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The potential for land sparing to offset greenhouse gas emissions from agriculture

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Greenhouse gas emissions from global agriculture are increasing at around 1% per annum, yet substantial cuts in emissions are needed across all sectors[1]. The challenge of reducing agricultural emissions is particularly acute, because the reductions achievable by changing farming practices are limited[2,3] and are hampered by rapidly rising food demand[4,5]. Here we assess the technical mitigation potential offered by land sparing - increasing agricultural yields, reducing farmland area and actively restoring natural habitats on the land spared[6]. Restored habitats can sequester carbon and can offset emissions from agriculture. Using the United Kingdom as an example, we estimate net emissions in 2050 under a range of future agricultural scenarios. We find that a land-sparing strategy has the technical potential to achieve significant reductions in net emissions from agriculture and land-use change. Coupling land sparing with demand-side strategies to reduce meat consumption and food waste can further increase the technical mitigation potential, however economic and implementation considerations might limit the degree to which this technical potential could be realised in practice.

We projected the mitigation potential of land sparing in the United Kingdom with reference to its binding commitment to reduce emissions by 80% by 2050 (relative to 1990 levels)[7]. We began by identifying a technically plausible range in the future yields of all major crop and livestock commodities produced in the UK, based on historic trends and future potential. We define yields as the annual tonnage of production per hectare for crops and the feed conversion ratio (feed consumed per kilogram of production) for livestock. Future yields could vary across a wide range, driven by a number of biophysical, technical and socioeconomic factors[8–11]. We assessed the likely bounds of this range based on an assessment of technical potential and reflect this in our projections, which span yield declines through to sustained long-term growth averaging 1.3% per annum across all commodities

(Table 1; Supplementary Fig. 1; Supplementary Discussion). For the avoidance of doubt, we do not equate our lower yielding scenarios with 'land sharing'.

We next projected emissions attributable to UK agricultural production out to 2050, quantifying all sources of emissions that would be affected by a land-sparing strategy. We therefore quantified not only emissions reported under 'Agriculture' in the UK's greenhouse gas inventory[12], but also emissions related to agriculture but reported in other sectors (e.g. farm energy use, agro-chemical production and land-use change), and emissions arising overseas due to imported feed for livestock (see Supplementary Table 2 for all emissions sources quantified). Our projections assumed that agricultural production increases from present levels in proportion to projected demand growth (Supplementary Table 1). In certain scenarios, projected UK farming capacity does not keep pace with demand growth. In such cases we assumed an increase in imports and accounted for the overseas emissions associated with those imports.

Next we formulated a land-sparing strategy. As yields increase, the area of farmland required for a given level of production declines, allowing land to be spared. Our definition of land sparing includes the active restoration of habitats on spared land and our main scenario assumed the restoration of wet peatland (on spared organic soils) and native broadleaved forest (on spared mineral soils) (Supplementary Table 3). We quantified the greenhouse gas fluxes from the soils and biomass of these habitats, drawing on the UK's carbon accounting methodology[12] and IPCC guidelines[13].

The fourth step in our calculation was to combine emissions from farming with emissions from land-use change and compare projected net emissions in 2050 with the equivalent baseline emissions in 1990 (Supplementary Table 2). We find that there is significant scope to mitigate emissions through land sparing (Fig. 1a). At the lower-bound of our yield projections, emissions are projected to increase relative to current levels, reflecting increased agricultural production in 2050. In contrast, if yield growth towards the upper-bound of our projections could be realised, emissions from farming are lower (due primarily to more efficient livestock production; Fig. 1b) and the active restoration of habitats on spared land leads to significant carbon sequestration. The upper-bound of technical potential approaches a decline in net emissions of 80% relative to the 1990 baseline (the UK's greenhouse gas reduction target), though economic and implementation considerations are likely to limit the degree to which that technical potential could be realised in practice.

To explore the scope for combining emissions reduction strategies, we next assessed two promising demand-side measures[14] implemented alongside land sparing. We quantified the effect of replacing some animal products in the diet with vegetarian substitutes (Fig. 2a) and the effect of reducing food waste (Fig. 2b), in both cases maintaining the land-sparing strategy based on active restoration of natural habitats. Reducing meat consumption appears to offer greater mitigation potential than reducing food waste, but more importantly, our results highlight the benefits of combining measures. For example, coupling even moderate yield growth with land sparing and reductions in meat consumption has the technical potential to surpass an 80% reduction in net emissions (Fig. 2a).

Last, we quantified the technical mitigation potential of a number of possible alternative uses of spared land: allowing natural regeneration (a low-cost option); establishing faster growing coniferous rather than native broadleaved forest; and growing bioenergy crops (which can mitigate emissions by displacing fossil fuels) (Fig. 3). We find that actively restoring forest increases the rate of carbon sequestration compared with natural regeneration, and coniferous woodland sequesters more carbon than native broadleaved woodland. Our results suggest that the mitigation potential of oilseed rape for biodiesel is negligible, and the potential of

Miscanthus and short-rotation coppice depends strongly on the fossil fuel being displaced, only outperforming natural regeneration if displacing coal.

The scenarios we have assessed indicate that land sparing offers the technical potential for substantial mitigation. The degree to which that technical potential could be realised in practice depends on a number of factors. Our upper-bound scenario entails large, ongoing and environmentally sustainable increases in farm yields. A key issue, therefore, is identifying the mechanisms that could contribute to this outcome. Rates of yield growth in key crops have declined in recent years (Supplementary Fig. 1). Competing hypotheses explain the decline (see Supplementary Discussion). The first argues that insurmountable biophysical limits are constraining yield growth[9], a situation that might be compounded by climate change[15], and this outcome is reflected at the lower-bound of our yield projections. The second hypothesis argues that yields are well within biophysical limits, but that regulatory and market conditions and declines in research and development have reduced incentives to invest in yield growth[9–11]. These factors are controllable so under the second hypothesis there is significant scope for future yield growth. Our results highlight the technical potential for substantial mitigation if these barriers to yield growth can be overcome as part of a land-sparing strategy.

A large proportion of projected upper-bound mitigation arises due to assumed growth in livestock productivity (Fig. 1b). Our upper-bound livestock productivity gains (Table 1) assume that technological advancements lead to continued genetic gains through breeding, coupled with improved livestock health and nutrition. These gains contribute approximately half of the upper-bound mitigation in 2050 (Fig. 1b) but might be untenable in practice on economic, animal welfare or technical grounds and we note that other studies predict much lower future livestock productivity growth in Europe (see Supplementary Discussion). Encouragingly however, if even moderate productivity gains could be realised and coupled with policies that encourage reduced meat diets, technical mitigation potential is pronounced (Fig. 2a). Altering consumer dietary preferences is challenging, but aided by expected health benefits[16], a number of policy options are available. Taxes and subsidies in particular are demonstrably effective at driving diet change[17] (see Supplementary Discussion).

We have assessed the technical potential but not the economic feasibility of a land-sparing strategy. UK land use and production decisions are affected by global food prices[18], so realising land sparing in practice requires policies that couple yield increases with habitat restoration on spared land. In the UK, the obvious mechanism to effect this is via reform of the EU's Common Agricultural Policy[18]. Any mechanism would need to be carefully designed so as to function given the UK's role in the world food economy. Leakage and rebound effects might reduce the mitigation achieved, and increases in global food prices might compromise a land-sparing strategy by creating an incentive to farm, rather than spare, land[19,20]. Integrating our approach with models linking the global agricultural economy, land use and the changing climate[21] would enable a broader assessment of land sparing in the context of global markets, emissions and food security. Economic considerations will also inform the most appropriate use of spared land. Natural regeneration represents a low-cost option, so any incremental mitigation benefits from managed forestry or bioenergy should be balanced against the additional management costs under these options. Similarly, displacing fossil fuels using bioenergy might not be the best overall strategy: if the UK energy sector could reduce emissions by 80% using other clean energy sources (thereby limiting the mitigation achievable using bioenergy), using spared land to grow forests rather than bioenergy crops would result in greater overall mitigation.

Our results are robust to uncertainties in key parameters (Supplementary Table 4; Supplementary Fig. 2), but need to be interpreted cautiously. Firstly, restored habitats will – over a period of one hundred or more years – eventually reach a new equilibrium and net carbon sequestration will decline to zero[1,22]. Actively managing the carbon sink by growing bioenergy crops or by managing forests for fuel-wood or timber might in some circumstances extend the timeframe for mitigation[23], but might also compromise biodiversity objectives. Secondly, climate change feedbacks might affect our findings by altering soil carbon dynamics and the yields of food crops, livestock, bioenergy crops and trees. However, these effects are likely to be reduced by adaptation measures[15,24], and provided that non-farmed habitats continue to store much more carbon than farmland we think our conclusions will hold. Thirdly, it is essential to assess the sustainability of yield increases[25]. For example, due regard for animal welfare, local air and water quality and soil function is essential when increasing yields[8,25]. Encouragingly, the techniques we consider that increase yield also have the potential to reduce externalities per unit of production (Supplementary Table 5) and modern livestock breeding techniques allow multiple traits, including health, welfare and productivity, to be considered simultaneously[8] (see Supplementary Discussion). Last, managing water resources in higher-yielding landscapes will require a focus on improving water use efficiency in crops alongside careful spatial planning of spared land.

Land sparing would have far reaching implications for the UK countryside and would affect landowners, rural communities, ecosystem services and biodiversity. Our projections in Fig. 1 would result in UK forest cover increasing from 12% to reach 30% by 2050 – close to that of Germany and France but still less than the European average[26] – and the restoration of up to 0.7 Mha of wet peatland (Supplementary Table 3). Such large-scale restoration is likely to benefit ecosystem service provision, including water purification, recreation and flood mitigation[18,27]. Land sparing has the potential to be beneficial for biodiversity, including for many species of conservation concern[6,27,28], but benefits will depend strongly on the use of spared land. In addition, high yield farming involves trade-offs and is likely to be detrimental for wild species associated with farmland. Careful implementation – by retaining seminatural pastures of high conservation value, for example – will be important to minimise any detrimental impacts. Growing bioenergy crops on spared land (rather than land needed for food production) addresses concerns over indirect land-use change[1], but compared with natural habitats might compromise ecosystem services and biodiversity objectives[29].

Finally, how relevant are our results to other parts of the world? The UK presents a challenging test for the implementation of a land-sparing strategy. Relatively low yield gaps in the UK[30] mean that achieving yield increases into the long term will require continued genetic advances. This is compounded by relatively high projected demand growth in the UK driven by a projected population increase of 26% over the forecast period (Supplementary Table 1). In contrast, in many global regions, yield gaps are quite large[30] compared with projected growth in agricultural demand[5] (Supplementary Fig. 3). Clearly the technical and economic feasibility would need to be assessed in each location, but our findings suggest that land sparing may be a promising strategy for reducing greenhouse gas emissions from agriculture and land-use change in several parts of the world besides the UK.

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Author contributions A.B., A.L. and R.G. conceived the study. A.L. conducted the analysis and prepared the manuscript. A.H., D.K., E.W., K.G., P.C., P.S. and R.F supplied data. All authors contributed in the writing and editing of the manuscript.

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Table legends

Table 1: Scenarios of yield and feed conversion ratio

Commodity	Yield (t ha^{-1} yr^{-1}) or FCR (MJ kg^{-1}) 2010	2050 Lower-bound	2050 Upper-bound	Average rate of change 2010-2050 (% yr^{-1}) Lower-bound	Upper-bound†
Cereals	7.0	6.5	13.0	-0.2%	1.6%
Oilseeds	3.5	3.5	6.8	0.0%	1.7%
Potatoes	43.7	43.7	74.0	0.0%	1.3%
Sugar beet	68.0	68.0	113.0	0.0%	1.3%
Fruit and vegetables	20.0	20.0	30.0	0.0%	1.0%
Forage maize	8.1	7.1	10.7	-0.3%	0.7%
Forage legumes	3.7	3.7	6.0	0.0%	1.2%
Other forage crops	7.6	7.6	12.3	0.0%	1.2%
Temporary grass*	1.0	1.0	1.8	0.0%	1.5%
Permanent grass*	1.0	1.0	1.8	0.0%	1.5%
Rough grazing*	1.0	1.0	1.0	0.0%	0.0%
Beef meat	147	147	98	0.0%	-1.0%
Milk	11	11	7	0.0%	-1.0%
Pig meat	38	38	25	0.0%	-1.0%
Sheep meat	214	214	161	0.0%	-0.7%
Poultry meat	33	33	24	0.0%	-0.8%
Eggs	31	31	23	0.0%	-0.8%

Crop yields and livestock feed conversion ratios (FCRs) in 2010 and lower- and upper-bound assumptions in 2050. FCRs apply to animals producing meat, milk or eggs, not the entire herd; a negative change indicates improving feed conversion efficiency. *For modelling purposes, grassland yields are expressed relative to the 2010 yield which was set to a value of 1. †Mean upper-bound yield growth of 1.3% yr^{-1} reported in the text is the average of the figures shown (with FCR growth expressed as a positive quantity), weighted by the energy content of production of each commodity in 2010.

Figure legends

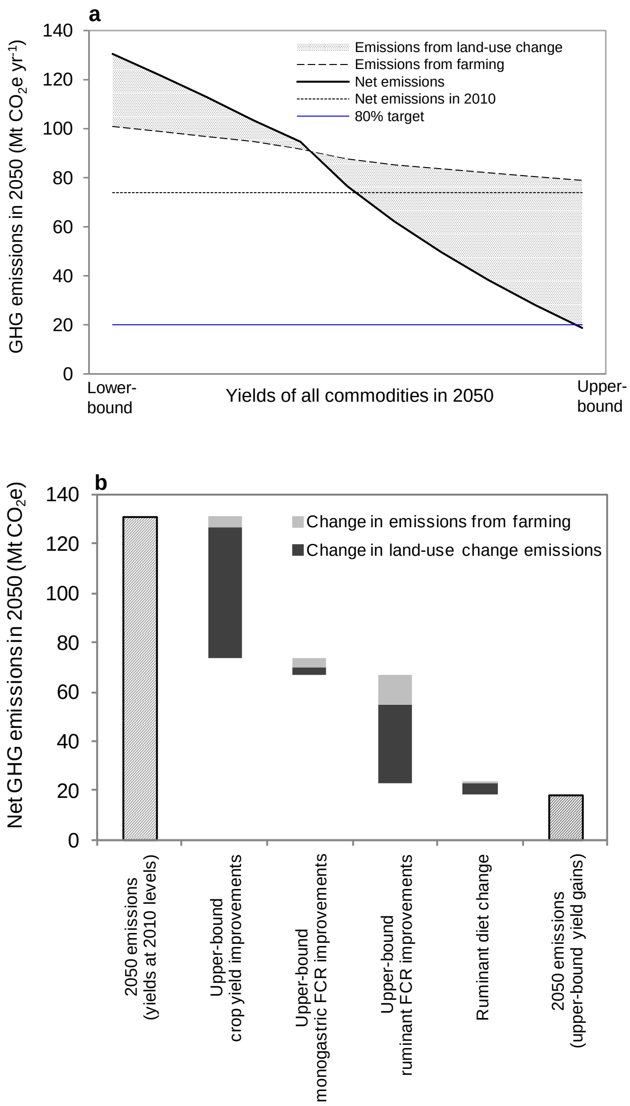


Figure 1. Mitigation of greenhouse gas emissions from agriculture by land sparing. a. Net greenhouse gas (GHG) emissions in 2050 are shown as the sum of emissions from farming and emissions from land-use change (which may be positive or negative). Yields of all commodities in 2050 are scaled linearly between the lower- and upper-bounds shown in Table 1. Emissions representing an 80% reduction relative to baseline net emissions in 1990, and equivalent net emissions in 2010, are shown for reference (20.1 Mt CO_2e yr^{-1} and 73.9 Mt CO_2e yr^{-1} respectively, see Supplementary Table 2). **b**. Contribution of crop yield and

livestock feeding efficiency gains to projected upper-bound mitigation in 2050. Projected net emissions in 2050 with yields, FCRs and ruminant diets at 2010 levels (left-hand bar; see Table 1); the effect of upper-bound assumptions (Table 1) on emissions from farming and land-use change emissions (intermediate bars); and the cumulative effect of all changes, projected net emissions in 2050 under upper-bound yield assumptions (right-hand bar).

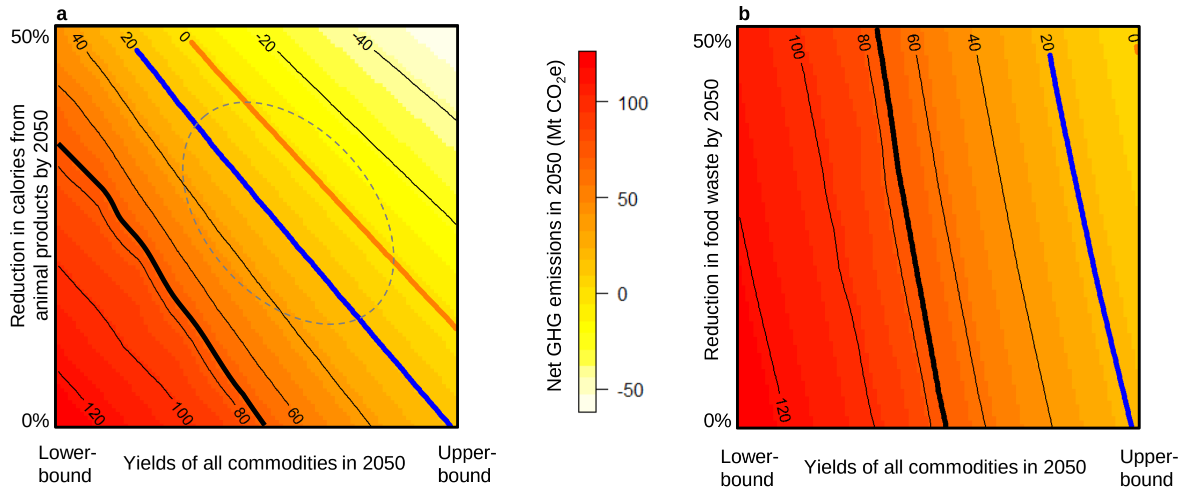


Figure 2: **Greenhouse gas mitigation by coupling land sparing with demand management. a.** Reduction in the consumption of animal products. Shading and contours indicate net greenhouse gas (GHG) emissions in 2050 as a function of the reduction in calories from animal products by 2050 (vertical axis; see Supplementary Methods) and yields in 2050 (horizontal axis; scaled linearly between the lower- and upper-bounds shown in Table 1). Emissions representing an 80% reduction relative to baseline net emissions in 1990 (thick blue contour; 20.1 Mt CO_2e yr^{-1}), equivalent net emissions in 2010 (thick black contour; 73.9 Mt CO_2e yr^{-1}) and zero net emissions (thick orange contour) are also shown for reference. The enclosed dashed region indicates the mitigation potential of coupling moderate reductions in meat consumption with moderate yield increases under land sparing. **b.** Reduction in food waste. As for (a) but the vertical axis represents the reduction in post-harvest food waste by 2050 (see Supplementary Methods).

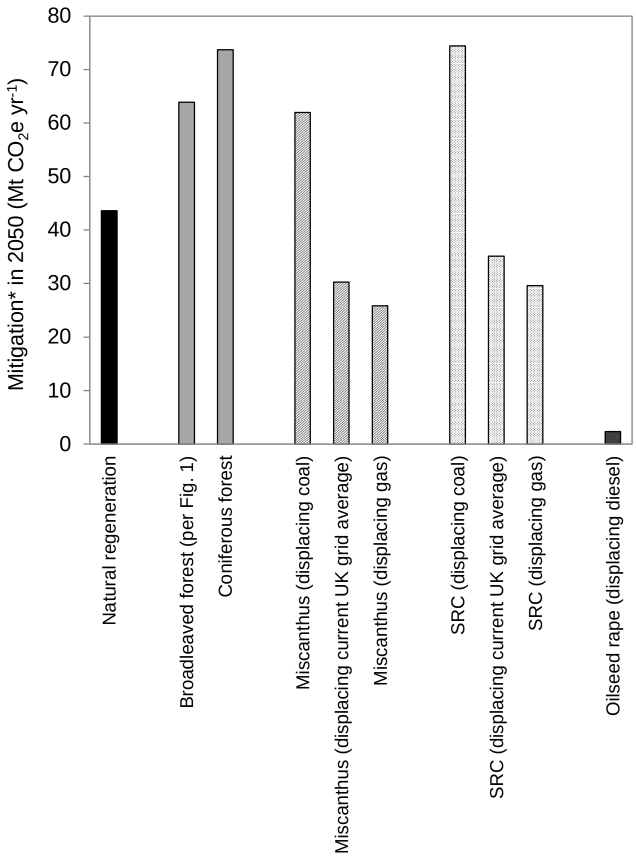


Figure 3: **Upper-bound mitigation potential in 2050 under different uses of spared land.** Results assume upper-bound yield increases and different uses of spared land: natural regeneration; broadleaved woodland (the main scenario presented in Fig. 1); coniferous woodland; and bioenergy crops. *Miscanthus* and short-rotation coppice (SRC) are shown assuming three different fossil fuel displacement pathways: coal, the current UK electricity grid average, and natural gas. *The nature of mitigation is different depending on the use of spared land. Mitigation under natural regeneration and forestry is primarily due to carbon sequestered in the soils and biomass of restored habitats and would normally be reported in the ‘Land use, land-use change and forestry’ sector. For bioenergy crops, the mitigation arises primarily due to avoided emissions from displaced fossil fuels, and would normally be reported in the energy sector.

Supplementary Information

Contains Supplementary Methods, Supplementary Discussion, Supplementary Tables and Supplementary Figures.

Supplementary Methods

Model. Calculations were performed using a spreadsheet model, available for download in the Supplementary Information. The logical structure of the model is illustrated in Supplementary Fig. 4. Each element of the model is described in further detail below.

Future agricultural production. We projected the future production of all major UK crops (grouped as cereals, oilseeds, potatoes, sugar beet, fruit and vegetables, forage maize, forage legumes and other forage crops) and livestock products (beef meat, poultry meat, pig meat, sheep meat, milk and eggs). The production of livestock feed was calculated by our livestock model (see below). For all other production, a baseline was set at the mean of reported production in the three years 2009–2011[31] and centred on 2010. Future production P_t^j of commodity *j* in year *t* was calculated as: $P_t^j = P_{t-1}^j . Pop_t / Pop_{t-1} . D_t^j / D_{t-1}^j$, where Pop_t is the projected UK population in year *t* (ref. 32) and D_t^j is the projected demand per capita for commodity *j* in year *t* for the EU-27 (provided by J. Bruinsma (*pers. comm.*) and consistent with ref. 5). Supplementary Table 1 shows the projected growth in the production of each commodity to 2050 using this approach. To ensure a like-for-like comparison we maintained this level of production (before any demand management) in all of our scenarios.

Changes in yield and feed conversion ratio. We specified a range in future crop yields (expressed in tonnes per hectare per year) and livestock feed conversion ratios (FCR; MJ feed energy required per kilogram of production; production expressed as either kilogram dressed carcase weight, kilogram milk or kilogram eggs as appropriate; see Table 1). For each commodity we specified a lower- and an upper-bound for yield or FCR in 2050. We changed yields and FCRs on a linear basis between 2010 and 2050 (e.g. Supplementary Fig. 1). On the horizontal axis of our results figures, the yields and FCRs of all commodities in 2050 are scaled uniformly and linearly between their respective lower- and upper-bounds. Mathematically, the yield (or FCR) Y_i of the i^{th} commodity in 2050 is varied according to $Y_i = LB_i + k\ (UB_i - LB_i)$, where LB_i and UB_i are the lower- and upper-bounds; and k varies between 0 and 1 and is applied uniformly to all commodities. Specific yield and FCR assumptions are discussed further in the Supplementary Discussion.

Livestock model and livestock feed requirement. We modelled ten feed categories: cereals, forage maize, maize grain, rapeseed meal, forage legumes, other forage crops, concentrates, grass, wheat straw and silage and hay. We modelled livestock reared for meat, milk or egg production (producing animals) differently to those kept for breeding purposes (breeding animals). For producing animals, the required annual tonnage F of each feedstuff i was calculated as $F_i = \sum_j P_j . FCR_j . D_{i,j} . \frac{1}{E_{i,j} . U_i}$, where P_j is the annual tonnage of production of the j^{th} livestock commodity; FCR_j is the feed conversion ratio; $D_{i,j}$ is the proportion (in energy terms) of each feedstuff in the diet; $E_{i,j}$ is the feed energy density relevant to each animal (from refs. 33,34); and U_i is a factor for uneaten and wasted feed (based on refs. 35,36). We established present day diets and feed conversion ratios drawing primarily upon ref. 37 and with reference to the literature and standard agricultural references[33,38–42], and cross-checked these by comparing the total consumption of different feedstuffs predicted by our calculations (Supplementary Table 6) with published UK feed statistics[31,43,44]. For monogastric animals (pigs and poultry), FCR improvements are projected to arise through genetic improvement rather than changes in diet[8,45]. For ruminant livestock, FCR gains from genetic improvement will be accompanied by changes in diets, principally the reduction of grass in favour of more nutritious feeds[8,46]. To quantify diet changes, we looked at the gap (in terms of $D_{i,j}$) between present day average herd diets and the best performing animals in ref. 37. We assumed that herd diets would shift towards those of the best performing animals, closing between 0% (lower-bound yield growth) and 50% (upper-bound yield growth) of the gap by 2050 (see Supplementary Table 6). For breeding animals, we assumed no FCR improvements and no changes in diet, so baseline feed consumed by breeding animals was projected forward in proportion to the production of the relevant livestock commodity.

Area needed for crop and grass production, and area spared. The area of cropland and grassland required to meet our assumed level of future agricultural production was calculated for each crop and grass commodity using the relationship *crop area* = *production* / *yield*; the area of spared land is then the difference between the current area under this crop and its projected future area. We assumed that spared land arising for each crop was spatially distributed in direct proportion to the present land area occupied by that crop in each of 11 UK regions (the NUTS 1 administrative regions[47]; see Supplementary Table 3).

Habitat restoration on spared land. We assumed the establishment of forest or bioenergy crops on spared land arising in all locations except on organic soils, where rewetting – creating fen at low altitudes or bog at high altitudes – prevents further peat oxidation and so maximises greenhouse gas abatement[48]. To implement this, we conducted a GIS analysis using ArcMap 10[(49)]. Working at a 1 km^2 resolution we first extracted the average altitude of each square using ref. 50, and applied a 300 metre threshold to classify squares as either lowland or upland. Next we used the 25 metre resolution CEH UK Land Cover Map 2007[51] (LCM) to aggregate over each 1 km square the areas of arable (LCM class 'Arable and horticulture'), improved grassland (LCM class 'Improved grassland') and rough grazing (LCM classes 'Rough grassland', 'Neutral grassland', 'Calcareous grassland', 'Acid grassland', 'Fen, marsh and swamp', 'Heather' and 'Heather grassland'). Cross-checking against published agricultural land-use data[31] indicated that the LCM misclassified some improved grassland as arable, but correcting for this had negligible impact on our results. So that we could align land cover with soil type we next classified the soil in each square as either 'mineral' or 'organic' by comparing the soil carbon density to 1 metre depth at each location[52] with country- and habitat-specific thresholds (published in the UK inventory[53] and based on refs. 52,54,55) and using the published value for organo-mineral soils as a threshold to delineate organic and mineral soils. Finally we summarised across the UK's 11 NUTS 1 administrative regions, computing for each of existing arable, improved grass and rough grazing land, the proportion suitable for forest (or bioenergy crops), fen or bog creation. Spared land arising in each region under a given scenario was then allocated in accordance with these proportions (Supplementary Table 3). This approach predicted a greater area of lowland peatland available for restoration than the 150,000 ha reported in the UK inventory[12] so we modified our restoration assumptions in this regard to reflect the reported figure (see below).

Greenhouse gas emissions attributable to agriculture.

Emissions reported in the following section are in general reported under agriculture in the UK inventory[12], however we also report certain emissions that are attributable to agriculture but reported in other sectors, and in certain cases we have re-allocated emissions between the agriculture sector and the 'land use, land-use change and forestry' (LULUCF) sector to improve clarity. Baseline emissions were set at the mean of reported emissions in the three years 2009-2011 and centred on 2010 (see Supplementary Table 2). Emissions reported in the UK inventory were projected forward using emissions factors from the inventory and functional relationships drawn from standard IPCC guidelines[13,56]. All emissions factors and other key parameters are reported in Supplementary Table 4.

Enteric fermentation methane emissions were varied in proportion to the gross energy content of feed consumed by livestock (ref. 13, vol. 4, equation 10.21).

Manure management methane $CH_{4MM,T}$ for each livestock class T was projected forward from baseline values using two relationships from ref. 13 (vol.4, equations 10.23 and 10.24): $CH_{4MM,T} = 0.67.VS_T.B_{o(T)}.\sum_S MS_{T,S}.MCF_S$ and $VS_T \propto ME_T$, where VS_T is the volatile solids excreted; $B_{o(T)}$ is the methane producing capacity of manure; ME_T is the metabolisable energy content of feed (obtained from our livestock model); $MS_{T,S}$ is the proportion of waste handled in each of five manure management systems S (obtained from ref. 12 and for ruminants adjusted over time reflecting our diet assumptions); and MCF_S are methane conversion factors (obtained from ref. 12 and held constant).

Manure management nitrous oxide N_2O_{MM} for each livestock class T was quantified according to ref. 13 (vol.4, equation 10.25) as $N_2O_{MM,T} \propto \sum_S Nex_T.MS_{T,S}.EF_{3,S}$, where Nex_T is the quantity of nitrogen excreted (assumed proportional to protein consumed in feed[13], obtained from our livestock model); $MS_{T,S}$ is as defined above; and $EF_{3,S}$ are emissions factors (obtained from ref. 12 and held constant).

Nitrous oxide from synthetic fertilisers N_2O_{SN} was quantified as a function of the tonnage of nitrogen in fertiliser applied per hectare R_i to each crop i; the area A_i of each crop; and an emissions factor EF_1 (ref. 13, vol.4, equation 11.1): $N_2O_{SN} = \sum_i R_i.A_i.EF_1$. R_i values were obtained from ref. 12 and were adjusted in future years in proportion to changes in yield. A_i was calculated as outlined above and EF_1 was obtained from ref. 12 and held constant.

Emissions from *animal manure applied to soils* N_2O_{OS} for each livestock class T were quantified according to ref. 13 (vol.4, equation 11.1) as: $N_2O_{OS} = \sum_S Nex_T.MS_{T,S}.EF_1$, where Nex_T and $MS_{T,S}$ are defined as above (with Nex_T is adjusted to exclude a small quantity of chicken waste incinerated[12]) and EF_1 is an emissions factor (obtained from ref. 12 and held constant).

Other direct soil emissions comprises emissions from nitrogen fixing crops and crop residues returned to soils which were obtained from ref. 12 and varied in in proportion to the total tonnage of crop production.

Atmospheric deposition emissions N_2O_{ATD} were quantified according to ref. 13 (vol.4, equation 11.9) as $N_2O_{ATD} = (F_{SN}.Frac_{GASF} + (F_{ON} + F_{PRP})\ .Frac_{GASM}).EF_4$, where F_{SN} is the tonnage of synthetic nitrogen applied to soils, of which $Frac_{GASF}$ is the fraction that volatilises; F_{ON} and F_{PRP} quantify nitrogen applied to soils from animal manures (calculated as above and adjusted to exclude a quantity of chicken waste incinerated) and sewage sludge (obtained from ref. 12 and increased in line with UK population growth), of which $Frac_{GASM}$ is the fraction that volatilises; and EF_4 is an emissions factor. F_{PRP}, $Frac_{GASF}$, $Frac_{GASM}$ and EF_4 were each obtained from ref. 12 and held constant.

Nitrogen runoff and leaching N_L follows a similar relationship (ref. 13, vol.4, equation 11.10): $N_L = (F_{SN} + F_{ON} + F_{PRP}).Frac_{LEACH}.EF_5$, where the definitions and approach follow directly from above.

Other indirect soil emissions comprises three sources of emissions. Emissions from nitrogen fixed by improved grassland were obtained from ref. 12 and were varied in proportion to the total area of improved grassland. Emissions from sewage sludge applied to soils and from overseas dependencies and crown territories were obtained from ref. 12 and increased in proportion to UK population growth.

The remainder of this section reports emissions that are attributable to agriculture but reported in other sectors or omitted from the UK inventory altogether. Emissions from *farm* *energy use* are reported under 'stationary and mobile combustion' in the energy sector (ref. 57) and were varied in proportion to the total tonnage of crop and livestock production.

For *imported livestock feed* we quantified emissions associated with farming, land-use change, processing and transporting feed by first establishing the quantity and composition of feedstuffs imported to the UK[43,44] and then reviewing the literature for applicable emissions factors, adopting conservative values where ranges were presented. The proportion that each component contributes to the total mass imported to the UK was obtained from ref. [43] for the year 2010 and was used to calculate a weighted average emissions factor of 1.54 kg CO_2e kg feed^{-1} (Supplementary Table 6). Our figure is conservative relative to values elsewhere in the literature[37,40,41], but our overall result is largely insensitive to variation in this parameter (Supplementary Fig. 2). We separately specified emissions factors for imported maize grain (0.66 kg CO_2e kg feed^{-1}; refs. 37,58) and for co- and bi-products fed to livestock (0.05 kg CO_2e kg feed^{-1}; ref. 37).

For emissions from the *manufacture of synthetic fertiliser* we used an emissions factor of 6.2 kg CO_2e kg N^{-1} [(59)] declining to 3.5 kg CO_2e kg N^{-1} by 2050 in all scenarios reflecting the ongoing uptake of nitrous oxide abatement technology in nitric acid manufacturing plants across the UK and Europe[60]. This reduction has only a small impact on our results and we show this in our sensitivity analysis (Supplementary Table 4; Supplementary Fig. 2).

Emissions from *machinery manufacture and maintenance* were quantified as a fixed 35% of emissions from farm energy use. This ratio was obtained from ref. 37 as the area weighted average across six major cropping systems.

Emissions from *pesticide manufacture and breakdown* were obtained from refs. 61 and 57 respectively and were varied in proportion to the total area under crop production in the UK.

Emissions from the *liming of agricultural fields* (reported in the LULUCF inventory[12]) were varied in proportion to the total tonnage of crop production.

Greenhouse gas emissions associated with land use and land-use change.

Emissions reported in the following section are in general reported under 'land use, land-use change and forestry' (LULUCF) in the UK inventory although in certain instances we have re-allocated emissions between LULUCF and agriculture to improve clarity.

Emissions from drained fen. These comprise several sources of emissions reported in different sections of the UK inventory or not reported at all. Emissions of nitrous oxide are reported under 'cultivation of histosols' in the agriculture section of the UK inventory[12].We used the figure from the inventory but updated the emissions factor based on recent IPCC guidelines[56]. Carbon dioxide emissions were obtained from the 'lowland drainage' category in the LULUCF inventory[12]. In addition we used IPCC tier 1 emissions factors[56] to quantify emission of dissolved organic carbon and methane. The area of drained fen under cultivation was set initially at 150,000 ha, the area reported in the UK inventory[12], and then reduced in accordance with our peatland restoration assumptions outlined below.

Emissions from drained bog. We obtained emissions factors for carbon dioxide from applicable UK studies[62–65] and used IPCC tier 1 emissions factors[56] for dissolved organic carbon, methane and nitrous oxide. We assumed an initial applicable area of 911,000 hectares (based on ref. 62), reducing it in accordance with our peatland restoration assumptions outlined below.

Conversion between grassland and arable. Under certain combinations of yield growth and demand management there is a need to convert grassland to cropland to meet shifting demand patterns. To quantify land conversion emissions we assumed an immediate loss of 10% of topsoil carbon on ploughing[66], a step change in biomass carbon, and a longer term asymptotic decay in soil carbon (assuming mineral soils in all cases) using the methodology of the UK inventory[12.] This models changes in soil carbon over time according to $C_t = C_f - (C_f - C_0).e^{-t/\tau}$, where C_t is the soil carbon density in year *t*; C_0 and C_f are the soil carbon densities of the initial and final land use, respectively; and τ is a time constant (Supplementary Table 7 contains the values assumed for these parameters broken down by country and land cover). We quantified nitrous oxide emissions using an emissions factor of 0.22 kg N_2O-N ha^{-1} yr^{-1} (ref. 12).

Greenhouse gas fluxes in forest biomass on spared land. We started with regional estimates of forest yield class (a standard metric of volume growth rate) for 21 common broadleaved and coniferous tree species derived from a spatially explicit study of species' suitability under local climatic and soil conditions[67,68]. We then cross-referenced these data with standard carbon accumulation curves for UK tree growth used in the UK inventory[12] (discussed also in refs. 69,70 and available at ref. 71) to identify the species with the highest carbon sequestration potential in each region (Supplementary Table 3). Data were not available for Northern Ireland so we used the values for the North East region which is closest in latitude. Carbon accumulation curves quantify the carbon density (t C ha^{-1}) in forest biomass as a function of time since planting; a different standard curve exists for each species and yield class combination. We projected total carbon stored in forest biomass C_t in calendar year *t* using: $C_t = \sum_R \sum_{t^*=1}^{t} CD_{t^*}^R . A_{t-t^*}^R$, where, for each of 11 regions R, $CD_{t^*}^R$ is the carbon density predicted by the applicable carbon accumulation curve t* years since planting; and $A_{t-t^*}^R$ is the area of new forest established in region *R* in the calendar year *t* - *t**. This approach aligns carbon sequestration curves (which are S-shaped curves specified on a years-since-planting basis) with the applicable areas of afforested spared land arising in each calendar year between 2010 and year *t*. In addition, we assumed an immediate loss of crop or grass biomass from the prior land use.

We sense-checked our results by running a sensitivity using the UK average yield class assumptions reported in the UK inventory[12] and found good agreement (Supplementary Fig. 2). We assumed that, once established, forest would be left as a carbon sink, without any ongoing management, though we acknowledge that management to extract wood products and fuel-wood can potentially enhance the carbon sink (ref. 23 but see also ref. 72).

Greenhouse gas fluxes in forest soils. On former grassland we assumed an immediate loss of 2% of topsoil carbon caused by ground disturbance[66] and no long-term soil carbon gains[73,74]. On former cropland we modelled soil carbon gains using $C_t = C_f - \left(C_f - C_0\right). e^{-t/\tau}$, where C_t is the soil carbon density in year *t*; C_0 and C_f are the soil carbon densities of the initial and final land use, respectively; and τ is a time constant[12] (Supplementary Table 7). Consistent with UK forestry guidelines and the UK inventory we assumed no use of nitrogen fertilisers on forest land[12]; high rates of nitrogen deposition in the UK make this unnecessary[23].

Site preparation and natural disturbance in forest. We included emissions associated with seedling production, fencing, tree shelters, ground preparation and herbicide use[70], in total amounting to around 3 t CO_2e ha^{-1}. We adopted European average rates of natural disturbance, assuming that 0.15% of timber volume was damaged each year (increasing by 40% by 2050[75]) and as an approximation quantified all emissions (from loss through fire, windstorm, pests and diseases) using IPCC tier 1 emissions factors for forest fires[13].

In aggregate, these assumptions result in a mean annual rate of carbon sequestration in the soils and biomass of forests across the 40 years of our projections of 2.5 t C ha^{-1} yr^{-1} and a rate in 2050 of 4.1 t C ha^{-1} yr^{-1} (Supplementary Figure 5). Average rates for British forests cited in the literature include 2.7 t C ha^{-1} yr^{-1} (ref. 70), 3.5 t C ha^{-1} yr^{-1} (ref 76), 2.7 t C ha^{-1} yr-

^{1} (ref. 77) and 3.8 t C ha^{-1} yr^{-1} (ref. 23). Maximum sequestration rates in fast growing British forests are reported anywhere from 6 t C ha^{-1} yr^{-1} to as high as 10 t C ha^{-1} yr^{-1} (refs. 70,76,78).

Greenhouse gas fluxes in re-wetted fen and bog. We quantified four greenhouse gas fluxes: carbon dioxide, dissolved organic carbon, methane and nitrous oxide, using UK specific values where available, supplemented by IPCC tier 1 emissions factors[56] (Supplementary Table 4). We assumed an additional 'spike' in methane emissions in the ten years following re-wetting (based on refs. 48,79) but otherwise assumed an immediate transition from drained to restored state. We assumed one-off greenhouse gas emissions of 2.5 t CO_2e ha^{-1} associated with fencing, drain-blocking and vegetation management, using estimates for comparable activities from the forestry sector[70]. We assumed low density grazing (0.1 livestock units ha^{-1}) by ponies and sheep to manage vegetation succession, and quantified emissions using IPCC tier 1[(13)] and UK inventory[12] emissions factors. Under certain scenarios, the area of lowland peatland available for restoration exceeded the 150,000 ha reported in the UK inventory; we conservatively capped the area restored at 150,000 ha and assumed nil greenhouse gas abatement on any additional spared lowland peatland (though this is likely to understate the mitigation achievable). In aggregate, these assumptions result in long-term abatement (the reduction in emissions in the re-wetted state versus the drained state) of around 4 t CO_2e yr^{-1} for each hectare of peatland restored.

LULUCF emissions unaffected by scenarios. Certain LULCF emissions associated with non-farmland habitats (pre-existing forest land, wetlands and settlements) are unaffected by our land-sparing scenarios. We obtained an estimate of these emissions in 2050 (3.6 Mt CO_2e) from the business as usual scenario in ref. (80) and include this estimate in our projections.

Baseline emissions in 1990. We quantified emissions in 1990 on an equivalent basis to the above to facilitate comparison with 2050 projections (Supplementary Table 2). Where reported, we obtained 1990 values directly from the UK inventory[12,57]. Remaining emissions were quantified using the methods above but making the following additional assumptions: for imported feed we performed a linear extrapolation using reported feed consumption data (available from 1997 to present[43]) backwards to 1990; for pesticide manufacture and breakdown we scaled emissions from manufacture in proportion to those from pesticide breakdown (available in the inventory); for emissions from drained fen we scaled emissions from dissolved organic carbon and methane in proportion to emissions of carbon dioxide (available in the inventory); and for emissions from drained bog we assumed that emissions in 1990 were equal to those in 2010.

Emissions from food imports. In scenarios with yield growth close to the lower-bound assumption, UK production growth did not keep pace with projected demand growth. In these cases we assumed an increase in imports to the UK and quantified the greenhouse gas emissions arising overseas due to these additional imports. This ensured that all of our scenarios quantified the emissions associated with the same quantity of agricultural production (before any demand management). This approach reflects the fact that reducing UK production and increasing imports will reduce UK emissions but will lead to an increase in emissions overseas. We used life-cycle emissions factors to quantify emissions associated with farming, farming inputs, transport to the UK, and (separately) land-use change, based on ref. 81 and cross-checked against refs. 82–85. Emissions due to land-use change in these studies can vary by an order of magnitude depending on whether land-use change emissions are allocated entirely to production on the converted land or are averaged over production on all land[83]. So that our results in the main text (Figs. 1 and 2) do not overstate the potential mitigation benefits of land sparing (which can reduce the need for food imports) we adopted conservative (low) emissions factors for overseas land-use change using ref. 81 (see Supplementary Table 8). This approach implicitly assumes that global market linkages and displacement effects mean that the total (rather than incremental) demand for a product determines its contribution to global land-use change[83]. Higher overseas emissions estimates would be obtained if we instead calculated overseas land-use change assuming that UK food imports were directly allocated an incremental share of overseas land-use change[83].

Reduced consumption of animal products. We based the upper-bound of our analysis on a dietary scenario assessed by the UK Committee on Climate Change (described in ref. 86). The diet involves a 64% reduction in beef, poultry, pig and sheep meat consumption, a 40% reduction in egg and dairy consumption and a 30% reduction in sugar consumption, offset by a 40% increase in cereal, vegetable oil and potato consumption and a 60% increase in the consumption of pulses, fruit and vegetables. The replacement diet is similar to present day diets in energy terms, but calories derived from animal products are halved and it is up to 14% lower in protein (though protein levels still comfortably exceed World Health Organization guidelines[87]). The diet was assessed as nutritionally viable in ref. 86, is consistent with healthy diets published elsewhere and is likely to provide a number of human health co-benefits[16,88–90]. We treated this diet as an upper-bound for the shift in diet that might plausibly be achieved by 2050 and then assessed the effect of diets shifting anywhere between nil and that upper-bound. We assumed that the diet shift would be phased in by a linear change between 2010 and 2050. The results in the main text assume that this scenario is implemented with broadleaved forest established on spared mineral soils and wet peatland on spared organic soils.

Reduced food waste. We first reviewed the literature for food waste estimates applicable to the UK[91–94]. Based on this we adopted the following values for the current proportion of human-edible food that is wasted in the post-harvest food supply chain: cereals (33%), oilseeds (11%), potatoes (40%), sugar beet (29%), fruit and vegetables (32%), beef, poultry, pig and sheep meat (19%), milk (9%) and eggs (25%). Following other studies[14,95,96], we adopted a 50% reduction in food waste as a reasonable upper-bound and then assessed the effect of reductions by 2050 of anywhere between nil and that upper-bound. We assumed that this was phased in by a linear change between 2010 and 2050, and adjusted production levels to maintain constant levels of post-waste food production. The results in the main text assume that this scenario is implemented with broadleaved forest established on spared mineral soils and wet peatland on spared organic soils.

Natural regeneration scenario. The natural regeneration scenario assumed that following the cessation of farming, a succession trajectory led to the establishment of a shrub / herb layer followed by secondary succession to woodland, the climax vegetation in the UK. We assumed a 16 year delay before the establishment of woody species based on observations in the UK and Europe[97–99] and reflecting the lag in seedling recruitment associated with wind-blown seeds of pioneer species[100]. We assumed the colonisation of broadleaved species everywhere in the UK with the exception of upland Scotland where we assumed colonisation by Scots Pine. During the shrub phase we assumed that carbon in biomass would increase to a maximum of 10 t C ha^{-1} based on data from UK and European shrublands (refs. 55,101,102). To model tree succession after 16 years we assumed the establishment of slow growing mixed broadleaved species representative of those found on abandoned UK farmland[100], which we modelled as sycamore-ash-birch of yield class 4; and in upland Scotland we modelled Scots Pine, also of yield class 4. The low yield class reflects observations in the UK[23,97,100] and Europe[98,103] that secondary succession results in lower biomass accumulation rates compared with managed forestry.

We assumed that soil carbon changes following natural regeneration on mineral soils would be the same as those assumed under managed forestry (except that we assumed no active ground preparation and no related loss of soil carbon). For soil emissions from natural regeneration on organic soils, we used emissions factors applicable to forestland on drained organic soils. For carbon dioxide emissions applicable to lowland organic soils, we assumed a value of 2.32 t CO_2e ha^{-1} yr^{-1}, reflecting reduced soil disturbance due to the cessation of ploughing and gradual afforestation of former arable land[36,95,112,113]. In upland areas we retained the emissions factor of 1.80 t CO_2e ha^{-1} yr^{-1} assumed for drained bog, assuming the soil disturbance regime would be unchanged following natural regeneration. We used IPCC tier 1 emissions factors[56] applicable to forestland on drained organic soils for dissolved organic carbon (1.14 t CO_2e ha^{-1} yr^{-1}), methane (0.28 t CO_2e ha^{-1} yr^{-1}) and nitrous oxide (1.36 t CO_2e ha^{-1} yr^{-1}).

In aggregate, these assumptions result in an annual rate of carbon sequestration in soils and biomass under natural regeneration of 0.6 t C ha^{-1} yr^{-1} during the shrub phase (a rate comparable with figures published elsewhere (refs. 70,106–108)) increasing to 2.4 t C ha^{-1} yr^{-1} by 2050 as woodland gradually becomes established (Supplementary Figure 5).

Bioenergy scenarios. We quantified both the emissions avoided due to the displacement of fossil fuels by bioenergy, and the emissions associated with growing, transporting and processing the bioenergy crops. To calculate avoided fossil fuel emissions we first calculated the energy content of biomass production as the product of biomass yield, energy density and crop area. We assumed a biomass yield for oilseed rape as in Table 1, and obtained regional yield estimates for *Miscanthus* and short-rotation coppice poplar from ref. 109. We used energy densities (all parameters quoted on a lower heating value basis) of 18.0 MJ kg^{-1} (*Miscanthus*), 18.5 MJ kg^{-1} (short-rotation coppice) and 37.2 MJ l^{-1} (oilseed rape; with a feedstock conversion yield of 364 l t^{-1})[59,110]. We assumed power plant combustion efficiencies of 35% for biomass, 45% for coal and 58%[(59)] for natural gas. In all cases these efficiencies represent modern, high efficiency plants (in the case of biomass plants assuming large plant sizes and the drying of biomass feedstock using flue gases; see ref. 111). We assumed that the electrical energy produced by combusting biomass would displace fossil fuels of a quantity that would yield the equivalent electrical energy. We calculated avoided emissions using carbon intensities of 89 g CO_2e MJ fuel^{-1} for diesel (displaced by oilseed rape); and 110 g CO_2e MJ fuel^{-1} for coal[59], 65 g CO_2e MJ fuel^{-1} for natural gas[59] and 128 g CO_2e MJ elec^{-1} for the UK electricity grid average[112] (displaced by *Miscanthus* and short-rotation coppice). These figures include lifecycle emissions from extracting, transporting, refining and combusting fuel. We similarly obtained lifecycle carbon intensities accounting for farming, farm inputs, drying, transporting, processing and converting biomass feedstock for *Miscanthus* (5.5 g CO_2e MJ fuel^{-1}; ref 112), short-rotation coppice (8.9 g CO_2e MJ fuel^{-1}; ref 112) and oilseed rape (53 g CO_2e MJ fuel^{-1}; ref 59). We quantified emissions of methane and nitrous oxide from biomass combustion (because unlike carbon dioxide these are not reabsorbed during biomass regrowth) using emissions factors of 1.9 g CO_2e MJ fuel^{-1} (*Miscanthus* and short-rotation coppice biomass[13]) and 0.25 g CO_2e MJ fuel^{-1} (biodiesel[13]). In all cases we cross-checked our parameter values against ranges in the literature (e.g. refs. 29,110,113). We quantified the increase in carbon stored in biomass, averaged across a harvest cycle, relative to former arable or grassland. Finally, we quantified changes in soil carbon from land conversion for each bioenergy crop based on the methodology in the UK inventory[12] and treating oilseed rape as cropland and *Miscanthus* and short-rotation coppice as grassland for soil carbon purposes[114]. Soil carbon changes were modelled as $C_t = C_f - \left(C_f - C_0\right). e^{-t/\tau}$, where C_t is the soil carbon density in year *t*; C_0 and C_f are the soil carbon densities of the initial and final land use, respectively; and τ is a time constant[12] (Supplementary Table 7). This resulted in long term soil carbon losses if spared grassland was planted with oilseed rape, and soil carbon gains if spared cropland was planted with *Miscanthus* or short-rotation coppice. In addition, on former grassland we assumed an immediate loss of 2% of topsoil carbon due to soil disturbance on crop establishment[66].

Technical potential for land sparing in other regions. We compiled data on projected demand growth and the existing scope for yield growth (indicated by current yield gaps) in different regions (Supplementary Fig. 3). If yield growth outstrips demand growth, future demand could in principle be met from a smaller farmland area and therefore land sparing might be possible. We quantified demand growth in different global regions across all commodities to 2050, obtained from ref. 5 for all regions except the UK, which uses per-capita demand projections for the EU-27 underlying ref. 5 obtained from J. Bruinsma (*pers. comm.*) and UK population projections[32]. We used data on yield gaps (the percentage by which present day realised yields are below those attainable in a given region) from ref. 30 as a comparative indicator of the potential for future yield growth across different regions. We calculated the percentage increase in yield that would result from closing entirely the present day yield gap (as *yield gap* / (1 – *yield gap*)) for nine major crops (rice, maize, wheat, barley, cassava, potato, soybean, sugar cane and sugar beet) and weighted by the energy value of crop production in each region. Yield gaps reflect yield increases that might be achievable through improved farm management but not through genetic improvement, so understate growth potential, but nonetheless provide a like-for-like comparison across regions.

Sensitivity to key parameters. We quantified the sensitivity of our overall result to uncertainty in key parameters and assumptions. We first established the uncertainty in each key parameter using 95% confidence intervals where available (Supplementary Table 4). Next, we re-calculated net emissions in 2050 by varying each parameter in sequence and non-cumulatively to the upper-and lower-bound of its uncertainty range. Results are presented in Supplementary Fig. 2.

Supplementary Discussion

Yield growth in crops. Rates of yield growth in key crops have declined in recent years to the extent that UK cereal yields have plateaued (Supplementary Fig. 1). There are two main hypotheses put forward to explain the declines. Firstly, it is argued that yields in the UK (and in other industrial countries) are approaching a biophysical yield 'ceiling', whereby the capacity of crops to assimilate sunlight, water and nutrients into useful biomass has reached a physiological limit[9,115,116]. Under this hypothesis, future yields will be constrained by this ceiling and yield growth will ultimately decline to zero. In addition, climate change might constrain future yield growth or may even cause yield declines by altering temperature, rainfall and nutrient cycles[15].

The alternative hypothesis proposes that various other, controllable, factors are responsible for the declines. In particular, it is suggested that low commodity prices have reduced the incentive to invest in yield growth and have led to declining investment in research and development, farmer education, farm labour and farm capital investment[9–11]. In addition, the regulatory environment in the European Union has in recent decades balanced the pursuit of productivity gains with environmental and other objectives[9,117–121]. Finally, a number of aspects of present day agricultural practice may be contributing to declining yield growth. These are numerous and crop-specific but include, for example, declines in fertiliser application rates, sub-optimal crop rotations and declines in effective crop protection[117,122,123].

Consistent with this alternative hypothesis, crop technologists argue that there is considerable technical scope to further increase crop yields[124,125]. Principle opportunities include optimising crop nutrition and crop protection, improving mechanised operations and breeding for improved use of sunlight, water and nutrients or for increased useful biomass in the plant[121,122,124,126–128] (Supplementary Table 5). This hypothesis gains support in the fact that the yields in official crop variety trials have not plateaued[117,122–124,126], despite the decline in yield growth on-farm. Further, calculations of the physiological yield potential of key crops produce estimates substantially higher than current yields[121,122,124,126].

Our yield projections reflect both of these broad hypotheses. The lower-bound of our yield range reflects an outcome in which future yields are limited by a biophysical ceiling, by climate change or by regulatory, market or other controllable factors that remain unfavourable for yield growth. For cereals (occupying around 70% of UK arable land), we assume that the plateau in yields in recent years could transition into a decline in yields from 7.0 to 6.5 t ha^{-1} yr^{-1}. We similarly allow for a decline in forage maize yields. For remaining arable crops we assumed nil yield growth at the lower-bound of our projections, though these crops have not exhibited signs of a plateau to-date (Supplementary Fig. 1).

The upper-bound of our yield range reflects the view that biophysical yield ceilings are in fact substantially higher than present day yields[121,122,124,126] and will not limit yield growth in the foreseeable future. It also reflects an outcome in which any detrimental effects of climate change on yields are small (or even positive, as might be the case in the UK[18,125,129,130]) and are mitigated through adaption measures[15]. In parallel it is assumed that market conditions and regulatory and policy settings provide incentives for yield growth, that research and development programs are well-funded and that agricultural practices are optimised. Yields can respond strongly and positively under such conditions, as evidenced by the role of breeding programs in historic yield gains[123], the demonstrated link between yields and commodity prices[131], the substantial return on investment in agricultural research and development[10] and the importance of agricultural policy settings in determining yield growth[118]. To determine the yield growth that might plausibly be achievable under these conditions we referred to yield projections by agricultural technologists, studies of biophysical yield potentials and the current rates of yield growth in official variety trials. We also referred to historic rates of yield growth and ensured that our projections did not exceed the highest rates observed historically (Supplementary Fig. 1).

At the upper-bound of our projections, for cereals, a yield of 13 t ha^{-1} yr^{-1} was assumed based on refs. 125,126, well within an estimated biophysical potential of 17.4 t ha^{-1} yr^{-1} (ref. 126). For oilseeds, the upper-bound of 6.8 t ha^{-1} yr^{-1} is based on ref. 122 and is well within an estimated biophysical potential of 9.2 t ha^{-1} yr^{-1} (ref. 122). For potatoes, the upper-bound of 74 t ha^{-1} yr^{-1} is consistent with growth projections in ref. 125, is more conservative than projections in ref. 124 and is well within an estimated biophysical yield potential of 145 t ha^{-1} yr^{-1} (ref. 132). For sugar beet, the upper-bound of 113 t ha^{-1} yr^{-1} is conservative relative to ref. 124 but was adopted to maintain yield growth rates within observed historic rates. Relatively little is published on the future yield potential of fruit and vegetables. Our upper-bound assumes a 50% increase in yields by 2050, but as a relatively minor crop (3% of UK arable land), results are insensitive to this assumption. For forage maize, the upper-bound assumption of a 33% increase in yields by 2050 is conservative relative to refs. 124,125 but was chosen so that future yield growth does not exceed observed historic yield growth. For forage legumes, the upper-bound of 6.0 t ha^{-1} yr^{-1} equates to a 63% increase by 2050 which is more conservative than estimates in ref. 124 and is well within estimated biophysical potentials of 8.9 t ha^{-1} yr^{-1} and 10 t ha^{-1} yr^{-1} for spring-sown combining peas and winter-sown field beans respectively[133]. For temporary and permanent grass, the upper-bound of 1.5% yr^{-1} reflects both yield improvements[134] and increases in pasture utilisation (the proportion of edible biomass actually consumed[34]). The scope for yield improvements on rough grazing land is limited by topography, soil and climatic factors and consequently no yield improvements are assumed.

Yield growth in livestock. For livestock, the lower- and upper-bounds of yield growth were defined based on the same principles as those for crops. The lower-bound assumes no future growth in yields, reflecting an outcome in which biophysical limits and/or regulatory, market or other factors constrain yield growth. Our upper-bound livestock productivity gains assume that technological advancements lead to continued genetic gains through breeding, coupled with improved livestock health and nutrition. These gains might be untenable in practice on economic, animal welfare or technical grounds and we note that other studies predict much lower future livestock productivity growth in Europe[38,135].

Beef cattle and sheep. Improvements in FCR can arise through both genetic gain and through changes in diet. Rates of genetic gain in beef cattle and sheep have lagged those in monogastrics due to difficulty in measuring the traits of interest and in targeting selection programs[136]. As a result there is significant untapped genetic potential in the beef cattle population. This is reflected in the considerable variation in FCR among cattle breeds[137] and among individuals of the same breed[138]. Consequently there is significant scope to increase beef cattle FCR through genetic improvement[137]. This is confirmed by recent breeding programs that report improvements in FCRs in beef cattle of between 7% and 25% after just one generation of selection[139]. In the past these selection methods have proved impractical for the beef and sheep industry (due to cost and the difficulty in measuring feed intake). However, recent advancements in molecular genetics have reduced costs by making available cheaper indirect biochemical or DNA markers for feed efficiency[139]. These tools are already increasing the rates of genetic gain in dairy cattle[140] and are similarly expected to accelerate the rate of genetic gain in beef cattle[141,142].

In ruminant livestock there is also significant scope to improve FCR by changing the diet of the animals. In the UK, beef cattle finished on a mainly cereal-based diet exhibit FCRs around 50% lower (dry matter basis; 30% lower on an energy basis) than animals finished on a mainly grass-based diet[143]. In UK sheep meat production, the difference is around 45%[(144)]. Similar FCR differences due to diet are reported in beef cattle in the United States[142].

Kerley et al. (2012) (ref. 138) concluded that the combination of genetic selection and improved nutrition have the theoretical potential to improve beef cattle feeding efficiencies by 50% or more, though there is considerable uncertainty attached to this upper-bound estimate. Basarab et al. 2013 (ref. 145) estimated that future improvements in FCR of -0.75% yr^{-1} to -1.0% yr^{-1} are achievable. Our upper-bound assumption for beef cattle equates to a -33% improvement by 2050 (producing animals; -25% across all animals) or -1.0% yr^{-1} (producing animals; -0.8% yr^{-1} across all animals). For sheep, our upper-bound of -0.7% yr^{-1} is based on ref. 42.

Dairy cattle, pigs and poultry. Rates of genetic change of 1-3% per year have been achieved over the past few decades in dairy cattle, pigs and poultry[8]. These gains have come about because of the ease of measuring production traits (including feed conversion), the high heritability of production traits, and the availability of large databases containing genetic information. The new tools of molecular genetics are expected to increase these rates of gain by providing greater accuracy in predicting genetic merit, by shortening the generation interval and by increasing the number of potentially elite animals that can be screened[136,146]. These technologies have already been implemented by breeders in the dairy industry[136,146] where rates of genetic gain are increasing[140] and may as much as double compared to recent rates of gain[146,147]. There is also scope to improve feed conversion in broilers[148,149], laying hens[150] and pigs[151] although there are technical and cost barriers to be overcome.

Although biophysical limits to yield gains could well constrain future FCRs, there is little evidence to-date of a ceiling on genetic gains[8,46,152] so there is an expectation that in the medium term, rates of gain will continue at present levels or higher. Specifically in a UK context, a study commissioned by DEFRA reported recent FCR gains of around -0.015, -0.025 and -0.024 kg / kg feed yr^{-1} in broilers, layers and pigs (equivalent to approximately -0.9% yr^{-1}, -1.3% yr^{-1} and -1.0% yr^{-1}, respectively) and outlined an expectation, based on expert judgement, that rates of gain will be similar or greater in the medium term[153]. Similar projections of FCR improvements in UK pigs, amounting to -0.9% yr^{-1}, are outlined in ref. 154.

There is also the technical potential to close 'yield gaps' in production systems. Free range and organic poultry production systems tend to exhibit much lower FCRs than caged systems. The FCR of caged laying hens (accounting for 55% of UK egg production) is 12% and 14% lower than free range and organic systems, respectively (which account for 45% of UK production in aggregate)[40]. The equivalent yield gaps are 22% and 36% for broiler chickens, though standard indoor systems represent the vast bulk of UK production[41]. Clearly the choice between these systems will be dictated by many factors including animal welfare considerations, but here we simply highlight the technical differences between systems, without advocating any particular approach. There are also differences in monogastric FCRs between different flocks or herds, highlighting an opportunity to improve overall FCRs. In UK pig production, the gap in FCR between the national average and the top 10% of herds is approximately 12%[(154)].

Our upper-bound assumptions for dairy cattle, pigs and poultry reflect this technical potential. For dairy cattle, we assume a -1.0% yr^{-1} improvement[155]. For pigs, upper-bound FCR improvements assume a continuation of historic FCR gains of -0.9 to -1.1% yr^{-1} (refs. 153,154,156). For poultry meat, we assume that future rates of gain reduce from recent levels of between -0.9% yr^{-1} and -1.2% yr^{-1} [(45,152,153)] to -0.8% yr^{-1} at the upper-bound. For laying hens, we assume that future rates of gain reduce from recent levels of between -1.0% yr^{-1} and -1.3% yr^{-1} [(152,153)] to -0.8% yr^{-1} at the upper-bound.

Animal welfare considerations. Our upper-bound scenarios consider the technical potential of increases in livestock productivity to reduce greenhouse gas emissions, but there are other important considerations associated with animal welfare. Historical productivity gains have often come at the expense of welfare, particularly in the poultry and dairy sectors, where breeding programs have focussed almost exclusively on production gains at the expense of immune function and fertility[8,156]. These are important factors that may ultimately influence decisions about future productivity gains. It is therefore encouraging that modern breeding techniques (including genomic tools) allow multiple traits to be considered simultaneously, including health, welfare and productivity[156]. Multi-trait selection can help to avoid the deleterious effects of yield increases and also offers potential productivity dividends: non-stressed, healthy livestock are more productive[8,25].

Mechanisms to reduce the consumption of animal products. Achieving meaningful reductions in the consumption of animal products will be challenging as it will require changes in consumer behaviour[157] and changes in the operating practices of food producers and retailers[86,157,158]. However, the climate mitigation benefits and the expected health benefits provide a strong incentive for policymakers to act[90]. Encouragingly, taxes and subsidies are demonstrably effective at driving diet change. A recent systematic review of 38 studies found that taxes (on unhealthy foods) and subsidies (on healthy foods) are consistently effective at changing consumption patterns[17]. Other studies have explicitly considered a tax on meat consumption as a tool for reducing greenhouse gas emissions[159,160]. Other policy options include consumer education programs and the integration of climate considerations into healthy eating guidelines[89,158]. The growing trend of eco-certification might be extended to certifying and labelling products according to greenhouse gas impacts[158]. Finally, meat consumption could in principle be reduced through direct regulation, for example by banning meat imports or by regulating the purchase of meat in public procurement[158].

Mechanisms to reduce food waste. There are a number of policy options that might promote reductions in food waste ranging from actions directed at consumers to actions directed at food producers and retailers. Educating consumers about the use and storage of perishable goods and the environmental and economic benefits of reducing waste might lead to behavioural change in the home[92,95,161]. Similarly, a targeted education program aimed at consumers and retailers could encourage the consumption of produce currently rejected on purely cosmetic grounds[95,161]. Effective policy options might include promoting investments in infrastructure to improve processing, storage, transportation and supply chain management [92,95,161]. Addressing regulatory impediments to the use of food waste for charitable purposes or livestock feed, and encouraging the use of anaerobic digestion plants (provided these are used only for genuine waste) might also be beneficial[92,95,161,162]. Finally, a financial incentive to minimise waste could be created through effective taxation (e.g. by taxing foods with the highest wastage rates, or by increasing taxes on waste disposal)[92]. Ultimately the best solution is likely to be a combination of these measures and encouragingly there are signs that the levels of waste of many commodities has been declining in recent decades[92].

Supplementary Table 1: Assumed growth in population, demand and production

a. Projected population growth

Population in 2010 (millions; ref 32)	62.3
Projected population in 2050 (millions; principal projection in ref.32)	78.4
Projected change in population between 2010 and 2050	26%

b. Growth in demand and production

Commodity	Production in 2010 (kt; food and industrial uses but excluding feed)	Projected change in demand per capita between 2010 and 2050 (%)	Assumed production in 2050 (kt; food and industrial uses but excluding feed)	Increase in production between 2010 and 2050 (%)
Cereals	11,485	14%	16,489	44%
Oilseeds	2,366	69%	5,021	112%
Potatoes	6,254	-4%	7,525	20%
Sugar beet	7,829	6%	10,483	34%
Fruit and vegetables	3,022	10%	4,204	39%
Beef meat	884	-6%	1,045	18%
Milk	13,699	5%	18,153	33%
Pig meat	717	8%	975	36%
Sheep meat	300	-4%	363	21%
Poultry meat	1,529	18%	2,279	49%
Eggs	646	12%	910	41%
Total	48,732		67,447	38%

a. Projected population growth between 2010 and 2050 (ref. 32). **b.** Baseline production in 2010 (ref. 31); projected change in demand per capita between 2010 and 2050 (J. Bruinsma (*pers. comm.*) and consistent with ref. (5); assumed production in 2050; and production growth between 2010 and 2050. Figures exclude livestock feed which is treated separately in our projections. The large increase in oilseed demand reflects an assumed increase in biofuel production in the European Union[5].

Supplementary Table 2: Sources of emissions quantified

	Reported and estimated 1990 emissions (Mt CO_2e yr^{-1})	Mean of 2009-2011 emissions (Mt CO_2e yr^{-1})	Relative contributions to 2009-2011 emissions
Emissions from agriculture per UK GHG inventory			
Enteric fermentation methane	18.8	15.3	21%
Manure management methane	3.5	2.6	3%
Manure management nitrous oxide	2.0	1.6	2%
Nitrous oxide from synthetic fertilisers	8.7	6.7	9%
Animal manure applied to soils	9.2	7.4	10%
Other direct soil emissions	3.0	3.8	5%
Atmospheric deposition	2.0	1.5	2%
Nitrogen runnoff and leaching	10.3	7.5	10%
Other indirect soil emissions	0.3	0.6	1%
Field burning of agricultural residues	0.3	0.0	0%
Sub-total	58.2	47.0	64%
Other emissions attributable to agriculture			
Farm energy use	9.6	7.1	10%
Imported livestock feed	9.4	7.3	10%
Manufacture of synthetic fertiliser	8.9	6.8	9%
Machinery manufacture and maintenance	3.4	2.5	3%
Pesticide manufacture and breakdown	0.7	0.7	1%
Emissions from land use, land-use change and forestry (LULUCF)			
LULUCF emissions per UK GHG inventory	4.0	-3.6	-5%
Additional emissions from drained fen	0.6	0.4	0%
Emissions from drained bog	5.7	5.7	8%
*Total of all emissions**	100.4	73.9	
Emissions target: 80% below 1990 levels	20.1		

Tabulated values are the reported and estimated emissions in 1990 and the mean annual emissions over the three years 2009-11, centred on 2010 and used as the starting point in our projections. Emissions sources are described in the Supplementary Methods. The contribution of each emissions source to the total is shown as a percentage. *The decline in reported emissions between 1990 and 2009-11 arose in large part due to reduced fertiliser application rates in the UK, particularly on improved grassland, and a decline in the domestic production of beef in the UK[12] (offset by an increase in beef imports).

Supplementary Table 3: Regional characteristics of spared land

a. Cumulative area of land spared between 2010 and 2050 under upper-bound yield increases with no demand management

	Origin			End-use	
(000 ha)	Arable	Impr. grass	Rough grazing	Peat-land	Forest or bioenergy
East of England	258	89	3	29	322
West Midlands	124	198	2	6	317
North West	64	264	21	37	312
North East	50	128	18	16	180
Yorkshire & The Humber	147	165	19	23	307
East Midlands	185	142	5	11	321
South East & London	150	196	4	4	346
South West	197	449	12	32	626
Wales	67	506	38	84	527
Scotland	353	474	346	360	813
Northern Ireland	72	328	16	91	325
UK total	1,669	2,939	482	694	4,396

b. Forestry yield class and mean annual carbon sequestration in forest biomass by region

	Broadleaved species			Coniferous species		
Region	Species	Yield class (m^3 ha^{-1} yr^{-1})	Mean annual sequestration in biomass (t C ha^{-1} yr^{-1})	Species	Yield class (m^3 ha^{-1} yr^{-1})	Mean annual sequestration in biomass (t C ha^{-1} yr^{-1})
East of England	Sycamore, Ash, Birch*	6	3.8	Douglas fir	16	5.3
West Midlands	Sycamore, Ash, Birch*	8	4.7	Douglas fir	18	5.7
North West	Birch	6	3.8	Sitka spruce	14	4.2
North East	Birch	6	3.8	Sitka spruce	14	4.2
Yorkshire & The Humber	Sycamore, Ash, Birch*	6	3.8	Douglas fir	12	4.2
East Midlands	Birch	8	4.7	Douglas fir	16	5.3
South East & London	Birch	8	4.7	Douglas fir	16	5.3
South West	Beech	8	4.1	Douglas fir	14	4.8
Wales	Birch	6	3.8	Sitka spruce	16	4.8
Scotland	Birch	4	2.9	Sitka spruce	10	3.0
Northern Ireland	Birch	6	3.8	Sitka spruce	14	4.2

a. Entries show the cumulative area of land spared between 2010 and 2050 under upper-bound yield increases, categorised by origin (arable, improved (Impr.) grass or rough grazing) and use (peatland or forestry/bioenergy crops). No demand management was assumed in deriving these entries. **b.** Entries show the tree species assessed as having the highest carbon sequestration potential in each region, the corresponding forestry yield class and the mean annual carbon sequestration in forest biomass over the 40 year period following planting. *Sycamore, Ash and Birch are each predicted to have the same carbon sequestration potential in these regions.

Supplementary Table 4: Key parameter values and uncertainties

Parameter	Parameter value and source	Uncertainty range and source
Enteric fermentation methane emissions factor ($kg\ CH_4\ head^{-1}\ yr^{-1}$)	Beef cattle: 43 Dairy cattle: 111 Sheep: 5 Pigs: 1.5 Poultry: nil[12]	± 50%[13]
Manure management methane conversion factor (%)	Liquid system: 39.0% Daily spread: 0.1% Solid storage and dry lot: 1.0% Pasture, range & paddock: 1.0% Poultry systems: 1.5%[12]	± 30%[13]
Manure management nitrous oxide emissions factor (EF_3; $kg\ N_2O\text{-}N\ kg\ N^{-1}$)	Liquid system: 0.001 Solid storage and dry lot: 0.02 Pasture, range & paddock: 0.02 Poultry systems: 0.017[12]	-70% / +200%[13]
Emissions factor for nitrous oxide from synthetic fertilisers and animal manure applied to soils (EF_1)	0.0125 kg N_2O-N kg N^{-1} (12)	-70% / +200%[13]
Atmospheric deposition fraction volatilised	Synthetic fertiliser ($Frac_{GASF}$): 0.1 Organic sources ($Frac_{GASM}$): 0.2[12]	-70% / +200%[13]
Atmospheric deposition emissions factor (EF_4)	0.01 kg N_2O-N kg N^{-1} (12)	-80% / +400%[13]
Nitrogen runoff and leaching: fraction leached ($Frac_{LEACH}$)	0.3[12]	-67% / +167%[13]
Nitrogen runoff and leaching emissions factor (EF_5)	0.025 kg N_2O-N kg N^{-1} (12)	-93% / +233%[13]
Farm energy use	7 Mt CO_2e yr^{-1} (57) growing with total agricultural production	± 50% (authors' assumption)
Imported livestock feed emissions factor (kg CO_2e kg $feed^{-1}$)	Concentrates: 1.54 Maize grain: 0.66	± 50% (authors' assumption)
Manufacture of synthetic fertiliser	6.2 kg N_2O-N kg N^{-1} (59) declining to 3.5 kg N_2O-N kg N^{-1} by 2050 due to nitrous oxide abatement technology[60]	Declining to 2.7 kg N_2O-N kg N^{-1} by 2050[60] / no decline
Machinery manufacture and maintenance	35% of farm energy emissions (based on ref. 37, see text)	± 50% (authors' assumption)
Drained fen carbon dioxide	7.0 t CO_2e ha^{-1} yr^{-1} (12)	-18% / +19%[56]
Drained fen dissolved organic carbon	1.1 t CO_2e ha^{-1} yr^{-1} (56)	-39% / +48%[56]
Drained fen methane	1.2 t CO_2e ha^{-1} yr^{-1} (56)	-76% / +76%[56]
Drained fen nitrous oxide	6.3 t CO_2e ha^{-1} yr^{-1} (56)	-37% / +38%[56]
Drained bog carbon dioxide	1.8 t CO_2e ha^{-1} yr^{-1} (62–65)	-30% / +30%[56]
Drained bog dissolved organic carbon	1.1 t CO_2e ha^{-1} yr^{-1} (56)	-39% / +48%[56]
Drained bog methane	1.3 t CO_2e ha^{-1} yr^{-1} (56)	-71% / +71%[56]
Drained bog nitrous oxide	2.1 t CO_2e ha^{-1} yr^{-1} (56)	-56% / +58%[56]
Re-wetted fen carbon dioxide	1.8 t CO_2e ha^{-1} yr^{-1} (56)	-242% / +242%[56]
Re-wetted fen dissolved organic carbon	0.9 t CO_2e ha^{-1} yr^{-1} (56)	-42% / +50%[56]
Re-wetted fen methane	6.0 t CO_2e ha^{-1} yr^{-1} (56)	-100% / +296%[56]
Re-wetted fen nitrous oxide	Nil[56]	NA
Re-wetted bog carbon dioxide	-0.8 t CO_2e ha^{-1} yr^{-1} (56)	-178% / +178%[56]
Re-wetted bog dissolved organic carbon	0.9 t CO_2e ha^{-1} yr^{-1} (56)	-42% / +50%[56]
Re-wetted bog methane	2.6 t CO_2e ha^{-1} yr^{-1} (56)	-97% / +384%[56]
Re-wetted bog nitrous oxide	Nil[56]	NA
Methane spike on re-wetting	2.5 t CO_2e ha^{-1} yr^{-1} for 10 years[48,79]	Nil / 5 t CO_2e ha^{-1} yr^{-1} for 10 years (authors' assumption)
Forest yield class	All broadleaves per Supplementary Table 3	-2 / +2 change in yield class, all regions
Forest type	All broadleaves per Supplementary Table 3	All conifers per UK inventory (Sitka spruce yield class 12 in Britain and 14 in N. Ireland)[12] / all conifers per Supplementary Table 3
Soil carbon gains on afforestation	Soil carbon gains on former cropland only (see Supplementary Methods)	Nil / soil carbon gains in both former cropland and former grassland
Soil carbon gains time constants (years)	525 (Scotland), 200 (elsewhere), see Supplementary Table 7[12]	750 (Scotland), 300 (elsewhere) / 300 (Scotland), 100 (elsewhere)[12]

Table entries indicate the key parameters used in our projections including the value of each parameter and its uncertainty range. Calculations are described in the Supplementary Methods. The sensitivity of our results to the uncertainty in each parameter is shown in Supplementary Fig. 2.

Supplementary Table 5: Qualitative assessment of technologies to increase yield

Technology	Yield impact	GHG impact per tonne	Evidence
Crop management			
Optimise crop nutrition	+	-	***
Improve crop protection	+	-	**
Improve sowing, treatment and harvesting operations	+	-	*
Crop genetic improvement			
Increase harvestable ratio (the useful proportion of crop biomass)	+	-	***
Increase radiation use efficiency / photosynthetic efficiency	++	--	*
Improve nutrient capture and nutrient use efficiency	++	---	**
Increase water use efficiency	++	--	*
Livestock genetic improvement			
Select for higher growth rates and productivity	+++	--	***
Improve reproductive rates in breeding stock	+	-	**
Livestock nutrition			
Increase the nutrition quality of diets	++	---	***
Dietary additives	+	-	**
Livestock disease			
Improve drugs and vaccines	+	-	**
Enhanced disease surveillance and control	+	-	*

Table entries are assessments of the capacity of the principal technologies expected to increase future crop and livestock yields in the UK. The magnitude and direction of the effect on yields and greenhouse gas emissions (per tonne of product) are indicated by the number of "+" and "-" symbols. The strength of evidence in favour of yield increases being realised from a given measure is indicated by the number of "*" symbols. Based on refs. 8,121,122,124,126–128,163–165.

Supplementary Table 6: Livestock diet assumptions

a. Estimated feed consumed by livestock in the UK in 2010 (thousand tonnes dry matter)

	All animals						Breeding animals						Producing animals					
	Beef cattle	Dairy cattle	Sheep	Pigs	Poultry (meat)	Poultry (eggs)	Beef cattle	Dairy cattle	Sheep	Pigs	Poultry (meat)	Poultry (eggs)	Beef cattle	Dairy cattle	Sheep	Pigs	Poultry (meat)	Poultry (eggs)
Cereals	2,084	277	71	1,911	3,177	1,358	512	34	34	760	282	214	1,572	243	38	1,151	2,895	1,144
Forage maize	0	1,132	0	0	0	0	0	0	0	0	0	0	0	1,132	0	0	0	0
Maize grain	113	218	1	63	48	23	28	27	0	24	4	4	85	191	0	39	43	19
Rapeseed meal	212	326	84	131	141	0	52	40	39	35	13	0	160	286	44	96	129	0
Forage legumes	144	269	88	63	0	0	35	33	42	24	0	0	109	236	47	39	0	0
Other forage crops	0	286	151	0	0	0	0	73	71	0	0	0	0	212	80	0	0	0
Co- and by-products	981	1,342	386	114	283	25	241	166	181	33	25	4	740	1,176	204	81	257	21
Concentrates	399	1,065	153	772	1,118	657	98	132	72	267	99	104	301	933	81	505	1,019	554
Grass	5,787	6,265	9,387	0	0	0	1,421	1,608	4,411	0	0	0	4,366	4,657	4,976	0	0	0
Wheat straw	204	224	80	0	0	0	50	28	38	0	0	0	154	196	43	0	0	0
Silage and hay	5,389	5,096	358	0	0	0	1,323	1,453	168	0	0	0	4,066	3,643	190	0	0	0

b. Assumed changes in diet composition for ruminant livestock (producing animals only)

	Beef cattle				Dairy cattle				Sheep			
			2050				2050				2050	
	2010	Eff.	Lower-bound	Upper-bound	2010	Eff.	Lower-bound	Upper-bound	2010	Eff.	Lower-bound	Upper-bound
Cereals	17%	47%	17%	32%	2%	2%	2%	2%	1%	0%	1%	1%
Forage maize	0%	0%	0%	0%	9%	18%	9%	14%	0%	0%	0%	0%
Maize grain	1%	1%	1%	1%	2%	2%	2%	2%	0%	0%	0%	0%
Rapeseed meal	2%	2%	2%	2%	3%	3%	3%	3%	1%	1%	1%	1%
Forage legumes	1%	1%	1%	1%	2%	2%	2%	2%	1%	1%	1%	1%
Other forage crops	0%	0%	0%	0%	2%	2%	2%	2%	2%	4%	2%	3%
Co- and by-products	7%	7%	7%	7%	10%	10%	10%	10%	4%	5%	4%	4%
Concentrates	3%	4%	3%	3%	8%	8%	8%	8%	2%	2%	2%	2%
Grass	38%	18%	38%	28%	36%	35%	36%	36%	87%	78%	87%	82%
Wheat straw	1%	1%	1%	1%	1%	1%	1%	1%	0%	1%	0%	0%
Silage and hay	32%	20%	32%	26%	25%	16%	25%	21%	3%	8%	3%	5%
Summarised as:												
Cereals	17%	47%	17%	32%	2%	2%	2%	2%	1%	0%	1%	1%
Concentrates	12%	14%	12%	13%	23%	23%	23%	23%	6%	8%	6%	7%
Forage crops	1%	1%	1%	1%	13%	22%	13%	18%	3%	5%	3%	4%
Grass	70%	38%	70%	54%	62%	52%	62%	57%	90%	86%	90%	88%

c. Emissions intensity of imported livestock concentrate feed

Feed component	Proportion by mass	Emissions factor (kg CO_2e kg^{-1})	Refs.
Rice bran extractions	0%	0.11	81,166
Maize gluten feed	3%	0.34	37
Soya cake and meal	31%	3.54	37,58,167–170
Sunflower cake and meal	7%	0.75	81,167
Other oilseed cake and meal	12%	0.72	58,167
Dried sugar beet pulp	7%	0.82	58,171
Molasses	7%	0.11	167,171
Fish, poultry & other meal	3%	1.17	167,172
Minerals	12%	0.02	171
Oil and fat	5%	0.80	81
Protein concentrates*	0%	3.54	
Other materials†	7%	1.08	
Confectionery by-products†	5%	1.08	
Weighted average		1.54	
Maize grain		0.66	37,58
Co- and bi-products		0.05	37

a. Estimated tonnage of feed consumed by livestock in the UK in 2010, sub-divided into breeding and producing animals. **b**. Assumed changes in diet composition for ruminant producing animals. Entries correspond to the proportion (in energy terms) of each feedstuff in the diet ($D_{i,j}$ as defined in the Supplementary Methods). Columns show average diets in 2010, the diets of the most efficient present day animals (Eff.; see methods text), and 2050 diets under lower- and upper-bound yield growth. **c.** Entries indicate the components of concentrate feed imported to the UK. [*]Assumed equal to soya cake and meal. [†]No data available so assumed to equal the arithmetic average of other components.

Supplementary Table 7: Soil carbon assumptions

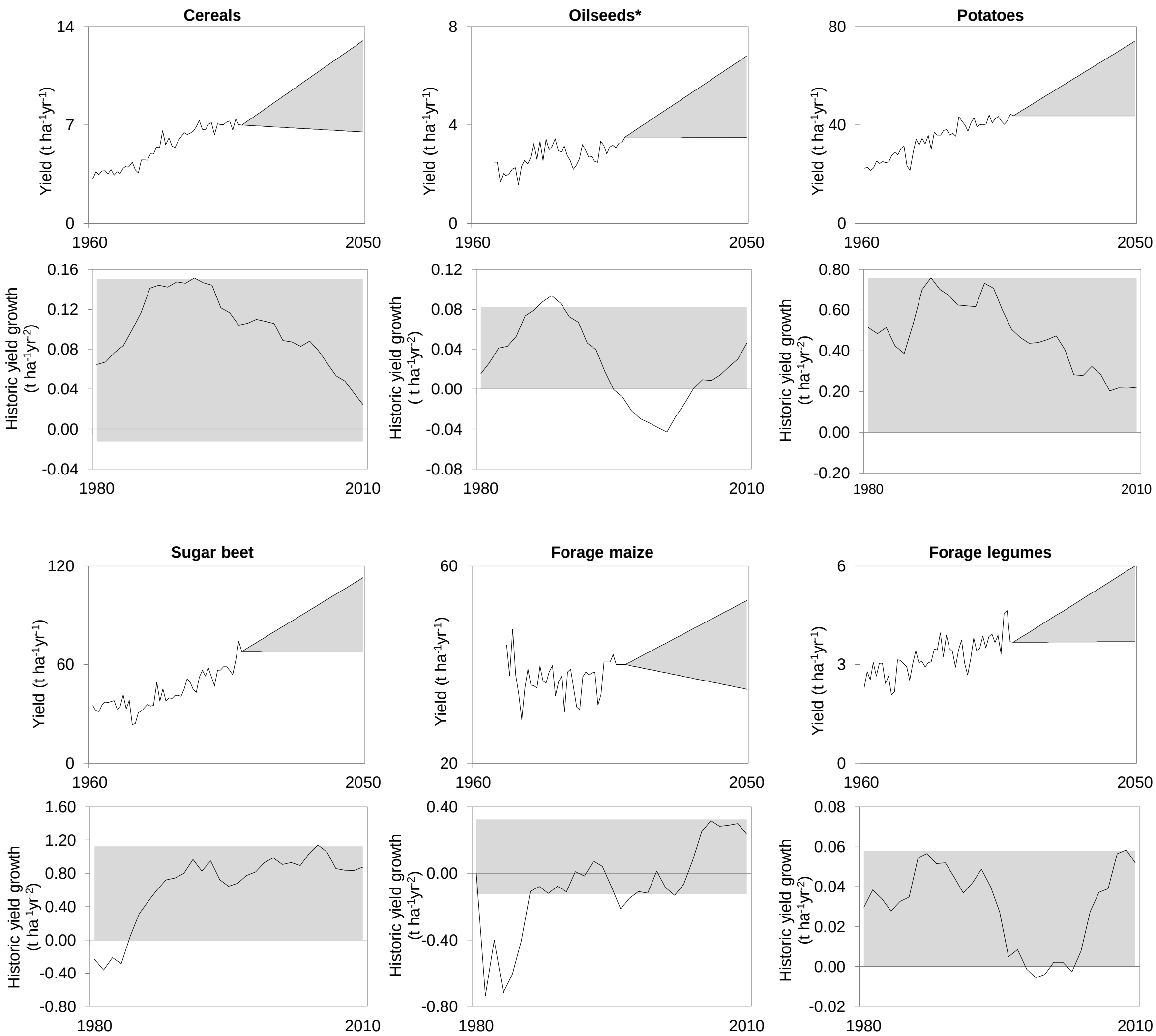
	England	Scotland	Wales	Northern Ireland
Carbon density to 1 m in mineral soils (t C ha^{-1})				
Forestland	150	341	177	335
Cropland	120	154	122	215
Grassland	146	246	164	276
Time constant (years for 99% change)				
Loss of soil carbon	100	100	100	100
Gain of soil carbon	200	525	200	200

Entries show the average soil carbon density for mineral soils in the UK, to 1 metre depth, by country and land-cover, sourced from the UK greenhouse gas inventory (ref. 53, Table 1-22 and based on refs. 52,54,55) and the time constants used to model soil carbon change, specified differently for soil carbon gains and losses, also from the UK inventory.

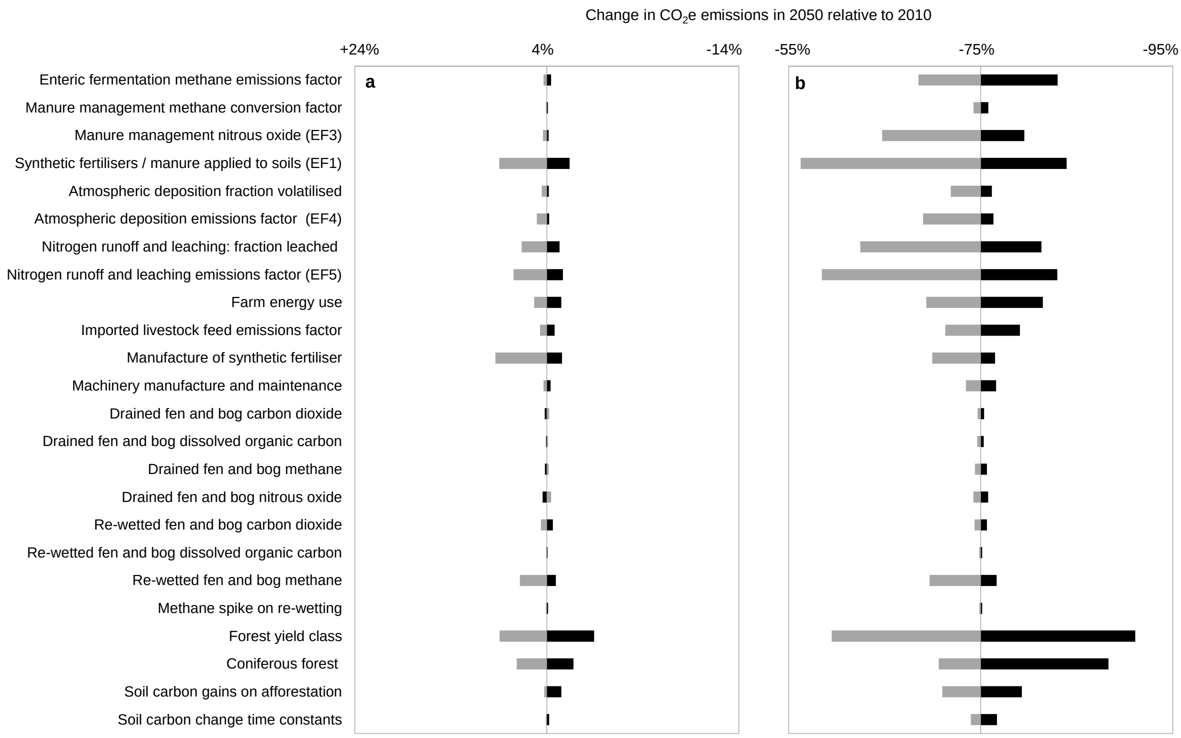
Supplementary Table 8: Emissions factors for imported food

	Emissions per kg of commodity (kg CO_2e kg^{-1})		
Commodity	Farming and transport	Land use change	Total
Cereals	0.6	0.5	1.1
Oilseeds	2.2	0.8	3.0
Potatoes	0.5	0.1	0.6
Sugar beet	0.1	0.0	0.1
Fruit and vegetables	2.0	0.1	2.1
Forage legumes	3.2	0.5	3.8
Beef	22.1	52.7	74.8
Poultry	2.8	2.6	5.3
Pig	4.6	3.4	7.9
Sheep	11.6	50.3	61.9
Milk	1.0	0.7	1.7
Eggs	3.0	2.0	5.0

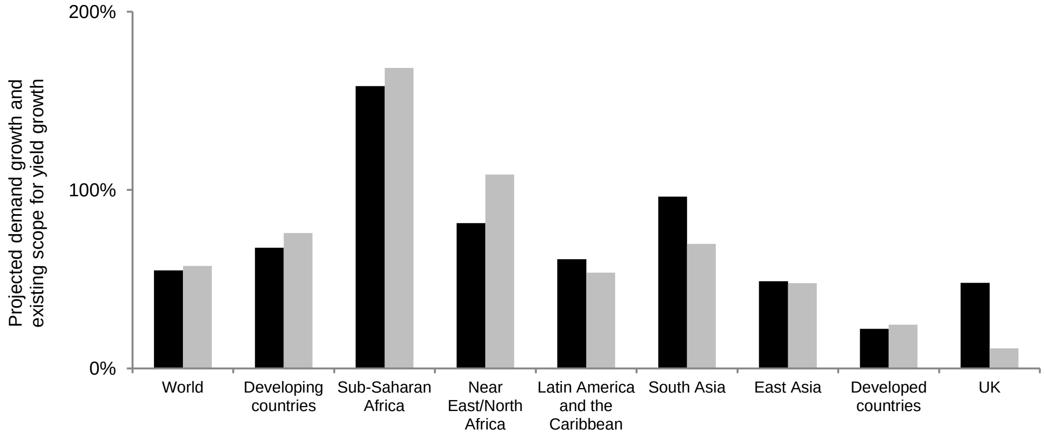
Entries show the assumed emissions intensity of food imported into the UK. Emissions arise overseas and are broken down into emissions from farming and transportation and emissions due to overseas land-use change. Sourced from ref. 81.



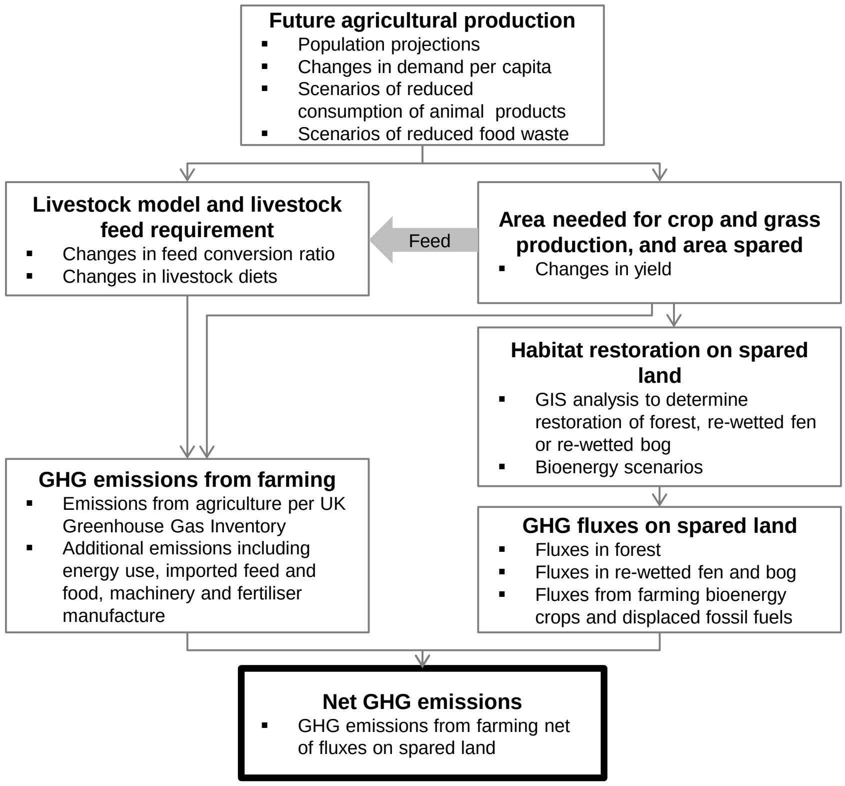
Supplementary Figure 1: Yield scenarios for six major crops. The upper figure for each crop indicates realised UK yields during the period 1961 to 2010 (ref. 173) and (in grey shading) the range from the lower- to the upper-bound projected under our scenarios. The lower figures indicate the historic rate of yield growth (ten-year, backwards-looking rolling mean) and (in grey shading) the range in yield growth projected under our scenarios. The six crops shown together occupy approximately 95% of UK cropland area. *The decline in oilseed yields in historic periods was due the introduction of new varieties more suitable for use as livestock feed; the consequent decline in yields was a one-off[122] and we do not reflect this in our projections.



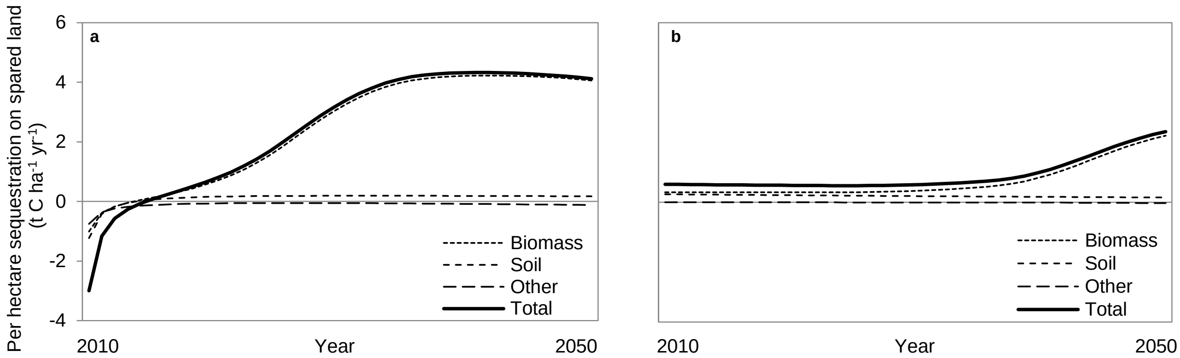
Supplementary Figure 2: Sensitivity analysis. Figure shows the effect of uncertainty in key parameters on our results at two levels of yield growth: **a**. Yield growth mid-way between the lower- and upper-bounds shown in Table 1; **b**. Yield growth at the upper-bound. The charts are centred on the reduction in 2050 emissions relative to 2010 under each yield growth assumption (corresponding to the results in Fig. 1). Bars show the range in the result when parameter values are varied in sequence and non-cumulatively over the range of uncertainty presented in Supplementary Table 4.



Supplementary Figure 3: Regional differences in yield gaps and demand growth. Projected demand growth between 2010 and 2050 (black bars; ref. 5) and existing scope for yield growth based on current yield gaps (grey bars; ref. 30).



Supplementary Figure 4: Simplified logical structure of calculations. Boxes indicate the core calculations involved in our projections and the logical structure of the model used. Arrows indicate the flow of information between calculations. Full detail is provided in the Supplementary Information.



Supplementary Figure 5: Sequestration in managed broadleaved forests and natural regeneration on spared land. Per hectare annual sequestration under upper-bound yield assumptions in **a**: the managed broadleaved scenario; and **b**: natural regeneration. The contribution due to biomass, soils, natural disturbance and site preparation (the latter two grouped as "other") are separately identified. Positive values indicate a net carbon uptake by the ecosystem.

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