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The carbon opportunity cost of animal-sourced food production on land

Matthew N. Hayek[1]✉, Helen Harwatt[2], William J. Ripple[3] and Nathaniel D. Mueller[4,5]

Extensive land uses to meet dietary preferences incur a 'carbon opportunity cost' given the potential for carbon sequestration through ecosystem restoration. Here we map the magnitude of this opportunity, finding that shifts in global food production to plant-based diets by 2050 could lead to sequestration of 332–547 GtCO$_2$, equivalent to 99–163% of the CO$_2$ emissions budget consistent with a 66% chance of limiting warming to 1.5 °C.

Restoration of native ecosystems, including forests, is a land-based option for atmospheric carbon dioxide (CO$_2$) removal[1]. Ecosystem restoration is constrained largely by land requirements of food production, the largest human use of land globally[2]. Food production therefore incurs a 'carbon opportunity cost', that is, the potential for natural CO$_2$ removal via ecosystem restoration on land[3,4]. This cost can vary greatly depending on the 'potential' or 'native' vegetation of a given region and types of food produced. Animal-sourced foods such as meat and dairy have large land footprints because animals typically consume more food macronutrients than they produce[5]. Quantifying the spatial distribution of agriculture's cumulative carbon opportunity cost within this century can inform efforts to limit global warming to 1.5 °C.

Ongoing agricultural emissions can be abated by shifts to less-resource-intensive, plant-based diets[6,7], but the potential for cumulative CO$_2$ removal from native vegetation regrowth in areas occupied by animal agriculture has not previously been calculated in a spatially explicit manner. Here we quantify the total carbon opportunity cost of animal agricultural production to be 152.5 (94.2–207.1) gigatons of carbon (GtC) in living plant biomass across all continents and biomes (Fig. 1 and Supplementary Table 3).

We approximated the potential for CO$_2$ removal in soil and litter as an additional 63 GtC (Supplementary Table 4). This estimate is associated with large but unknown uncertainty because of a deficit of data and the complexity of dynamics of non-living carbon pools in restored ecosystems.

Pastures for ruminant meat and dairy production represent the majority of the total carbon opportunity cost—72%—compared with animal feed croplands, which suppress the remaining 28% of native vegetation carbon (Supplementary Table 3). Potential productivity on remaining cropland is sufficient to supply the current global population with 78 g capita^{-1} day^{-1} of protein (after factoring losses from both storage and consumer waste), an amount exceeding dietary recommendations, accounting for variation in nutritional requirements among demographic groups and for disparities in food availability[8].

The cumulative potential of CO$_2$ removal on land currently occupied by animal agriculture is comparable in order of magnitude to the past decade of global fossil fuel emissions. The largest potential for negative emissions—74 GtC or 48% of the global total—lies in upper-middle-income countries (Fig. 2), which will further increase as meat and dairy production expand. This is approximately equal to the past 19 years of fossil fuel emissions in these countries. In high-income countries, in which animal-sourced food demand is high but plateauing[8], the total carbon opportunity cost of animal-sourced food production is 32 GtC, approximately equal to the past 9 years of their domestic fossil fuel emissions.

Present-day pasturelands exist in areas of both native forests and grasslands within all continents (Supplementary Table 3). Pastures in native forest areas displace 72 GtC—accounting for 68% of pastures' carbon opportunity cost but only 22% of total pasture area (Supplementary Table 3 and Supplementary Fig. 2). In native grasslands, vegetation may be partially restored by improved grazing management[9], rather than removing animals altogether, although trade-offs remain with respect to non-CO$_2$ ruminant emissions. In addition, optimal grazing does not always promote restoration because ruminants selectively browse native species[10] and translocate nutrients[11].

To understand the potential future consequences of animal-sourced food consumption on global CO$_2$ budgets, we modelled land use of three global dietary scenarios to the year 2050 relative to the present day (base year 2015). The net CO$_2$ balance was calculated for a business-as-usual (BAU) diet following economic trends[12], a healthier diet with approximately 70% meat reduction globally relative to BAU[13] (the EAT-*Lancet* Commission or ELC diet) and a vegan (VGN) diet with no animal-sourced foods[8].

The BAU diet results in land clearing, with land-use-change emissions of 86 (68–105) GtCO$_2$ (Fig. 3) because optimistic future improvements in yields are insufficient to meet expected animal feed demands[11].

The ELC and VGN diets result in 332 (210 to 459) and 547 (358 to 743) total GtCO$_2$ removal, respectively, approximately equal to the past 9 and 16 years of fossil fuel emissions. Ecosystem soil and litter could remove an additional 135 and 225 GtCO$_2$ for ELC and VGN, respectively (Supplementary Table 6), but this estimate is highly uncertain.

Smaller future increases in crop yields would result in less land sparing and CO$_2$ removal from ELC and VGN diets compared with present day: 199 and 424 GtCO$_2$, respectively (Supplementary Table 5). However, plant-rich diets would permit even greater mitigation compared with BAU; lower yields result in greater land-clearing emissions of 247 GtCO$_2$.

Ceasing fossil fuel use is necessary to limit global warming, but CO$_2$ removal following plant-rich dietary shifts could substantially

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[1]Department of Environmental Studies, New York University, New York, NY, USA. [2]Animal Law and Policy Program, Harvard Law School, Cambridge, MA, USA. [3]Department of Forest Ecosystems and Society, Oregon State University, Corvallis, OR, USA. [4]Department of Ecosystem Science and Sustainability, Colorado State University, Fort Collins, CO, USA. [5]Department of Soil and Crop Sciences, Colorado State University, Fort Collins, CO, USA.
✉e-mail: matthew.hayek@nyu.edu

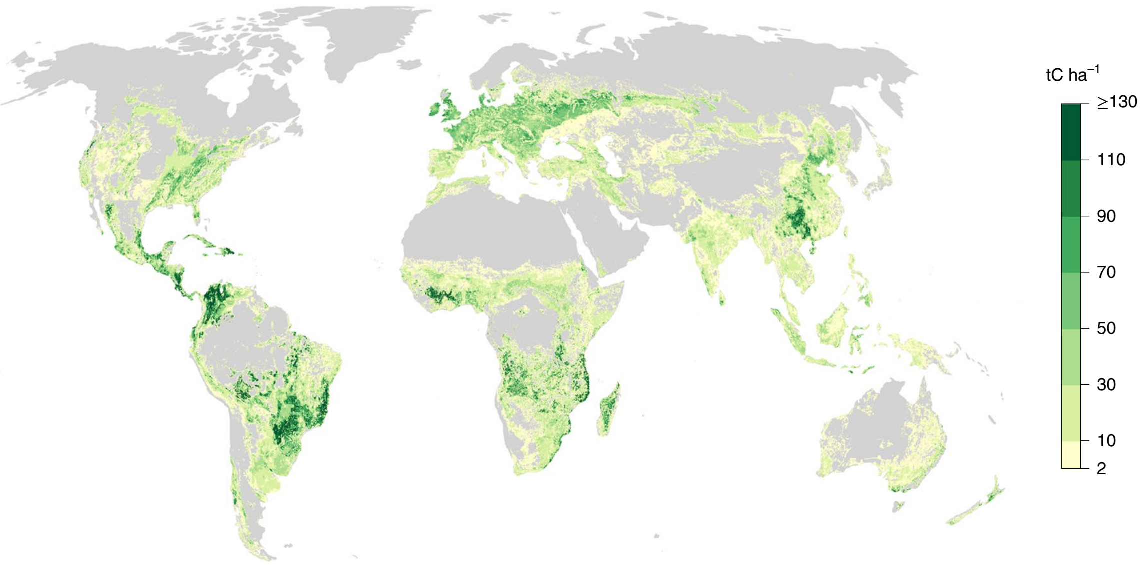

Fig. 1 | Distribution of carbon in potential vegetation in areas of present-day animal feed croplands and pastures combined for each 5 arcmin grid cell. Colour corresponds to the product of land area presently under cultivation multiplied by the potential vegetation carbon density, minus the quantity presently stored in agricultural vegetation.

contribute to international greenhouse gas reduction targets. Cumulative CO_2 emissions (anthropogenic emissions minus removal) must remain below 335 $GtCO_2$ after 2019 to limit warming to 1.5 °C at a 66% likelihood level[14]. CO_2 removal from terrestrial vegetation following ELC or VGN dietary shifts would increase permissible CO_2 emissions by 99% (63%–137%) or 163% (107%–222%), respectively. Adding net CO_2 uptake by native ecosystem soil and litter to this total increases the 1.5 °C budget by 139% or 230%, respectively. By contrast, most future scenarios of 1.5 °C warming rely on nascent bioenergy carbon capture and storage technology to remove 151 to 1,191 $GtCO_2$ from the atmosphere[13]—an amount of CO_2 comparable to plant-rich diets.

Across all scenarios, additional system-wide improvements in waste and efficiency are possible, including using crop residues and waste for animal feed. We do not model these interventions explicitly; previous analyses demonstrate that they could provide some additional 'cropland-free' animal food or spare additional land for ecosystem restoration[15,16].

The likelihood of limiting warming to 1.5 °C without overshoot is improved by reaching carbon neutrality before 2050[13]. Carbon uptake saturates after around 25 years for tropical forests and around 30 years for temperate forests[17]. Changes in diets and agricultural land use within the next two decades could contribute substantially toward carbon neutrality by 2050. Overshooting 1.5 °C warming poses substantial risks to human and natural systems, including a weakened terrestrial ecosystem carbon sink. However, even in high-emission pathways, terrestrial ecosystems are expected to act as a net carbon sink through 2100[18], although the precise magnitude is subject to ongoing investigation. In addition, temperate reforestation can lead to local warming effects due to albedo changes—impacts that warrant further analysis—although temperate reforestation would still result in net cooling globally[18].

Our results do not reflect additional non-CO_2 greenhouse gases and their respective twenty-first-century emissions budgets. Dietary shifts could mitigate 49% to 70% of annual BAU food system emissions (4.8 to 6.6 $GtCO_2$-equivalent yr^{-1} of predominantly non-CO_2 gases) in 2050[6,12]. This non-CO_2 mitigation further improves the likelihood of remaining under 1.5 °C warming.

Our estimates of CO_2 removal differ from prior approaches, which have been calculated on an annual basis[3,19,20] and therefore depend on rates of hypothetical dietary transitions and ecosystem regrowth; modulating these rates produces different estimates. Such rate dependencies are complex, or derived from process-based models; fully reconstructing these assumptions for direct comparison with our results was outside of our scope. Our approach avoids temporal dependencies, directly addressing the cumulative twenty-first-century potential for CO_2 removal. One previous study has reported a cumulative potential of 30 GtC or 110 $GtCO_2$ via dietary shifts; this analysis used a single native vegetation dataset at a coarser spatial resolution[21].

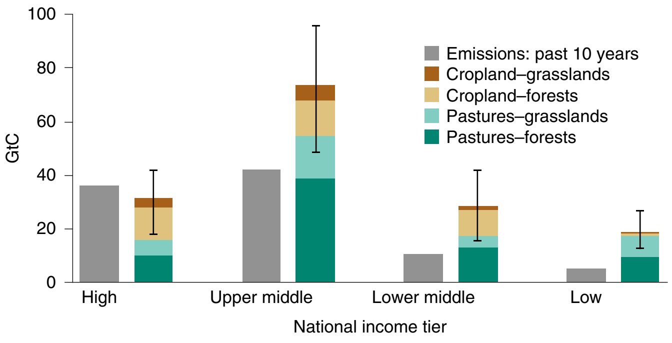

Fig. 2 | Carbon opportunity cost of animal agriculture and atmospheric CO_2 emissions grouped by national income tiers. CO_2 emissions include fossil fuel and cement (grey bars). Carbon opportunity costs are disaggregated by present-day agricultural land type and potential vegetation biomes: croplands in native grassland areas (dark brown), croplands in native forest areas (light brown), pastures in native grassland areas (light green) and pastures in native forest areas (dark green). Error bars are combined 95% confidence intervals for the total carbon opportunity cost across all production categories and biomes in each income category.

Changes to global agricultural production would be economically disruptive and could incur sociocultural costs, which must be compared with the costs of climate warming from unabated agricultural emissions. Restoration efforts could minimize trade-offs by targeting the highest-carbon areas (Fig. 1 and Supplementary

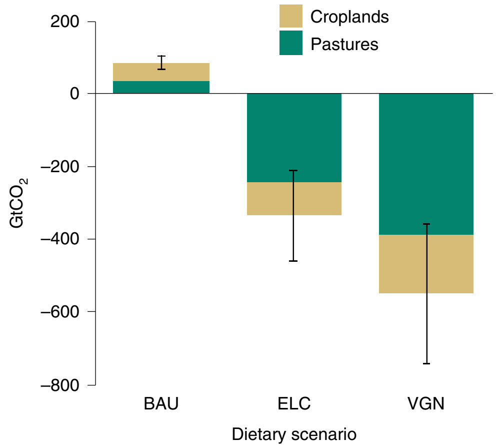

Fig. 3 | Cumulative changes in terrestrial carbon from three dietary scenarios in 2050: BAU, ELC and VGN. Scenarios do not include abated emissions associated with agricultural production (for example, ref. [7]). Positive CO_2 indicates a loss of ecosystem vegetation carbon and emissions to the atmosphere; negative indicates CO_2 removal via vegetation growth. Error bars are 95% confidence intervals, reflecting various estimates of potential vegetation and distributions of cropland removal from low- and high-carbon biomes.

Figs. 2 and 5). Financial incentives to restore high-carbon forests may come from higher-income, higher-emitting nations, providing investments to protect livelihoods, strengthen food security and improve agricultural productivity. Our analysis also reveals substantial opportunities for CO_2 removal in high-income countries and temperate ecoregions that are often neglected in scientific and policy conversations (Fig. 1 and 2).

This analysis uses the most up-to-date and high-resolution data to map ecosystem carbon trade-offs associated with animal-sourced food production. Our results demonstrate substantial carbon opportunity costs incurred by resource-intensive diets, comparable to the remaining carbon budget to 1.5 °C. Animal agriculture across all continents and income categories represents a profound trade-off when compared with potential GHG mitigation. If future dietary shifts do not occur, carbon trade-offs are expected to grow, even with large improvements in yields and optimized cropland distribution. Our carbon accounting approach illuminates areas where policies could prioritize ecosystem restoration and CO_2 removal, including but not limited to tropical Latin American forests outside of the Amazon basin and temperate forests in Western Europe and East Asia, where carbon trade-offs are largest.

Methods

The carbon opportunity cost of present-day animal agriculture (Fig. 1 and Supplementary Table 3) was calculated as the difference between carbon stocks in potential vegetation[2] (that is, vegetation following human abandonment) and vegetation carbon stocks in animal feed croplands and permanent pastures[4,22,23], all at 5 arcmin spatial resolution. Cropland carbon stocks were assumed equal to carbon in annual maximum biomass, estimated from harvested yields, per West et al.[4]. This produces a conservative estimate for the difference between cropland and native biomass. Animal feed fractions for crops were taken from a previous analysis[24], which used data consistent with our analysis.

Carbon in potential vegetation was taken from six datasets, and carbon in present-day pastures from seven datasets[2] (Supplementary Methods), at 5 arcmin, the highest-resolution global estimates available. We refer to potential vegetation as 'native vegetation' interchangeably, although restored vegetation may consist of non-native species. We do not consider forest plantations representative of commercial forestry, or tree planting.

In native forest areas, we assumed pastures exist on cleared land (Supplementary Fig. 2). In native grasslands areas (including savannas of sufficiently low tree density <75 MgC ha^{-1}), we assumed pastures exist on managed lands (Supplementary Fig. 3), where carbon was assumed equal to that in present-day vegetation, which is lower than carbon in potential vegetation in most areas[2]. Our soil and litter carbon estimates are described in Supplementary Methods.

For 2050 dietary scenarios, we developed a low-parameter, top-down representation of land use that adopts literature BAU estimates (Supplementary Methods). This flexible approach is used to parsimoniously calculate the fraction of literature BAU agricultural land that ELC and VGN diets could spare for ecosystem restoration, provided key parameters reflecting production, consumption and feed allocation are available.

In the 2050 BAU scenario in the main text, we used cropland expansion within each continent directly from Alexandratos and Bruinsma[11]. We assumed a global pasture expansion of 6% by 2050[25], consistent with a literature estimate that assumes optimistic grazing improvements. Pasture expansion was distributed proportionally over the same distribution potential vegetation biomes as the present day, a conservative assumption because expansion is presently occurring disproportionately in carbon-rich tropical areas[26].

In the VGN scenario, all permanent pastureland was taken out of production, as well as feed croplands minus land necessary to provide macronutrients of removed animal-sourced foods (with approximately 25% excess[8] after wastes and losses; Supplementary Table 1). ELC requirements were derived from recent guidelines[11]. We calculated fractions of feed cropland and pastureland necessary for each animal-sourced food category in ELC relative to BAU diets, using crop[11] and forage and pasture[27] allocation parameters from the literature.

Alternatively, we adopted a pessimistic BAU projection (Supplementary Methods), which assumes relatively lower crop yields and pasture productivity, in contrast to the more optimistic assumptions in the BAU scenario in the main text (Supplementary Table 5).

All errors and ranges presented are 95% confidence intervals calculated over all combinations of carbon estimates and area distributions: carbon in potential vegetation from six spatial datasets[2], carbon in present-day pasturelands from seven spatial datasets[2] and simulations wherein crops are removed from areas of highest versus lowest carbon in potential vegetation (Supplementary Figs. 4 and 5). For other assumptions, we were not able to calculate uncertainties; we therefore used the most conservative data or parameter estimates available in the literature for crop plant biomass[4], biomass in artificial pastures (areas of native forest)[28] and spatial estimates of pasture area[21,29].

Data availability

Geospatial data for land-use area and carbon opportunity costs are available via the NYU Faculty Data Archive Spatial Data Repository, accessible online at https://doi.org/10.17609/q5pe-7r68.

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Author contributions

M.N.H. and H.H. developed the core research questions and conceptual approach of this study. M.N.H. and N.D.M. performed geospatial modelling and statistical analysis. M.N.H. developed the low-parameter model representation of literature 2050 BAU projections for the future land-use scenarios. All authors contributed to identifying and conceptually implementing the alternative 2050 dietary scenarios and contributed to the writing, editing and revising of the manuscript.

Competing interests

The authors declare no competing interests.

Additional information

Supplementary information is available for this paper at https://doi.org/10.1038/s41893-020-00603-4.

Correspondence and requests for materials should be addressed to M.N.H.

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