SPECIAL FEATURE: ORIGINAL ARTICLE

Globally-Consistent National Pathways towards Sustainable Food and Land-use Systems

Contributions of healthier diets and agricultural productivity toward sustainability and climate goals in the United States

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Abstract

Meeting ambitious climate targets will require deploying the full suite of mitigation options, including those that indirectly reduce greenhouse-gas (GHG) emissions. Healthy diets have sustainability co-benefits by directly reducing livestock emissions as well as indirectly reducing land use emissions. Increased crop productivity could indirectly avoid emissions by reducing cropland area. However, there is disagreement on the sustainability of proposed healthy U.S. diets and a lack of clarity on how long-term sustainability benefits may change in response to shifts in the livestock sector. Here, we explore the GHG emissions impacts of seven scenarios that vary U.S. crop yields and healthier diets in the U.S. and overseas. We also examine how impacts vary across assumptions of future ruminant livestock productivity and ruminant stocking density in the U.S. We employ two complementary land use models—the US FABLE Calculator, an agricultural and forestry sector accounting model with high agricultural commodity representation, and GLOBIOM, a spatially explicit partial equilibrium optimization model for global land use systems. Results suggest that healthier U.S. diets that follow the Dietary Guidelines for Americans reduce agricultural and land use greenhouse gas emissions by 25–57% (approx 120–310 MtCO$_{2e}$/y) and pastureland area by 28–38%. The potential emissions and land sparing benefits of U.S. agricultural productivity growth are modest within the U.S. due to the increasing comparative advantage of U.S. crops. Our findings suggest that healthy U.S. diets can significantly contribute toward meeting U.S. long-term climate goals for the land use sectors.

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Introduction

Sustainability and climate-focused initiatives announced by the United States federal government, states, and private sector entities could have meaningful impacts on land use sectors (agriculture and forestry) by affecting trends in land use and management as well as shifting commodity markets. Recent policy announcements include potential land-based greenhouse-gas (GHG) mitigation strategies associated with ambitious new climate targets as part of rejoining the Paris Agreement (United States Department of State & United States Executive Office of the President 2021), as well as a recent presidential executive order protecting 30% of U.S. lands and waters by 2030. The US Department of Agriculture (USDA) Innovation Initiative (2020) has established ambitious targets for the next three decades to increase agricultural productivity by 40%, reduce food waste by 50%, reduce nutrient loss to runoff by 30%, reduce carbon emissions, and increase biofuel and biomass production.

Other policies may not have a primary objective that is environmental or sustainability-focused, but could nonetheless support policies in this domain by shifting resource demands and improving environmental outcomes. Two examples of indirect policy objectives that could interact with sustainability and climate initiatives include enhancing agricultural productivity growth and promoting healthier diets. If widely adopted, U.S. government recommendations for healthier diets (as per the USDA's healthy dietary guidelines; Dietary Guidelines Advisory Committee 2015) could alter protein consumption away from beef and pork and toward plant-based foods, which could indirectly benefit climate and sustainability goals (Willett et al. 2019). Furthermore, previous research suggests that agricultural productivity growth can complement climate change mitigation (Baker et al. 2013; Havlik et al. 2013; Stehfest et al. 2019). However, it is unclear how these policy targets could be achieved in isolation, what role market adjustments will play, and how healthier diet transitions and agricultural productivity enhancement might interact.

The sustainability of U.S. healthy diets

While there have been several recent studies examining combinations of sustainability-related U.S. policy targets (Graham et al. 2021; Gurgel et al. 2021; Wade et al. 2022), the literature modeling U.S. agriculture and forestry is currently lacking in its representation of demand-side sustainability policies, including transitions to healthier diets. While shifting to healthier diets is critical to reducing the noncommunicable disease burden (Willett et al. 2019), understanding how dietary change could shift resource-intensive commodity production, land use and ecosystem services can help inform complementary sustainability and climate policy actions.

U.S. food systems are characterized by high levels of grain and oilseed production to support a highly productive domestic livestock sector and domestic diets that are relatively rich in meat-based proteins and oils (Wu et al. 2020), as well as international demands for U.S.-sourced agricultural products. Sustainability priorities such as increasing biodiversity protection or ecosystem service provision could benefit from dietary shifts that reduce pressure on U.S. agriculture's intensive and extensive margins. Simultaneously, increasing productivity growth in U.S. agriculture could increase incomes and increase comparative advantage for international trade, which may or may not have land sparing effects.

The literature on environmental impact of human diets has converged on the multiple sustainability benefits (lower GHGs, land use, water use) of diets lower in animal-based foods and higher in plant-based foods (Aleksandrowicz et al. 2016; Jarmul et al. 2020; Peters et al. 2016; Springmann

et al. 2018). These studies have either examined the global impacts of all countries adopting more sustainable or healthier diets (Springmann et al. 2016; Stehfest et al. 2009) or the domestic impacts of changes to a single country's dietary preferences (Jones et al. 2016). Rarely have studies quantified both domestic and global sustainability metrics of a single county's dietary changes or the country-specific sustainability impacts of the rest of the world adopting healthier diets. In addition, many studies focus on quantifying the impacts of specific personal dietary preferences (e.g., vegetarian, lacto-ovo, pescatarian, Mediterranean), rather than a healthier average national diet. Several studies in the U.S. have quantified the sustainability impacts of omnivorous healthy diets recommended by the Dietary Guidelines for Americans (DGA) (Dietary Guidelines Advisory Committee 2015). However, there is significant disagreement about whether the DGA diets have lower GHG, land use, or water use than the average American diet today (Reinhardt et al. 2020). A handful of these studies have reported slightly lower land use requirements (Behrens et al. 2017; Birney et al. 2017; Peters et al. 2016), and three out of four available studies showed similar or greater GHG emissions (Birney et al. 2017; Hitaj et al. 2019; Tom et al. 2016).

The majority of studies quantifying the sustainability of alternative diets and dietary shifts in the U.S. use life-cycle assessments (LCA) to measure environmental impacts of food production chains (Jones et al. 2016; Reinhardt et al. 2020). However, LCA studies are limited in being able to quantify land use and land use change and allow for regional variation (Heller et al. 2013). Moreover, for projecting the environmental impacts of future dietary changes, it is critical to provide estimates that represent dynamic, rather than steady-state, industry and economic conditions.

Modeling approaches for sustainable diets

Alternative approaches such as economic partial-equilibrium models represent the agricultural, forestry, and other land use sectors in detail, and are deliberately designed to estimate land-use-related impacts, a key gap in the existing literature on the sustainability of U.S. diets (Peters et al. 2016; Reinhardt et al. 2020). The global scale of many of these models allows representation of international trade and thus evaluation of leakage effects of domestic policies. Indirect sustainability levers such as shifting dietary preferences have received substantially less attention in the land use modeling literature relative to carbon pricing (Wade et al. 2022), bioenergy, and traditional conservation incentives. However, recent analysis has started to move in this direction (Leclère et al. 2020; Pérez-Domínguez et al. 2021; Jha et al. 2022; Mosnier et al. 2022; Lehtonen and Ramo 2022).

Partial-equilibrium models of the land sectors, such as GLOBIOM, which we employ in this study, are designed to

maintain empirically observed market relationships between supply, demand, and prices. These models endogenously determine the demand for certain foods, productivity of specific crops, and the productivity of the livestock sector. Typically, they allow for endogenous structural adjustments in land use, management, commodity production, and consumption in response to exogenous scenario drivers (e.g., policy shocks or environmental change). However, with several components of productivity parameters endogenously determined, it can be difficult to isolate the potential role of livestock efficiency changes due to technological breakthroughs or policy incentives. For example, as production decreases due to decreasing demand, so could productivity. In this case, a design feature can be a design flaw for sensitivity analysis and policy assessment focused on individual key system parameters, even if model results can be further decomposed to disentangle endogenous and exogenous productivity contributions (Frank et al. 2018; Leclère et al. 2014). Accounting-based land sector models, such as the FABLE Calculator, which we also employ in this current study, can offer similarly detailed sector representation, without the governing market mechanisms, thus allowing fully tunable parameters for exploring policy impacts (Mosnier et al. 2020). This feature facilitates quantifying uncertainty and bounding estimates through sensitivity analyses. The FABLE Calculator is a sophisticated land use accounting model that can capture several of the key determinants of agricultural land use change and GHG emissions without the complexity of an optimization based economic model. Its high degree of transparency and accessibility also make it an appealing tool to facilitate stakeholder engagement.

Objectives and contributions

This paper explores the impacts of healthier diets (in the U.S. and abroad separately) and increased crop yields on U.S. GHG emissions and land use, as well as how these impacts vary across assumptions of future livestock productivity and ruminant density in the U.S. We employ two complementary land use modeling approaches. The first is the FABLE Calculator (Mosnier et al. 2020 and Mosnier et al. 2022 in this issue), a land use and GHG accounting model based on biophysical characteristics of the agricultural and land use sectors with high agricultural commodity representation. The second is a spatially-explicit partial equilibrium optimization model for global land use systems (the Global Biosphere Management Model, GLOBIOM; Havlik et al. 2013). The combination of these modeling approaches allows us to provide both detailed representation of agricultural commodities with high flexibility in scenario design (FABLE Calculator) and a dynamic representation of land use in response to known economic forces (GLOBIOM), qualities that are difficult to achieve in a single model. Both

modeling frameworks allow us to project to 2050 U.S. national scale agricultural production, diets, land-use, and carbon emissions and sequestration under varying policy and productivity assumptions.

Our work makes several advances to sustainability research. First, using agricultural and forestry models that capture market and intersectoral dynamics, this is the first non-LCA study to examine the sustainability of a healthier average U.S. diet (based on the USDA Dietary Guidelines for Americans). Second, using two complementary modeling approaches, this is the first study to explore the GHG and land use effects of the interaction of healthy diets and agricultural productivity. Specifically, we examined key assumptions about diet, livestock productivity, ruminant density, and crop productivity. Two of the key production parameters we consider—livestock productivity and (ruminant) stocking density—are affected by a transition to healthier diets but have not been extensively discussed in the agricultural economic modeling literature. Third, we isolate the effects of healthier diets in the U.S. alone, in the rest of the world, and globally, which is especially important given the comparative advantage of U.S. agriculture in global trade.

Materials and methods

In the sections that follow we introduce the modeling frameworks applied in this manuscript, document the scenario elements (including their justifications), and describe calibration steps between GLOBIOM and the FABLE Calculator.

Overview of modeling approach

FABLE Calculator

To model multiple policy assumptions across dimensions of food and land use (agriculture, biodiversity, waste, water use, bioenergy) and have full flexibility in terms of parameter assumptions and choice of underlying data sets, we customized a land use accounting model built in Excel, the FABLE Calculator (Mosnier et al. 2020), for the U.S. Below we describe the design of the Calculator, but for more details we direct the reader to the complete model documentation (Mosnier et al. 2020). The FABLE Calculator represents 76 crop and livestock products using data from the FAOSTAT database. The model first specifies demand for these commodities under selected scenarios (including to satisfy human dietary needs, livestock feed, and international trade assumptions), the Calculator computes agricultural production and other metrics, land use change, food consumption, trade, GHG emissions, water use, and land for biodiversity. The key advantages of the Calculator include its speed, the number and diversity of scenario design elements (e.g.,

diets, food waste, trade, land use constraints, productivity changes), simplicity, and its transparency. However, unlike economic models using optimization techniques, the Calculator does not consider commodity prices in generating the results, does not have any spatial representation, and does not represent different production practices.

The following assumptions can be adjusted in the Calculator to create scenarios: GDP, population, diet composition, population activity level, food waste, imports, exports, livestock productivity, crop productivity, agricultural land expansion or contraction, reforestation, climate impacts on crop production, protected areas, post-harvest losses, biofuels. Scenario assumptions (e.g., productivity increases, reforestation targets, population growth) in the Calculator rely on "shifters" or time-step-specific relative changes that are applied to an initial historic (2000, 2010, 2015) value using a user-specified implementation rate.

The Calculator performs a model run through a sequence of steps or calculations, as follows: (1) calculate human demand for each commodity; (2) calculate livestock production; (3) calculate crop production; (4) calculate pasture and cropland requirements; (5) compare the land use requirements with the available land accounting for restrictions imposed and reforestation targets; (6) calculate the amount of feasible pasture and cropland; (7) and (8) calculate the feasible (constrained) crop and livestock production; (9) calculate feasible (constrained) human demand; (10) calculate indicators (e.g., GHG emissions, kcal consumed, water use). See Figure S1 in the Supplementary Materials for a diagram of these steps.

Using U.S. national data sources, we modified or replaced the US FABLE Calculator's default data inputs and growth assumptions based on Food and Agriculture Organization (FAO) data. Specifically, we used crop and livestock productivity assumptions from the U.S. Department of Agriculture (USDA), grazing/stock intensity using literature from U.S. studies, miscanthus and switchgrass bioenergy feedstock productivity assumptions from the Billion Ton study (Langholtz et al. 2016), updated beef and other commodity exports using USDA data, and created a "Healthy Style Diet for Americans" diet using the 2015–2020 USDA Dietary Guidelines for Americans (SM Tables S1–S5). See SM Table S6 for all other US Calculator data and assumptions. We used these U.S.-specific data updates to construct U.S. diet, yield, and livestock scenarios and sensitivities (described below). See (Mosnier et al. 2020) for a full description of the other assumptions and data sources used in the default version of the FABLE Calculator.

GLOBIOM

As a complement to the FABLE Calculator's exogenously determined trade flows, we used GLOBIOM [a widely used and well-documented global spatially explicit partial equilibrium model of the forestry and agricultural sectors. Documentation can be found at the GLOBIOM github development site[1]] to capture the dynamics of endogenously determined international trade. Unlike the FABLE Calculator, GLOBIOM is a spatial equilibrium economic optimization model based on calibrated demand and supply curves as typically employed in economic models. GLOBIOM represents 37 economic production regions, with regional consumers optimizing consumption based on relative output prices, income, and preferences. The model maximizes the sum of consumer and producer surplus by solving for market equilibrium and using the spatial equilibrium modeling approach described in McCarl and Spreen (1980) and Takayama and Judge (1971). Product-specific demand curves and growth rates over time allow for selective analysis of preference or dietary change through augmenting demand shift parameters over time to reflect differences in relative demand for specific commodities (e.g., sugar).

Production possibilities in GLOBIOM apply spatially explicit information aggregated to Simulation Units, which are aggregates of 5 pixels of the same altitude, slope, and soil class, within the same 30 arcmin pixel, and within the same country. Land use, production (including regional crop mix choices) and prices are calibrated to FAOSTAT from the 2000 historic period. Production systems parameters and emissions coefficients for specific crop and livestock technologies are based on detailed biophysical process models, including EPIC for crops (Williams 1995) and RUMINANT for livestock (Herrero et al. 2013).

Livestock and crop productivity changes are reflected by both endogenous and exogenous components. For crop production, GLOBIOM yields can be shifted exogenously to reflect technological or environmental change assumptions and their associated impact on yields. Exogenous yield changes are accompanied by changes in input use intensity (nitrogen, phosphorus, and water) and costs (i.e., an exogenous increase in corn yields sees a corresponding increase in fertilizer use and production costs, where the input intensity varies depending on the socio-economic scenario).[2] A similar approach (exogenous yield growth coupled with input intensification) has been applied in other U.S.-centric land sector models, including the intertemporal approach outlined in Wade et al. (2022). Furthermore, reflecting potential yield growth with input intensification per unit area (but not necessarily per unit output) is consistent with observed

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[1] https://iiasa.github.io/GLOBIOM/.

[2] We note that this approach differs from the concept of total factor productivity improvement, which recognizes that technology change-induced yield growth (e.g., genetic improvements) could potentially occur with constant or reduced input use (see Hertel & Baldos (2016) for additional discussion of total factor productivity versus production intensification).

intensification of some inputs in the U.S. agricultural system. This includes nitrogen fertilizer intensity (per unit area), which grew approximately 0.4% per year from 1988 to 2018 (calculated from U.S. Department of Agriculture, Economic Research Service 2019, 2021).

Crop yields can also vary endogenously in response to demand and price changes. Higher prices can induce production system intensification or crop mix shifts across regions to exploit regional comparative advantages. GLOBIOM accounts for several different crop management techniques, including subsistence-level (confined to specific regions), low input, high input, and high input irrigated systems.

The model simulates spatiotemporal allocation of production patterns and bilateral trade flows for key agriculture and forest commodities. Regional trade patterns can shift depending on changes in market or policy factors that Baker et al. (2018) and Janssens et al. (2020) explore in greater detail in addition to providing a more comprehensive documentation of the GLOBIOM approach to international trade dynamics, including cost structures and drivers of trade expansion or contraction, or establishing new bilateral trade flows. This approach allows for flexibility in trade adjustments at both the intensive and extensive margins given a policy or productivity change in a given region.

GLOBIOM has been applied extensively to a wide range of relevant topics, including climate impacts assessment (Baker et al. 2018; Janssens et al. 2020), mitigation policy analysis (Havlik et al. 2013; Frank et al. 2018), diet transitions (Latka et al. 2021), and sustainable development goals (Frank et al. 2021). We designed new U.S. and rest-of-the-world (ROW) diet and yield scenarios (described below), and ran all scenarios at medium resolution for the U.S. and coarse resolution for ROW. We chose Shared Socioeconomic Pathway 2 (SSP2, "Middle of the Road"; Fricko et al. 2017) macroeconomic and population growth assumptions for all parameters across all scenarios when not specified or overridden by scenario assumptions (e.g., healthy diets in ROW as opposed to current diets in SSP2).

Overview of inter-model alignment of assumptions

We aligned multiple assumptions in the FABLE Calculator with GLOBIOM inputs and/or outputs to isolate the impacts of specific parameter changes in livestock productivity and ruminant density. Specifically, we used the same set of U.S. healthy diet shifters in both models, but aligned the US FABLE Calculator's crop yields and trade assumptions with GLOBIOM outputs to isolate the effects of increasing the ruminant livestock productivity growth rate and reducing the ruminant grazing density using the Calculator (Fig. 1).

While we developed high and baseline (BAU) crop yield inputs for GLOBIOM, actual yields are reported because of the endogenous nature of yields in GLOBIOM. This two model approach allows us to explore the impact of exogenous changes to the livestock sector that cannot be fully exogenous in GLOBIOM. Subsequent methods sections describe each of these scenarios and sensitivity inputs in greater detail.

Scenario and sensitivity assumptions

Diet scenario assumptions

We constructed a "Healthy U.S. diet" using the "Healthy U.S.-style Eating Pattern" from the USDA and US Department of Health and Human Services' 2015–2020 Dietary Guidelines for Americans (DGA) (U.S. Department of Agriculture & U.S. Department of Health and Human Services 2020 Appendix 3). We use a 2600 kcal average diet. This is a reduction of about 300 kcal from the current average U.S. diet given that the current diet is well over the Minimum Dietary Energy Recommendations of 2075 kcal, computed as a weighted average of energy requirement per sex, age, and activity level and the population projections by sex and age class (UN DESA 2017) following the FAO methodology (Wanner et al. 2014). The DGA recommends quantities of aggregate and specific food groups in units of ounces and cup-equivalents on a daily or weekly basis. We chose representative foods in each grouping to convert volume or mass recommendations into kcal/day equivalents and assigned groupings and foods to their closest equivalent US Calculator product grouping (SM Table S1). For DGA food groups that consist of more than one US Calculator product group, e.g., "Meats, poultry, eggs", we used the proportion of each product group in the baseline American diet (2010) expressed in kcal/day (reported by the FAO) and applied it to the aggregated kcal from the DGA to get the recommended DGA kcal for each product group (see SM Table S2 for these proportions). We made one manual modification to this process by increasing the DGA recommendation for beef from a calculated value of 36 kcal/day to 50 kcal/day, since trends in the last decade have shown per capita beef consumption exceeding that of pork (estimated 45 kcal in the healthy U.S. diet). This process led to a total daily intake of 2576 kcal for the healthy U.S. diet (SM Table S2, Fig. 2A).

The Baseline, average U.S. diet is modeled in the US FABLE Calculator using FAO reported values on livestock and crop production by commodity in weight (tonnes) for use as food in the U.S., applying the share of each commodity that is wasted, then allocating weight of each commodity to specific food product groups (e.g., corn cereals vs. corn syrup), converting weight to kcal, and finally dividing by the total population (without modeling the breakdown of
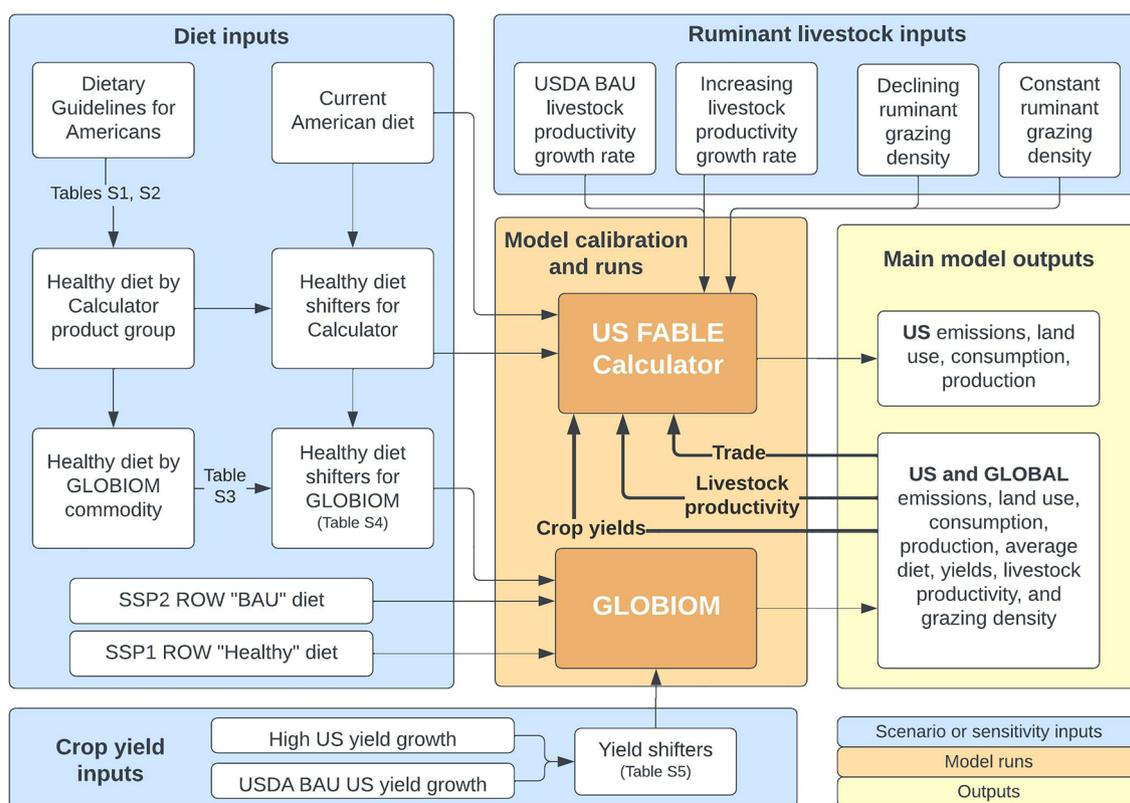
Fig. 1 Methods diagram illustrating the key scenario inputs for each model and how the two models were used in conjunction for comparative purposes

sub-populations by demographic group) and days in a year to get per capita kcal/day. See the Calculator for more details and commodity specific assumptions (available as supplementary data).

This healthy U.S. diet expressed in kcal was used directly in the Calculator as a basis for human consumption demand calculations for specific crop and livestock commodities. To represent this healthy U.S. diet in GLOBIOM, we performed a series of additional conversions. First, we determined the allocation of GLOBIOM items (crop or livestock commodities) across Calculator product groups (SM Table S3) based on how commodities are currently allocated across each product group. For example, the majority (91%) of barley is used for making alcohols and the remaining 9% is consumed as cereals, and about 21% of corn that is consumed by humans is consumed as a cereal, whereas the remaining 79% is used for making corn-based sugars (corn syrups). We then calculated healthy diet "shifters" for each Calculator product group by dividing the healthy diet kcal by the baseline diet kcal. A "shifter", as we define it here, is a constant multiplier that allows conversion between scenario values. Food product group shifters allow for the creation of a healthy U.S. diet scenario using any baseline diet kcal values (e.g., we know that beef consumption should reduce by 50% between 2010

and 2050 in the healthy diets scenario). We then combined (matrix multiplied) the healthy diet shifters (based on Calculator product groups) with the GLOBIOM-to-Calculator product group allocations (SM Table S3) to calculate diet shifters for GLOBIOM items (SM Table S4). These shifters were used directly in GLOBIOM to create the Healthy US, Healthy World, and Sustainability scenarios. Unlike in the Calculator, shifters were applied to the demand curve in GLOBIOM, since final human consumption (diets) is determined endogenously (supply and demand equilibrium). This means that dietary changes between Calculator and GLOBIOM may not be identical, though they are highly similar (Fig. 2A).

Yield scenario assumptions

Using the US FABLE calculator, we developed two sets of yield shifters. The "BAU yields" shifters apply 2000–2015 yield growth trends in the U.S. to simulation years 2000–2050 (SM Table S5). The Higher "U.S. Yields" shifters increase the growth rate by 200% between 2015 and 2050 if the annual positive rate is lower than 1%/year, 80% if the annual rate is higher than 1%/year, and turns negative historic growth rates into positive growth rates (by multiplying
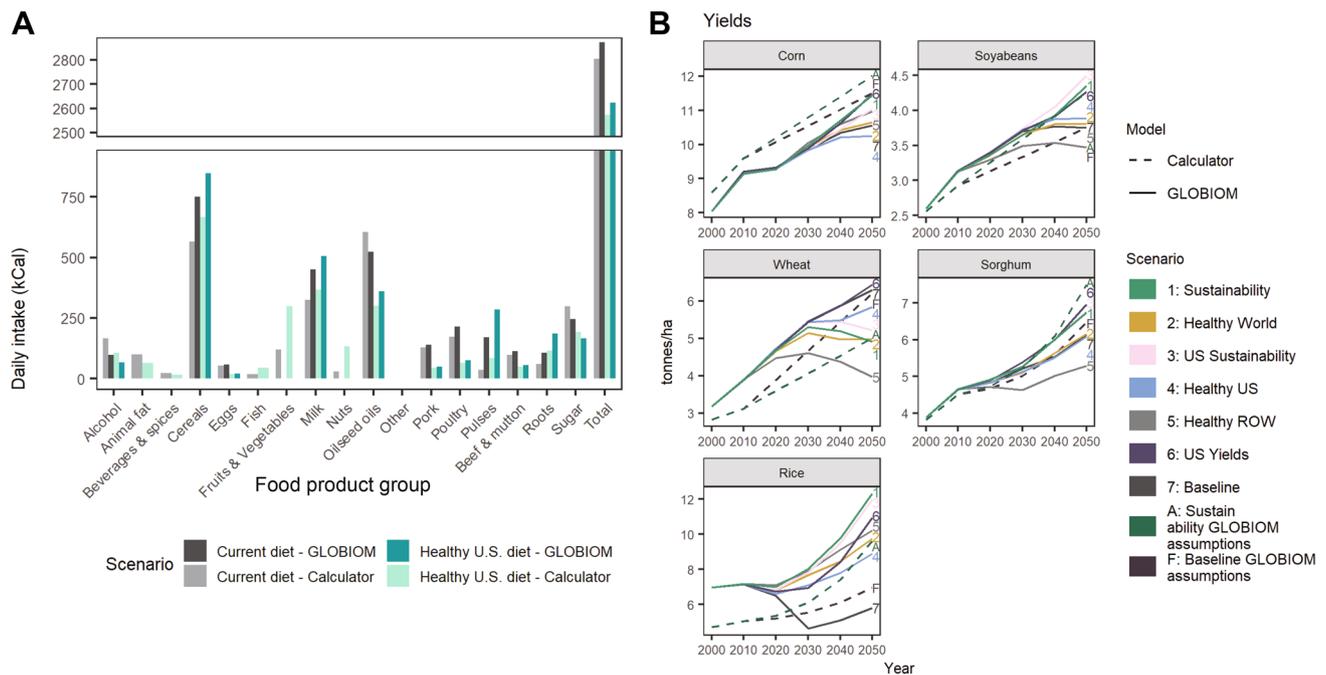
Fig. 2 Caloric intake of specific food product groups for Current and Healthy U.S. diets when applied to the Calculator and GLOBIOM (**A**). The percentage change from current diets were calculated for Healthy U.S. diets and applied to the food product demand curves in GLOBIOM. Calories reported here reflect the new food prod- ucts' equilibrium from shifting the demand curve using the percent changes. Crop yields for Calculator and GLOBIOM scenarios (**B**). Dashed lines correspond to Calculator scenarios and sensitivities and solid lines correspond to GLOBIOM scenarios

by −1), but only applying these adjusted growth rates on the yields after 2020 (SM Table S5). For example, if crop yields were declining at a rate of 0.5% per year historically, and the yield in 2020 was 4.5 tons/ha, we changed this in the higher "U.S. Yields" scenario to increase at a rate of 0.5%/ year starting in 2020 and thus the yield would be 4.6 tons/ ha in 2025. GLOBIOM endogenously adjusts yields based on cropping mix (e.g., yield drags occur when corn follows corn) and management (e.g., higher corn prices may make additional fertilizer applications economical). Thus, GLO-BIOM yields are a combination of our exogenously applied yield increases (e.g., as can be achieved through improved crop cultivars and precision agriculture) and GLOBIOM endogenous adjustments. As a result, the yields between GLOBIOM and the Calculator may not match exactly (Fig. 2B).

Grazing livestock sensitivity assumptions

We used the Calculator to explore the exogenous effects of changes in livestock productivity parameters. These live-stock changes may represent technological innovations or management systems shifts (e.g., feedlots to grassfed cat-tle). The Calculator uses the historic USDA growth rate from 2010 to 2020 linearly extrapolated out to 2050 in the "BAU productivity" livestock productivity scenario, and we

increased this growth rate by 20% in the "High productiv-ity" livestock productivity scenario (Table 1). For ruminant grazing density, the "Constant density" scenario uses the same ruminant density from 2010 to 2050, and reduces this by 6% by 2050 in the "Declining density" scenario. Though these changes were applied to all grazing livestock in the U.S., the vast majority of grazing livestock is cattle, thus, these changes effectively alter beef productivity and graz-ing density. We conducted these sensitivity analyses in the Calculator, because livestock productivity in GLOBIOM is a more complex combination of endogenous and exogenous factors than for crop yields. There is an exogenous SSP-specific component for the livestock density. The amount of livestock product per unit of land area (meat or dairy products per ha) depends on the average feed conversion ratio (mass of feed per mass of output) and the grass yield. The grass yield is exogenous and can change over time under different climate scenarios (see Baker et al. 2018), whereas the average feed conversion ratio is endogenous as the pro-duction system composition is endogenous.

Scenarios and sensitivities

We constructed two main scenarios—Baseline and Sustain-ability—in both GLOBIOM and the US FABLE Calcula-tor. The values of all variables chosen for the Sustainability

Table 1 Calculator and GLOBIOM scenarios and sensitivities assumptions

Model	Scenario or Sensitivity	Scenario variables			Sensitivity variables	
		US diets	ROW diets	US yields	Livestock productivity[1]	Ruminant Density[2]
GLOBIOM	1: Sustainability	Healthy US	Healthy ROW	Higher yields	Partially endogenous	Partially endogenous
	2: Healthy World	Healthy US	Healthy ROW	BAU yields	Partially endogenous	Partially endogenous
	3: US Sustainability	Healthy US	Current ROW	Higher yields	Partially endogenous	Partially endogenous
	4: Healthy US	Healthy US	Current ROW	BAU yields	Partially endogenous	Partially endogenous
	5: Healthy ROW	Current US	Healthy ROW	BAU yields	Partially endogenous	Partially endogenous
	6: US Yields	Current US	Current ROW	Higher yields	Partially endogenous	Partially endogenous
	7: Baseline	Current US	SSP/BAU ROW	BAU yields	Partially endogenous	Partially endogenous
Calculator	A: Sustainability - GLOBIOM assumptions	Healthy US	N/A	GLOBIOM sustainability scenario values	GLOBIOM Sustainability scenario values	GLOBIOM Sustainability scenario values
	B: BAU Livestock Productivity	Healthy US	N/A	GLOBIOM sustainability scenario values	BAU productivity	GLOBIOM Sustainability scenario values
	C: High Livestock Productivity	Healthy US	N/A	GLOBIOM sustainability scenario values	Higher productivity	GLOBIOM Sustainability scenario values
	D: Constant Ruminant Density	Healthy US	N/A	GLOBIOM sustainability scenario values	GLOBIOM Sustainability scenario values	Constant density
	E: Lower Ruminant Density	Healthy US	N/A	GLOBIOM sustainability scenario values	GLOBIOM Sustainability scenario values	Declining density
	F: Baseline - GLOBIOM assumptions	Current US	N/A	GLOBIOM Baseline scenario values	GLOBIOM Baseline values	GLOBIOM Baseline values

Green cells indicate variable values that should result in more sustainable outcomes

[1]For GLOBIOM, livestock productivity is a combination of endogenous and exogenous factors. There is an exogenous SSP specific component for the feed conversion efficiency

[2]For GLOBIOM, the density per ha of pasture depends on the average feed ratio and the grass yield. The grass yield is exogenous and constant, the average feed ratio is mostly endogenous as the production system composition is endogenous

scenario are expected to favor sustainable outcomes (healthy U.S. diets, healthy ROW diets using SSP1-Sustainability assumptions, and higher yields; Table 1). For the Baseline scenarios (Scenarios 7 and F), we assume no change from the current average U.S. diet, SSP2-Middle-of-the-Road diets for ROW, and SSP2 baseline yields. GLOBIOM model runs generated scenario-specific values that were used as inputs in the Calculator for yields, livestock productivity, ruminant density, imports, and exports (Table 1; Fig. 1).

In GLOBIOM, we ran five additional scenarios that isolate the roles of U.S. diets, ROW diets, and crop productivity assumptions to examine every combination of input assumptions. We could not replicate these scenarios in the Calculator because it cannot represent global demand and production. We simulated alternative crop productivity futures in GLOBIOM. As described above, yields are a function of both endogenous decisions (crop mix, management intensity, and the spatial distribution of crops) and exogenous productivity growth rates that vary between business-as-usual and high yield scenarios (SM Table S5). In this analysis we vary the latter (exogenous growth) to represent a range in expected technological change from business-as-usual to optimistic growth. The remaining five scenarios are as follows (with abbreviated names used in text hereafter): 2: healthy U.S. diets and healthy ROW diets (Healthy World), 3: healthy U.S. diets and high U.S. yields (U.S. Sustainability); 4: healthy U.S. diets only (Healthy U.S.); 5: healthy ROW diets only (Healthy ROW); and 6: high U.S. yields only (U.S. Yields).

For the Calculator sensitivity analysis (Scenarios B–E), we used the A: sustainability scenario assumptions, but changed either the livestock productivity to be higher than

in GLOBIOM (Scenarios B: BAU Livestock Productivity, C: High Livestock Productivity) or ruminant density (number of cattle per unit area of pastureland) to be lower than in GLOBIOM (Scenarios D: Constant Ruminant Density, E: Lower Ruminant Density). Because of inherent differences in underlying data, model infrastructure, and system boundaries between the FABLE Calculator and GLOBIOM approaches, we report only the difference and percentage change from each model's BAU scenario.

Scenario validation of exogenous assumptions with endogenous responses

Simulated diets and crop yields reflect scenario adjustments. Scenario adjustments to commodity demand curves and crop yields in GLOBIOM resulted in both production and consumption changes (Fig. 2). That is, instead of perfect alignment with assumed diet and productivity assumptions in a domestic-only LCA or mass balance approach, simulated diets and yields in GLOBIOM reflect endogenous prices and supply-side adjustments that cause variation in crop yields (Fig. 2).

GLOBIOM uses commodity-specific demand curves for representing human demand. Thus, applying the healthy U.S. diet shifters essentially shifts the entire demand curve, as opposed to the final demand for each commodity, which is determined by both the demand and supply curves and market dynamics. As a result, applying the same set of shifters to both the Calculator and GLOBIOM does not necessarily ensure the same percentage change in final per capita consumption across all items. However, demand curve adjustments to reflect healthy diets in particular, led to expected changes in consumption across all food product groups (Fig. 2A). Results indicate that the final per capita consumption in GLOBIOM very closely resembles that of the Calculator (Fig. 2A). Similarly, simulated yields from GLOBIOM vary across scenarios due to market adjustments in the U.S. and the rest of the world, illustrating the sensitivity of the U.S. production system to global market forces (Fig. 2B).

Results

Pastureland declines significantly while cropland contracts slightly in response to healthier U.S. diets (Fig. 3). Healthier diets in the rest of the world and increases in U.S. crop yields only modestly reduce cropland in the U.S., but significantly reduce cropland in the rest of the world. In the Sustainability scenarios, domestic land used for livestock forage and grazing (henceforth, pastureland) decline by 37 mil ha (38%) in the US FABLE Calculator (henceforth, Calculator) and 28 mil ha (28%) in GLOBIOM scenarios if the average American diet resembled the Healthy-style DGA diet by 2050

(Fig. 3). These declines in pastureland are far more dramatic than for cropland, which declines by only 3.9 mil ha (2.8%) in the Calculator scenarios and 2–3.3 mil ha (1–1.8%) in GLOBIOM scenarios due to healthier U.S. diets (Fig. 3). Percentage reductions in both cropland and pastureland are similar across the two models, with the reductions in the Calculator about 1% and 10% points greater, respectively. Both models assume that reductions of pastureland and cropland result in a commensurate increase in natural lands.

Across GLOBIOM scenarios, healthy U.S. diets have the greatest single impact on pastureland changes (Scenarios 1–4 vs. 5, 6; Fig. 2). Pastureland use is more sensitive to dietary changes than cropland due to the low relative land use efficiency of beef production (ranging approximately 0.13–0.17 tonnes per hectare in the U.S. across GLOBIOM scenarios; Fig. 4). Increasing crop productivity has no discernible impact on pastureland use. Simultaneously shifting to healthy diets in the rest of the world (ROW) and the U.S. (Scenarios 1 and 2) only negligibly changes pastureland requirements in the U.S. by 1–1.8 mil ha relative to only shifting to healthy diets in the U.S. (Scenario 4), because most beef produced in the U.S. is domestically, as opposed to being exported. Thus, U.S. pastureland should be most responsive to changes in domestic beef consumption. Correspondingly, shifting just the ROW to healthier diets (Scenario 5) actually slightly increases pastureland over the baseline by 1.8 mil ha (1.7%) despite a slight reduction in U.S. beef production, likely a result of decreased beef land use efficiency (Fig. 4C). As the ROW demand for U.S. beef declines, these small decreases in U.S. production result in beef land use efficiency reduction. For cropland, there is a similar spread of about 1 mil ha (< 1%) across the GLOBIOM scenarios that adopt healthier diets in the U.S., the ROW, or both. The greatest declines in cropland are observed with healthier diets. Increased crop productivity in the U.S. (1: Sustainability vs. 2: Healthy World) only reduces domestic cropland by less than 200,000 ha (0.2%), due to increased production and exports from the greater global comparative advantage (lower costs) of U.S. crop commodities (SM Table S10). As a result, higher U.S. yields alone cause a 7.5 mil ha (0.7%) decrease in croplands globally by 2050 relative to the baseline, which is partially offset by a 1.9 mil ha (0.1%) increase in grassland globally (SM Tables S7, S10).

Annual domestic GHG emissions decrease due to shifts to healthier diets in the U.S. and declines are primarily driven by livestock methane emissions reductions and land sequestration. As a result of a healthier U.S. diet, annual CO_{2e} emissions from the agriculture, forestry, and other land use sectors reduces by 176–197 MT (25–27%) for GLOBIOM scenarios and 187 MT (57%) for the Calculator Sustainability scenario (Scenario A) compared to the baseline (Fig. 4) by 2050. Livestock methane emissions drive the majority
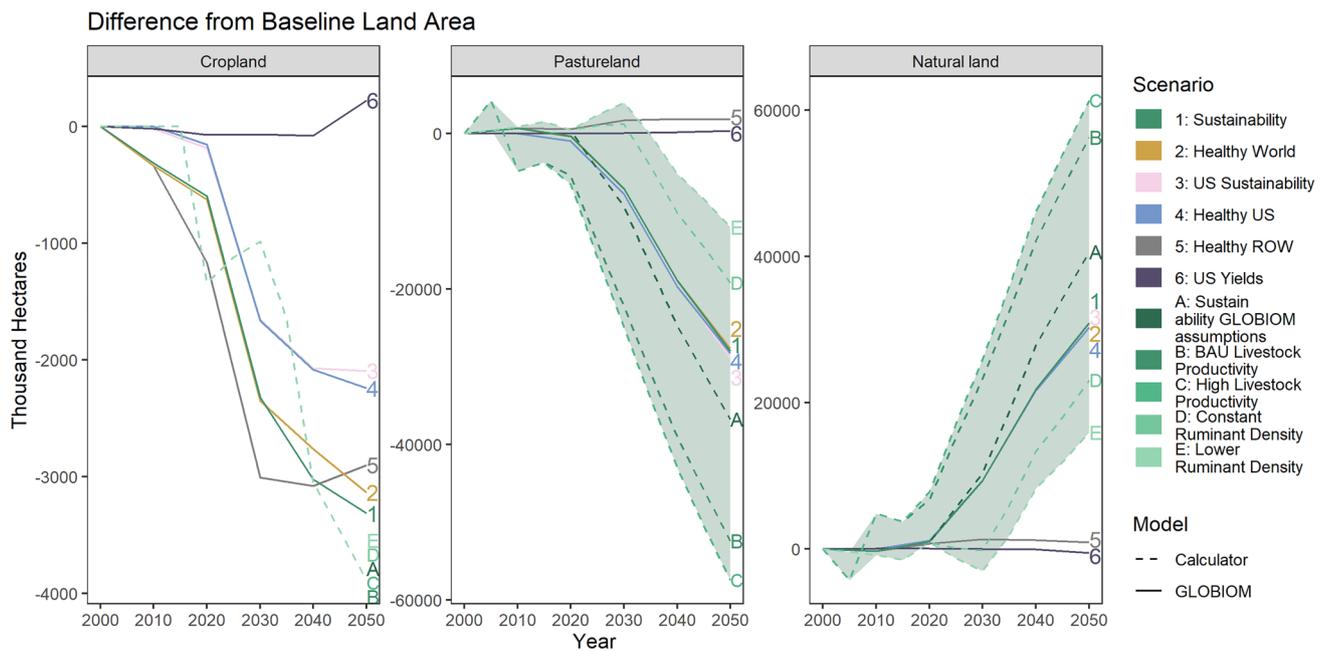
Fig. 3 Land area differences from Baseline scenarios for three land use and land cover types. Dashed lines correspond to Calculator sensitivity scenarios and solid lines correspond to GLOBIOM scenarios. The shaded light green area indicates the range of results for Calculator sensitivity runs. Numeric line labels correspond to the scenario names
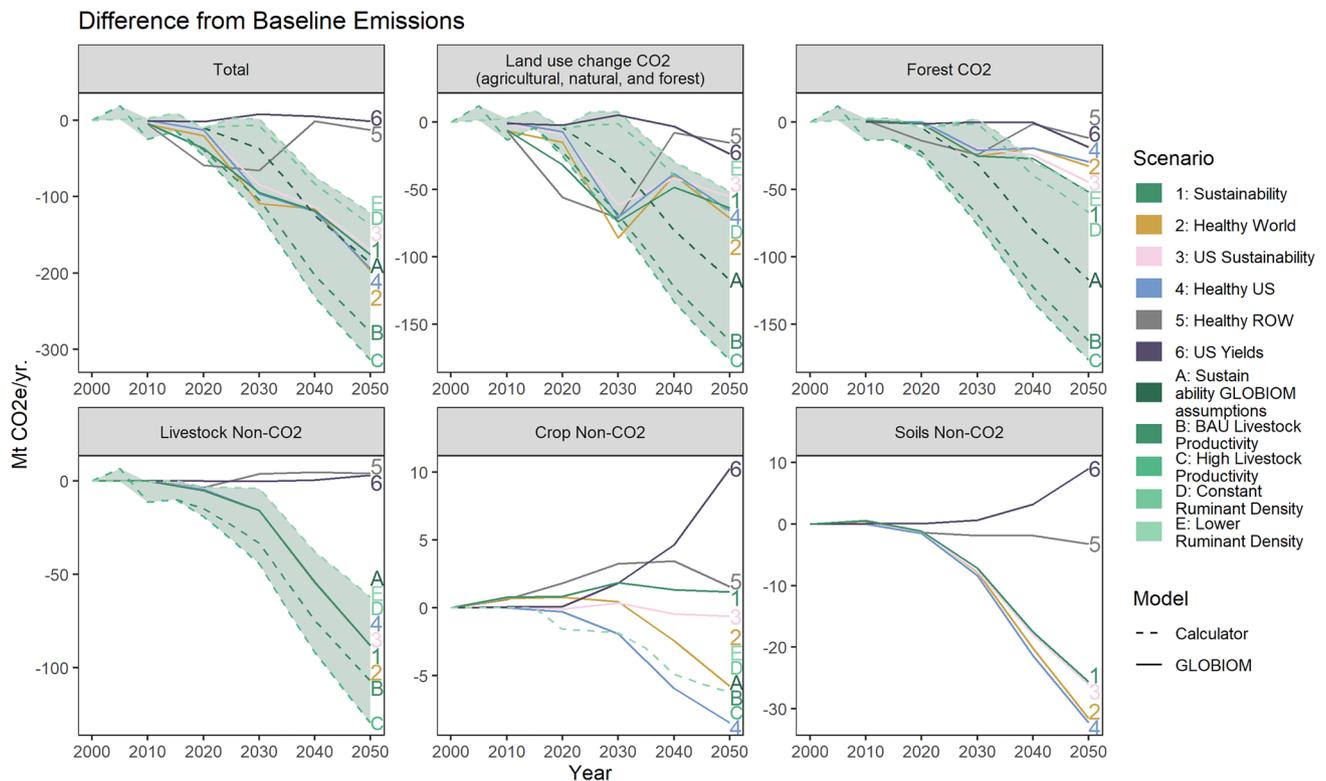
Fig. 4 U.S. GHG emissions differences from Baseline scenarios. Total emissions include crop non-CO_2, livestock non-CO_2, soils non-CO_2, and land use change (agricultural, natural, and forested) CO_2 emissions. Forest CO_2, while shown separately, is a component of land use change CO_2 emissions. Dashed lines correspond to Calculator sensitivity scenarios and solid lines correspond to GLOBIOM scenarios. The shaded light green area indicates the range of results for Calculator sensitivity runs
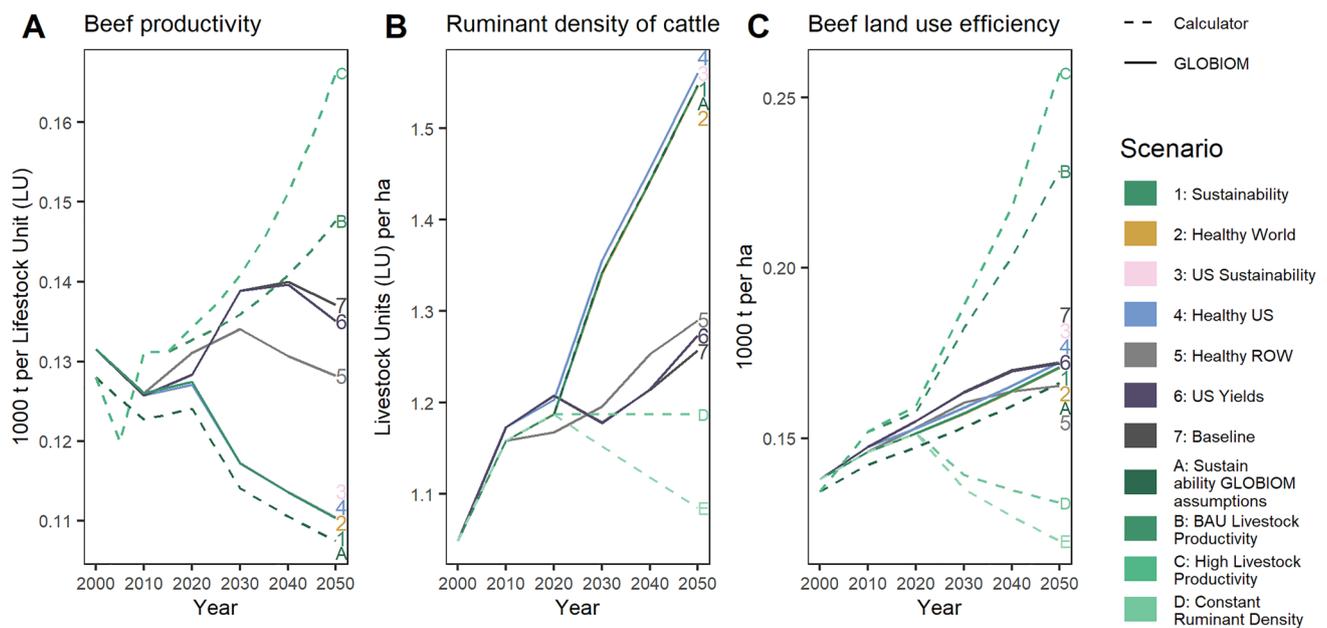
Fig. 5 Beef productivity (**A**), ruminant density (**B**), and overall beef production land use efficiency (**C**) for all GLOBIOM scenarios (solid lines) and all Calculator sensitivity scenarios (dashed lines). Beef productivity and ruminant density are endogenous parameters in GLOBIOM, but exogenous parameters in the Calculator. These parameters were multiplied to calculate beef production land use efficiency (1000 tonnes per ha)

of total reductions (65–70%) for GLOBIOM scenarios, whereas land use change emissions drive the majority of reductions (55–63%) for the Calculator. Most of the land use change emissions reductions are due to increases in forest sequestration from natural regeneration on former cropland and pastureland (Fig. 4).

As with land use changes, domestic emissions reductions by 2050 show minor differences in U.S. emissions between GLOBIOM scenarios that vary yields and diets in the ROW. These differences are only apparent for cropland-related emissions—crop and soils non-CO_2. Increasing yields alone (Scenario 6) has little to no effect on total emissions, since any additional sequestration from land use change is negated by increased crop and soil non-CO_2 emissions due to more intensive farming practices. In particular, N2O emissions from fertilizer use increases as fertilizer intensity expands with higher yields; higher fertilizer application and associated input costs are exogenously required to increase to achieve higher exogenous yield growth rates. Healthy ROW (Scenario 5) results in near-term total emissions reductions of 50–60 MT CO_{2e}/year, but these diminish to less than 10 MT CO_{2e}/year by 2050. We do not find evidence of international leakage when the U.S. shifts to healthier diets (SM Table S8). In fact, we find slight declines in global emissions in the Healthy U.S. and U.S. Yields scenarios (SM Table 8). We do find that Healthy ROW alone reduces global AFOLU emissions by 26% (SM Table 8) despite having minor impacts on U.S. emissions (SM Table 8).

The future trajectory of beef productivity and ruminant density provide bounds for the range of possible land use and emissions impacts from healthy U.S. diets (Figs. 3, 4, 5). To explore the role of technology improvements in the cattle industry and changes in production system or intensification in response to changes in demand, we use the Calculator to run a range of sensitivity scenarios that exogenously alter beef productivity and ruminant density of cattle. We find that beef productivity (tonnes/head or tonnes/ LU) decreases significantly in response to lower domestic beef consumption and production after 2020 in the healthier U.S. diet GLOBIOM scenarios (Scenarios 1–4; Fig. 5A). Productivity increases and then decreases after 2030 or 2040 for the scenarios that maintain the current average U.S. diet (Scenarios 5–7; Fig. 5A). The business-as-usual beef productivity trajectory in the U.S., based on USDA data from the last 20 years (Scenario B) is comparable with GLOBIOM baseline until 2040, when the productivity growth in GLOBIOM starts to level off due to market conditions. The sensitivity that increases this BAU livestock productivity growth rate (Scenario C) causes beef production to exceed that of all GLOBIOM scenarios (Fig. 5A). These productivity increases result in the greatest pastureland reduction by 2050 (52–57 mil ha or 55–60% reduction from Baseline; Fig. 3) across all scenarios. Emissions follow similar trends with increases in beef productivity resulting in significantly greater total emissions reductions compared to baseline (277–314 MT/year; Fig. 3) or 90–127 MT/year greater

reductions than the Calculator Sustainability scenario that uses GLOBIOM productivity assumptions (Scenario A).

Ruminant density (head/ha) increases over time in all GLOBIOM scenarios, with the greatest increases in healthier U.S. diet scenarios (Fig. 5B). Since cattle are smaller at the point of slaughter in these scenarios with lower beef productivity, it is possible to increase the number of animals per unit of land as each animal requires less feed. The constant (Scenario D) and lower ruminant density (Scenario E) scenarios track the current declining trend of grazing intensity in the U.S. This lower intensity trend may also continue if consumer demand for pasture-raised and finished beef continues to rise. These changes increase the amount of land required by cattle and provide lower bound estimates for pastureland reduction (12–19 mil ha or 13–20% reduction; Fig. 3). Lower ruminant density, despite dampening the effect of reduced beef consumption, does result in total emission reductions (121–137 MT/year over Baseline). For land use change CO_2 emissions, constant and lower ruminant density closely resembles results for GLOBIOM scenarios, whereas higher livestock productivity Calculator sensitivity scenarios estimate greater land sequestration compared to GLOBIOM scenarios (Figs. 3, 4), suggesting that livestock productivity values may play an important role in determining the sustainability of reducing beef consumption. As expected, changes to either beef productivity or cattle density do not impact cropland or crop-related emissions.

Despite changes in productivity and ruminant density, overall land use efficiency of beef production (measured in tonnes of beef per ha of land used for cattle fodder or grazing) are very similar across GLOBIOM scenarios and increases over time (Fig. 5C). Increasing rates of beef productivity (historic rates—accelerated rates) increase this efficiency by 35–53% in 2050, and reducing ruminant density reduces this efficiency by 21–28%.

With healthier diets, domestic production and consumption of livestock and corn decline significantly, and the U.S. increases its export share. Consumption, production, import, and export patterns for the top three livestock and crop commodities explain the overall trends in land use and emissions (Figs. 6, 7). Consistent with healthier diet scenario assumptions, U.S. per-capita consumption of beef declines by approximately 50%, while poultry and pork consumption fall by more than two-thirds (Fig. 6). Under Healthy U.S. scenarios, corn and soybean consumption fall (101 MT [33%] and 12 MT [22%], respectively, SM Table S10) with lower demand for livestock feed and dietary shifts away from oilseeds and sugar (which includes corn syrup). Corn and soybean consumption are constant to slightly increasing for the U.S. Yields and Healthy ROW scenarios, with the latter being driven by lower prices as the rest of the world shifts to healthier diets.

Wheat consumption increases up to 14.6% in 2050 as diets shift to a higher proportion of cereals.

Production changes for livestock and corn mirror shifts in consumption, but soybean and wheat production vary considerably across scenarios (Fig. 7). Soybean production changes range from a slight decrease (under Healthy ROW) to an increase of up to 27% under Healthy U.S. and U.S. Yields. The variability in soybean production differences is primarily driven by yield changes, while wheat production differences are driven primarily by diet assumptions (Fig. 2). U.S. wheat production declines relative to the baseline under the Healthy ROW scenario as dietary changes in other regions cause cereal production to increase outside the U.S.

Exports for meat products fall under Healthy ROW and a larger share is consumed domestically (an increase of 14 thousand tonnes relative to baseline) (Fig. 8). However, meat exports increase for all other scenarios, except Healthy ROW (Scenario 5), relative to the Baseline (and by similar volumes). Reduced demand outside of the U.S. causes global prices to fall, reducing the competitive edge that U.S. beef production has in other scenarios. Exports for corn, wheat, and soybeans also increase for all combinations with Healthy U.S. and U.S. Yields. A shift to healthier diets in the U.S. shifts the final disposition of crop production to a higher volume of exports, while higher productivity enhances U.S. comparative advantage. In scenarios where the U.S. moves to healthier diets, by 2050 the U.S. shifts from a net importer of beef to a net exporter.

Discussion

We find that healthier diets in the U.S. can complement sustainability and climate change goals, both directly and indirectly. Reduced feed grain and meat production results in the direct benefit of lower non-CO_2 emissions from U.S. crop and livestock systems. This direct mitigation is supported by additional indirect sources of mitigation from land use and management that occur in response to changing diets and associated market shifts. These land use changes, including reforestation of retired pastureland and cropland, increases carbon sequestration and reduces net emissions relative to the baseline. It is important to distinguish between rangeland that historically was grazed (e.g., by bison) and pastureland that used to be forest. Grazing on well-managed rangeland can promote habitat values directly by limiting woody encroachment and maintaining plant diversity and indirectly by providing economic returns that prevent the conversion of the land to other uses such as urban development. Biodiversity conservation benefits of pasture abandonment can be achieved by targeting
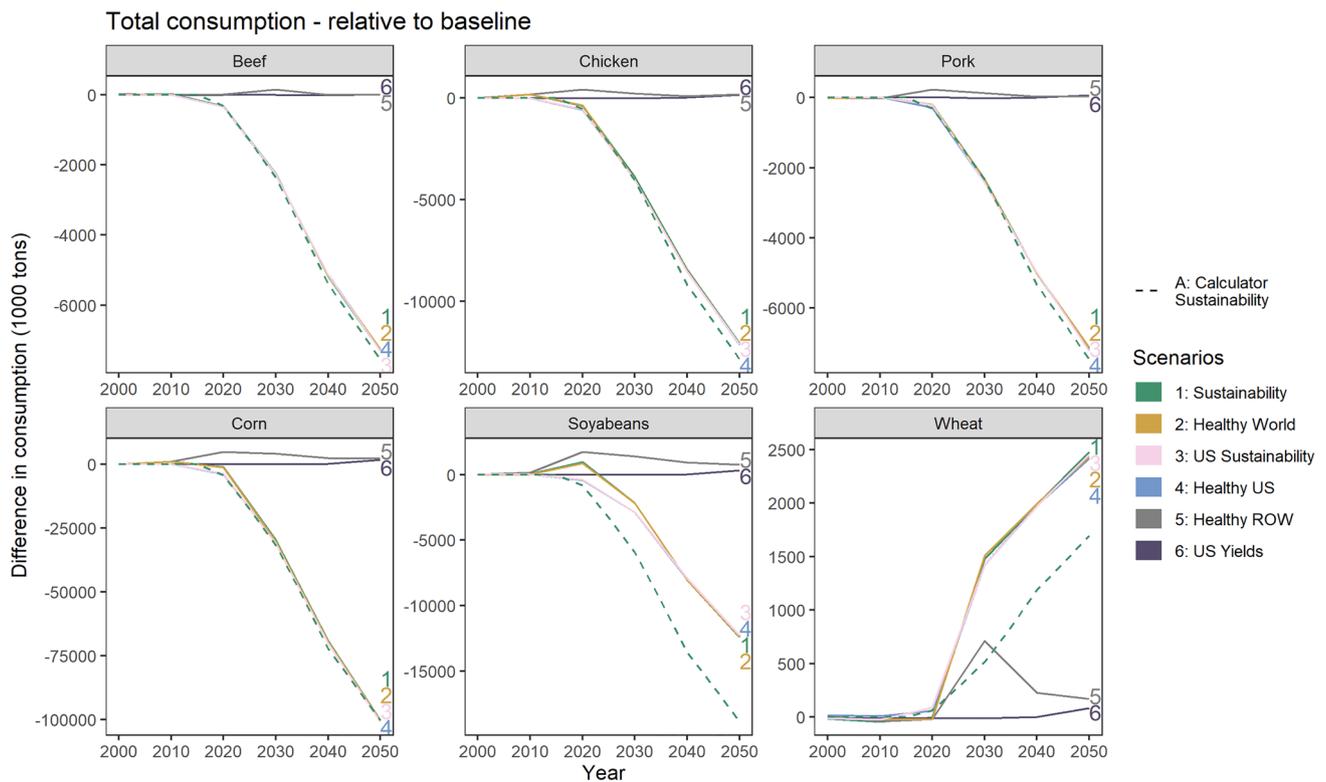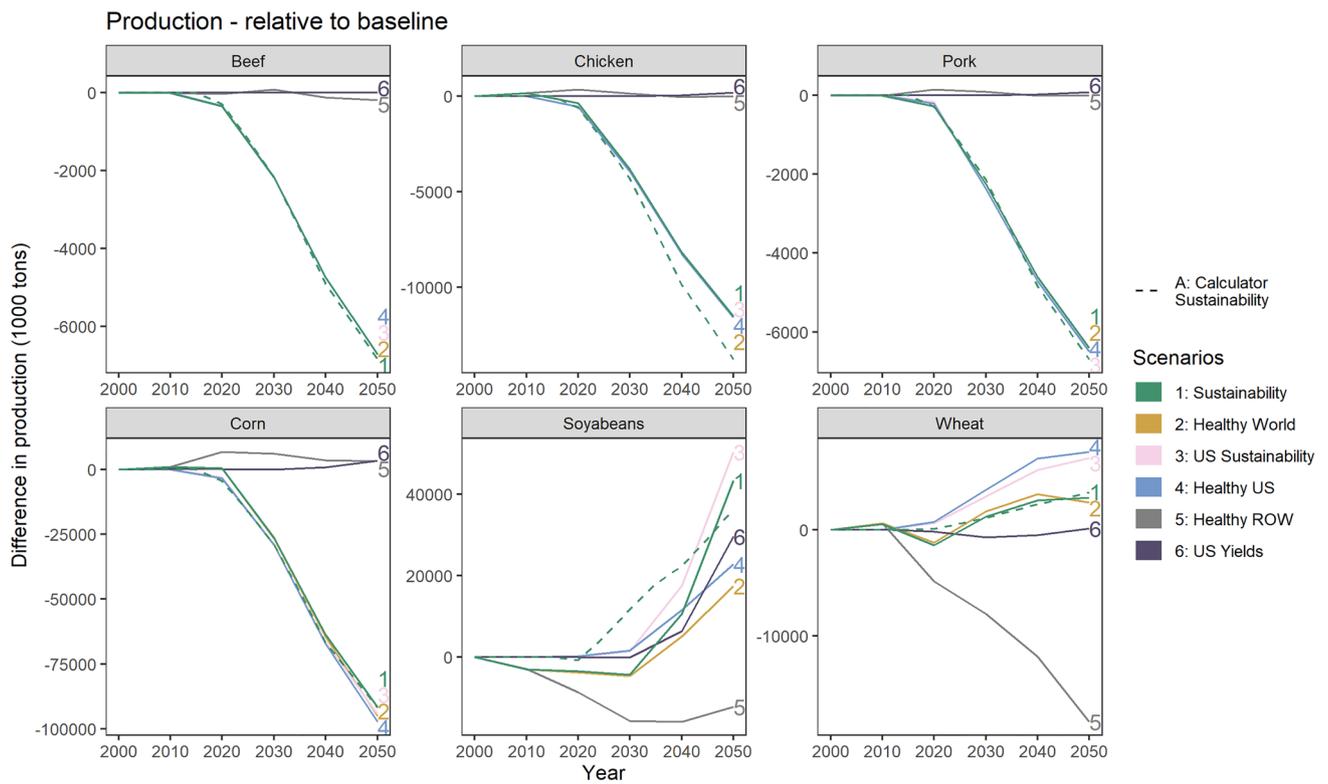
Fig. 6 Total consumption differences from Baseline scenarios in the U.S. Dashed line corresponds to the Calculator. Sustainability pathway and solid lines correspond to GLOBIOM scenarios

lands for reforestation. A recent analysis identified 32 Mha of current pasture that used to be forest and thus would be candidate areas for reforestation (Cook-Patton et al. 2020).

Additional sensitivity analysis with the US FABLE Calculator shows that livestock sector intensification and improved livestock productivity could significantly support further mitigation. Production intensification (ruminant density) and higher animal productivity frees up additional pastureland (note that the Calculator does not differentiate across production systems, so intensification does not necessarily imply switching to feedlots). In the Calculator sensitivity results, some of this land is converted to forests, providing additional indirect mitigation benefits (50–170 $MtCO_{2e}$) that outweigh the direct non-CO_2 emissions reduction from dietary shifts. In isolation, healthier diets reduce the demand for meat products, which theoretically reduces prices and production intensity on a per head of livestock basis (e.g., animals become smaller at slaughter). However, this relationship between demand and productivity may not hold in industries experiencing reduced production (e.g., efficiencies gained from learning by doing may still be achieved under lower production). Thus, measures that maintain or boost livestock intensity and productivity could counter these impacts and spare land for conservation or climate mitigation purposes. However, constant or

declining ruminant density sensitivity results, which reduce beef land use efficiency by 25% compared to 2020, provide an indication of the possible attenuated pastureland reductions (30–70% less) if demand for beef is both reduced and shifts toward pasture-finished products. Pasture-fed beef systems have 30% lower land use efficiency but have lower total GHG emissions (including methane emissions) if assuming increased soil organic carbon sequestration (Pelletier et al. 2010).

Conversely, our results indicate that increasing U.S. crop productivity in the future may have a sizable land sparing effect globally, but only modestly in the U.S. In our simulations, higher crop productivity alone results in increased production and additional land used for crop production in the U.S. between 2040 and 2050. In GLOBIOM, higher crop productivity expands the U.S. comparative advantage in cropping systems, leading to increased exports of staple crops such as corn and soybeans, regardless of dietary preferences. Thus, regardless of whether healthier diets shift regional demands or productivity growth improves the U.S. comparative advantage in agricultural systems, interactions between the U.S. land use system and global markets should be accounted for in sustainability assessments. Ignoring these market interactions could result in biased environmental impact projections of policies, technological

Fig. 7 Production differences from baseline scenarios in the U.S. Dashed line corresponds to Calculator Sustainable pathway and solid lines correspond to GLOBIOM scenarios
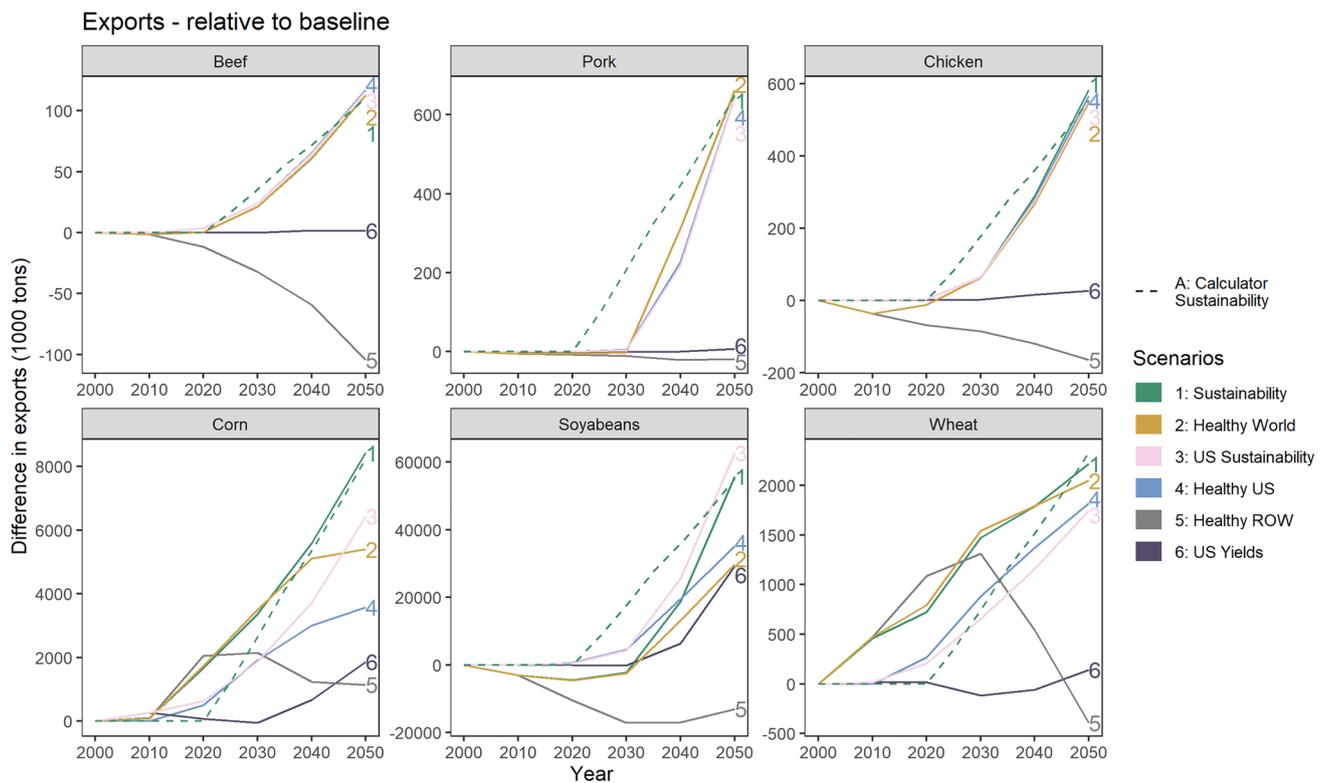
Fig. 8 Change in U.S. exports to the rest of the world for key commodity groups in 1000 tons

improvements, or demand-side changes (Baker et al. 2018; Zhao et al. 2021).

Our results are consistent with studies that have explored healthier diet transitions in the U.S., as summarized in SM Table S9. We project a general (~29–40%, depending on the model) decline in U.S. agricultural land demand under dietary transitions that reduce the domestic demand for meats and feed grains, consistent with 45% and 19% reduction in Behrens et al. (2017) and Birney et al. (2017), respectively (SM Table S9). Our GHG estimates are also in line with Behrens et al. (2017), but are greater than Birney et al. (2017), Hitaj et al. (2019) and Tom et al. (2016), which report the same or greater carbon emissions from adopting the DGA (SM Table S9). The LCA approaches used in these studies do not capture industry adjustments (e.g., industry productivity in response to changes in demand) of healthier diets and use static levels of input use intensity. However, we note that of the four studies reporting GHG emissions of healthier U.S. diets, the two that used an environmentally extended input–output (EIO) modeling approach, which are more comprehensive than processed-based approaches, found lower carbon emissions (0–23%) associated with healthier diets (Behrens et al. 2017; Hitaj et al. 2019). We distinguish our results from previous LCA studies as our use of partial equilibrium and land use/GHG accounting modeling illustrates how healthier, but still omnivorous, diet transitions can alter markets and thus land management decisions at the intensive and extensive margins. Similar to EAT-Lancet (Willett et al. 2019), we show that healthier diet transitions could have other environmental co-benefits by reducing total nitrogen and phosphorus application under most healthier diet scenarios (Fig. S2), though further analysis is needed to better understand the spatial distribution of nutrient application changes.

While diets are a personal choice, government policy has more influence on diets than is widely appreciated. The federal government provides dietary guidelines and the government directly pays for meals for 30 million school children through the free and reduced lunch program, 2 million incarcerated people, 2 million active military members, and 2 million people in nursing homes or assisted living. Guidelines are used by non-federal organizations to provide information on diet and health to the general public, influencing the dietary preferences of millions of additional Americans. Government food and agriculture policy has historically helped drive large shifts in diets and can do so again (Jahns et al. 2018).

Study limitations and future work

There are important limitations of this study that require future research and model development. First, it is important to note that our dietary scenarios are not isocaloric. We designed the healthy U.S. diets to reflect not only changes in food group composition (to improve the macro- and micro-nutritional qualities of the diet), but also to reduce caloric intake which reduces diseases associated with obesity (Mozaffarian 2016). In our results, total U.S. per capita caloric intake declines by 7% in 2050 under the healthier U.S. diet scenarios, which better matches the EAT-Lancet recommendations (Willett et al. 2019). While this is not strictly a limitation, as we intentionally defined 'healthy' more holistically (calories and nutrition), it does reduce the comparability of our study results with those that isolate the effects of diet composition alone.

Second, our approach for diet modeling may differ from other studies. To use the Calculator and GLOBIOM modeling approaches, we converted USDA Dietary Guidelines for Americans volumetric and weight-based recommendations for aggregate food groups into caloric equivalents using representative foods within those groups. The existing baseline diet in both models are based on the Food and Agriculture Organization (FAO) reporting of total U.S. human demand for crop commodities. Thus, differences between the modeled healthier U.S. diet and the baseline U.S. diet (SM Table S2) may not be exactly the same as related U.S.-specific diet studies (Reinhardt et al. 2020).

Finally, each model is limited in its representation of U.S. food systems and the variety of food options available to consumers. For example, both the FABLE Calculator and this version of GLOBIOM do not account for calories from fish, and GLOBIOM does not offer a detailed breakdown of fruit and vegetable production systems. Healthier diets demand more alternative proteins and fruits and vegetables, which could drive the allocation of cropland toward a higher proportion of specialty crops. Importantly, some of these crops create other resource challenges, such as the high water demand of almonds. Representing specialty crops spatially in partial equilibrium frameworks is an important research gap that warrants future work and model development.

Furthermore, each model is also limited in its representation of the U.S. forestry system, with minimal differentiation between planted/managed forest systems and unmanaged systems and their respective carbon dynamics. Responses to policy signals that influence the allocation of land between agriculture and forestry could also alter the distribution of passively and actively managed forest resource systems with different associated carbon profiles. Future work will be necessary to improve the representation of fruit and vegetable production systems and forest management dynamics in the U.S. for a more comprehensive sustainability policy assessment.

Notably, we do not quantify a full suite of benefits and costs associated with healthier diet transitions, including improved health outcomes (potential benefit) and distributional implications of agricultural transitions on rural

communities (potential costs). Future analysis should carefully consider a wider-range of policy implications to offer a more holistic perspective on healthier diet transitions.

Future research on healthier diet transitions in the U.S. (and other regions) can build on this analysis by quantifying a broader range of economic costs and benefits of healthier diet transitions. Furthermore, this analysis assumes dietary change occurs through general preference shifts and does not consider the costs or associated tradeoffs of incentive structures needed to support dietary change. We also do not consider potential research and development costs needed to increase crop and livestock yields and to facilitate technology transfer. While this omission does not limit the scope of our current analyses, the magnitude of these costs remains an important policy design question. Nor do we quantify the sustainability and climate benefits of productivity improvement through novel technologies that also reduce input use intensity. If productivity gains can support sustainability, climate, and rural development goals, then more explicit consideration and potential yield-enhancing (and input-reducing) technologies is needed to design effective policy instruments. Future analyses can benefit from consideration of these factors for a more comprehensive assessment of environmental and health impacts of dietary transitions.

Conclusions

Our results suggest that healthier diets could support climate mitigation and sustainability goals (e.g., biodiversity conservation) through direct and indirect emissions abatement and effects on land use. Improved agricultural productivity growth is likely to lead to increased production and export of U.S. products. This likely means that GHGs emissions are not reduced in the U.S., but may provide significant benefits globally through avoided deforestation. The effect of healthier diets in the U.S. would result in a reduction of 120–310 MT CO_{2e}/year by 2050 compared to our business as usual baseline. The scenario-based land use mitigation component of the U.S. long-term climate strategy, calculated as the range of differences between the BAU and NCS action scenario ranges and does not assume changes in U.S. dietary preferences, is approximately 150–350 Mt/year reduction by 2050 (United States Department of State & United States Executive Office of the President 2021). By capturing interactions between U.S. and global diet assumptions and agricultural productivity growth (for livestock and crop systems), our results provide bounds around the potential environmental impacts of a particular dietary transition (U.S. Department of Agriculture & U.S. Department of Health and Human Services 2020). We provide key insight into policy goals or investments that could complement dietary transitions (e.g., livestock intensification) vs. those that may

require additional policy incentives to improve environmental outcomes (e.g., crop productivity growth).

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