C. If we assume the UK would be allocated the same share (i.e. 1%) of this CO_2 budget, the UK would have a CO_2 budget of 4,336 million tonnes (Mt) CO_2. This equates to only 11.6 years of current CO_2 emissions before the budget for limiting warming to 1.5°C is used. Taking into account full global equity, the UK's 1.5°C[1] budget must be even lower. Either way, it is imperative that strong and rapid emissions reductions are implemented across all sectors, in addition to CDR[5].

[a] Global CO_2 in 2017 was 36,153 million tonnes. UK CO_2 in 2017 was 373.2 million tonnes[32]

2.1 UK agricultural land use and greenhouse gas emissions

The UK is far off from contributing equitably to reducing greenhouse gas emissions. Most reductions to date have occurred in the energy sector, with reductions from agriculture lagging far behind[15]. Emissions from the agriculture sector have not decreased over the past 5 years, and current policies are insufficient to meet the UK's fifth carbon budget, as set out in the UK Climate Change Act – which does not conform with limiting warming to 1.5°C. Even meeting the UK Climate Change Act, which legally binds the UK to reduce GHGs to 80% below 1990 levels by 2050, will require more challenging measures to be implemented in the land use sector[13]. The current policy framework is not on track to deliver its industry-led voluntary approach to reduce agricultural emissions, or the additional target to afforest 27,000 hectares each year by 2024[13].

Although agricultural emissions remain high, the UK is presently not self-sufficient in food production. UK farming currently provides less than 50% of food eaten in the UK (by value)[16]. Agricultural land used for food production is expected to be insufficient in terms of maintaining current levels of per capita food production for a growing UK population. By 2050, the area of cropland required could increase by 15%[13]. If the needs could be met, this would result in higher GHGs and other adverse environmental impacts. Hence, balancing land used for food production with the need to mitigate climate change and other pressures requires fundamental changes to how land in the UK is used. Bold decisions are needed – improving farming practices alone is insufficient, delivering emissions reductions of only 9 Mt CO_2e by 2050 and leaving agriculture as one of the UKs biggest emitters[13].

The production of livestock is a large source of agricultural emissions in the UK[13]. While technology has the potential to reduce GHGs from livestock by around 10%[17], this amount is insufficient compared to the reductions needed to create Paris-compliant food systems – radical changes to both food production and consumption are required, necessitating a large-scale shift to plant-based foods[18].

At the time of preparing our report, the UK is planning to leave the European Union (EU). Should this occur, greater competitive pressures and challenges are likely to be exerted on the UK agricultural sector, further increasing the urgent need for a transition to low-emission, high-productivity farming and land use[13]. Any changes in trade and regulatory regimes between the UK, the EU and non-EU entities will pose serious challenges to the UK food system, having adverse impacts not only for agricultural trade and production, but also for dietary risks and diet-related health in the UK[19]. For example, more than 90% of fruits and vegetables consumed in the UK, by value, are imported[16]. Maximising the productivity of agricultural land in terms of increasing the production of high nutritional value crops for human consumption could help tackle the numerous challenges to the UK food system. For example, an analysis of the US food system found that reconfiguring cropland from animal feed to 100% human edible crops that promote positive health outcomes (including fruits, vegetables, and pulses) would feed an additional 350 million people compared to what the same area of land currently produces[20]. This is mainly due to the relatively large losses involved in producing animal-sourced foods. For example, to produce 1 calorie of beef requires 37 calories of plants, 1 calorie of pork requires 12 calories of plants, 1 calorie of chicken requires 9 plant calories, 1 calorie of eggs and 1 calorie of dairy each require 6 plant calories[11]. Reconfiguring food systems to grow crops directly for human consumption therefore allows for a higher production of health promoting foods, such as fruits, vegetables, pulses, nuts, seeds and whole grains. In addition to reducing food related GHG emissions by 70% and land used for food production by 76%, shifting food systems from animal-based to plant-based can actually increase, not decrease, the protein supply[8,21,22].

It is imperative to repurpose UK agricultural land to mitigate climate change, and increase the resiliency of UK agriculture in the face of population rise and adverse impacts of rising temperatures on food supply and availability. While there may be some opportunities from climate change such as longer growing seasons, the net effect is expected to be negative[13]. Food security is a key consideration in the Paris Agreement: 'Recognizing the fundamental priority of safeguarding food security and ending hunger, and the particular vulnerabilities of food production systems to the adverse impacts of climate change'[2]. Hence it is a reasonable expectation for commitments to meeting the Paris Agreement to factor in agriculture and food systems. The agricultural shifts we present in this report have the potential to help meet GHG reduction goals, and simultaneously increase food security through increasing the provision of health-promoting foods by reconfiguring crop production on arable land.

3. ASSESSING THE CARBON REMOVAL POTENTIAL OF UK AGRICULTURAL LAND: METHODS SUMMARY

We address the following research questions:

1. How much land currently used for agriculture in the UK could be restored to forest?
2. How much carbon dioxide could be removed from the atmosphere through this process?
3. What impact would this farming shift have on food provisions?

The methodology used to answer these questions is detailed in a global analysis of this farming shift (see Hayek et al, forthcoming[23]) – hence a summary version is provided here.

The first step was mapping the distribution of agricultural food production in the UK, using the following:

- Earthstat dataset for "Cropland and Pasture Area in the Year 2000"[24].
- Estimates for pasture area that correspond with the Food and Agriculture Organization (FAO) definition of "land under permanent meadows and pastures", which includes lands utilized predominantly for grazing for a minimum of 5 years and 100 days per year (not including lands managed mostly for other purposes e.g., recreation, forestry, conservation)[25].
- Earthstat crop yields updated from the year 2000 to 2015 using FAOSTAT database[25].
- Distributions of yields for 175 most abundant agricultural products[24].
- A 5 arcminute resolution of 9.3 km by 5.2 km at Glasgow, modelled using R software (version 3.5.1).

Step two required the mapping of crop allocation for human food and animal feed, using:

- Data for 41 human-edible crops and 18 crops exclusively for animal feed[26].

The third step calculated the carbon content of vegetation:

- Carbon in terrestrial potential vegetation that would naturally regrow following abandonment from human activities[27], was taken from 6 global datasets[28].

- The average timeframe for temperate forest regeneration of approximately 30 years was assumed[29].
- Carbon currently in pasture and cropland was accounted for, hence our scenarios represent additional CDR to that occurring under current land use.
- Carbon in present-day croplands at time of harvest was estimated using a published methodology that relates harvested biomass to net primary productivity[30].
- Carbon currently in pastures (which were assumed to exist on cleared land as climax vegetation in the UK is forest[12]) was calculated using a literature estimate of 6 MgC ha^{-1} (representative of high-productivity artificial grassland in humid climates)[31].

We assessed the CDR potential of 2 scenarios:

1 Pasture and feed cropland restoration

All permanent pasturelands and feed/forage croplands are taken out of production and restored to their natural vegetation cover. This scenario maximises CDR by restoring land currently under permanent pasture and cropland used to produce farmed animal feed to climax vegetation (forest), but might not meet micronutrient needs of the UK population, and thus keep some reliance on food imports.

2 Pasture land restoration

All permanent pasturelands are taken out of production and restored to forest cover. All cropland currently used for feed/forage crops remains in production and is repurposed to grow crops for human consumption only. This scenario reduces the potential for CDR compared to scenario 1, but increases the potential for meeting population-wide nutritional needs and reducing dependence on food imports by increasing the production of fruits, vegetables, and pulses for human consumption.

To calculate CDR in both scenarios, we take the average of 6 maps[28] that contain potential vegetation rates for temperate climates. Although carbon sequestration rates are largely dependent upon species composition, climate, and other factors, prior analyses of reforestation on marginal and under-utilized agricultural land estimate that carbon uptake saturates after around 25 years for tropical forests and around 30 years for temperature forests. We therefore assume a saturation rate of 30 years[29]. The results assume that both scenarios are implemented with broadleaved forest (primarily oak, sycamore, ash, beech and birch in England, Wales and Northern Ireland, and Scots pine in Scotland[12]).

Our analysis did not include:

- Restoration of temporary pasture/grazing lands i.e. lands managed predominantly for other purposes including recreation, forestry, conservation, or other activity where grazing is occasionally or intermittently permitted.
- Changes in soil carbon levels.
- Restoration of wetlands/peatlands.
- Changes to cropland availability under scenarios that restore peatland currently used as cropland.

- Changes in CDR rate/trajectory over the 30 year period - according to a secondary succession of vegetation, such as shrub/herb layer progressing to woodland.
- A method of forestation, such as reliance on natural seed banks versus planting/afforestation.
- Forest management techniques that might increase the rate of CDR (but not the final amounts).
- Potential yield increases over time, due to potentially more favourable growing conditions in the UK related to temperature increase and weather pattern changes, or otherwise.
- Technology improvements to lower GHGs from crop production.
- Intensification of crop production.
- Any increase in crop production to satisfy a growing UK population up to 2050.
- Any changes to imports and exports.
- Any economic impacts related to changing agricultural production and land use.
- Any economic incentives to enable our modelled land use shifts.

4. THE CARBON DIOXIDE REMOVAL POTENTIAL OF REPURPOSED UK AGRICULTURAL LAND: FINDINGS

The UK has ~84,000 km^2 of permanent pastureland and ~58,000 km^2 cropland, of which 55% is currently used to produce feed for farmed animals **(table 1)**. Overall, 48% of land in the UK is used for animal agriculture – either for pasture or feed crop production[b]. **(figure 1, page 8)**

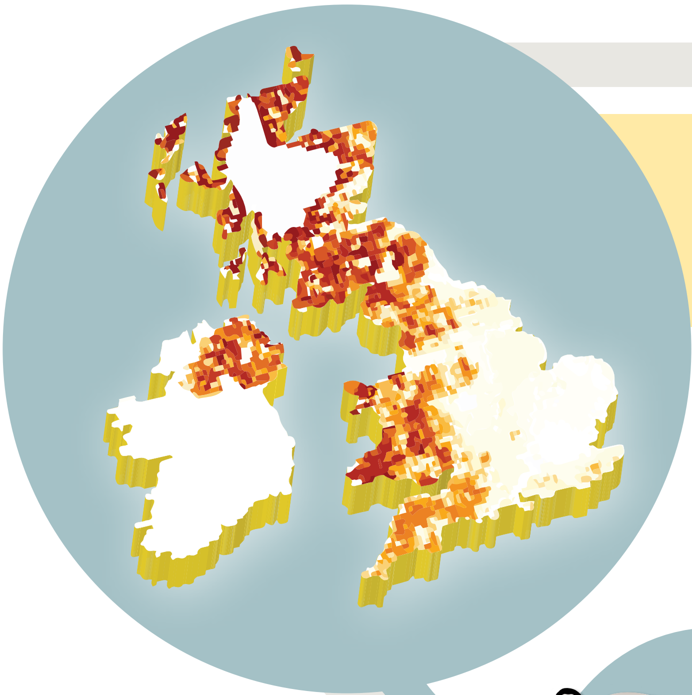
Table 1 provides country-level data on cropland areas currently in production, and by type of production (animal feed crops and human food crops).

	Current cropland area km^2	% of cropland used for animal feed	% of cropland used for human food
England	51,449	56%	44%
Scotland	4,737	49%	51%
Wales	812	49%	51%
Northern Ireland	530	58%	42%
Total	57,528	55%	45%

Table 1: Current cropland in England, Wales, Scotland and Northern Ireland by use.

[b] The UK has a total land area of 241,930 km^2. Animal agriculture occupies 115,900 km^2, which is 48% of the total (115,900 km^2/241,930 km^2 = 0.479).

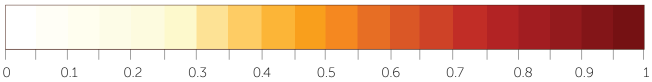
Figure 1: Current UK land use under pasture and cropland.

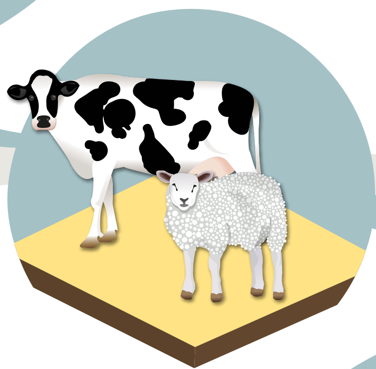


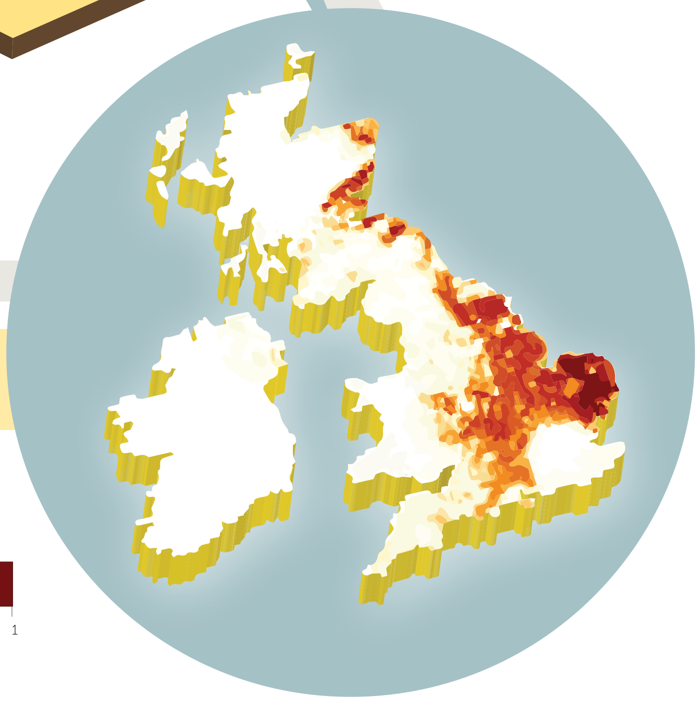
LAND UNDER PASTURE: 84,000 km²

Current spatial distribution of land used for pasture. Given the map resolution at a large scale of 5 arc-minutes (9.3 km by 5.2 km at Glasgow), the colour gradient serves to improve the interpretation of land use by representing the varying spatial concentration.

all pasture: land fraction



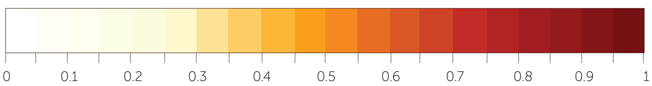




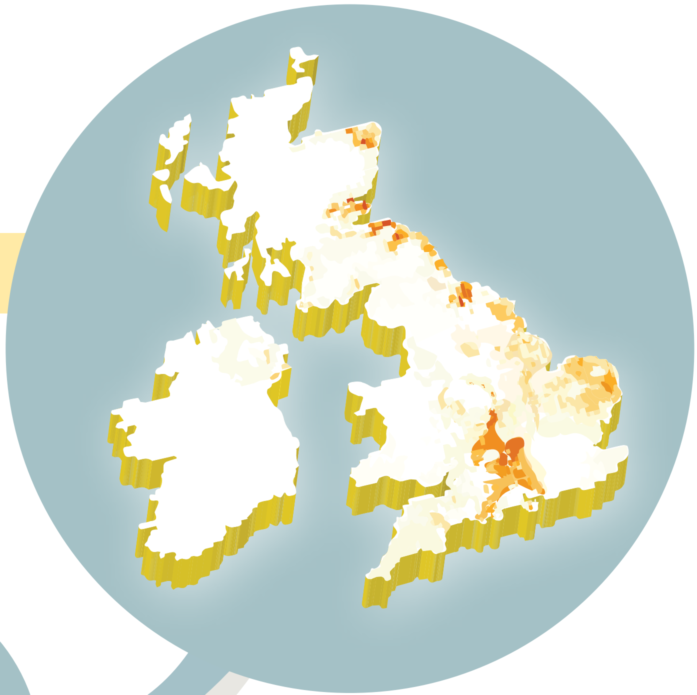
LAND UNDER CROPS: 58,000 km²

Current spatial distribution of land used for crop production of which 55% is for animal agriculture

all crops: land fraction presently in production



For scenario 1 (Pasture and feed cropland restoration) which maximises CDR, figure 2 shows the area of cropland area taken out of production for farmed animal feed crops and figure 3 shows the land area remaining under human food production.



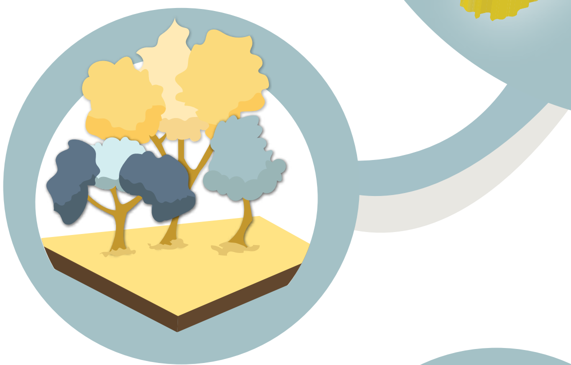
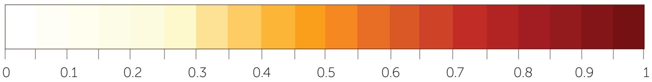


Figure 2:

Cropland area for animal agriculture restored to forest in scenario 1

feed crops: land fraction removed from production



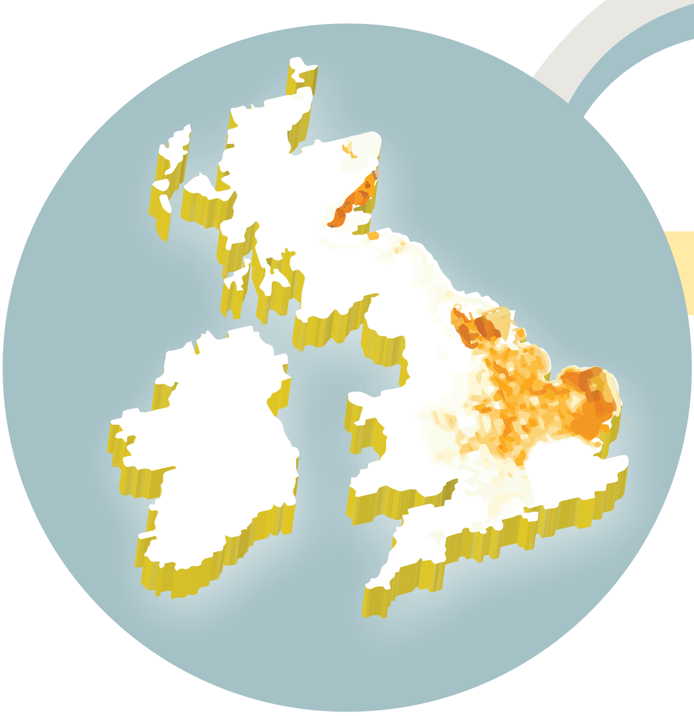
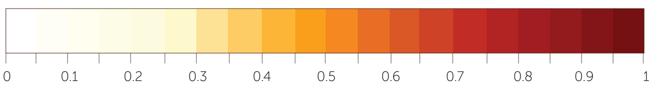


Figure 3:

Cropland area remaining for human food production in scenario 1

food crops: land fraction remaining in production



Scenario 1 (Pasture and feed cropland restoration) would repurpose 55% of UK cropland from its current production of farmed animal feed, to CDR for helping meet climate targets. Scenario 2 (Pasture land restoration), retains all 58,000 km^2 of UK cropland for food production. (i.e. 100% of the cropland shown spatially in figure 1).

Figure 4 shows the spatial distribution of CDR that would occur if all agricultural land currently used for animal agriculture was restored to forest cover (Scenario 1 - Pasture and feed cropland restoration). The colour grading represents the varying amount of CDR spatially. This scenario would remove 4,472 million tonnes (Mt) of CO_2 (table 2), with 27% of this total coming from restored cropland and 73% from restored pastureland.

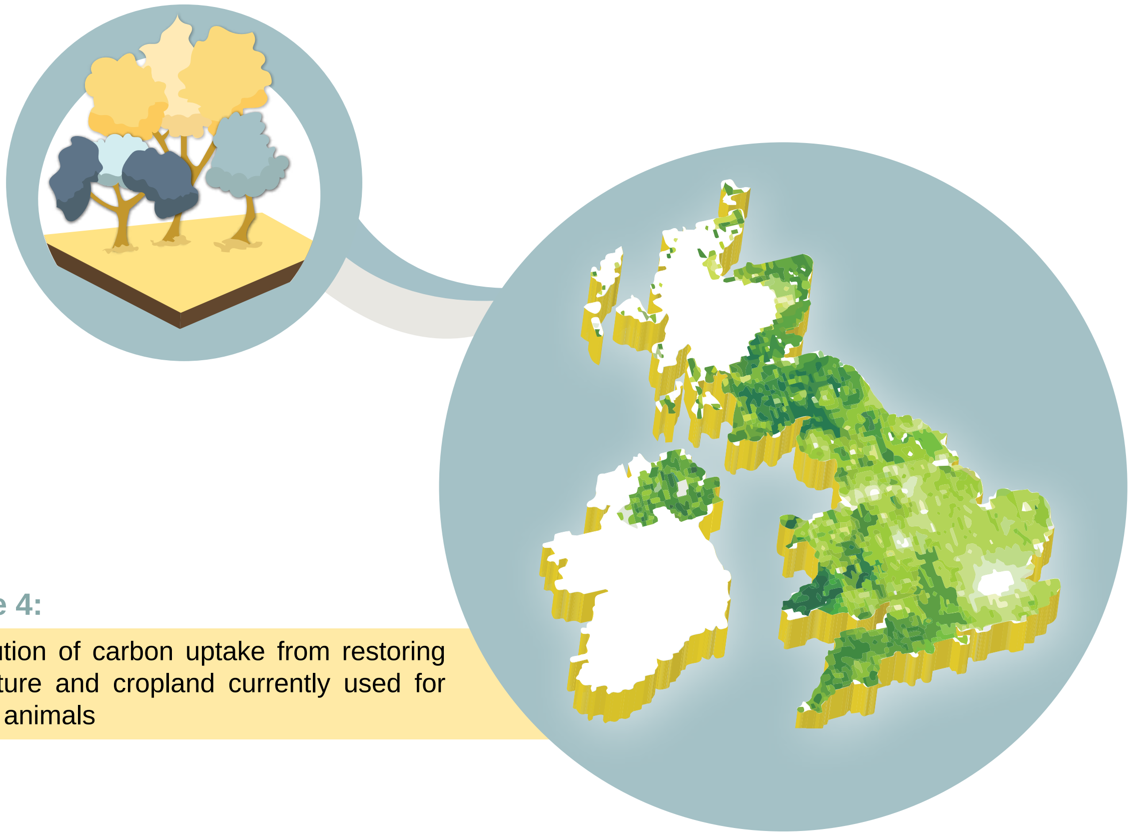
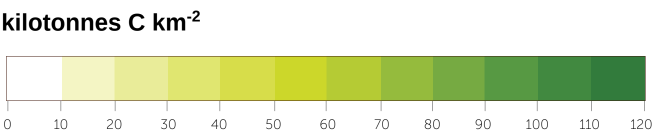


Figure 4:

Distribution of carbon uptake from restoring all pasture and cropland currently used for farmed animals



Under scenario 1 (Pasture and feed cropland restoration), the UK would still produce enough food for the current population of 66 million people, at 2,587 calories and 70 grams of protein per person per day. There might be some reliance on food imports to meet micronutrient needs from fruits and vegetables and/or to satisfy the needs of a growing population. This shortfall is potentially addressed in scenario 2, where all cropland remains in production in order to provide more cropland for fruit and vegetable production. The result is a CDR of 3,236 Mt CO_2 from restoring land currently used for farmed animal pasture to forest (table 2). Figure 5 shows the spatial distribution of carbon uptake in scenario 2.

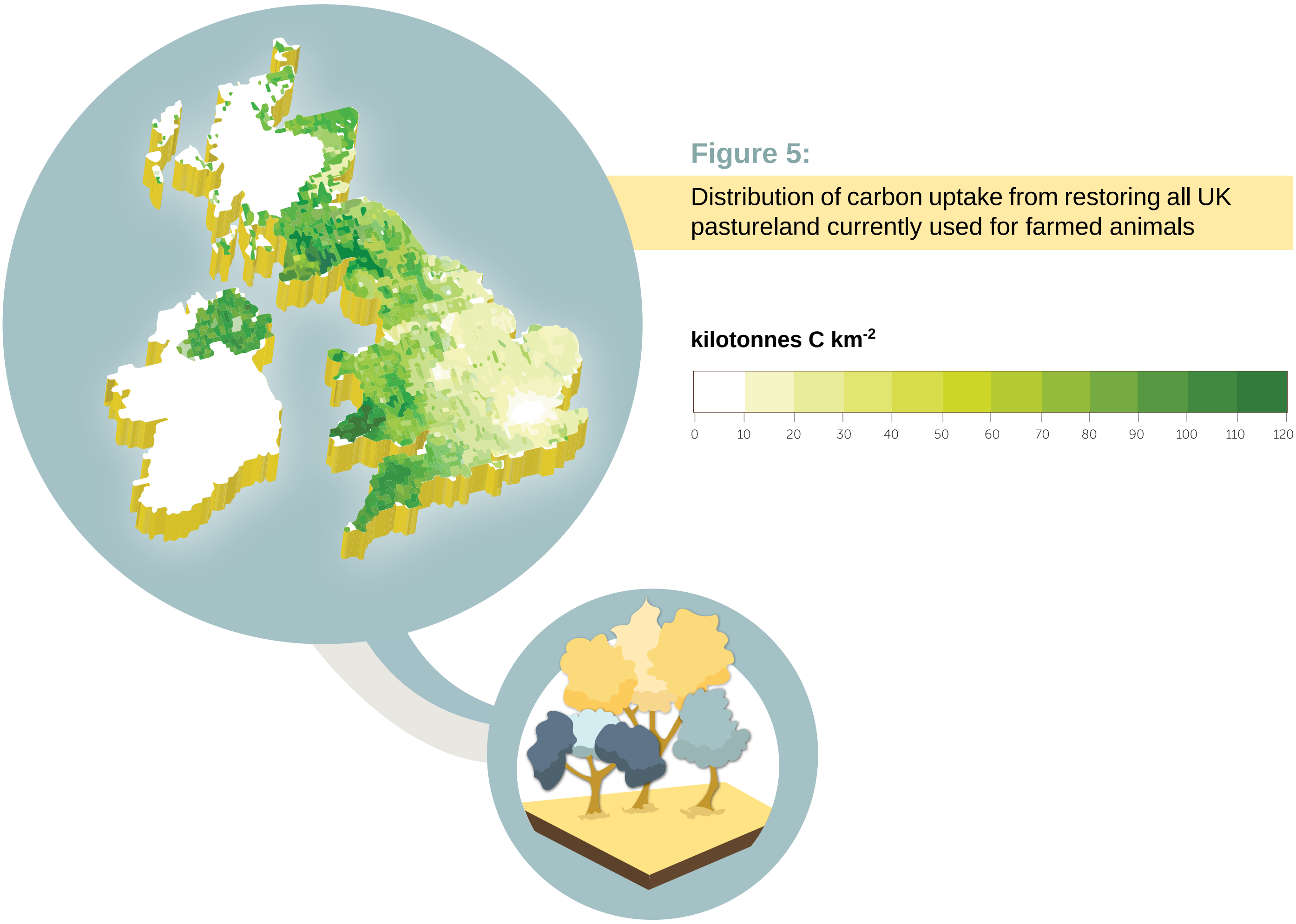


Figure 5:
Distribution of carbon uptake from restoring all UK pastureland currently used for farmed animals

	Scenario 1: Pasture and feed cropland restoration		Scenario 2: Pasture land restoration	
	CO_2 removed Mt (mean and range)	% contribution to total CDR for the UK	CO_2 removed Mt (mean and range)	% contribution to total CDR for the UK
England	2,378 (1,481; 2,934)	53.2%	1,391 (892; 1,700)	43.0%
Scotland	1,228 (904; 1,791)	27.5%	1,052 (674; 1,283)	32.5%
Wales	517 (320; 634)	11.5%	476 (306; 582)	14.7%
Northern Ireland	349 (217; 430)	7.8%	316 (204; 388)	9.8%
Total CDR for the UK	4,472 (766; 4,517)	100%	3,236 (2,075; 3,952)	100%

Table 2: Carbon Dioxide Removal by country and scenario

The CDR from our scenarios 1 and 2 equate, respectively, to approximately 12 and 9 years of current UK territorial CO_2 emissions of 373.2 Mt CO_2[32]. The UK has allocated a GHG budget of 6,219 Mt CO_2e for territorial emissions from 2018 to 2032 – an annual average of 415 Mt CO_2e over this 15 year period, under its commitment to meeting the Climate Change Act (CCA). The carbon budgets under the CCA restrict the amount of GHG the UK can legally emit in each 5 year period. The UK is currently off track to remain within this budget from 2023 onwards. Assuming CO_2 will continue to account for the same proportion of total GHGs, this gives a CO_2 budget from 2018 to 2032 of 5,043 Mt CO_2[c], and an annual average budget of 336 Mt CO_2 up to 2032 (figure 6). Our first scenario which restores natural vegetation cover on all land currently used for animal agriculture (pasture and feed cropland) in the UK, provides an annual average CDR of 149 Mt CO_2, and our second scenario (restoring pasture land only) provides an annual average CDR of 108 Mt CO_2. Our scenario could be interpreted as adding 1,938 – 1,402 Mt CO_2 to the UK territorial emissions budget up to 2032 (for scenarios 1 and 2 respectively) – assuming CDR in our scenarios commences in 2020.

Our estimated CO_2 budget under the Climate Change Act for the UK of 5,043 Mt CO_2 exceeds the CO_2 budget consistent with limiting warming to 1.5°C by 708 Mt CO_2 (figure 6). It should be noted that our estimated UK budget of 4,336 Mt CO_2 for limiting warming to 1.5°C is likely to be an overestimate as it is based on the contribution of current emissions to the global total. Using an equitable allocation of emissions from the global 1.5°C CO_2 budget would reduce the relative share for regions such as the UK which has one of the highest historical per capita GHG emissions.

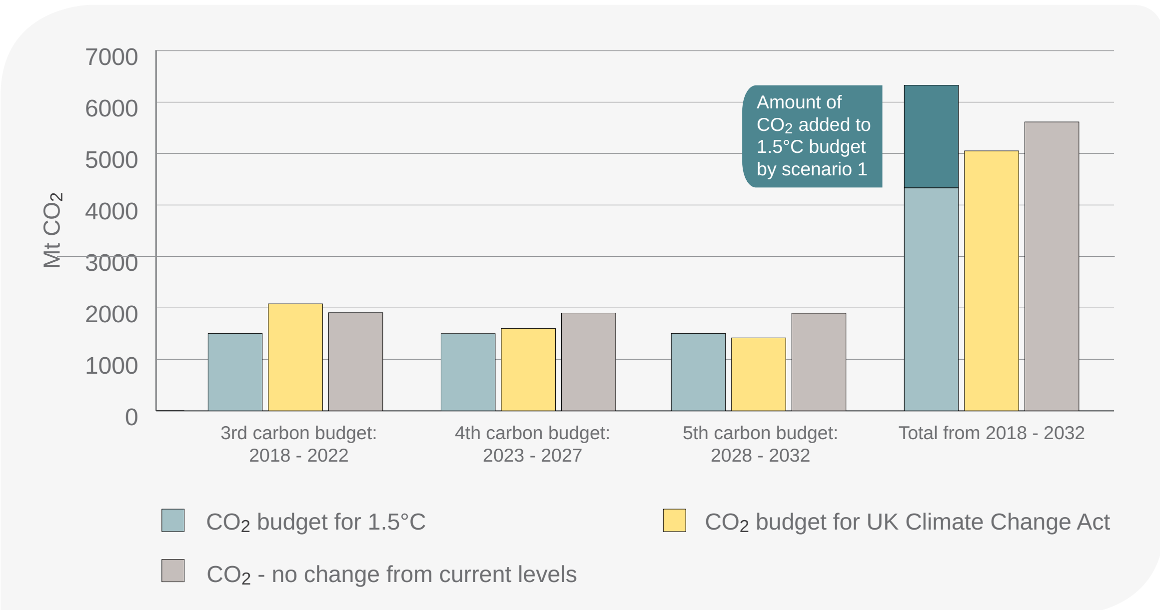


Figure 6: UK CO_2 emissions from 2018 to 2032 under business as usual, the Climate Change Act, and 1.5°C of warming.

Our scenarios 1 and 2 meet, respectively, 273% and 198% of the 1.5°C budget shortfall for the UK up to 2032, in comparison to our estimated CO_2 budgets under the UK Climate Change Act[d]. The UK budget for limiting warming to 1.5°C would be fully used by 2032. As an alternative perspective, our scenarios 1 and 2 extend the permissible GHG budget for 1.5°C by 103% and 75%, respectively, up to 2050. Hence, our scenarios greatly increase the possibility of the UK aligning its CO_2 emissions with a warming limit of 1.5°C.

For further context, the UK CCC is currently exploring options to achieve net zero GHGs in the UK by 2050. A recent analysis estimated that taking all feasible options to reduce UK GHGs would leave emissions of around 130 $MtCO_2$ per year by 2050[5], which would need to be removed through some form/s of CDR. Our scenarios deliver an average CDR of 108 – 149 $MtCO_2$ per year across a 30 year period – which would more than offset the 130 $MtCO_2$ under our scenario 1 (by 115%), and offset 83% under scenario 2. While our scenarios offer substantial, and likely necessary, contributions to meeting emissions budgets, they do not offset the need for strong and rapid GHG reductions across all sectors in the short term.

Our analysis assessed CDR potential from agricultural land use shifts and did not quantify the reduction in GHGs that our scenarios would deliver in addition to the CDR – such as methane and nitrous oxide from ruminant digestion and animal manure. We did not assess any production shifts, such as a replacement of the highest emitting animals (cows, sheep and goats) to those with relatively lower emissions (chickens and pigs) as this is more akin to problem shifting than problem solving. Such a shift would require an expansion of arable cropland to produce additional animal feed, and could bring further problems such as increased application of antibiotics (which is a major and growing global issue[33]), and an increased number of farmed animals in the food system. In terms of achieving strong and rapid GHG reductions to the levels required, such a shift is suboptimal given that plant-based proteins have lower emissions[8,34], and could in turn reduce the speed and scope of GHG reductions by introducing a middle ground, potentially locking in food producers and preventing further changes to reduce GHGs more steeply.

6. REPURPOSING ANIMAL FEED CROPLAND FOR HUMAN-EDIBLE FRUIT AND VEGETABLE CROP PRODUCTION

Crop production in the UK is currently dominated by only 7 crops, which take up 91% of UK cropland[25]. In order of highest production quantity first, these are wheat, grass/other forage, barley, rapeseed/canola, sugar beet, potatoes, and oats. For some crops, continuing production and reallocating usage from animal feed to human food would be an attractive option. Oats for example are a nutritious, fibre-containing, whole grain that have a variety of uses as a whole ingredient, or can be used in value-added products such as oat milk. Shifting to fruit and vegetable crops could be another option, helping to increase micronutrient provisions, align with dietary recommendations, and improve food sovereignty (producing a higher share of the food consumed domestically). Table 3 elaborates upon scenario 2 (Pasture land restoration), demonstrating how much food could be grown on only one hundredth of the cropland currently used to grow animal feed (1% of 31,640 km^2, or 316 km^2). The crops listed are currently grown as field crops in the UK (using current production data from FAOSTAT[25]). Potential crop yields were calculated using median observed yields of crops growing in other countries under similar climates[35].

[c] CO_2 emissions account for 81% of total CO_2e in 2017[32]. 81% of 6,219 = 5,043.

[d] The contribution of our scenarios was calculated taking an annual average of the CDR over a 30 year period, and applying to the 13 year period from 2020 – 2032, to coincide with the remainder of the 3rd, 4th and 5th carbon budgets.

Crop name	Total current UK production (tonnes)	Amount that could be produced on 1% of current UK animal feed cropland (tonnes)	Increase to domestic supply
apple	299,685	348,963	116%
cabbage	292,805	510,648	174%
carrot	1,088,551	431,374	40%
cauliflower	148,938	48,180	32%
chilli	13,137	228,224	1,737%
cucumber	153,227	314,272	205%
currant	12,046	148,888	1,236%
gooseberry	1,603	80,595	5,028%
green peas	394,940	78,206	20%
linseed	127,728	4,122	3%
onion	377,596	483,160	128%
split pea	325,607	59,236	18%
pear	48,906	203,171	415%
plum	11,922	37,869	318%
raspberry	13,223	182,660	1,381%
strawberry	56,973	270,635	475%
tomato	142,909	303,056	212%

Table 3: Field crops currently grown in the UK by crop and production quantity, and the additional amount produced on 1% of repurposed animal feed cropland.

For context, a serving of fruits or vegetables according to the UK Eatwell dietary guidelines is 80g for adults, and the minimum recommended intake is 5 servings per day. Pulses such as beans and chickpeas also count as 1 of the '5 a day' foods[36]. As an example, the amount of strawberries that could be produced on 1/100th of cropland currently used to grow animal feed (270,635 tonnes – table 3), could provide 1.9 million adults their 5 a day for an entire year[e]; or 1.3 million, 2.4 million, and 2.1 million, respectively, for raspberries, apples and tomatoes. Grossing these numbers up to include just one third of cropland currently used to grow animal feed could provide 62 million adults their 5 a day for an entire year – almost the entire UK population.

[e] The figure was calculated by converting strawberry yield from tonnes (270,635) to grams (270,635,000,000), dividing by 80g servings and 5 servings per day, and 365 days. This gives 270,635,000,000/80/5/365 = 1,853,664.

The crops listed in table 4 are not currently grown in significant quantities in the UK, for which wide-scale production could potentially be introduced under scenario 2 (Pasture land restoration).

Crop name	Potential production (tonnes) on 1% (316 km^2) of current UK animal feed cropland
apricot	28,818
beans	53,023
chickpea	28,711
eggplant	161,052
garlic	137,908
groundnut (peanut)	67,745
lentil	35,753
peach	256,511
pumpkin	616,357
sesame	29,697
cherry	61,827
sunflower	51,680
sweet potato	690,188

Table 4: Field crops currently grown in the UK in very small quantities by crop, and additional potential production quantity on 1% of repurposed animal feed cropland.

The production data in tables 3 and 4 was averaged over the entirety of the UK, over all of its climate zones and hence does not necessarily represent one specific area or region.

7. CO-BENEFITS OF REPURPOSING LAND CURRENTLY USED FOR ANIMAL AGRICULTURE

Our scenarios could potentially deliver benefits across a range of environmental, biodiversity and public health issues – as summarised in the following sections.

7.1 Environmental and wildlife benefits

In addition to sparing land and creating CDR, our scenarios have potential benefits in terms of reducing non-CO_2 emissions. Temperature rise is determined by the accumulation of both CO_2 and non-CO_2 GHGs. Hence, non-CO_2 emissions are important in limiting warming and must be reduced in addition to CO_2[1]. In 2016, cattle and sheep directly accounted for around 58% of UK non-CO_2 agriculture emissions[13]. To limit warming to 1.5°C, non-CO_2 emissions must decline by around 25% over the next decade. If implemented in the short-term, our scenarios could reduce CO_2 and non-CO_2 substantially over the next few decades and in turn reduce the risks and impacts of climate change by limiting warming in 2050 and beyond[1].

Animal agriculture is the largest contributor to nitrogen and phosphorus pollution (from animal manure and chemical fertilizers applied to farm animal feed crops), leading to eutrophication and 'dead zones'[37]. A global switch to plant-based food systems has been estimated to reduce eutrophication by 49%[8]. In the UK, grasslands are the main user of nitrogen, with 425 kilo-tonnes applied in 2015. Permanent grassland used 73% of this amount[38]. Hence our scenarios could deliver a substantial reduction in nitrogen pollution.

Most natural climate solutions, such as our scenarios 1 and 2, can provide additional benefits including water filtration, flood buffering, soil health, habitats for wildlife, and enhanced resiliency to climate change impacts[29]. Repurposing land from animal agriculture to forest could provide habitat for wild species reintroductions and help address the global wildlife crisis[39,40]. Additionally, forests provide opportunities for recreation[13]. Our scenarios could also help meet existing commitments for tree planting in the UK – such as the commitment to reforest ~2,000 hectares per year in England by 2022[15].

7.2 Public Health benefits (non-communicable and communicable diseases)

Increasing the production of health-promoting foods to help meet recommended dietary intakes of fruits, vegetables, nuts, seeds and pulses, could improve public health outcomes. Diet-related health problems linked to a low consumption of fruits and vegetables and high consumption of red and processed meat are the second biggest risk factor for mortality in the UK[41]. Changing agricultural production could increase the UK's self-sufficiency to meet the populations' nutritional requirements.

As farmed animals are a major user of antibiotics[42], reducing the number of farmed animals through our scenarios could help tackle antibiotic resistance, which is a growing issue globally and regarded by the World Health Organisation as one of the biggest threats to public health[43].

7.3 Societal benefits

A recent survey by Waitrose in the UK found that from a sample of respondents representative of UK adults, there is evidence of a trend toward 'flexitarian' diets which are mostly plant-based with animal-sourced foods consumed occasionally, and much less frequently compared to a standard diet. Over 12% identified as either vegan or vegetarian, and 21% as flexitarian. Recent research by the Institute of Grocery Distribution found that from 2,055 respondents representing the UK, 15% expect to eat less meat in five years' time, with health cited as the main reason for the change. Over 50% either now follow or would be interested in following more of a plant based diet either as a flexitarian, vegetarian or vegan[44]. Our scenarios provide additional opportunities to increase production of plant-based foods to align with a growing demand and transform consumers' food environment to encourage healthier choices.

The public health benefits mentioned in section 7.2 translate into health care cost savings, and can represent a substantial amount. For example, a global shift to plant-based diets has been estimated to reduce health care costs by $31 trillion[22]. Such savings are an important social benefit of shifting food consumption, which could be better enabled in the UK through our scenarios.

7.4 Food producer benefits

As demonstrated in section 6, the cropland spared in scenario 2 could provide new possibilities for better serving a growing consumer demand for plant-based foods – giving food producers an opportunity to diversify. Owners of land restored to forest could potentially diversify their business to include ecotourism, and be compensated through rewilding and climate finance mechanisms to convert their land to a carbon sink. The need to provide adequate incentives and support for food producers and land owners must be addressed and is included in our next steps (section 8).

The multitude of co-benefits related to our scenarios, spanning across public health, ecosystems restoration, wildlife reintroductions and protection, climate change mitigation, and environmental issues such as eutrophication could form the basis of joined up policy making across multiple Sustainable Development Goals (SDGs). It is possible that joining up policy across a range of remits could gain more support and resource allocation. Implementing our scenarios would position the UK as a global leader in addressing multiple crises across climate, environment, and public health.

8. NEXT STEPS

Our scenarios provide an insightful step in identifying a 'Paris compliant' food system for the UK. Next steps could usefully include:

- A measurement of the implications for UK food production quantities, including reductions in the production of farmed animals and changes in crop production.
- A detailed assessment of growing opportunities for cropland currently used for animal feed, in terms of identifying which crops are suited to specific regions and potential yields, with case studies.
- An analysis of the potential to convert pasture land to cropland for scenarios where more food production is preferred at the cost of CDR. We assumed pasture land would be best suited to CDR due to potential constraints such as topography, inaccessibility for farm machinery, and suboptimal soil quality. However, a detailed assessment would be helpful to determine the best use for pasture land.
- The inclusion of soil carbon sequestration - estimates for the UK potential for soil carbon sequestration are 1 to 31 $MtCO_2$ per year over 10-20 years and could be applied to the remaining cropland in our scenarios[5]. The effect of soil carbon sequestration on grazing land is substantially outweighed by GHGs from animal production[45] – but the potential for soil carbon sequestration on cropland could be explored.
- Identification of new and existing agricultural, land management or climate financial incentives and/or subsidies to enable food producers to shift their crop production from animal feed to human edible crops, and for pasture land owners to repurpose their land as a carbon sink to help meet climate goals. This could usefully include the CCC recommendation for the new UK Agriculture Bill, to link financial support to agricultural emissions reduction and increased CDR, and to allocate the £90m Industrial Strategy Challenge Fund to projects that deliver GHG reductions from agriculture[15].

- Integrating CDR through repurposing agricultural lands, as in our scenarios, into the UK's 2020 revised Nationally Determined Contributions to meeting the Paris Agreement.
- An analysis of non-financial barriers to implementing our scenarios, such as current protections and constraints to habitat and land use changes; practitioner skills shortages and labour shortages for fruit and vegetable production.
- A detailed implementation pathway of our scenarios, with timeframes, CDR rates, forestation methods and (finer resolution) area-specific opportunities for farmers and land owners in terms of crop production and reforestation.

In addition to identifying potential benefits and co-benefits (summarised in section 7), during the next steps it is important to consider the potential trade-offs in our scenarios.

9. CONCLUSIONS

Repurposing portions of agricultural land for CDR is essential to meet the Paris Agreement. This in turn necessitates shifting from animal to plant based food production. Our scenarios demonstrate that the UK could greatly increase the chance of meeting its legally binding commitments to GHG reductions under the Climate Change Act, and moreover, could make a substantial contribution to aligning UK GHG emissions with a warming limit of 1.5°C by restoring forest cover on land currently used for animal agriculture. The two scenarios provide a variation in benefits – our first scenario delivers maximum CDR from restoring all land (pasture and crop) currently used for farmed animals; and our second scenario trades off around 28% of the CDR by keeping all present-day cropland in production, allowing for increased and diversified provisions of fruits, vegetables, nuts, seeds, and pulses to the UK population. Both scenarios meet protein and calorie requirements for the entire UK population, while scenario 2 maximises the potential for increased domestic provision of healthy foods. Our scenarios 1 and 2 extend the permissible CO_2 budget for 1.5°C by 103% and 75%, respectively, up to 2050. Our scenarios are not a substitute for strong and rapid GHG reductions in the short term, and should be considered alongside other measures to bring emissions in line with the Paris goals.

Returning spared agricultural land to natural forest cover maximises climate benefits, and provides opportunities for wildlife species reintroduction. Improving UK food security by reducing reliance on fruit and vegetable imports, and producing plant-based foods in line with public health improvements and changing consumer preferences provides additional opportunities for co-benefits. Our scenarios provide substantial potential for joined up policy making across food production, land use, climate change mitigation, wildlife loss and public health – helping address multiple crises simultaneously. It is essential that revised UK commitments to meeting the Paris Agreement include carbon dioxide removal from restoring a portion of agricultural land to forest, and that comprehensive policies are developed and implemented to enable this shift and optimise for climate, ecosystem and human health benefits.

ACKNOWLEDGEMENTS

The content of this report remains the sole responsibility of the authors. This report may be published in other formats with the addition of forthcoming analysis, and readers are encouraged to check for updated versions. HH and MNH acknowledge fellowship support from the Animal Law and Policy Program at the Harvard Law School. The authors are grateful to Violeta Pereira for contributing the graphic design to this report.

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