Dietary change in high-income nations alone can lead to substantial double climate dividend

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Editor's Summary

The contribution of planetary diets to climate change mitigation depends on several factors, including where these diets are adopted. This study quantifies avoided greenhouse gas emissions that would result from a shift to EAT-Lancet diets in 54 high-income countries through agricultural production and the restoration of natural vegetation in saved lands.

Abstract

A dietary shift from animal-based to plant-based foods in high-income nations could reduce greenhouse gas (GHG) emissions from direct agricultural production and increase carbon sequestration if resulting spared land was restored to its antecedent natural vegetation. We estimate this double effect by simulating the adoption of the EAT-Lancet planetary health diet by 54 high-income nations representing 68% of global GDP and 17% of population. Our results show that such dietary change could reduce annual agricultural production emissions of high-income nation diets by 61% while sequestering as much as 98.3 (55.6-143.7) Gt CO_2e, equivalent to ~14 years of current global agricultural emissions until natural vegetation matures. This amount could potentially fulfil high-income nations' future sum of carbon dioxide removal (CDR) obligations under the principle of equal per-capita CDR responsibilities. Linking land, food, climate and public health policy will be vital to harnessing the opportunities of a double climate dividend.

Main

Agriculture is key to determining the rate and depth of climatic change. Current food system emissions may preclude the limiting of climate warming to 1.5 or even 2 degrees Celsius [1], yet simultaneously, radical land use and agricultural management interventions may be crucial strategies for limiting climatic change [2]. Dietary change, for one, has been found to be a practical and effective strategy in multiple studies [3,4]. The global food system is responsible for ~13.7 Gt of carbon dioxide equivalent (CO_2e) emissions per year (yr^{-1}), accounting for 26% of anthropogenic greenhouse gas (GHG) emissions[5]. Agricultural production, particularly animal-derived products and land-use change, accounts for the largest proportion of these emissions[6].In 2013, per-capita meat consumption in high-income countries was almost six times greater than that in low-income countries[6]. Animal-derived products account for 70% of food-system emissions in high-income countries but only 22% in low-middle-income countries[7]. Attribution of these emissions is complicated by agricultural globalization, whereby food consumption in high-income countries drives overseas GHG emissions through international trade[8]. Dietary change in high-income countries may therein hold the potential to substantially reduce agricultural emissions around the world—a potential climate 'dividend'.

Shifting from current dietary patterns in high-income nations to healthier alternatives with few or no animal products could simultaneously spare agricultural land for other uses. While a portion of this land may ultimately be used for various types of development and/or bioenergy, its use for intentional ecosystem restoration – a so-called 'natural climate solution' [2,9] would represent a second, additive carbon dividend of dietary change. In many regions, reverting cropland to its antecedent or 'potential' natural vegetation (PNV) can substantially increase aboveground biomass carbon (AGBC), belowground biomass carbon (BGBC) and soil organic carbon (SOC) stocks [8,10–13] with additional co-benefits for biodiversity [14] and other ecosystem services. Recent studies highlight the large magnitude of this sequestration potential. Global vegetation is believed to currently store less than 50% (450 GtC) of its potential C stock (916 GtC) due to appropriative land use [11]. Likewise, global soils have lost 116 GtC over the course of agricultural history due to C-cycle imbalances imposed by cultivation and other human appropriation [15]. A substantial portion of these carbon stocks could be recovered if land is spared by dietary change and subsequently restored to PNV. However, the extent to which land could be spared has not been comprehensively assessed due, in part, to the complex trade relationships between food producers and consumers[8]. Such relationships are particularly relevant to the land use footprints of high-income nations which import large amounts of food from around the world[16].

We assess the potential for a 'double dividend' for GHG emissions mitigation via dietary change from both reduced direct agricultural production emissions and carbon sequestration via the land sparing whereby agricultural lands can revert to other uses. While linked, these elements play out over two different timeframes: the first—reduced production emissions—influences the sector's annual GHG contribution, while the second—sequestration—often requires decades or even centuries to realise its full potential. We conceptualize the latter effect, below, as a one-time "committed" mass of C that is sequestered over an unspecified period after restoration is initiated (see methods). In addition, information and knowledge nudges could motivate the public's perception and individual intrinsic identity on sustainable diets, which would facilitate value-driven actions on diet change [17,18]. However, such climate benefits will only materialize if land upstream in the supply chain indeed is spared from agricultural activities. We use data for the year 2010 from the Food and Agriculture Biomass Input–Output dataset (FABIO) [19] to relate the international final demand for food items with primary agricultural production. FABIO is a physical global multi-regional input-output table and so avoids price-based impacts and issues in estimating environmental pressures embodied in global supply chains [19]. As our focus is on emissions from agricultural activities and the carbon opportunity as a result of land spared due to dietary change, we include all food consumption (i.e. in households and through service activities such as restaurants) and do not include GHG emissions from non-agricultural sectors such as transportation, processing, refrigeration, wholesale and retail. A GHG emission dataset derived from FAOSTAT at the national level is linked to FABIO to quantify emissions from agriculture embodied in diets [20]. Agricultural production is mapped to spatially explicit cropland and pastureland, which we linked to the latest harmonized global AGBC and BGBC map[21]; a SOC stock map of the top 100 cm[15]; and a PNV map with AGBC, BGBC, and SOC[11,12]. The result is a spatially explicit multiregional input-output (SMRIO) model with a uniform resolution of 5 arcmin[22,23]. We use the recommendations of the EAT-Lancet Commission as a basis for dietary change in high-income countries[3]. The EAT-Lancet Commission aims to develop human healthy diets and sustainable food production while meeting UN Sustainable Development Goals (SDGs) and climate goals [3]. Such diets are characterized by reduced meat products consumption and result in lower agricultural land requirements (for detailed recommendations per food group see methods and Supplementary Table 3). For our double dividend scenario, we assume spared land is restored to PNV (see Methods and Supplementary Information) and determine the ensuing carbon sequestration potential as the difference between the carbon stock of PNV and that of current use.

Results

Dietary change mitigation potential

A shift to the country-specific EAT-Lancet diet from current dietary pattern (i.e. benchmark year 2010) in high-income nations would reduce annual emissions from direct agricultural production by 61.5% or 0.75 Gt CO_2e yr^{-1}. This results in an average per-capita reduction in high-income nations of 0.65 ton CO_2e yr^{-1} . Our estimate of GHG reduction due to dietary change is in line with those in the literature[24] (Fig. 1, Supplementary Fig.2). Based on other recent estimates a further 0.54 Gt CO_2e yr^{-1} of reduction could be possible from downstream sectors (e.g. transportation, processing, packaging, retail, consumption, and end of life) proportional to these sectors for the same high-income nations we look at [25]. About half of this reduction would collectively occur in the US (29.9%), France (7.1%), Australia (6.5%), and Germany (4.4%) (Fig. 1B). Some large exporting middle- and low-income countries would also see emission reductions via reduced exports of agricultural products to high-income countries. These include India (3.1% of India's emissions from agricultural production), and Brazil (3.2% of Brazil's emissions from agricultural production).

A dietary shift from national average diets to the country-specific EAT-Lancet diet across high-income countries would also result in substantial opportunities for carbon sequestration. We find that a shift of this nature could spare more than 426.35 million hectares (Mha)—an equivalent area slightly larger than that of the EU. Subsequent committed sequestration over the long term on this land could increase C stocks by 98.25 (55.62 to 143.68) Gt CO_2e. This is about 60% of the global carbon accumulation estimated by Cook-Patton et al.(2020) from 349 Mha potential natural forest regrowth for the first 30 years [13], and 21% carbon sequestration over the long term if all global population adopt the country-specific EAT-Lancet diet [26].If the committed sequestration can be achieved by the end of the twenty-first century (2010-2100), the annual average sequestration rate would be 1.09 (0.62 to 1.60) Gt CO2e yr^{-1}. This rate is about 1.5 times the benefit from production emissions due to dietary change in high-income nations. However, this average hides substantial differences in annual sequestration rates over time which varies depending on 1) different land use conversions to different potential natural vegetation across different sites [27,28], 2) non-linear carbon update of vegetation over time [29,30] and 3) variations in sequestration based on uncertain climate conditions, soil, and land management techniques [30]. It also ignores potential losses due to climate related events such as wildfires, changing albedo with the recovery of potential natural vegetation, and changes to albedo from forest-related cloud cover changes [31,32] . Further discussion on the non-linear sequestration of carbon by soils and biomass is given in Supplementary Table 10. Spared agricultural land would be comprised of 343.62 Mha pastureland and 82.73 Mha cropland, with major abandonment hotspots expected in the western half of the US, Central Europe, and eastern states of Australia (Supplementary Fig.3). The spared pastureland and cropland would increase carbon sequestration by 56.20 (29.93 to 84.59) Gt CO_2e and 42.05 (25.69 to 59.09) Gt CO_2e, respectively (Supplementary Fig 7).

Carbon sequestration would be achieved predominately in large countries with large amounts of agricultural production, especially feed crops and pasture. For example, more than a half of the increase in global carbon sequestration would occur in four nations alone: the US (26.3%, 25.85 Gt CO_2e), Australia (13.5%, 13.28 Gt CO_2e), Germany (7.7%, 7.55 Gt CO_2e), and France (7.6%, 7.45 Gt CO_2e), collectively (Fig. 1A). Regionally, major hotspots for sequestration include the Midwest US, Central Europe, and the eastern states of Australia (Fig. 1A, Supplementary Fig.2) where the potential natural vegetation is forest with a high carbon density[11,26]. Australian dietary changes would see the largest per-capita carbon benefit overall at 574.90 Mg CO_2e of sequestration (6.7 times the average of all high-income countries, see Supplementary Fig.11.), driven largely by a shift away from animal products and restoration of mixed native grassland and native forest [26].

As a percentage of the total sequestration potential of dietary change, 35.5% lies outside of the consuming country (i.e. dietary change in a high-income country influences production in another country)—23.6% would be located in other high-income countries and around 11.9% would be located in middle- and low-income regions (Fig. 1A, and Supplementary Fig.2). These latter regions would also be located mainly in countries providing large amounts of agricultural production for high-income nations, such as Brazil (1.63 Gt CO_2e) and Botswana (1.23 Gt CO_2e)

Fig. 1. Changes in net carbon sequestration (A) and net GHG emissions due to dietary change in high-income countries. In (A), net carbon sequestration is the sum of aboveground biomass carbon (AGBC), belowground biomass carbon (BGBC) and soil organic carbon (SOC). In (B), net GHG emissions are shown in Robinson projection. Three major hotspots of carbon sequestration are shown for the US Midwest (a, shown in USA Albers Equal Area Conic projection), central Europe (b, shown in Europe Albers Equal Area Conic projection) and coastal regions in Australia (c, shown in Australian Albers projection). Further maps of the global spatial distribution of changes in these variables are in Supplementary Fig.8. The lower and upper bound for the global spatial distribution of changes in these variables are shown in Supplementary Figs. 9 and 10.

Animal products' role in the carbon cycle

Given the large land requirement and high emission intensity of animal agriculture, a shift away from animal product consumption comprises the largest opportunity for both increased carbon sequestration via land sparing and emission reductions from the food system itself [7,24,26]. Reductions in meat products consumption would result in 103.90 (58.62 to 151.75) Gt CO_2e of sequestration over the long term, along with annual agricultural emission reductions of 0.69 Gt CO_2e yr^{-1} (Fig. 2). The reduced consumption of dairy products and eggs would result in an additional sequestration of 18.99 (10.87 to 27.52) Gt CO_2e, and emission reductions of 0.02 Gt CO_2e yr^{-1} (Fig. 2). A further 0.05 Gt CO_2 yr^{-1} reduction in emissions come from reduced added fats and sugars, grains, tubers, and vegetables (Fig. 2). Land spared by reducing the consumption of meat products, dairy products and eggs could capture and store 81 times the annual GHG emissions from annual agricultural production (1.22 Gt CO_2e yr^{-1}) of food consumed in high-income countries in 2010.

Climate mitigation due to dietary change depends on both local agricultural production practices and local dietary preferences. Dietary changes in the US and Australia contribute the largest carbon benefits since they are mostly comprised of reductions in animal product consumption (Fig. 2 and Supplementary Fig.11). This is due to the preponderance of grass-fed beef production systems in the US and Australia[7]. We find a different situation in East Asian countries with high population. In South Korea and Japan, the opportunity for carbon sequestration is offset slightly—by 0.28 Gt CO_2e and 0.35 Gt CO_2e due to an expected increase in dairy products consumption under the EAT-Lancet diet recommendations (Fig. 2 and Supplementary Fig.11). Given that the current low levels of dairy consumption in East Asia are driven by high levels of lactose intolerance [33] our finding highlights the need for locally appropriate dietary recommendations that consider both public health and environmental outcomes.

The reduction in meat products would be offset slightly by an increase in plant-protein production. Increased production of plant-based alternatives would also be needed to satisfy other nutrient demands such as vitamin B12 and Omega-3[34]. Increasing plant proteins and fruit production would result in a small offset—35.07 Gt CO_2e—of the gains made from reducing animal products. The increase in direct emissions from the agriculture sector would be very small, at just 0.01 Gt CO_2e yr^{-1} (Fig. 2). This is somewhat unsurprising when we consider that the energy feed-to-food conversion efficiency of animal products is low and varies from 3% for beef to 17% for eggs within animal products[35,36]. In addition, the grains fed to livestock (e.g. maize and soybean) could be redirected to human consumption or spared land could be used to produce plant-based products without expanding agricultural land in net (Supplementary Fig. 3).

Fig. 2. Potential carbon sequestration (A) and potential GHG emission change (B) by food category due to dietary change in high-income nations. Food categories are divided into (a) animal products (b) mixed animal- and plant-based products, (c) plant-based products. We show detailed sectors for animal-protein groups given its important role. For detailed reporting of all products, please see methods and Supplementary Table 2. In the case where sequestration is increased (e.g. with the reduction of animal agriculture activities), the carbon sequestration opportunity is calculated as the difference between the potential natural vegetation and the current agricultural vegetation. In the case where sequestration is decreased (by increased plant protein production), the carbon sequestration opportunity is calculated as the difference between potential natural vegetation minus that of increased agricultural vegetation. The red line in (A) shows an equivalent +5 Gt CO_2e sequestration across product groups. The red line in (B) shows a -0.01 Gt CO_2e emission across product groups. The error bar means the range of potential carbon sequestration.

Mitigation potential of non-EAT-Lancet food items.

There has been little discussion of stimulants (coffee and products, cocoa beans and products, tea including mate), alcoholic beverages (wine, beer, fermented beverages, alcoholic beverages), edible offal, and other meat (e.g. horse, donkey, camel, rabbit, game meat) in previous studies, as these were not a focus of the EAT-Lancet diet [24,37]. We did not include these items in our main analysis but perform a separate assessment here to identify the additional climate mitigation benefit. We find the maximum opportunity of climate mitigation if high-income nations cease all consumption of these items as the additional climate mitigation benefit on the above basis. Although these items only comprise 5.8% of dietary

GHG emissions, they represent a non-negligible carbon sequestration opportunity. The cumulative total of these items represents a sequestration opportunity of 19.32 (10.72 to 28.34) Gt CO_2e (Fig. 3) or 19.7% of the total sequestration opportunity identified above (Fig. 1A) if high-income nations cease all consumption of these items.

While others have pointed to opportunities for sustainable intensification by abandoning luxury, low-nutrition crops such as feedstock for alcoholic beverages [38], it would be a big challenge to model potential reductions in practice due to many sociological and policy complications. While stimulant consumption can be related to risks of anxiety and depression and there are relationships between alcohol consumption and cancer, substantial reductions in these items would be a controversial cultural topic[39–42]. Nevertheless, per-capita alcohol consumption of high-income countries, for example, is much higher than that of middle- and low-income countries, and some high-income countries (e.g. in Europe) have been reducing alcohol consumption[42,43].

Since edible offal is a co-product of meat production, it cannot be reduced unilaterally from other meats. However, offal is not typically consumed in high-income nations due to convention and consumer preference [44]. It is an effective way to reduce overall meat consumption and its associated carbon cost as a meat substitute in some products [45,46]. Finally, if the meat products listed in the country-specific EAT-Lancet diet were to satisfy human demand, other meat consumption (consumption not listed in the country-specific EAT-Lancet diet for meat varieties such as horse, donkey, rabbit and others) could be avoided, resulting in a sequestration opportunity of ~4.38 (2.33 to 6.58) Gt CO_2e (Fig. 3A).

Fig. 3. Potential carbon sequestration (A) and potential GHG emission change (B) due to removal of ignored food items in the EAT-Lancet diet for high-income countries. These food items are covered in the FAO diets but not considered in the EAT-Lancet diet. The error bar means the range of potential carbon sequestration.

Implications for natural climate solutions

Emission trajectories as reported by the IPCC 1.5°C special report suggest that limiting global average temperature increase to 1.5°C could require a cumulative carbon dioxide removal (CDR) of 348-1218 Gt CO_2 by 2100, with a 'middle-of-the-road' scenario—one in which societal and technological development follows historical patterns—requiring a ~687 Gt CO_2 reduction[47,48]. As with mitigation efforts under existing international frameworks for 'shared but differentiated responsibilities', there may be highly differentiated CDR targets for high-income countries. Others have allocated global CDR requirements to countries based on responsibility (per-capita production-based carbon emission since 1850), capability (per-capita GDP) and equality (per-capita CDR quotas) principles[48]. Cumulative allocations to the 54 high-income countries we investigate here vary from 84.70 Gt CO_2 to 530.98 Gt CO_2 depending on the allocation principle (ranging from equality to capability respectively), compared to our calculated 98.25 Gt CO_2 CDR by PNV restoration due to dietary change[48]. Our results thus suggest that ecosystem restoration facilitated by dietary change alone could potentially fulfil between less than 1% and over 100% of these countries' CDR obligations needed to limit warming to 1.5°C (Supplementary Table 11).

Discussion

Uniform adoption of the country-specific EAT-Lancet diet across high-income nations would benefit both the global environment and human health in high-income countries[24,37]. Land spared due to dietary change would expand opportunities for the implementation of natural climate solutions, such as regrowth of natural forest which is arguably the single most effective natural climate solution throughout much of the world[2,9,13]. Nevertheless, it would likely be a challenging, long-term, and complex process to restore the agricultural land spared by dietary change. A comprehensive analysis of social acceptance of land sparing is lacking but would likely find that success greatly depends upon local contexts[49]. In our analysis, we assume a scenario in which all spared land is restored to the potential natural vegetation associated with today's climate to delineate the maximum potential[11]. However, this idealized opportunity is likely confounded by more nuanced biophysical and socioeconomic characteristics of various world regions.

Restoration is also just one of many potential end uses for spared land. Competition among end uses inevitably precludes 100% adoption of any one type of land use and strategies are needed to identify ways in which trade-offs among uses can be optimally balanced [50]. For example, from an emissions mitigation perspective some have recently proposed that restoration be prioritized based on the rate and degree to which candidate lands can recover C [51]. Yet, even recovery rates are not a trivial criterion. Many contingencies determine theses rates—e.g. subsequent management, local climate, soil properties, surrounding ecology, etc.—that ultimately influence the efficacy of restoration[27]. Passive restoration, for example, is sometimes desirable as species on spared land can undergo natural succession and recover quickly at no or low cost[27]. Even so, passive restoration may be a less effective means sequestering C than active restoration in systems in which successional dynamics favor the dominance of less productive plant communities [52]. In either case, restoration is a relatively slow process requiring decades or centuries to manifest its full effects. It therein requires a long-term mindset and commitment that may not be politically tenable.

Spared land could also potentially be used for bioenergy cultivation – albeit with different outcomes[27,53]. Traditionally, bioenergy has been regarded as an economically costly strategy for climate change mitigation with a lower efficacy per unit of land use compared to alternatives[2,27,53,54]. In addition, costly transportation, long-distance shipping, and limited refinery plant capacity all have a critical impact on the economic and environmental sustainability of bioenergy production[55]. However, bioenergy cultivation may have higher cumulative carbon sequestration opportunities due to short rotation and sustainable harvest management [56,57]. For instance, a recent US case study suggests that the climate mitigation potential of second-generation bioenergy crops such as switchgrass (including carbon sequestration, avoided emissions from fossil fuels, and carbon capture and storage during bioenergy production) in some US contexts could be 4 to 15 times greater than the sequestration attained by restoring current cropland or pastureland to natural forest and grassland over the first 30 years [58]. However, these efficiencies remain contingent upon ensuing improvements to energy crop yields and biofuel conversion technology in addition to carbon capture and storage technology as part of bioenergy carbon capture and sequestration approaches [58]. CO_2 emissions from biorefinery operations are assumed to be captured and injected into geological storage. Bioenergy production on spared land could bring economic benefits and may offer an opportunity to offset impacts on rural livelihoods driven by dietary change, such as meat reduction. Moreover, unlike a return to PNV, the efficacy of bioenergy depends on technological and agricultural development [59,60]; it may depend on, or drive, greater use of agricultural inputs like fertilizer, pesticides, or irrigation; and its effects on biodiversity, water quality or other ecosystem services remain mixed for different generations of bioenergy (i.e. first- compared to second-generation biofuels) but are likely less than those expected from PNV restoration[58].

In addition to natural climate solutions that ensue from the sequestration element of the double dividend, other supplementary natural climate solutions address production emissions. These solutions, including improved nutrient management, cover crops, and biochar (see Supplementary Information), do not require extra land but instead target emissions reductions from remaining cropland[2,27]. Moreover, their effects are realized quicker (days to years) than those of PNV restoration which may make them more tractable for producers and policy makers. Even so, governance of land use changes implied by both elements of the double dividend will likely require new technological (e.g. remote-sensing monitoring) and financial support (e.g. reforestation and afforestation) [27,61,62]. In addition, payments for ecosystem services (e.g. for carbon sequestration) from consumers to producers could offset some of the loss of income landowners may face due to land sparing from fodder and livestock reductions [63].

In order to harness the GHG mitigation potential of dietary change, a holistic social policy that coordinates between food, environment, and public health systems will be essential. Decision-makers could repurpose taxes and regulations on unhealthy food[64]. However, nutritious foods can, in some regions, have higher prices than unhealthy foods high in saturated fat, sugar, or starch. This could result in a substantial financial burden on lower-income consumers. Food assistance programs may need to be adopted in some locations to provide better access to planetary healthy foods [65]. The question is not necessarily one of available investment, global agricultural subsidies currently reach ~\$700 billion yr^{-1}, and yet result in unsustainable production and consumption [64,66]. These subsidies could instead be redirected along the lines of environmentally sustainable agricultural practices and healthy diets[66]. In addition, actions to reduce food loss and waste are an essential climate intervention along with dietary change. For example, a reduction in global food waste of 50% would result in further GHG mitigation of 0.9 Gt CO2e yr^{-1} [67]. Without additional policies – especially support for local producers that provide most agricultural products for the international market – this could cause a massive social upheaval as livelihoods in export-oriented commodity crops or animal agriculture face rapid and deep change.

High-income countries stand to achieve the largest per-capita carbon reductions by shifting to the country-specific EAT-Lancet diet due to the large proportion of their average diet currently devoted to carbon-intensive meat products consumption[24,26]. We aim to isolate the current carbon opportunity due to dietary change in high-income nations alone, assuming all other economic conditions are unchanged. With such a change in diets and production systems there may be direct and indirect rebound effects which could be modelled in future work. Rebound effects may offset mitigation efforts [68,69] but research into rebound effects in the food system is highly challenging given the uncertainty surrounding future food prices, differences in meat and meat-substitute prices, and potential future policy controls on rebounds. What we present here is the total current opportunity based on production structure in the benchmarked year (i.e. the year 2010 in the study). We leave rebound assessments for future studies (which may involve lower sectoral and spatial resolution along with different social and economic modelling approaches)[70].

To provide a more transparent assessment of today's overall carbon sequestration opportunities (and opportunity costs), we also take a static approach for economic structures. It is very challenging to predict future production structures and trade patterns between economic sectors within and among nations. For example, production structures are heavily determined by technological change and do not evolve linearly [71]. Future trade patterns are also difficult to predict since they are impacted by many factors such as labour and land costs, not to mention geopolitical tensions, trade agreements, and governmental policies [71]. While other studies, for example on biofuels, have attempted to investigate some aspects of these changes using scenarios and models with a lower sectoral resolution and lower spatial resolution, their findings are contested and highly sensitive to assumptions [70]. Since we assess carbon sequestration/mitigation based on physical flows, we avoid some of the issues that price-based analyses may face. However, the total opportunity assessed here represents an upper bound of possibilities.

While we estimate the magnitude of the potential carbon sequestration benefit due to dietary change in high-income nations, we do not include non-agricultural sectors such as transportation, processing, wholesale and retail, hotel and restaurant food emissions. Further, given the number of datasets integrated into this analysis, uncertainties in both data[11,21] and modelling[19] mean that estimates for specific crops in individual nations should be interpreted cautiously. Nevertheless, our analysis sheds light on the indirect ways in which dietary change may offer substantial opportunities for GHG reductions via enhanced natural climate solutions and the deep and complex policy changes upon which they are predicated.

Methods

In this paper, we employed a Spatially-explicit Multi-Regional Input-Output (SMRIO) model to derive GHG emission and carbon sequestration change after a dietary shift from national average diets in the year 2010 to a planetary health diet proposed by the EAT-Lancet Commission in high-income countries[3]. We focus on GHG emissions and sequestration – the latter distinguishing aboveground biomass carbon (AGBC), belowground biomass carbon (BGBC), and soil organic carbon (SOC) of crop and livestock production for human consumption. GHG emissions and sequestration requires two different timeframes: the reduced production emission influences the sector's annual GHG contribution, while sequestration requires decades or even centuries to realise its full potential. Therefore, we assess a 'double dividend' for emission mitigation from (1) annual reduced direct agricultural production emissions [24] and (2) carbon sequestration via the land sparing over the long term [11,26]. To keep the geographic data consistent, we aggregate all spatial maps to a uniform resolution of 5 arcmin. We outline the construction of the model for each plant type in turn.

Biomass carbon and soil organic carbon in current vegetation

Primary crops and fodder:

We calculated AGBC and BGBC for herbaceous crops and fodder using the approach of Spawn et al. [21] (equations 1 and 2) based on the crop production data at national scale from FAOSTAT [20] (detailed parameters in Supplementary Table 1, and detailed description see Supplementary Methods). We then allocated AGBC and BGBC into grid cells based on the spatial distribution of the 29 herbaceous crops in SPAM [72] and the fodder crop map in EarthStat [73].

$$AGBC = y\omega(0.451h^{-1} + 1.025c - 0.451) \quad (1)$$

$$BGBC = 0.451yrh^{-1} \quad (2)$$

where *y* is the production of a specific crop or fodder item (in tons), *ω* is the dry matter fraction of its harvested biomass, *h* is its harvest index (fraction of total AGBC collected at harvest), *c* is the carbon content fraction of its harvested dry mass, and *r* is the root-to-shoot ratio of the crop (detailed values in Supplementary Table 1). We assume that 2.5% of all harvested biomass is lost between the field and farm gate and that unharvested residue and root mass is composed of 44% carbon (following Wolf et al. [74])

Since some regions saw multiple harvests in a single year, we further determined the harvest frequency (*f*) of each grid cell by dividing a cell's harvested area by its physical area as reported in SPAM. If *f* was greater than one, multiple harvests were assumed and AGBC and BGBC were divided by *f* to ensure that AGBC and BGBC estimates did not exceed the maximum standing biomass density [21].

Woody crops like fruit, nuts, and oil palms were addressed separately and their biomass was assumed to be captured by the harmonized biomass AGBC and BGBC map from Spawn et al. [21]. The AGBC and BGBC were extracted based on the share of the physical area of 11 woody crops in SPAM on the grid cell area. We then allocated the AGBC and BGBC of 11 woody crop groups into individual crops based on the share of AGBC and BGBC calculated in equations 1 and 2 at the national level.

Soil organic carbon (SOC), the carbon remaining in the soil after partial decomposition of any material produced by living organisms, constitutes a primary element of the global carbon cycle through the atmosphere, vegetation, soil, rivers, and the ocean. About 50% of total global SOC (i.e. top 300 cm depth) is stored in the top 100 cm depth, so SOC stock change assessment should be made to at least 100 cm depth [75]. In this paper, we used a soil organic carbon stock map for the year 2010 by Sanderman et al.[15] representing stocks integrated to a depth of 100 cm. It is the result of machine learning ensemble models run at a spatial resolution of 5 arcmin. A similar dataset recently produced by ISRIC (https://www.isric.org/) known as SoilGrids v2.0 [76] provides a lower comparable estimate of global SOC stocks in the upper 30 cm of soil and is in better agreement with a recent comprehensive empirical inventory [77]. Downward revisions by SoilGrids v2.0 are most pronounced in permafrost regions such that they minimally affect our estimates for modern agricultural areas[15,76]. Notwithstanding, because SoilGrids v2.0 only provides SOC estimates for the topsoil (0-30 cm depth), we used the ratio between mean SOC from SoilGrids v2.0 and the comparable estimate by Sanderman et al. for the top 30 cm to scale SOC in the top 100 cm provided by Sanderman et al. such that estimates for subsoil C stocks (30-100 cm depth) are similarly revised[15,76]. We used the share of the physical area of 40 crops in SPAM and a fodder map from EarthStat to extract the value of SOC, and we then allocated the value into separate crops based on their harvested area in FAOSTAT and SPAM in 2010.

Pastureland

We used the latest year of pastureland for feeding livestock in the year 2010 provided by Sloat et al. [78] and calibrated it based on capping 100% total land-use coverage in each grid cell (see Supplementary Methods). AGBC and BGBC of pasture are from the harmonized biomass carbon map of pasture provided by Spawn et al.[21]. SOC is based on the same dataset as above cropland. We extracted the value of AGBC, BGBC, and SOC based on the percentage of pasture in a grid cell.

GHG emissions

The GHG emissions for agricultural production in tonnes of CO_2e yr^{-1} were calculated following the tier 1 methodology of FAOSTAT for the year 2010 [20] applied at the national level rather than the grid cell level (see Supplementary Methods).

AGBC, BGBC, and SOC of potential natural vegetation

To calculate the potential additional carbon storage of returning land to natural vegetation, we used the work of Erb et al. [11] and Sanderman et al. [15]. Erb et al. generated a land-use induced biomass stock (AGBC and BGBC) reduction percentage map based on 42 potential–actual biomass-stock difference maps by combining the seven actual biomass-stock maps with the six potential biomass-stock maps [11]. In addition, Erb et al. adjusted the maps to guarantee the actual biomass stocks would not surpass the potential biomass stocks [11]. We used the AGBC and BGBC maps constructed as above as the actual biomass stocks map, and used a reduction percentage map from Erb et al.[11] to get AGBC and BGBC of potential natural vegetation. Sanderman et al. estimated SOC stock loss between historical natural vegetation and current land use for 2010 at 5 arcmin, using machine learning techniques [15]. Sanderman et al. provided three layers of SOC stock in the upper 30 cm, 100 cm, and 200 cm. We used the percentage SOC loss from Sanderman et al. in the upper 100 cm for the spatially explicit vegetation potential of SOC. Although many grid cells may contain both agricultural and natural land, which leads to some inaccuracy, the overestimation of absolute SOC stocks might compensate for the underestimation of relative SOC losses and vice versa so that our absolute SOC loss estimates might remain representative.

Dietary change in high-income countries

Source data for average national diets were obtained from FAO food balance sheets (FBSs) in 2010 [20]. FBSs are available as calories (kilocalories per person per day) and weights (grams per person per day) [20] which can be used to compute the food-specific energy content (calories per unit food) for each country. We used food supply from FBSs, and did not include stock variation and food loss, because these are not consumed in human diets. The food used in feeding and processing are reflected by the input-output relationship in The Food and Agriculture Biomass Input-Output model (FABIO).

For targeted healthier diets in high-income countries, we chose the food recommendations from the Universal Healthy Reference Diet (EAT-Lancet) which follows the guidelines on healthy diets and sustainable food systems [3,37]. For each country, we aggregated food demand (in grams/capita/day) for each classification of the EAT-Lancet diet (for the detailed mapping relationship between FABIO sectors and EAT-Lancet classification, see Supplementary Table 2), calculated the energy content (kilocalories/capita/day) in each classification, adjusted the energy intake for each classification to conform with the recommendation of EAT-Lancet, and adjusted all energy intake to 2500 kcal/capita/day similar to the method in previous studies [24,37]. Most food items reduced shifting from the average national diet to the country-specific EAT-Lancet diet across high-income countries (for specific food item changes, see Supplementary Table 9). However, some food items (especially fruits and plant-protein food) increased in some high-income countries (for specific food item changes, see Supplementary Table 9). Food quantities (in grams/capita/day) in each classification were split using proportions in the national average diets for reduced and increased food items. As a result of these changes we would witness an increase in soybean food supply for the plant-protein group in the country-specific EAT-Lancet diet due to increased availability of soybeans from land producing soybeans as feed for animal product consumption. The difference between the average national diet and the country-specific EAT-Lancet diet is the dietary change used in this study. There are no recommendations for alcohol, coffee, tea, cocoa, other meat (e.g. horse, mule, camel, rabbit, snails) and edible offal intake in the EAT-Lancet diet, so we assumed these items to stay unchanged at the national average level [37].

It is important to note several critiques of the country-specific EAT-Lancet diet, most of which centre on the use of the universal diet for middle- and low-income nations [79,80]. Here we avoid much of this critique by focusing on high-income dietary changes. However, as noted above, there are some food groups and regions where the universal diet may need localisation even in high-income nations (for instance with respect to dairy intake in East Asia).

Physical input-output model for agricultural products: *FABIO*

The Food and Agriculture Biomass Input-Output model (FABIO) is a consistent, balanced, physical input-output database based on FAOSTAT data, covering 191 countries and 128 agriculture, food, and forestry products from 1986 to 2013 [19]. For further information on its construction see Bruckner et al.[19]. In this paper, we use the 2010 version of FABIO.

Environmentally extended multi-regional input-output model

Environmentally extended MRIO models have been widely used in studying environmental impacts driven by global consumption. In this work, we followed the standard Leontief model to compute the biomass carbon and GHG emissions driven by food consumption changes in high-income countries. The standard approach is:

$$\Delta \boldsymbol{F} = \boldsymbol{diag}(\boldsymbol{e})(\boldsymbol{I} - \boldsymbol{A})^{-\boldsymbol{1}}(\Delta \boldsymbol{Y})$$

If the number of countries is R, of agricultural sectors is N and of high-income countries is H, then: $\boldsymbol{\Delta F}$ is a ($RN \times H$) matrix of environmental impact change driven by final demand change in every country.

- $\boldsymbol{e}$ is an environmental impact intensity row vector with dimension $1 \times RN$. ***diag(e)*** is a matrix of vector e when diagonalized. In this paper, the e stands for the production of crops, fodder, and pasture, or GHG emissions of crops, fodder, and livestock (including those emissions from enteric fermentation and manure management).
- $\boldsymbol{A}$ is a matrix of technical coefficients with dimension $RN \times RN$, which gives the number of inputs that are required to produce a unit of output.
- $\boldsymbol{\Delta Y}$ is a matrix of food demand change (measured in physical units) in high-income countries with dimensions $RN \times H$. The vector is derived from the last part (“Dietary change in high-income countries”) based on the difference between FBS and country-specific EAT-Lancet diet.
- $\boldsymbol{I}$ is an identity matrix with dimension $RN \times RN$.

Carbon change due to dietary shift

We calculated GHG emissions at the national level, so the GHG change due to a dietary shift from average national diets to the country-specific EAT-Lancet diet can directly derive from the environmentally extended multi-regional input-output model.

For decreased crops and forage (fodder and pasture) production, firstly, we calculated the production change of crops or forage at the national level, and then allocated them to grid cells proportionally, as done in previous SMRIO studies [23]. We used AGBC as a proxy of production for pasture because aboveground biomass is used to feed livestock. Secondly, we used gridded production change divided by yield to get the spatial distribution of harvested area. The change in physical area was calculated by dividing harvested area by harvest frequency. The spared physical area of cropland and pastureland is where the potential natural vegetation can be restored.

For increased crop or forage production, firstly, we multiply the spared physical area map with the harvest frequency map to get the spatial distribution of harvested area, and then multiply with the yield maps of existing crops and pasture to get the spatial distribution of potential additional production. This means the potential production maps consist of grid cells where the products are already produced, and the land is spared. Secondly, we allocate national increased production derived from the MRIO model into the aforementioned potential production maps. We redirect some production to other countries if the spared land is not enough to produce more of specific crops. In our research, the redirection occurs in just a few small countries or countries with little production for some specific crops. Thirdly, we used the increased production of crops and forage divided by their yield maps to get the spatial distribution of the harvested area, and then we can get physical area change through the harvested area divided by the harvest frequency. The physical area offset the spared cropland or pastureland to restore potential natural vegetation.

We used the physical area maps to calculate the change of AGBC, BGBC and SOC between actual vegetation and potential natural vegetation as in the aforementioned method. In this paper, we focus on net carbon sequestration change, which is the sum of carbon sequestration of potential natural vegetation and increased agricultural vegetation minus the carbon stock in current agricultural vegetation.

Reporting of Results

The analysis was performed for the 54 high-income countries available in FABIO (there is no food supply data in FAOSTAT for 4 small high-income countries in FABIO: Bahrain, Puerto Rico, Qatar, and Singapore). Carbon change analysis was reported in 10 categories for ease of inspection, as done in previous studies [24]: Whole grains, tubers or starchy vegetables, vegetables, fruits, dairy and eggs, meat and seafood, plant proteins (nuts and legumes), added fats, added sugars, and others (namely, missing items in the EAT-Lancet diet) (details see Supplementary Tables 2 and 3).

Data availability

All generated data are available in the main text or the supplementary materials. Secondary data used in this study are all from publicly available sources and referenced in the Methods section.

Code availability

All codes used in the analysis are available upon request.

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Contributions

All authors provided input into the final manuscript. P.B designed the study. Z.S., S.A.S., and M.B. contributed data. Z.S. performed the analysis with the help of P.B. and L.S. Z.S., L.S. and P.B led the writing, with contributions of A.T., S.A.S., M.B, and H.K.G.

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Ethics declaration – Competing interests

The authors declare no competing interests.

Additional information

Supplementary information The online version contains supplementary material available at

Correspondence and requests for materials should be addressed to Z.S.

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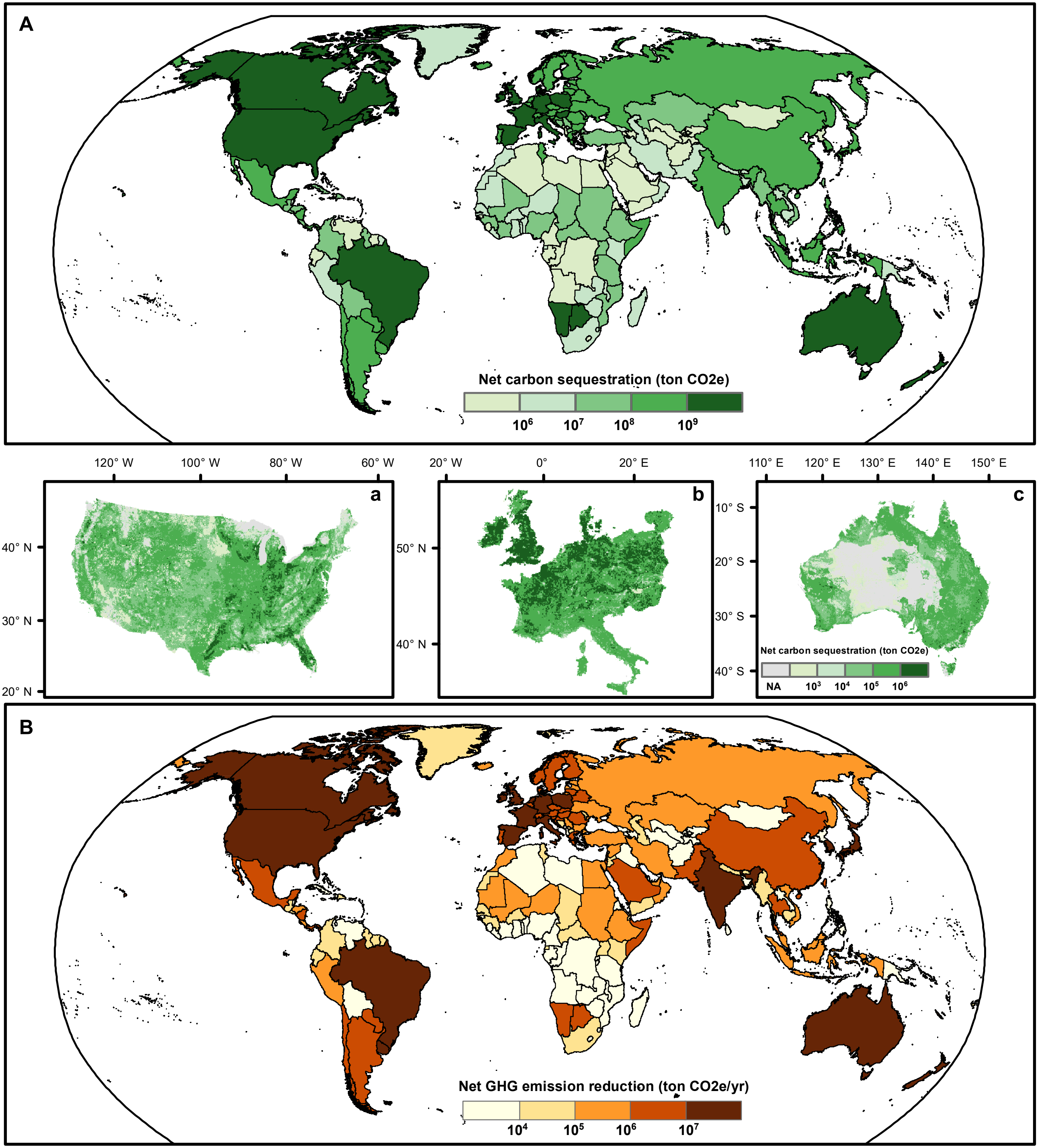
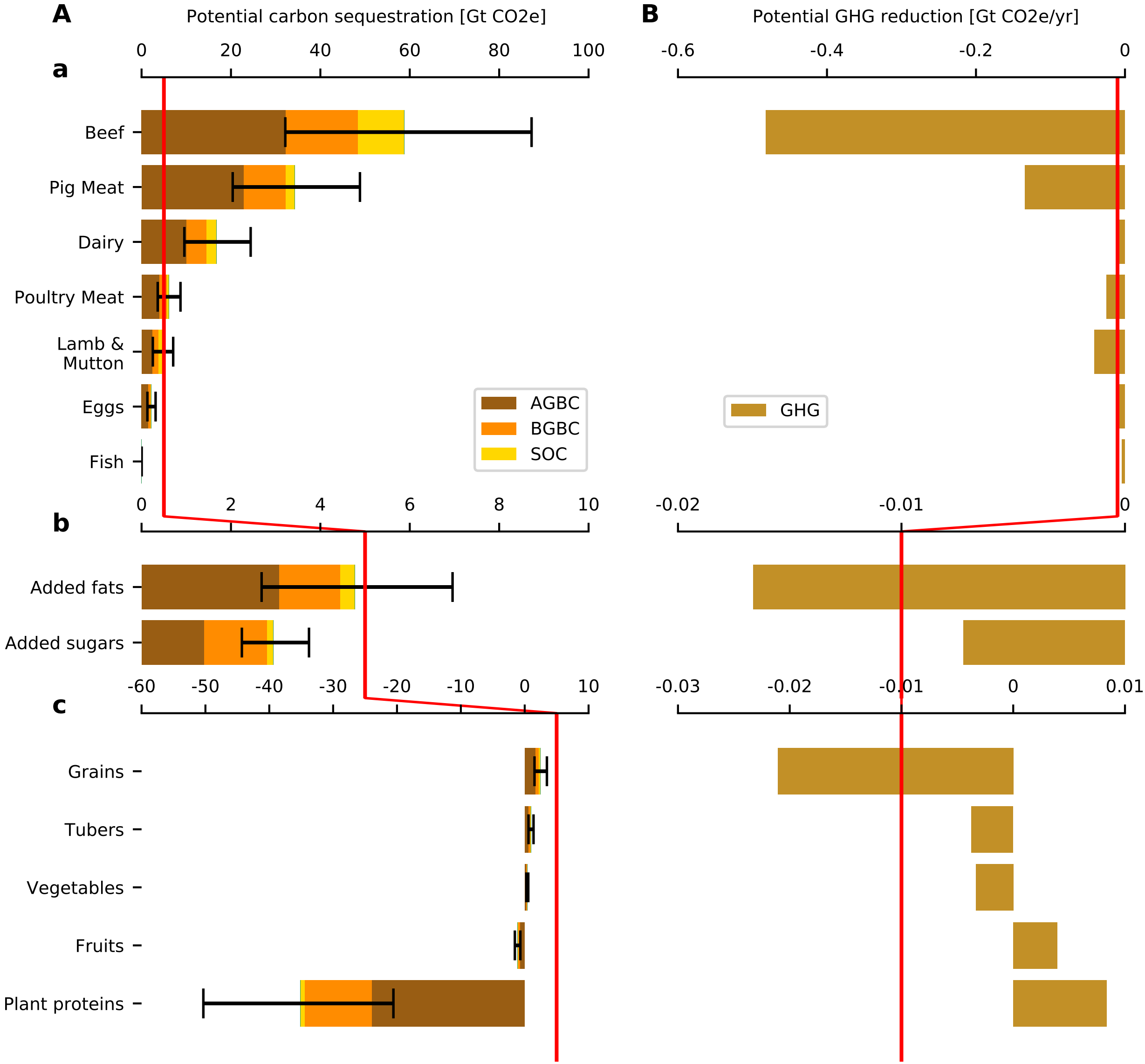
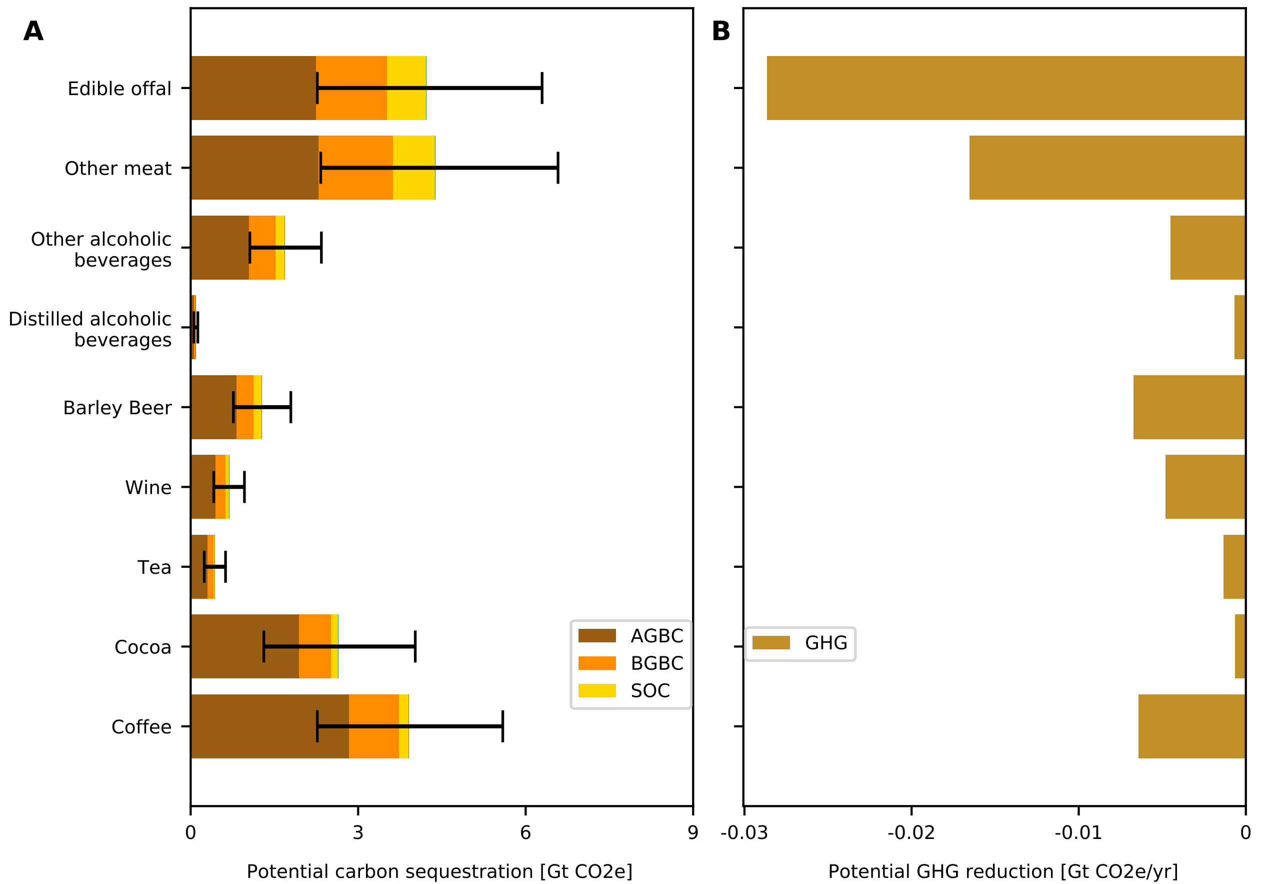


A
Net carbon sequestration (ton CO2e)
10^6 10^7 10^8 10^9
120° W 100° W 80° W 60° W
20° W 0° 20° E
110° E 120° E 130° E 140° E 150° E
a
b
c
40° N
30° N
20° N
50° N
40° N
10° S
20° S
30° S
40° S
Net carbon sequestration (ton CO2e)
NA 10^3 10^4 10^5 10^6
B
Net GHG emission reduction (ton CO2e/yr)
10^4 10^5 10^6 10^7


A
Potential carbon sequestration [Gt CO2e]
B
Potential GHG reduction [Gt CO2e/yr]
a
b
c
Beef
Pig Meat
Dairy
Poultry Meat
Lamb &
Mutton
Eggs
Fish
Added fats
Added sugars
Grains
Tubers
Vegetables
Fruits
Plant proteins
AGBC
BGBC
SOC
GHG
0
20
40
60
80
100
-0.6
-0.4
-0.2
0
2
4
6
8
10
-0.02
-0.01
-60
-50
-40
-30
-20
-10
-0.03
0.01



A
B
Edible offal
Other meat
Other alcoholic beverages
Distilled alcoholic beverages
Barley Beer
Wine
Tea
Cocoa
Coffee
AGBC
BGBC
SOC
GHG
0
3
6
9
-0.03
-0.02
-0.01
0
Potential carbon sequestration [Gt CO2e]
Potential GHG reduction [Gt CO2e/yr]