nature research

https://doi.org/10.1038/s41893-020-00603-4

Supplementary information

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

In the format provided by the authors and unedited

Supplement to '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]

Table of Contents

[1] Department of Environmental Studies, New York University, New York, NY USA
[*] email: matthew.hayek@nyu.edu
[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

1. Supplementary Methods

1.1. Present-day carbon opportunity cost of animal-sourced food production

1.1.1. Croplands and animal feed

The global distribution of crop yields and harvest areas for 175 crops at a 5 arcminute resolution (approximately 10 km^2 at the equator) were taken from Monfreda et al.[1] and are provided on Earthstat.org. We updated mean agricultural yields in the spatial data (7-year mean centered around the year 2000) by the mean yields centered around 2015 (3-year mean of 2014 to 2016) derived from FAOSTAT[2]. In doing so, we assumed static within-country spatial distributions of crop yields relative to the year-2000-centered distributions.

Geospatial data on the proportion of 37 human-edible crops within each 5 arcminute grid cell used for animal feed were taken from Cassidy et al.[3] Forage crops were all assumed to be used exclusively for animal feed. All remaining crops were assumed to be used exclusively for humans.

1.1.2. Pastures

Global pasturelands were taken from the Ramankutty et al. 5 arcminute data, also available on Earthstat.org[4]. The total area that pasturelands occupy according to this dataset is 28 Mkm^2. Spatial estimates for pasture correspond with the Food and Agriculture Organization (FAO) definition of "land under permanent meadows and pastures", which includes lands utilized predominantly for grazing for a minimum of 5 years and 100 days per year.

Other estimates exist at similar spatial resolutions[5,6], in which total pastureland area ranges from amounts slightly to substantially higher (29 – 47 Mkm^2). Not all datasets are consistent with the FAO permanent pastures definition, and therefore may undergo additional land uses or sporadic grazing. The Ramankutty et al. pastureland area data that we use therefore represents a conservative estimate that has two advantages over other datasets: it explicitly excludes croplands used in our calculations at each grid cell, providing internally consistent estimates within our analysis, and only includes land areas where the sole or predominant usage is grazing. Nonetheless, variations or errors in permanent pasture area estimates may still exist within continents and biomes and warrant further investigation.

Pasture estimates aside from the ones we used differ mostly in terms of their assumptions about marginal, impermanent, and low-productivity areas[7] (e.g. Asian drylands), where carbon in potential vegetation is lowest. As we note in our analysis in the main text, approximately 68% of the carbon in potential vegetation lies in 22% of the total overall pasture area, in areas where native forest have been replaced by pastures (Supplementary Table 3). In these areas, good agreement exists between the pasture area datasets[7]. It is therefore reasonable expect that the large difference in pastureland areas between the datasets would translate into a relatively smaller differences in potential carbon sequestration following abandonment. Dry marginal areas also tend to have the lowest grazing intensity[5].

1.1.3. Carbon in terrestrial vegetation

The carbon present in croplands was approximated as total crop plant NPP, using harvest amounts present in the crop productivity datasets and coefficients from the literature that relate harvest biomass to other plant tissues[8]. This approach represents an overestimate of average standing carbon stock on croplands, because crop biomass is present for only part of the year, and is expected to produce conservative results.

Global distribution of carbon in terrestrial potential vegetation, representing an equilibrium state of terrestrial vegetation following abandonment from human activities, was taken from 6 global datasets at 5 arcminute resolution as compiled by Erb et al.[9]. We also refer to potential vegetation as "native vegetation" interchangeably, although we recognize that in some cases, vegetation that recolonizes abandoned agricultural land may consist of non-native species, or size and species composition that differs from historical conditions before human settlement.

Carbon in pastures was estimated in two steps. First, in areas where the potential vegetation type is predominantly forest, pastures were assumed to exist on cleared land. For total pasture carbon in these areas, we used a literature estimate of 6 MgC ha^{-1}, an amount representative of NPP for high-productivity artificial grassland in humid climates[10], making this a likely overestimate for carbon in pastures globally, but one that is consistent with previous analyses, and leading to a conservative estimate for ecosystem restoration. Second, in areas where the natural vegetation type is predominantly shrublands, grasslands, or savannas of sufficiently low tree density (<75 MgC ha^{-1}) permanent pastures were assumed to exist on managed rather than cleared lands. In these areas, carbon in managed grasslands was assumed equal to the mean of seven global maps of estimated carbon stocks in present-day ecosystems[9].

1.1.4. Carbon opportunity cost of present-day animal-sourced food production

The "carbon opportunity cost", i.e. the amount of carbon that would be mitigated in terrestrial vegetation if agricultural lands were abandoned, was estimated using the "carbon for food" approach of West et al.[8]. The present-day carbon opportunity cost of animal agricultural production was calculated as the difference between carbon stocks in potential vegetation and carbon stocks in present-day animal feed croplands and permanent pasture.

This differencing approach has multiple advantages in determining resource tradeoffs compared with previous approaches. First, our approach relies on a more highly spatially resolved differencing than previous approaches, which model tradeoffs at the scale of continents, countries, or agro-ecological zones within countries[11,12]. Second, our approach considers carbon *stocks* foremost, rather than carbon *fluxes*. Previous similar approaches calculate and report carbon fluxes from various land use change decisions using dynamic vegetation models. Such flux calculations are sensitive to myriad assumptions and prone to errors. Models are highly parameterized[13] (prone to sampling biases that define important parameters[14]) and imperfectly represent ecosystem dynamics[15,16] (prone to errors in representing growth and succession rates). Errors in an annual flux rate can therefore be propagated when calculating cumulative long-term carbon opportunity costs. Our approach "cuts to the chase" by calculating the cumulative change in carbon stock over long time scales directly. This approach also follows a core methodological principle in sustainability science that long-term sustainability measures should focus primarily on cumulative stocks and only secondarily on flows or fluxes[17,18].

Our primary results reflect changes in aboveground and belowground biomass, and do not consider soil carbon, leaf litter, residues, and woody debris. The possible additional carbon opportunity cost associated with these non-living carbon pools is additionally addressed in Supplementary section 1.1.6.

Crop harvesting area, for which we had data on all individual crops and may reflect multiple harvests per year[1], is not the same as the physical cropping area, which may include intermittent fallow areas across multiple years over which averages were calculated[4]. To estimate the physical cropping area for individual crops in each grid cell, we normalized the harvest area of each individual crop by the total physical crop area of all crops for that cell to calculate the physical area of each individual crop (Eq 1)

$$(1) \qquad CA_{i,j} = HA_{i,j} \frac{\sum_{i=1}^{175} HA_{i,j}}{CA_j}$$

where for each grid cell j, CA_j is the total physical cropping area, $HA_{i,j}$ is the harvested area for each crop i, and $CA_{i,j}$ is the physical cropping area associated with each crop.

The proportion of each human-edible crop that is allocated toward animal feed in ref [3], as well as all human-inedible forage crops grown for ruminants, is assumed to be taken out of production when calculating the carbon opportunity cost, with some exceptions: we adjusted proportions for certain protein crops, notably oilseeds (e.g. peanuts, sesame, sunflower but excluding inedible whole seeds like rapeseed) and legumes uniformly, to provide additional supply of calories and protein[19] (Supplementary Table 1), until global production of each macronutrient was at least 25% higher than dietary requirements, after accounting for wastes[20].

We calculated the carbon stocks of the remaining feed production and pasture areas in each grid cell, i.e. that which is needed to support animal-sourced food production, then subtracted this quantity from carbon in potential vegetation over the same area in each grid cell to calculate the carbon opportunity cost of production (Fig. 1).

1.1.5. Uncertainty analysis

We used a wide range of available estimates and data to calculate errors in terrestrial carbon. For cropland areas growing human-edible feed for animals, we performed a range of simulations that spanned removing crops from the highest-carbon areas to the lowest-carbon areas, holding production constant.

For carbon in pasturelands in non-forested areas, we calculated the sample standard error of the mean (SEM) conditional on each grid cell for all seven datasets of actual biomass in areas of present-day permanent pastures. For carbon in potential vegetation, we also calculated grid cell-level SEMs across all 6 datasets.

From the aforementioned distributions, we calculated 95% confidence intervals for the total carbon opportunity cost of present-day animal agricultural production and future scenarios globally. Our errors therefore reflect uncertainties across all 126 possible combinations of carbon in potential vegetation, carbon in actual pastureland vegetation, and differing spatial distributions of animal feed removal (Figs. 2 & 2; Supplementary Tables 3 & 5).

The confidence intervals do not reflect errors in carbon in crop plant tissues, carbon in artificial pastures (in areas of potential forest vegetation), or differing spatial estimates of pasture area. For all of these factors, we used the most conservative data and/or parameter estimates available from the literature, taken from refs [4,7, 8], and discussed in Supplementary sections 1.1.2 and 1.1.3.

1.1.6. Carbon in Non-living pools

We approximated the carbon in non-living pools such as soil, dead wood, and leaf litter, using parameters for broad biome categories, derived from ref [21] and summarized in ref [22], to be consistent with previous analyses. From these parameters, we calculated the non-living carbon both in agricultural systems and in potential vegetation, and took their differences just as in Supplementary section 1.1.4.

We assume that cropland soil organic matter (SOM) is higher than in the aforementioned references: we set it 30% less than SOM in potential vegetation in their respective regions. This adjustment puts our estimate for cropland SOM more in line with estimates from other literature[8,23], is more representative of soil carbon dynamics occurring following land use change after relatively short time intervals (a few years rather than decades or centuries[21]), and makes our differencing approach more conservative overall.

High spatial resolution soil organic matter data are available from a variety of sources, but these data typically reflect present-day conditions only. Using them to produce counterfactual scenarios, wherein soil carbon is estimated for potential vegetation, or for agricultural expansion and tilling, would rely on a number of counterfactual assumptions, and is beyond the scope of our analysis.

We calculated the differences in agricultural vs. potential non-living carbon pools within each biome, deriving an approximate non-living-carbon opportunity cost of animal agriculture, which we summarize in Supplementary Table 4. Changes in non-living carbon for future dietary scenarios are summarized in Supplementary Table 6. Because our results are a low-parameter estimate averaged across entire biomes, and lack the spatial resolution and comprehensive uncertainty analysis of our results for living biomass, these results are not statistically robust and should be interpreted only as an approximation.

1.2. 2050 Scenario modeling framework

For our future scenario analysis, we developed a low-parameter, top down model to adopt prior literature estimates of Business as Usual (BAU) food systems, which are modified to produce Eat-Lancet Commission (ELC) diets and vegan (VGN) diet scenarios. This approach is adaptable to multiple choices of future projection, provided only a few key parameters are available in that literature (regional land expansion, total animal protein consumption, the fraction of crop production for feed, and production or yields of protein-rich crops) without requiring a full recreation or alternative model to those that have previously produced robust, fully represented systems.

A drawback of this approach is that it lacks the precision of an explicitly and originally modeled future scenario. For instance, we cannot precisely report the land use and production efficiency of peanuts vs. sunflower seed vs. pork with a high degree of confidence. Nonetheless, this approach assures agreement with past work, as we capture large-scale consequences of changes to production and consumption accurately from literature sources. It can also utilize a combination of literature sources when some key parameters are lacking, provided they are normalized by demand and population.

Our estimates of future cropland requirements for VGN and ELC diets, as well as pastureland usage for ELC diets, all stem from the choice of which BAU projection is adopted in the following steps. Our land use model takes the form

$$(2) \qquad A_{r,spared} = Ac_r\left(1 - Sc_{r,BAU} \cdot f\right) + Ap_r\left(1 - Sp_{r,BAU} \cdot g\right)$$

Where A_{spared} is the land use relative to present day (negative is land use expansion), Ac is present day land use by region r, Sc_{BAU} and Sp_{BAU} are the scale factors by which croplands and pastures on each continent are expanded in the BAU scenario of choice (e.g. a 20% increase in crop area corresponds to $Sc = 1.2$). The three dietary scenarios differ with respect to f and g, the fraction of crops and pastures, respectively, remaining in production.

For the BAU scenario

$$(3) \qquad f_{BAU} = 1; g_{BAU} = 1$$

For the VGN scenario, we calculate a revised fraction *f* for protein-rich crops such as legumes and edible oilseeds, which replace animal protein consumption, and all other human-edible crops. The product of f_{VGN} and Ac, summed across all these protein crops, can be decomposed to be approximated in the following way:

$$(4) \qquad \sum_{i \in protein\ crops} Ac_{r,i} \cdot f_{VGN,i} = \left(F_p + \frac{AP}{Prod \cdot R_p}\right) \cdot \sum_i Ac_{r,i}$$

Where F_p is the present area-weighted fraction of protein crops used as food. *AP* is total animal protein in tonnes for 2050 BAU. *Prod* is the total protein crop production in tonnes. R_p is the weighted average ratio of protein to harvested mass for all protein crops. Both *AP* and *Prod* are taken from BAU literature values, but can be approximated if they are not available in the literature:

$$(5) \qquad AP = Population \cdot DRI \cdot Q \cdot (1 + W_p)$$

AP determines the additional fraction of protein crops needed to support 2050 VGN diets (Eq. 4). *DRI* is the age-and-sex-weighted average daily recommended intake of protein (example value of 52 g capita^{-1} day^{-1} from Springmann et al.[19]), Q is the proportion of animal protein to total protein consumption in 2050 (example value of 0.41 or 41% from FAO[24]), which protein crops are replacing. W_p is a scalar for the proportion of protein crops lost as retail, consumer, and distribution wastes along the supply chain, which serve as replacements to animal protein in the VGN scenario (example value of 0.12, as 12% of pulses and oilseed harvests are lost as wastes, per weighted average, from Alexander et al.[20]). If *AP* is directly available, then the right side of this equation can be calculated to corroborate the *AP* estimate.

Protein crop production in BAU can be approximated as

$$(6) \qquad Prod = y \cdot Ac_r \cdot Sc_{r,BAU}$$

Where y is the area-weighted average yield of protein crops under BAU. The crop production fraction *f* is then calculated for all the remaining crops that are not replacing macronutrient contents of the excluded animal-sourced foods in the VGN scenario.

$$(7) \qquad \sum_{i \notin protein\ crops} A_{c,i} \cdot f_{VGN,i} = (1 - F_{feed}) \cdot \sum A_{c,i}$$

Where F_{feed} is the fraction of total crop production that is appropriated for animal feed in the BAU scenario literature source.

Lastly for VGN, the pasture fraction is set to zero. This term also includes forage crops, which are inedible to humans and primarily used to feed ruminants.

$$(8) \qquad g = 0$$

For the ELC scenario, the fraction of remaining crop production *f* is similar to that of VGN, but must account for a fraction of animal-sourced foods remaining in production,

$$(9) \qquad \sum_{i \in protein\ crops} A_{c,i} \cdot f_{ELC,i} = \left(F_p + \frac{AP \cdot G}{Prod \cdot R_p}\right) \cdot \sum A_{c,i}$$

$$(10) \quad \sum_{i \notin protein\ crops} A_{c,i} \cdot f_{ELC,i} = [1 - F_{feed} \cdot (1 - \sum_a F_a C_a)] \cdot \sum A_{c,i}$$

Where G is the consumption-weighted average fraction of each animal-sourced food remaining in production, F_a, the fraction of each animal sourced food category a remaining in production, and C_a is the proportion of total crop production allocated to each animal production category.

$$(11) \quad g_{ELC} = 1 - \sum_a F_a P_a$$

Where P_a is the proportion of total pasture resource allocated to each ruminant animal production category. The parameters C_a and P_a can either be explicitly calculated from literature animal feed conversion rates, or assumed to approximate present-day allocation fractions, for which literature estimates are available[29]. This is a reasonable simplification because all animal food categories and their respective feed efficiencies are expected to simultaneously increase in the future, albeit at varying rates; additionally, the final estimate is relatively insensitive to the individual feed and pasture allocation parameters C_a and P_a because the sum of their multiplicand, F_a, the proportion of total animal demand, remains constant.

1.2.1. Business-as-Usual Scenario

In the BAU scenario, we modeled agricultural expansion of cropland directly from area totals at the continent level from the Alexandratos and Bruinsma FAO projection [24], consistent with multiple other recent analyses wherein food systems are modeled to 2050[19,25].. We downscaled continental-scale cropland area expansion $A_{r,spared}$ to our 5-arcminute land use data by assuming that expansion will follow similar present-day spatial distribution of croplands. However, we include uncertainties associated with this spatial averaging assumption by varying crop expansion over a range of high- to low-carbon in potential vegetation according to Supplementary Methods section 1.1.6. We then multiplied the 2050 BAU area expansion by carbon per hectare in each 5-arcminute grid cell in the potential vegetation datasets.

For pasture area, we extrapolated land area expansion projections in Bouwman et al. [26] from 2030 to 2050 and scaled to be normalized to the human population of ref [24], producing an estimate of approximately 6% pasture expansion globally. Adopting these optimistic estimates was intended to produce a conservative estimate for the net land-sparing consequences of dietary change, relative to 2050 BAU. We modeled BAU pasture expansion proportionally over the same distribution of potential vegetation biomes as the present-day distribution of agricultural land within each continent. This likely represents a conservative estimate for the loss of carbon to the atmosphere because agricultural expansion is presently occurring disproportionately in tropical areas[27].

1.2.2. Dietary Change Scenarios

For the VGN scenario, we assumed all present-day pasture was taken out of production. For crop fractions f, we solved equation (4) using animal and protein crop production (*AP* and *Prod*) directly from ref [24] and protein content using weight-to-protein ratios R_p from FAOSTAT. We corroborated our calculations for f using equations (5) and (6) using age-adjusted protein *DRI* from ref [19] (similar to Supplementary section 1.1.4) and legume and oilseed food wastes W from ref [20]. Finally, we accounted for the remaining fraction of 2050 BAU production using F_{feed} from ref [23]. The pace of production of animal feeds through 2050 is expected to increase greater than pace of overall agricultural productivity as global diets become richer in meat and dairy, hence the feed fraction for most cereal crops increases and the food fraction decreases. Results for the population-scale micronutrition and the proportions and totals for crop productivity (feed + food) in 2050 BAU and VGN are presented in Supplementary Table 1.

The spatial distribution of 2050 crop removal follows the present-day distribution to provide the median estimate, but were also taken out of production in order of most and least carbon-rich potential vegetation to provide a range of estimates for our uncertainty analysis.

For the ELC scenario, we determined both cropland and pasture area as a fraction of the BAU and VGN endpoints (Eq. 9-11). We calculated the proportions of each animal food category in 2050 ELC diets, relative to BAU, from results in refs [19] and [28] (F_a, Supplementary Table 2). To connect each animal-sourced food product category to crop and pasture usage we approximated feed conversion ratios C_a and P_a from present-day from Herrero et al[29]. Allocation parameters from these two sources allowed us to calculate the proportion by which BAU animal feed production must be reduced, and subsequently calculate the proportional feed crops f and total needs associated with ELC diets (Supplementary Table 2) along with the proportional pasture area g (35% of BAU area).

Animal feed croplands were taken out of production in ELC based upon the present-day spatial distribution of animal feed croplands. To calculate errors associated with the ELC distribution assumptions, we also added and removed cropland in geographical order of both the highest and lowest carbon in potential vegetation.

Pastures in the ELC scenario assumed to be removed in equal distribution geographically. This is a reasonable assumption because stocking density and production of cattle tends to correlate well with the potential productivity of their pastures[29]. This assumption is also conservative because cattle operations in humid tropical middle-income countries are underperforming relative to their maximum potential production[30].

1.2.3. Lower-yield 2050 Scenarios

To test the sensitivity of our scenario results to using optimistic future yield assumptions from ref [24], we calculated the CO_2 emission/removal associated with land use in a scenario of low yields and high agricultural expansion, derived from ref [31] and summarized by continent in ref [22] (scenario CT1 in the text). For the BAU scenario, we used continental-level land area expansion $S_{r,BAU}$ directly from ref [22, scenario CT1 Supplementary Tables 13 and 14]. For the VGN and ELC scenarios, we used protein crop yields y from ref [31] summarized for each continent in ref [22, scenario CT1 Supplementary Table 6 for soybeans, pulses, oilcrops]. Animal-sourced food consumption is derived from the same FAO source, but production AP is normalized to a slightly higher population estimate. Results comparing these low-yield scenarios to the high-yield scenarios of the main text are presented in Supplementary Table (5).

1.3. Supplementary Tables 1–2

	Present day		2050	
	Feed + food crops (MMT)	Percentage for food	Feed + food crops in BAU (MMT)	Percentage for food in VGN
Maize	771	27%	1053	18%
barley	164	17%	225	13%
Wheat	701	82%	259	89%
Oats	31	17%	43	13%
Other grains (n=5)	825	89%	1129	88%
Soybean	198	51%*	314	58%*
Rapeseed**	49	66%	79	59%
Sunflower	35	63%	56	44%
Other oil crops (n=3)	214	85%*	340	98%*
Pulses (n=3)	65	100%*	94	100%*
Roots and Tubers (n=5)	760	76%	916	76%
Forages (n=16)	2379	0%	3520	0%
Other crops (n=13)	2519	93%	3401	93%
	Feed + food crops (MMT)	Food crops only	BAU feed + food crops	Food crops for VGN
kcal person^{-1} day^{-1}	4607	2754	4631	2845
g protein person^{-1} day^{-1}	123.1	73.6	125.4	76.1

* fraction changed from Cassidy et al. and Alexandratos and Bruinsma to provide sufficient nutrients in remaining food crop production.
** rapeseed is only assumed to provide oil and does not provide human protein

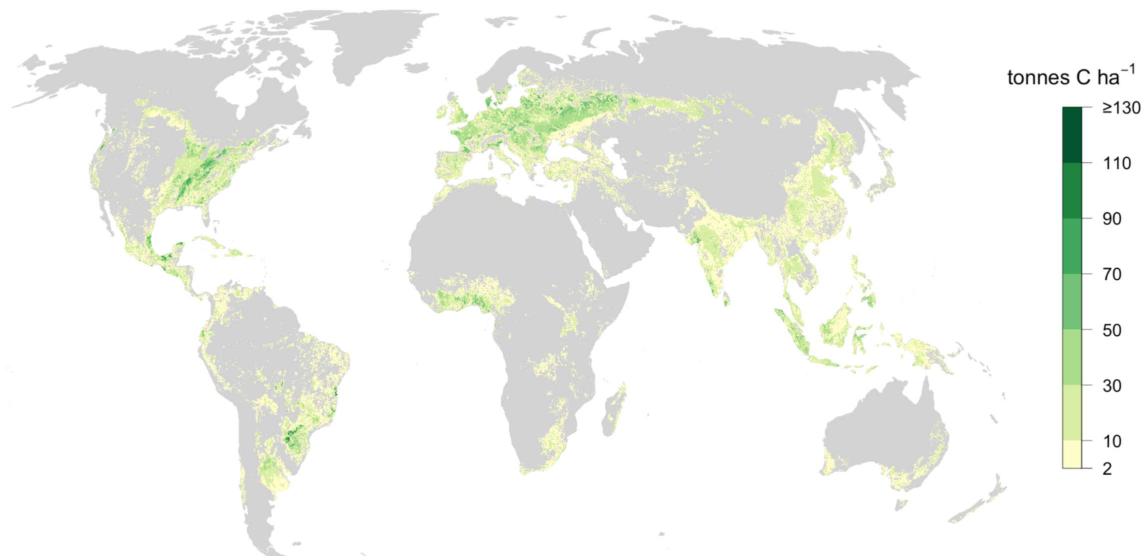
Supplementary Table 1. Crop production, human food consumption, and protein and energy production in present-day and 2050 future scenarios. Present-day food crop fraction is taken from Cassidy et al. [3]. For crops noted with an asterisk (*), the crop fraction was adjusted to provide sufficient nutrients without animal products. Food crop supply (shown in nutrients person^{-1} day^{-1}) is adjusted by consumer retail and consumer waste fractions from ref [20].

	2050 BAU	2050 ELC	Reduction
Average consumption	g person^{-1} day^{-1}		
Beef	33.2	6.7	80%
Small ruminant meat	9.1	2.7	70%
Dairy (raw milk equivalent)	263.9	191.6	27%
Pork	35.9	4.5	87%
Poultry	47.1	24.1	49%
Eggs	23.2	11.1	52%
Feed Requirements	**Production (for feed - MMT)**		**Reduction**
Cereal Crops	1445	434	70%
Oilseeds	358	123	66%
Other human-edible crops	445	289	65%
Forage crops	3520	2205	63%

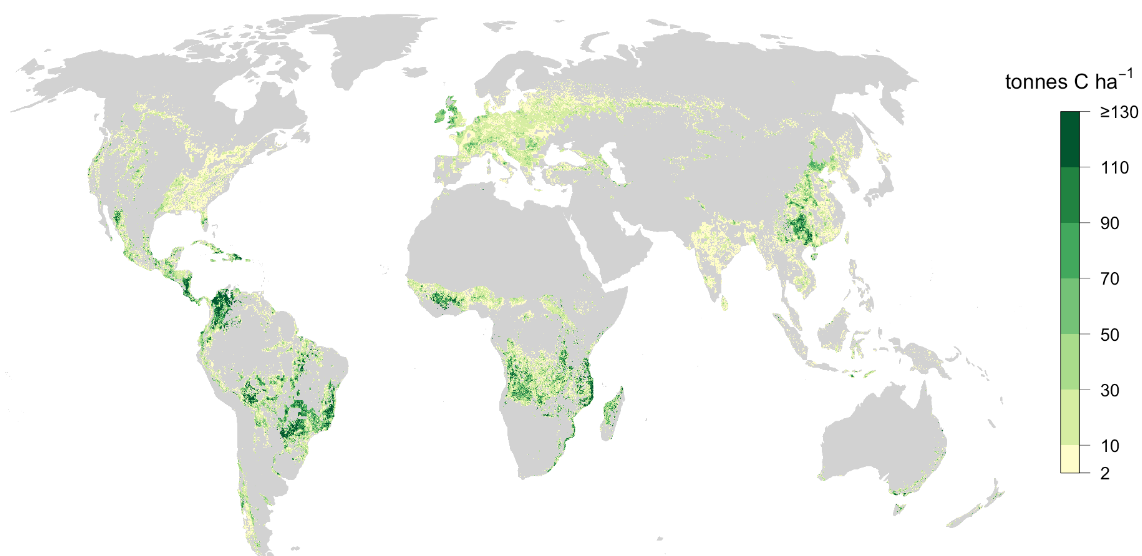
Supplementary Table 2. Per capita consumption of animal production for 2050 BAU and ELC dietary scenarios presented as global means. Reductions refer to 2050 ELC diets relative to 2050 BAU diets. Reductions in human-edible crop feed and forage feed were determined from reduction percentages for the animal-sourced food categories to which they are apportioned.

2. Supplementary Results

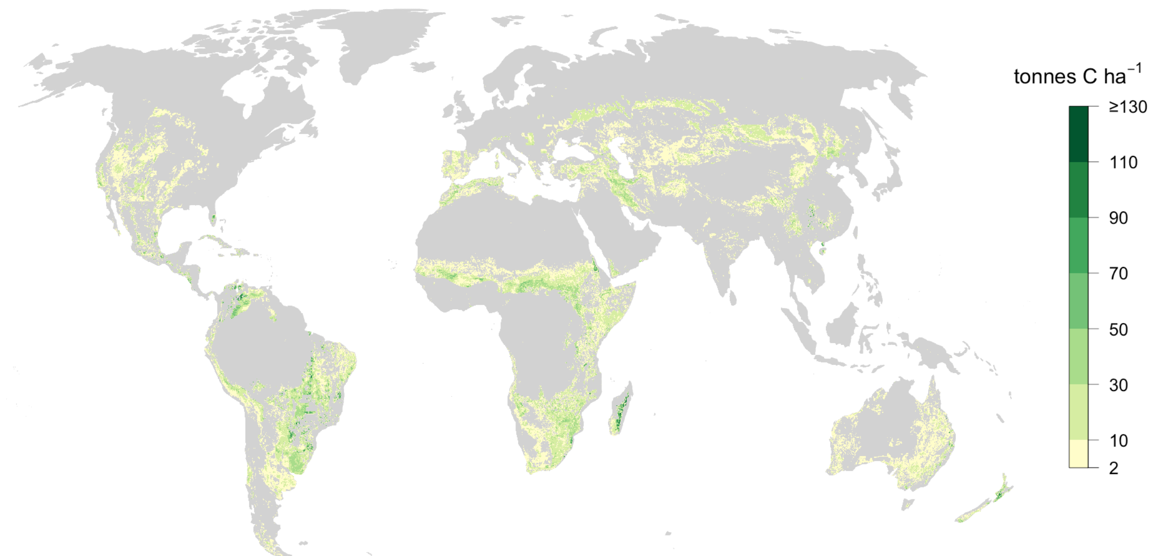
2.1. Supplementary Figures 1–5



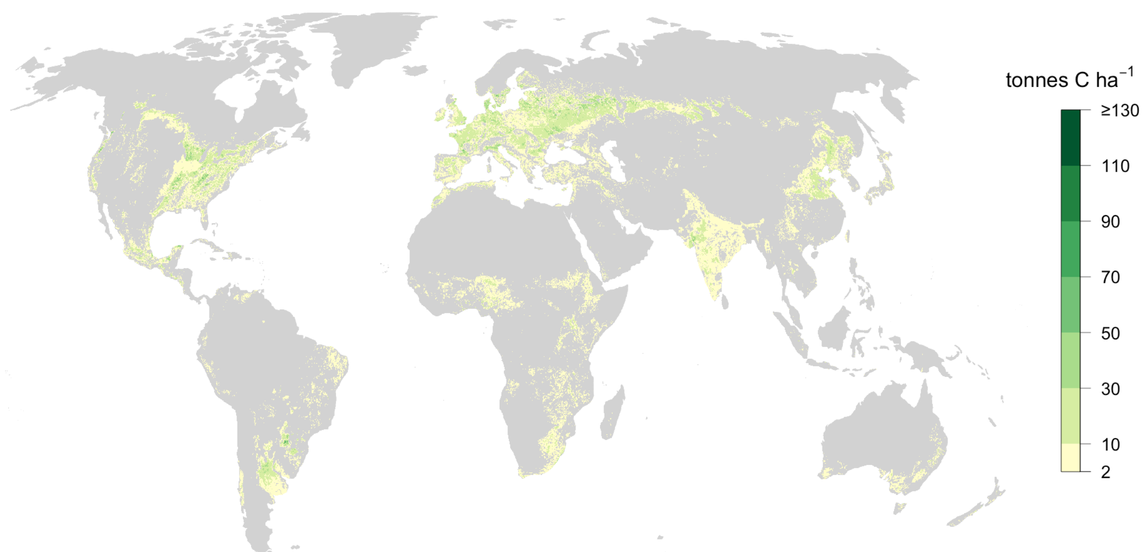
Supplementary Figure 1. Carbon opportunity cost of present-day animal feed croplands (potential C sequestration from ecosystem restoration). Carbon in each grid cell is the product of land area presently under crop cultivation multiplied by the potential vegetation carbon density, minus estimated carbon in croplands.



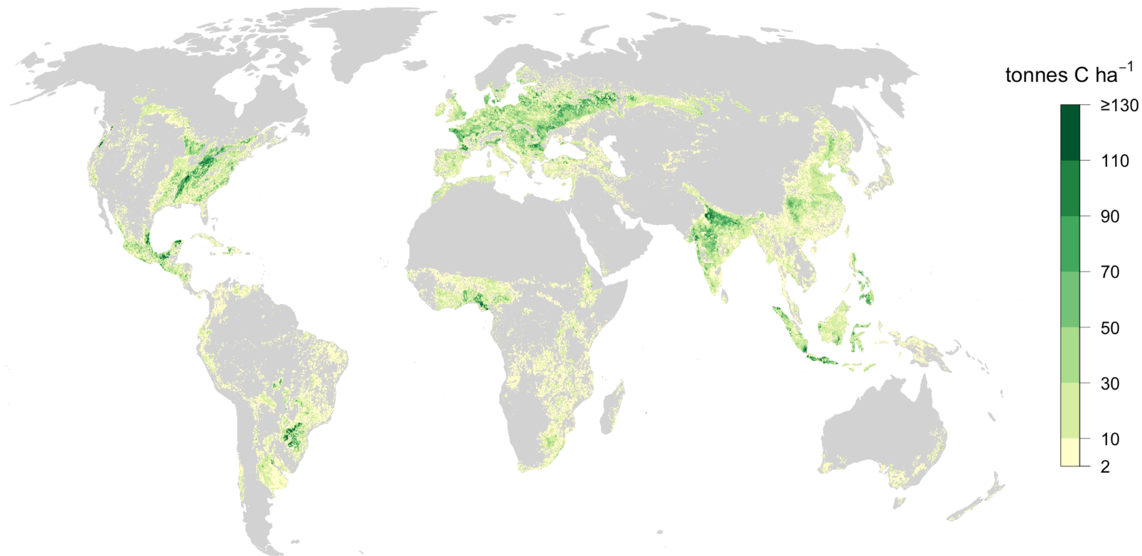
Supplementary Figure 2. Carbon opportunity cost of present-day permanent pastures (potential C sequestration from ecosystem restoration) in areas of potential forest vegetation. Carbon in each grid cell is the product of land area presently under cultivation multiplied by the potential vegetation carbon density of forests, minus estimated carbon in artificial pastures.



Supplementary Figure 3. Carbon opportunity cost of present-day permanent pastures (potential C sequestration from ecosystem restoration) in areas of potential grassland vegetation. Carbon in each grid cell is the product of land area presently under pasture management multiplied by the carbon density of potential vegetation in grasslands, minus estimated carbon in under present management.



Supplementary Figure 4. Carbon opportunity cost of present-day animal feed crops (potential C sequestration from ecosystem restoration) assuming animal feed removal is prioritized in areas of the lowest C potential vegetation.



Supplementary Figure 5. Carbon opportunity cost of present-day animal feed crops (potential C sequestration from ecosystem restoration) assuming animal feed removal is prioritized in areas of the highest C potential vegetation.

2.2. Supplementary Tables 3–6

	Area (Mkm^2)			Carbon in potential vegetation (GtC)		
	Pastures		Croplands	Pastures		Croplands
	native forest areas	native grassland areas		native forest areas	native grassland areas	
USA and Canada	0.36	2.08	1.46	3.5 (2.8 - 4.1)	1.8 (0.4 - 3.8)	7.2 (3.6 - 8.8)
Latin America and Caribbean	1.91	3.14	0.74	29.3 (25.7 - 32.9)	10.3 (5.4 – 16.1)	7.5 (2.2 - 9.0)
Europe	0.86	0.71	1.93	8.6 (7.0 – 10.1)	2.0 (1.1 - 2.8)	14.4 (7.8 - 17.4)
Central Asia, Middle East, and North Africa	0.07	3.91	0.40	0.5 (0.4 - 0.7)	3.4 (1.1 – 6.1)	1.2 (0.7 - 1.5)
Sub Saharan Africa	2.02	5.12	0.36	19.1 (14.7 - 23.7)	11.7 (5.7 - 18.4)	3.6 (2.0 - 6.7)
South Asia	0.09	0.39	0.35	1.2 (0.9 - 1.4)	0.4 (0.1 – 1.0)	3.1 (1.5-7.8)
Eastern Asia	0.67	2.94	0.44	7.6 (6.4 - 8.8)	2.8 (0.7 – 7.2)	3.5 (1.5-5.7)
Southeast Asia and Oceania	0.12	2.74	0.45	1.7 (1.5 - 2.0)	2.0 (0.7 – 4.5)	6.2 (0.4-6.5)
All	6.1	21.0	6.1	71.5 (59.5 - 83.8)	34.4 (15.2 - 59.9)	46.6 (19.5 - 63.4)

Supplementary Table 3. Present-day suppression of carbon stocks in native vegetation by animal agriculture. Cropland carbon refers to potential carbon stocks in geographic areas that presently provide animal feed crops. Pasturelands are disaggregated by the native ecosystems they have replaced: forests (tropical forests, temperate forests, and dense savannas) and grasslands (grasslands, shrublands, and sparse savannas). Parentheses contain 95% confidence intervals.

	Area (Million hectares)		Ecosystem carbon in non-living pools ($Mg\ ha^{-1}$)			Present-day Soil carbon ($Mg\ ha^{-1}$)		**Difference in non-living carbon (GtC)**	
	Cropland	Pasture	Dead wood	Litter	Soil	Cropland	Pasture	Cropland	Pasture
Tropical forest	98	427	10	5	52	36	40	3.0	11.5
Temperate forest	194	220	49	25	48	34	35	17.1	19.1
Boreal forest	9	15	3	29	28	20	48	0.4	0.2
Savanna	109	553		7	40	28	40	2.1	3.9
Grassland	134	761		3	35	25	35	1.7	2.3
Dense shrubland	40	191		3	27	19	27	0.4	0.6
Open shrubland	26	546			19	13	19	0.2	0
Desert	4				9	6		0.01	
Total	613	2713						**24.9**	**37.6**
								62.5	

Supplementary Table 4. Area presently in agricultural production for animal-sourced foods and ecosystem carbon (GtC) in non-living pools (soil and debris). Soil carbon in croplands is assumed to be 30% of total soil carbon for native ecosystems, a conservative estimate.

	High yields (main text Fig. 3)			Low yields		
	BAU	ELC	VGN	BAU	ELC	VGN
Cropland	36 (28, 45)	-87 (-126, -37)	-159 (-216, -84)	185 (176, 253)	34 (-80, 53)	-36 (-85, -20)
Pasture	50 (41, 60)	-245 (-332, -173)	-388 (-527, -274)	62 (40, 85)	-233 (-316, -164)	-388 (-527, -274)
Total	**86** (68, 105)	**-332** (-459, -210)	**-547** (-743, -358)	**247** (216, 339)	**-199** (-396, -112)	**-424** (-612, -294)
Difference from BAU		-418 (-563, -278)	-633 (-848, -426)		-446 (-734, -328)	-671 (-951, -510)

Supplementary Table 5. Changes from present day carbon in living biomass, comparing dietary scenarios assuming high yields (from Alexandratos and Bruinsma) as in the main text, and low yields (from Ray et al. and Bajzelj et al.). Lower yields lead to less uptake/more emission from land use change across all dietary scenarios than higher yields.

	High yields			Low yields		
	BAU	ELC	VGN	BAU	ELC	VGN
Cropland	11	-48	-87	63	20	-40
Pasture	8	-87	-138	14	-87	-138
Total	**19**	**-135**	**-225**	**78**	**-67**	**-178**
Difference from BAU		-154	-244		-86	-256

Supplementary Table 6. Changes in non-living carbon pools in 2050 scenarios, relative to present day.

References

[1] Monfreda, C., Ramankutty, N. & Foley, J. A. Farming the planet: 2. Geographic distribution of crop areas, yields, physiological types, and net primary production in the year 2000. *Global Biogeochem. Cycles* **22**, n/a-n/a (2008).

[2] FAOSTAT. *Statistical Databases.* http://faostat.fao.org (2019)

[3] Cassidy, E. S., West, P. C., Gerber, J. S. & Foley, J. A. Redefining agricultural yields: from tonnes to people nourished per hectare. *Environ. Res. Lett.* **8**, 034015 (2013).

[4] Ramankutty, N., Evan, A. T., Monfreda, C. & Foley, J. A. Farming the planet: 1. Geographic distribution of global agricultural lands in the year 2000. *Global Biogeochem. Cycles* **22**, n/a-n/a (2008).

[5] Fetzel, T. *et al.* Quantification of uncertainties in global grazing systems assessment. *Global Biogeochem. Cycles* **31**, 1089–1102 (2017).

[6] Goldewijk, K. K., Beusen, A., Doelman, J. & Stehfest, E. Anthropogenic land use estimates for the Holocene - HYDE 3.2. *Earth Syst. Sci. Data* **9**, 927–953 (2017).

[7] Erb, K. H. *et al.* A comprehensive global 5 min resolution land-use data set for the year 2000 consistent with national census data. *J. Land Use Sci.* **2**, 191–224 (2007).

[8] West, P. C. *et al.* Trading carbon for food: Global comparison of carbon stocks vs. crop yields on agricultural land. *Proc. Natl. Acad. ofr Sci.* **107**, 19645–19648 (2010).

[9] Erb, K. H. *et al.* Unexpectedly large impact of forest management and grazing on global vegetation biomass. *Nature* **553**, 73–76 (2018).

[10] Erb, K. H. *et al.* Biomass turnover time in terrestrial ecosystems halved by land use. *Nat. Geosci.* **9**, 674–678 (2016).

[11] Stehfest, E. *et al.* Climate benefits of changing diet. *Clim. Change* **95**, 83–102 (2009).

[12] Searchinger, T. D., Wirsenius, S., Beringer, T. & Dumas, P. Assessing the efficiency of changes in land use for mitigating climate change. *Nature* **564**, 249–253 (2018).

[13] Dietze, M. C. *et al.* Iterative near-term ecological forecasting: Needs, opportunities, and challenges. *Proc. Natl. Acad. Sci. U. S. A.* **115**, 1424–1432 (2018).

[14] Longo, M. *et al.* Ecosystem heterogeneity and diversity mitigate Amazon forest resilience to frequent extreme droughts. *New Phytol.* **219**, 914–931 (2018).
[15] Levine, N. M. *et al.* Ecosystem heterogeneity determines the ecological resilience of the Amazon to climate change. *Proc. Natl. Acad. Sci.* **113**, 793–797 (2016).
[16] Li, H., Renssen, H. & Roche, D. M. Global vegetation distribution driving factors in two Dynamic Global Vegetation Models of contrasting complexities. *Glob. Planet. Change* **180**, 51–65 (2019).
[17] Matson, P., Clark, W. C., & Andersson, K. *Pursuing sustainability: a guide to the science and practice*. Princeton University Press. (2016).
[18] Stiglitz, J. E., Fitoussi, J.-P. & Durand, M. *Beyond GDP: Measuring What Counts for Economic and Social Performance*. (OECD, 2018). doi:10.1787/9789264307292-en
[19] Springmann, M. *et al.* Health and nutritional aspects of sustainable diet strategies and their association with environmental impacts: a global modelling analysis with country-level detail. *Lancet Planet. Heal.* **2**, e451–e461 (2018).
[20] Alexander, P. *et al.* Supplement to Losses, inefficiencies and waste in the global food system. *Agric. Syst.* 1–5 (2017). doi.org/10.1016/j.agsy.2017.01.014
[21] Anderson-Teixeira, K. J. & Delucia, E. H. The greenhouse gas value of ecosystems. *Glob. Chang. Biol.* **17**, 425–438 (2011).
[22] Bajželj, B. *et al.* Importance of food-demand management for climate mitigation. *Nat. Clim. Chang.* **4**, 924–929 (2014).
[23] Murty, D., Kirschbaum, M. U. F., Mcmurtrie, R. E. & Mcgilvray, H. Does conversion of forest to agricultural land change soil carbon and nitrogen? A review of the literature. *Glob. Chang. Biol.* **8**, 105–123 (2002).
[24] Alexandratos, N. & Bruinsma, J. World agriculture towards 2030/2050: the 2012 revision. *FAO* **20**, 375 (2012).
[25] Erb, K.-H. *et al.* Exploring the biophysical option space for feeding the world without deforestation. *Nat. Commun.* **7**, 11382 (2016).
[26] Bouwman, A. F., Van der Hoek, K. W., Eickhout, B. & Soenario, I. Exploring changes in world ruminant production systems. *Agric. Syst.* **84**, 121–153 (2005).
[27] Hansen, M. C. *et al.* High-resolution global maps of 21st-century forest cover change. *Science.* **342**, 850–853 (2013).
[28] Willett, W. *et al.* Food in the Anthropocene: the EAT–Lancet Commission on healthy diets from sustainable food systems. *Lancet* **6736**, 3–49 (2019).
[29] Herrero, M. *et al.* Biomass use, production, feed efficiencies, and greenhouse gas emissions from global livestock systems. *Proc. Natl. Acad. Sci. U. S. A.* **110**, (2013).
[30] Thornton, P. K. & Herrero, M. Potential for reduced methane and carbon dioxide emissions from livestock and pasture management in the tropics. *Proc. Natl. Acad. Sci. U. S. A.* **107**, 19667–19672 (2010).
[31] Ray, D. K., Mueller, N. D., West, P. C. & Foley, J. A. Yield Trends Are Insufficient to Double Global Crop Production by 2050. *PLoS One* **8**, (2013).