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ORIGINAL ARTICLE

Benefits of air quality for human health resulting from climate change mitigation through dietary change and food loss prevention policy

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Abstract

Food production, particularly cattle husbandry, contributes significantly to air pollution and its associated health hazards. However, making changes in dietary habits, such as reducing red meat consumption and minimizing food waste, can lead to substantial improvements in both air quality and human health. In this study, we explored the impact of dietary changes on future air quality and human wellbeing. We also assessed the influence of dietary transformation policies in the context of climate change mitigation, with the objective of understanding how policies can effectively complement each other. We used a chemical transport model and an integrated assessment model to determine changes in fine particulate matter ($PM_{2.5}$) and ozone (O_3) concentrations. Then, an exposure model was applied to estimate premature deaths as a consequence of air pollution. Our results showed that dietary changes could play a crucial role in mitigating air pollution, particularly in regions where agricultural activities emit significant quantities of ammonia. In the European Union, for example, dietary changes could lead to a reduction of 5.34% in $PM_{2.5}$ by 2050. Similarly, in Asia, the models projected a reduction of 6.23% in $PM_{2.5}$ by 2100. Ground surface O_3 levels in Southeast Asia were projected to drop by as much as 12.93% by 2100. Our results further showed that dietary changes could lead to significant reductions in global mortality associated with $PM_{2.5}$ and O_3, with 187,500 and 131,110 avoided deaths per year expected by 2100. A combined approach that integrates dietary changes with climate change mitigation measures could lead to more comprehensive air quality improvements in specific regions. However, careful consideration is needed to address any potential adverse effects on O_3 concentrations in some areas.

Keywords Air pollution · Climate change · Dietary shifts · GEOS-Chem · Human health · Ozone · $PM_{2.5}$

Introduction

Food production significantly impacts the environment, serving as a major driver of greenhouse gas (GHG) emissions and air pollution. The food sector alone contributes to 10–12% of total global emissions (Bauer et al. 2016; Smith et al. 2014; Tai et al. 2014). Recent studies highlight ammonia emissions, especially from the agricultural sector, notably livestock production, as a significant contributor to $PM_{2.5}$ in ambient air (Bist et al. 2023; Choi and Sunwoo 2022; Liu et al. 2021b; Mazzeo et al. 2022; Ti et al. 2022; Wang et al. 2023). However, policies targeting NH_3 emissions from agricultural sources are yet to be implemented in numerous countries, particularly in developing nations where agricultural activities play a pivotal role in the economy (Ma et al. 2021). Urgent action and global cooperation are imperative to develop comprehensive strategies addressing these emissions and mitigating their environmental impact.

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The global population is projected to reach 9.7 billion by 2050. A 70% increase in global food production is forecasted to meet the demands of this growing population (High-Level Expert Forum 2009). However, the anticipated rise in food production may exacerbate air pollution, placing additional strain on the environment and human health. Therefore, proactive and comprehensive measures are essential to ensure sustainable and environmentally responsible approaches to meet the increasing food demands while minimizing adverse impacts on air quality and overall environmental health. The health consequences of unfavorable air quality are deeply intertwined with agricultural activities. A study conducted by Domingo et al. (2021) investigated the impact of air pollution on agricultural production in USA. Their research revealed that a significant portion of the 15,900 annual deaths caused by fine particulate matter ($PM_{2.5}$) pollution related to food is attributed to animal-based foods, accounting for 80% of these fatalities.

Climate change and air pollution are closely related, because both are caused by the release of GHGs and other pollutants into the atmosphere. Thus, climate change mitigation efforts may contribute to reducing air pollution, and clean air policies may have a mitigation effect on climate change (Jiang et al. 2013; Nemet et al. 2010; Thurston and Bell 2021; Vandyck et al. 2018; West et al. 2013). Dietary transformation has the potential to moderate GHG and pollutant emissions from the agricultural food chain (Pörtner et al. 2022). In 2019, the EAT-Lancet Commission published a summary report that provided guidelines for transforming the food system toward greater sustainability and healthiness. One of its recommendations was to reduce the consumption of red meat by 50% by 2050 and to explore new protein sources including plants (Willett et al. 2019). This adjustment in eating habits has the potential to lessen the severity of future climate change and pollution. Moreover, EAT-Lancet also aspires to cut food losses and waste in half by 2030, in line with Sustainable Development Goal (SDG) 12.3 (United Nations 2023). Although a number of investigations have attempted to establish a connection between dietary changes and GHG emissions, relatively few studies have investigated air pollution.

The connection between dietary changes and GHG emissions has been extensively researched. Currently studies have investigated the consequences of dietary choices and food production methods for GHG emissions. However, considerably fewer studies have examined the impact of dietary changes on air quality on a global scale. For example, in the EU, a 33% reduction in ammonia emissions was observed after the implementation of a flexitarian diet, leading to a decrease in the levels of $PM_{2.5}$ and the number of mortalities (Himics et al. 2022). Furthermore, the integration of policies that effectively address both GHG emissions and air quality, together with the health consequences of dietary choices, remains underexplored. While the Intergovernmental Panel on Climate Change (IPCC) report has delved into the role of food production in escalating GHG emissions and proposed mitigation policies for agricultural GHGs, a clear dietary framework for these policies remains ambiguous. For instance, the report recommends a shift toward more sustainable food choices, advocating a reduction in red meat consumption (Mbow et al. 2020). However, it does not specify the proportion of food that should be altered.

The primary objective of this study was to resolve deficits in our understanding of the connection between dietary changes and changes in air quality. Therefore, we have implemented a comprehensive and detailed framework for sustainable diets, taking from the EAT-Lancet Commission. Furthermore, we investigated the role of dietary change policies within the context of climate change mitigation scenarios to better understand their potential impact and contribute valuable insights to sustainable practices. By exploring the consequences of dietary choice and food production methods for GHG emissions and air pollution, we sought to shed light on the environmental consequences of our food consumption patterns, as well as their potential impacts on public health and wellbeing.

We also explored the potential health benefits associated with air quality improvements that could result from GHG mitigation policies proposed by the IPCC and dietary changes proposed by the EAT-Lancet Commission. Overall, we hope to improve our understanding of the complex interactions among dietary choice, climate change mitigation measures, air quality improvements, and public health. Our findings on the potential health benefits of adopting sustainable diets will support the development of integrated policies to simultaneously address environmental improvements and health concerns, thereby contributing to a more resilient and sustainable future.

Materials and methods

Overview

The Goddard Earth Observing System-Chemistry (GEOS-Chem) model was used to estimate surface-level concentrations of ambient $PM_{2.5}$ and O_3. Model simulations were generated using data inputs from a comprehensive inventory of anthropogenic emissions and meteorological data. To evaluate the prospective trajectory of air quality based on the simulation, we integrated future GHGs, and chemical pollutant emissions scenarios derived from the Asia-Pacific Integrated Model (AIM-Hub). Subsequently, a health exposure model was employed to estimate premature mortality attributable to exposure to $PM_{2.5}$ and O_3, as illustrated in Fig. 1.

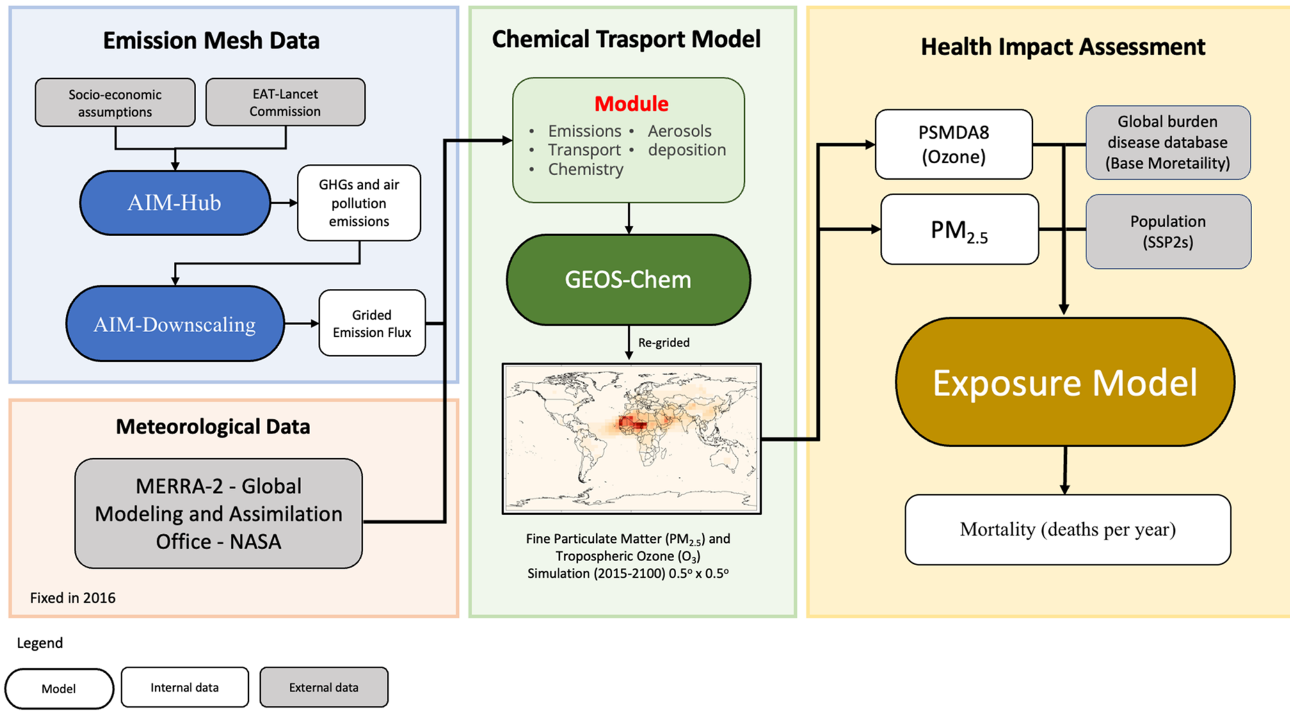

Fig. 1 Visualization of the research framework

Table 1 Summary of policy scenarios

Identifier	Descriptor	Reference pathway
SC1	Baseline	GDP[a] for each country and population projection
SC2	Dietary change and food loss prevention	Red meat and sugar consumption cut by 50% by 2050 Halving global per capita food waste in 2030 (EAT-Lancet)
SC3	Climate change mitigation	Maintain cumulative CO_2 emissions below 500 Gt after 2020 for a 50% chance of remaining within 1.5 °C warming (IPCC[b])
SC4	Integrated policy (SC2 + SC3)	Combination of strategies including climate change mitigation and healthy dietary change

[a]Gross Domestic Product

[b]The Intergovernmental Panel on Climate Change (IPCC)

Scenarios and experiment design

To examine the influence of dietary changes and climate change mitigation policies, we considered four scenarios for the study areas (Table 1). These included a baseline scenario with high GHG emissions (SC1), a dietary change and food loss prevention scenario (SC2), a climate change mitigation scenario (SC3), and a scenario based on the integration of climate change mitigation measures with dietary change and food loss prevention (SC4). By inputting these scenarios into the AIM-Hub Model, we can assess the potential air quality consequences based on specific assumptions about emissions, which may be influenced in part by dietary choices.

Baseline socioeconomic assumptions for all scenarios were derived from the Shared Socioeconomic Pathways (SSPs) scenario, also known as the "middle of the road" scenario (Riahi et al. 2017). In the SC2 scenario, we assumed that people would switch to a healthier diet by consuming more plant-based protein from beans, lentils, and pulses from a diet including red meat and dairy products. The EAT-Lancet Commission recommends reducing red meat and sugar consumption by 50% by 2050. Additionally, the total daily food demand should not exceed 2503 kcal per capita (Willett et al. 2019). We also considered food loss reduction under SDG 12.3, which aims to cut global per capita food waste by 50% by 2030 (Ardra and Barua 2022). These targets, stretching to 2100, emphasize sustained efforts for dietary change and food waste reduction, forming a critical part of our long-term sustainability strategy.

To assess climate change mitigation scenarios, we aligned our analysis with the objective of maintaining cumulative

CO_2 emissions below 500 Gt-CO_2 after 2020, which is consistent with a 50% chance of restraining warming to 1.5 °C under SSP2 (Fujimori et al. 2016). In our SC4 scenario, we examined the potential influence of future dietary patterns under climate change mitigation policy condition, which allowed us to explore the interconnected dynamics of climate change mitigation policies, dietary choices, and food loss reduction strategies on future air quality.

Model description

AIM-Hub

In this study, we used the AIM-Hub model framework coupled with other modeling tools for scenario quantification presented by Fujimori et al. (2018) which enabled the assessment of critical elements such as the energy system, land use, agriculture, GHG, and air pollutant emissions. In projecting future assumptions regarding population and income trends, we have employed the SSPs, originally designed for primary application in climate change research, as outlined by O'Neill et al. (2017). In this study, we focused on the "middle of the road" SSP2 scenario. Details of the model structure and mathematical formulae are described by Fujimori et al. (2012). The assumption is that production sectors seek to maximize profits using multi-nested constant elasticity substitution functions, taking into account the price of each input. Emissions resulting from changes in land use are calculated by multiplying the alteration in forest area compared to the previous year by the carbon stock density. This density is specific to global agroecological zones, providing a differentiated measure based on geographical and ecological considerations. Emissions not related to energy, excluding those associated with changes in land use, are presumed to be directly proportional to the magnitude of each respective activity, such as output (Fujimori et al. 2022).

The simulation in AIM was initiated from the year 2005 and extended until 2100, encompassing historical, present, and future periods. The choice of this timeframe is crucial for calibration purposes across various sectors. Specifically, the period from 2005 to 2015 serves as a calibration phase for all sectors, leveraging data from the Global Trade Analysis Project (GTAP) database (Dimaranan 2006). In the energy sector calibration, the simulation utilizes data from the period 2007 to 2015, drawing from the International Energy Agency (IEA) (IEA 2019). This focused calibration ensures that the AIM-Hub model aligns with the empirical data available during these specific time intervals, enhancing the accuracy and reliability of the simulation across sectors and time periods.

Utilizing the AIM-Hub model, we derived GHG and air pollutants emissions across various scenarios. This encompassed an array of pollutants, including carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), fluorine (F), black carbon (BC), carbon monoxide (CO), ammonia (NH_3), non-methane volatile organic compounds (NMVOC), nitrogen oxides (NOx), organic carbon (OC), and sulfur oxides (SOx). These emissions play a pivotal role in atmospheric processes, contributing to the formation of $PM_{2.5}$ and O_3. These derived emissions are linked to factors, such as food demand, supply, and trade dynamics based on population growth, Gross Domestic Product (GDP) evolution, food prices, consumer preferences, and technological developments.

To generate gridded emissions at a 0.5° × 0.5° resolution, we applied the AIM downscaling tool (AIM-DS) to the regionally aggregated 17-region emission inventory. The method for downscaling would depend on sector and sources of emission which would be segregated into three groups as shown in Table 2. Different downscaling mechanisms were applied to each sector. GDP and Population emerge as the principal catalysts behind emissions within the ambit of group 1 focusing on emissions from energy, industry, inland transport, building, solvent, and waste sectors. Within this framework, it is conjectured that the energy facet intertwined with emission dynamics could plausibly demonstrate an interconnection with either GDP or Population. The second group was established in proportion to the base year (2015) including emissions from agriculture, forestry, and land use. The third group was downscaled in proportion to the total global emissions from the base year's geographic distribution and was applied to aviation emissions. These approaches are described in greater methodological detail in Fujimori et al. (2017, 2018).

GEOS-Chem

We used a chemical transport model to estimate the gridded concentrations of $PM_{2.5}$ and O_3. The GEOS-Chem global three-dimensional model of atmospheric transport v13-04 (Bey et al. 2001; http://www.geos-chem.org) was used to simulate surface concentrations. To drive the

Table 2 Downscaling algorithm emission source groups and weight used (Fujimori et al. 2017)

Sector	Group	Weight
Energy	1	GDP
Industry	1	GDP
Inland transport	1	GDP
Building	1	Population
Solvent	1	GDP
Waste	1	Population
Agricultural	2	
Agricultural waste	2	
Land-use change	2	
Savana burning	2	
International navigation	3	
Aviation	3	

GEOS-Chem model, we employed the NASA Global Modeling Assimilation Office MERRA2 reanalysis meteorological data product, which aggregates data at a coarse resolution. The list of meteorological parameters used in our analysis can be accessed at https://wiki.seas.harvard.edu/geos-chem/index.php/List_of_MERRA-2_met_fields. The simulated surface concentrations of $PM_{2.5}$ and O_3 were generated at a horizontal resolution of $4.0° \times 5.0°$ with 72 vertical layers. The chemical mechanism used in the GEOS-Chem model included a detailed O_x–NO_x–hydrocarbon–aerosol–bromine mechanism (Mao et al. 2013; Parrella et al. 2012). The $PM_{2.5}$ components were natural mineral dust, sea salt, primary black carbon aerosols, primary organic aerosols, secondary inorganic aerosols (sulfate, nitrate, and ammonium), and secondary organic aerosols. To simulate the thermodynamics of secondary inorganic aerosols, we used ISORROPIA II (Fountoukis and Nenes 2007; Pye et al. 2010).

Data on GHG emissions and air pollution from the AIM-Hub model were fed into the GEOS-Chem model. To simulate natural emissions, we used the GEOS-Chem archived inventories from the Harmonized Emissions Component (HEMCO), which included NO_x emissions from lightning, dust, and sea salt emissions, biogenic emissions, and emissions from volcanic eruptions (Fritz et al. 2022; Lin et al. 2020).

In this study, we did not account for the influence of climate change on the climate system itself, particularly temperature changes. Consequently, meteorological conditions were assumed to be consistent across all scenarios and years, based on a 2016 baseline. Subsequently, emissions data were fed into the GEOS-Chem model for further analysis. The years 2015, 2030, 2050, and 2100 were selected for chemical transport model simulations to evaluate immediate, medium-term, and long-term implications of dietary change on air quality.

The quantification of the dietary change effect was done by percentage relative change (RC) for each $PM_{2.5}$ and O_3 between reference and target scenario using the following equation:

$$\mathrm{RC}_j(\%) = \frac{X_j - X_i}{X_i} \times 100, \tag{1}$$

where RC_j is a percentage RC of the target scenario compared with the reference scenario (%); X_i is a reference scenario in this study, we have two reference scenarios including SC1: baseline scenario and SC3: climate change mitigation scenario; X_j is target scenario (SC2 and SC4).

Premature mortality attributable to long-term exposure to ambient $PM_{2.5}$ and O_3

We estimated the premature mortality attributable to $PM_{2.5}$ and O_3 exposure as follows (Apte et al. 2015):

$$\Delta \mathrm{Mortality}_{i,j} = \frac{\mathrm{RR}_j(C_i) - 1}{\mathrm{RR}_j(C_i)} \times \mathrm{Pop}_i \times y_{0j}, \tag{2}$$

where $\Delta\mathrm{Mortality}_{i,j}$ is the premature death caused by long-term $PM_{2.5}$ or O_3 exposure for region i and disease j; C_i is the annual mean ambient $PM_{2.5}$ (μg/m^3) concentration in region i; $\mathrm{RR}_j\,(C_i)$ is the relative risk function for the disease j endpoints associated with the RC in $PM_{2.5}$ or O_3 concentration C_i; Pop_i is the population in region i; and y_{0j} is the baseline mortality rate for disease j by country according to the Global Burden of Disease (GBD) study.

In the present study, the integrated exposure–response (IER) function (Eq. 3) developed by Burnett et al. (2014) was used to estimate the burden of disease related to ambient $PM_{2.5}$ including ischemic heart disease, cerebrovascular disease (i.e., stroke), chronic obstructive pulmonary disease, lung cancer, and lower respiratory infection. The IER was defined for $PM_{2.5}$ concentrations exceeding C0 (7.5 μg/m^3), because concentrations lower than 7.5 were not found to be related to mortality in a cohort study (Long et al., 2014).

$$\mathrm{RR}_j(C_i) = 1 + \left(1 - \exp\left(-\beta\left(C_i - C_0\right)^{\delta}\right)\right), \tag{3}$$

where α, β, and δ are age- and disease-specific (j) IER constants provided in Table 3.

To estimate premature mortality attributable to long-term O_3 exposure, peak seasonal (6-month) maximum daily 8-h average (PSMDA8) O_3 concentrations in ambient air were used to calculate the relative global risk (RR) (Eq. 4)

$$\mathrm{RR}_j(C_i) = \exp[((\mathrm{PSMDA8} - \mathrm{TMREL}) \times \beta)], \tag{4}$$

where $\beta = 0.007696$, TMREL is the theoretical minimum risk exposure level, which was estimated as 29.1–35.7 ppb in the GBD study. In this study, we applied the beta coefficient (β) of Turner et al. (2016) to calculate RR. For all regions and people, TMREL was set at 32.4 ppb, which was the median value reported by Malashock et al. (2022).

Results

Impact of dietary changes on future global GHGs and air pollutant precursor gases

Our results showed that dietary changes can exert a profound influence on food demand, thereby potentially affecting future GHG emissions and air pollution. The EAT-Lancet report indicated that the implementation of dietary changes could lead to a reduction of approximately 300 kcal per capita per day in livestock demand, accompanied by a decline in food crop demand. These altered consumption patterns had the potential to lead to significant reductions in GHGs and air pollutant precursor gases such as NH_3 and NO_x. Dietary changes were also able to mitigate the adverse effects of air pollution on public health, including a decrease in premature mortality from direct and indirect causes (Fig. 2).

According to the baseline scenario, GHG emissions were projected to increase steadily, reaching nearly 90 Gt CO_2-eq by 2100. However, the implementation of SDG 12.3 in 2030, which focuses on reducing food loss and waste, was projected to lead to a reduced rate of increase in GHG emissions. Importantly, emissions were projected to continue to rise despite this intervention. By 2050, the adoption of dietary changes would result in a reduction of 5.89 Gt CO_2-equivalent in GHG emissions, or approximately 8% of the emissions reported in the baseline scenario.

The transformation of dietary patterns scenario (SC2) would primarily affect emissions of N_2O and CH_4, which are two significant GHGs produced by livestock operations. However, lower (but still important) impacts were projected for other GHG species. Although total GHG emissions would be dramatically reduced over time and would reach zero by 2100 under the climate change mitigation measures (SC3), the integration of dietary changes with these policies was not projected to lead to significant reductions in GHG emissions, except for CH_4 and N_2O (Fig. 3).

SC2 was forecast to yield reductions of approximately 12.8% (−8.655 Mt/year) in emissions of NH_3 in 2030. This downward trend was projected to persist, with continuous declines anticipated to reach 17% (− 13.03 Mt/year) by 2050 and 33% (−29.04 Mt/year) by 2100 compared to the baseline scenario. This decline was primarily attributable to reductions in the scale of the cattle industry. As shown in Fig. 4, dietary modifications could result in a significant reduction in animal production over time. By contrast, NH_3 emissions from the soil management sector increased by 2050 due to transformation of the food system from livestock to plant-based protein especially in China, as shown in Table 4.

Compared to the baseline scenario, NH_3 emissions in the climate change mitigation scenario (SC3) were projected to decrease from 2015 to 2050. These reductions in NH_3 emissions amounted to 23.33 Mt/year, representing a 17% decrease. A large portion of these emissions originated from crop production. In the integrated policy approach, which combined climate change mitigation with dietary changes (SC4), an even greater reduction in NH_3 emissions was forecast. The integrated policy could potentially achieve a reduction of 29.23 Mt/year, representing an additional decrease

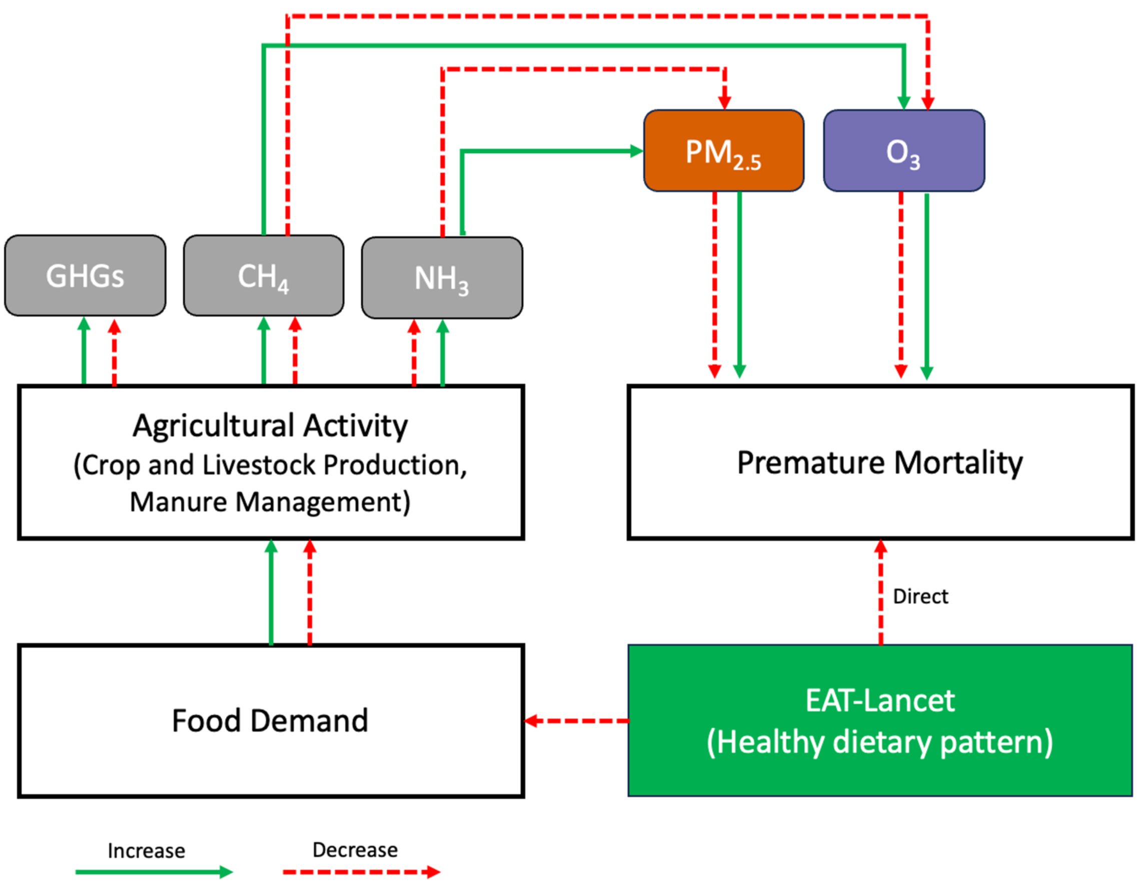

Fig. 2 Mechanisms of dietary changes on GHG emissions, air pollutant precursors, and human health

Table 3 IER parameter estimates by cause of death (Burnett et al. 2014)

Cause	Age	α	β	δ	C_0
LRI[a]	25+	2.2023	0.0028	1.1830	7.2834
COPD[b]	25+	15.2237	0.0009	0.6839	7.3744
IHD[c]	25	4.8248	0.0562	0.4176	7.5931
	30	4.1553	0.0607	0.4150	7.5791
	35	3.5727	0.0652	0.4119	7.5572
	40	3.0606	0.0702	0.4053	7.5402
	45	2.7991	0.0747	0.3486	7.6417
	50	2.2853	0.0782	0.3587	7.6121
	55	1.8853	0.0823	0.3591	7.5850
	60	1.5540	0.0869	0.3676	7.5337
	65	1.2631	0.0910	0.3733	7.5221
	70	1.0079	0.0965	0.3762	7.5221
	75	0.7844	0.1035	0.3835	7.4994
	80	0.5869	0.1102	0.3824	7.4946
	25+	1.4273	0.0476	0.3762	7.4624
LC[d]	25+	114.7418	0.0001	0.7409	7.3799
Stroke	25	5.8878	0.0157	0.6513	7.5558
	30	5.0565	0.0157	0.6839	7.5199
	35	4.2831	0.0167	0.6991	7.4571
	40	3.6171	0.0170	0.8078	7.5048
	45	3.0363	0.0165	0.9211	7.4904
	50	2.5199	0.0166	0.9570	7.5142
	55	2.0829	0.0172	0.9809	7.5168
	60	1.7075	0.0173	0.9945	7.4893
	65	1.4035	0.0222	0.8975	7.4893
	70	1.1060	0.0206	0.9612	7.4446
	75	0.8472	0.0198	1.0279	7.4371
	80	0.6250	0.0190	1.0900	7.4034
	25+	1.2641	0.0072	1.3137	7.3875

[a]Lower respiratory infection

[b]Chronic obstructive pulmonary disease

[c]Ischemic heart disease

[d]Lung cancer

of 11.4 Mt/year compared to the climate change mitigation scenario alone. Much of this 19% reduction in NH_3 emissions was forecast to come from the livestock sector represented in Table 4.

Effect of dietary change on future air quality

The impact of dietary changes on $PM_{2.5}$ (upper) and O_3 (lower), as compared to the Baseline (SC1) scenario, is illustrated in Fig. 5. Scenario SC2 demonstrated significant potential for mitigating $PM_{2.5}$ pollution, particularly in regions where agricultural activities are a significant source of NH_3, including Europe, Brazil, and Southeast Asia. Reductions in $PM_{2.5}$ induced by dietary changes were particularly prominent in Europe. Compared to their baseline concentrations, average $PM_{2.5}$ concentrations in the EU were forecast to decline by 1.79% (maximum: 3%, minimum: − 8%) by 2030, 5.34% (maximum: 0.98%, minimum: − 10.38%) by 2050, and 9.88% (maximum: − 0.39%, minimum: − 17%) by 2100. In Asia, the projected reductions in $PM_{2.5}$ were 1.08% (maximum: 2.49%, minimum: − 4.61%) by 2030, 2.36% (maximum: 1.73%, minimum: − 7.77%) by 2050, and 6.23% (maximum: 0.08%, minimum: − 16.72%) by 2100.

The initial adoption of dietary changes appeared to lead to a slight increase in average $PM_{2.5}$ levels in China. By 2030, $PM_{2.5}$ concentrations in China were projected to increase by approximately 2%. This temporary increase could be attributed to alterations in food production and consumption practices, which directly influence agricultural emissions especially from the soil management sector as detailed in Table 4. However, a long-term positive shift was observed, with $PM_{2.5}$ concentrations projected to decline by approximately 5% by 2100.

Dietary policies scenario (SC2) was able to achieve reductions in O_3 in Southeast Asia and South America between 2030 and 2100. In Southeast Asia, dietary modifications were forecast to play a part in mitigating surface-level O_3 concentrations, with declines of 3.21% by 2050 (maximum: − 2.06%, minimum: − 4.75%) and 9.29% by 2100 (maximum: − 4.56%, minimum: − 12.98%). However, in 2030, only minimal changes in O_3 concentrations were forecast, with an average decline of 1.75% (maximum: − 0.72%, minimum: − 2.73%). By contrast, dietary transformation was projected to lead to an initial upsurge in tropospheric O_3 concentrations in China, primarily in eastern China. However, as dietary changes become established, increases in O_3 are expected to be mitigated by 3–9% by 2100, as shown in Fig. 5.

The implementation of SC3 demonstrates significant potential for reducing $PM_{2.5}$ levels, particularly in Asia and Europe (Fig. 6a). Concurrently, the climate change mitigation scenario in the Americas and Asia is expected to contribute to a decline in O_3 concentration (Fig. 6b). Notably, despite the implementation of climate mitigation measures, Africa is not forecasted to experience substantial reductions in $PM_{2.5}$ and O_3 concentrations.

When considering the role of dietary change under climate mitigation policies (SC4), as shown in Fig. 7, it appears that its impact on $PM_{2.5}$ levels may be lower compared to the implementation of climate mitigation measures alone. The influence of dietary change within the climate change scenario is particularly evident in the Europe region, where it has the potential to further reduce annual average $PM_{2.5}$ concentrations by approximately 3.86% (maximum: − 2.11%, minimum: − 7.21%), 2.58% (maximum: − 0.17%, minimum: − 5.92%), and 2.68% (maximum: − 0.39%,

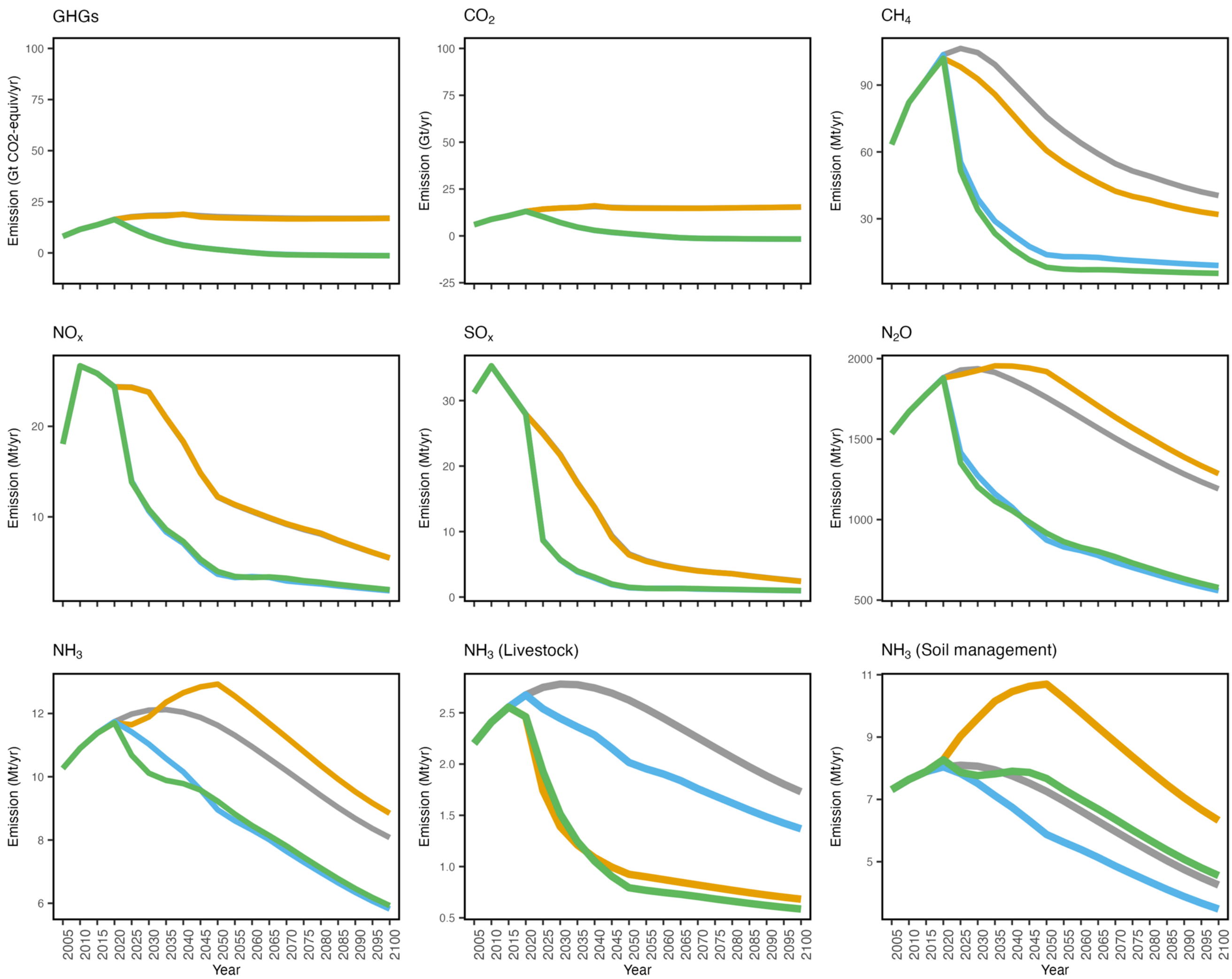

Fig. 3 Comparison of projected global GHG and air pollutant emissions from 2005 to 2100 for the baseline (SC1, gray), dietary change and food losses prevention (SC2, orange), climate change mitigation (SC3, blue), and integrated policy (SC4, green) scenarios

minimum: – 5.73%) by 2030, 2050, and 2100, respectively, in addition to the reductions achieved through the climate change mitigation scenario (SC3). However, our findings show that the reduced rate in $PM_{2.5}$ in 2050 begins to decelerate, persisting through 2100 because of a slight increase in NH_3 emissions from soil management observed in Europe, Brazil, and Latin America. Furthermore, an integrated policy approach could mitigate the expected increase in $PM_{2.5}$ concentrations in eastern China relative to the implementation of dietary changes alone. Specifically, the combined policy approach resulted in a smaller increase in $PM_{2.5}$ levels of approximately 4%. By contrast, dietary change as a standalone policy (SC2) was associated with an increase in $PM_{2.5}$ levels up to 12% by 2050. In Southeast Asia, the impact of dietary change under the climate change mitigation scenario on $PM_{2.5}$ is not as conspicuous as when SC3 mitigates alone (Fig. 7).

The role of dietary changes in O_3 concentrations would be inconsequential when implemented together with climate mitigation measures. The implementation of SC4 may result in a marginal increase in O_3 levels across all regions compared with SC3. The relative reductions in global average O_3 concentrations were – 0.50% by 2030, – 0.80% by 2050, and – 0.13% by 2100. These findings indicate that the implementation of dietary changes in conjunction with climate change mitigation measures would have a minimal additional impact on O_3 concentrations compared to climate mitigation alone. However, in South Africa, scenario SC4 was projected to increase tropospheric O_3 by 1–3% by 2050.

Reductions in premature mortality

The baseline scenario (SC1) projected a gradual increase in global mortality associated with $PM_{2.5}$ exposure between

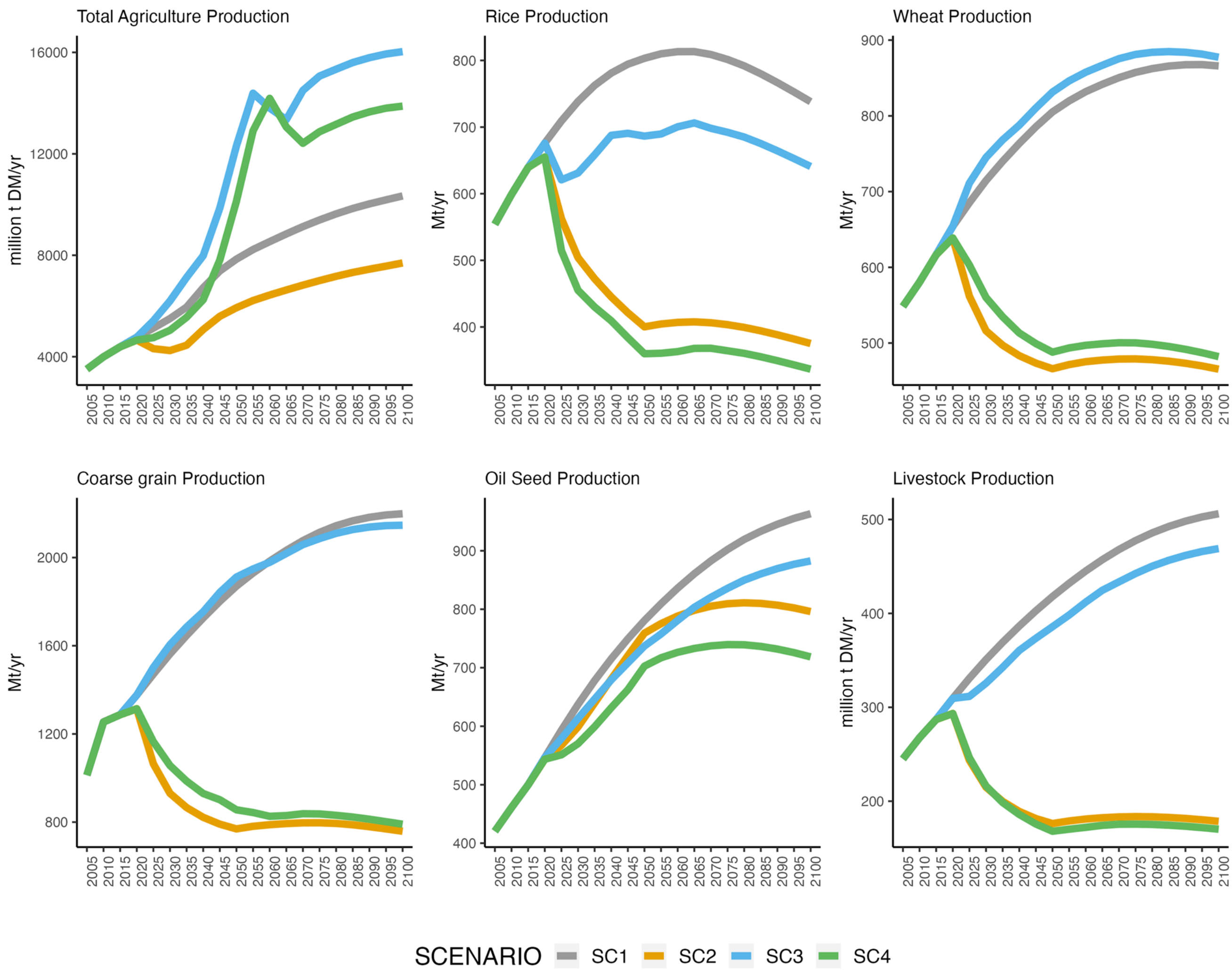

Fig. 4 Crop production for the baseline (SC1, gray), dietary change and food losses prevention (S2, orange), climate change mitigation (S3, blue), and integrated policy (S4, green) scenarios for 2005–2100

2015 and 2030. This trend was expected to be followed by a rapid decrease in mortality as $PM_{2.5}$ concentrations declined. Conversely, mortality from O_3 exposure was projected to continue to rise as tropospheric O_3 concentrations increased. Even with the implementation of scenarios SC2 and SC3, tropospheric O_3 levels were forecast to continue to rise, leading to a further increase in O_3-related mortality. Nevertheless, climate mitigation has the potential to bring about significant reductions in mortality compared to scenario SC1, saving a considerable amount of lives over various time frames.

To evaluate the additional benefits of dietary changes on air quality and mortality, we compared scenario SC2 with SC1 (Fig. 8: green line). The results indicated that dietary changes have the potential to contribute to significant improvements in air quality and mortality outcomes. Compared to the baseline scenario, SC2 could reduce $PM_{2.5}$-related mortality by 120 induced deaths per year in 2030, 40,300 deaths per year in 2050, and 187,500 deaths per year in 2100. Dietary changes were also projected to prevent 10,850, 25,560, and 131,110 O_3-related deaths per year in 2030, 2050, and 2100, respectively.

Scenario SC4 resulted in additional avoidance of premature deaths due to $PM_{2.5}$ compared to SC3 (Fig. 8: orange line). Additional avoided mortality of 51,260, 3920, and 44,010 deaths per year was forecast for 2030, 2050, and 2100, respectively. However, O_3-related mortality increased by 6090, 11,570, and 240 deaths per year compared to SC3.

Regional analysis revealed that the Southeast Asian and European regions experienced substantial benefits as a result of diet-related reductions in $PM_{2.5}$-related mortality (Fig. 8). In Southeast Asia, dietary changes were forecast to result in a 35% decline in mortality relative to scenario SC1. Furthermore, the adoption of dietary reform policies in 2100

Table 4 Regional ammonia (NH_3) emissions (Mt/year) comparing across sector, scenario and simulation year (2015, 2030, 2050, 2100)

Region	Scenario	NH_3 emission (total)				NH_3 emission (livestock)				NH_3 emission (soil management)			
		2015	2030	2050	2100	2015	2030	2050	2100	2015	2030	2050	2100
Brazil	SC1	3.460	3.922	4.399	4.525	0.506	0.688	0.817	0.915	1.002	1.163	1.380	1.493
	SC2		2.673	2.391	2.235		0.301	0.186	0.190		0.941	1.061	1.175
	SC3		3.168	3.065	2.914		0.536	0.525	0.546		1.054	1.068	1.038
	SC4		2.242	1.859	1.702		0.257	0.136	0.135		0.884	0.907	0.942
China	SC1	11.377	12.104	11.626	8.076	2.556	2.780	2.624	1.730	7.893	8.064	7.257	4.251
	SC2		11.890	12.928	8.844		1.390	0.925	0.682		9.601	10.699	6.325
	SC3		11.031	8.954	5.817		2.446	2.015	1.368		7.513	5.874	3.480
	SC4		10.112	9.226	5.926		1.513	0.793	0.586		7.763	7.671	4.554
USA	SC1	4.100	4.659	5.226	6.103	1.256	1.437	1.626	1.900	1.894	2.155	2.481	2.974
	SC2		3.791	4.209	4.817		0.668	0.370	0.425		2.296	3.119	3.636
	SC3		4.256	4.212	4.878		1.319	1.283	1.515		2.007	2.071	2.448
	SC4		3.300	3.060	3.398		0.646	0.315	0.363		1.939	2.198	2.492
Europe (EU25)	SC1	5.255	5.498	5.678	5.597	2.356	2.475	2.597	2.609	2.434	2.516	2.574	2.469
	SC2		4.164	3.500	3.374		1.449	0.647	0.622		2.324	2.569	2.460
	SC3		5.159	4.621	4.604		2.337	2.131	2.195		2.356	2.091	2.019
	SC4		3.950	2.775	2.645		1.478	0.586	0.570		2.103	1.966	1.869
North Africa	SC1	0.742	1.105	1.576	1.499	0.094	0.137	0.187	0.244	0.423	0.541	0.654	0.698
	SC2		0.940	1.328	1.049		0.090	0.078	0.078		0.496	0.683	0.680
	SC3		0.919	0.915	1.082		0.120	0.144	0.195		0.494	0.498	0.539
	SC4		0.776	0.736	0.713		0.084	0.063	0.063		0.450	0.534	0.526
Southeast Asia	SC1	8.062	8.438	8.210	5.986	1.067	1.403	1.685	1.727	2.341	2.716	2.896	2.395
	SC2		7.667	6.664	3.954		0.789	0.531	0.456		2.340	2.438	1.855
	SC3		7.318	6.199	4.445		1.229	1.252	1.325		2.360	1.923	1.700
	SC4		6.636	5.069	2.879		0.749	0.435	0.378		2.039	1.613	1.272
World	SC1	58.514	67.273	76.445	86.571	11.813	13.918	15.864	17.738	25.597	29.349	32.233	31.902
	SC2		58.618	63.144	57.526		8.018	5.810	5.633		29.749	36.864	32.493
	SC3		59.773	58.605	64.055		12.235	11.944	13.474		26.846	25.141	24.895
	SC4		51.267	47.208	41.308		7.703	4.516	4.411		25.288	26.557	23.465

could prevent 15,970 O_3-related deaths per year in Southeast Asia. In the EU and the USA, the impact of dietary changes under climate change mitigation policies was even greater and amplified the positive effects of reducing $PM_{2.5}$-related mortality. In China, the adoption of an integrated policy resulted in positive outcomes in reducing $PM_{2.5}$-related mortality following the implementation of dietary changes.

Discussion

Potential emission reduction through dietary change and food loss prevention policies

In accordance with the findings of the comprehensive study conducted by Poore and Nemecek (2018), it was revealed that livestock and fisheries collectively contribute to 31% of global GHG emissions, accompanied by co-pollutants, such as NH_3 and CH_4. In contrast, emissions from food processing constitute a modest 4% of the total GHGs. Moreover, 81% of global ammonia emissions are a result of agriculture, especially from livestock (Wyer et al. 2022). Thus, our discussion will strategically narrow its focus to NH_3 emissions from the agriculture sector. This deliberate choice stems from the recognition of NH_3 distinct significance as a pollutant, impacting not only global warming but also air quality, ecological integrity, and human health.

In this study, we found that a combination of reducing red meat consumption and implementing effective food loss and waste control policies could be highly effective in mitigating NH_3 and CH_4 emissions from the agricultural sector. These findings are consistent with numerous studies conducted over the past few decades (e.g., Domingo et al. 2021; Liu et al. 2021b; Ma et al. 2021; Malherbe et al. 2022). However, at the regional scale, particularly in China, our results forecast an increase in NH_3 emissions from the agricultural sector in 2030 due to a combination of high demand for plant-based foods and unsustainable agricultural practices.

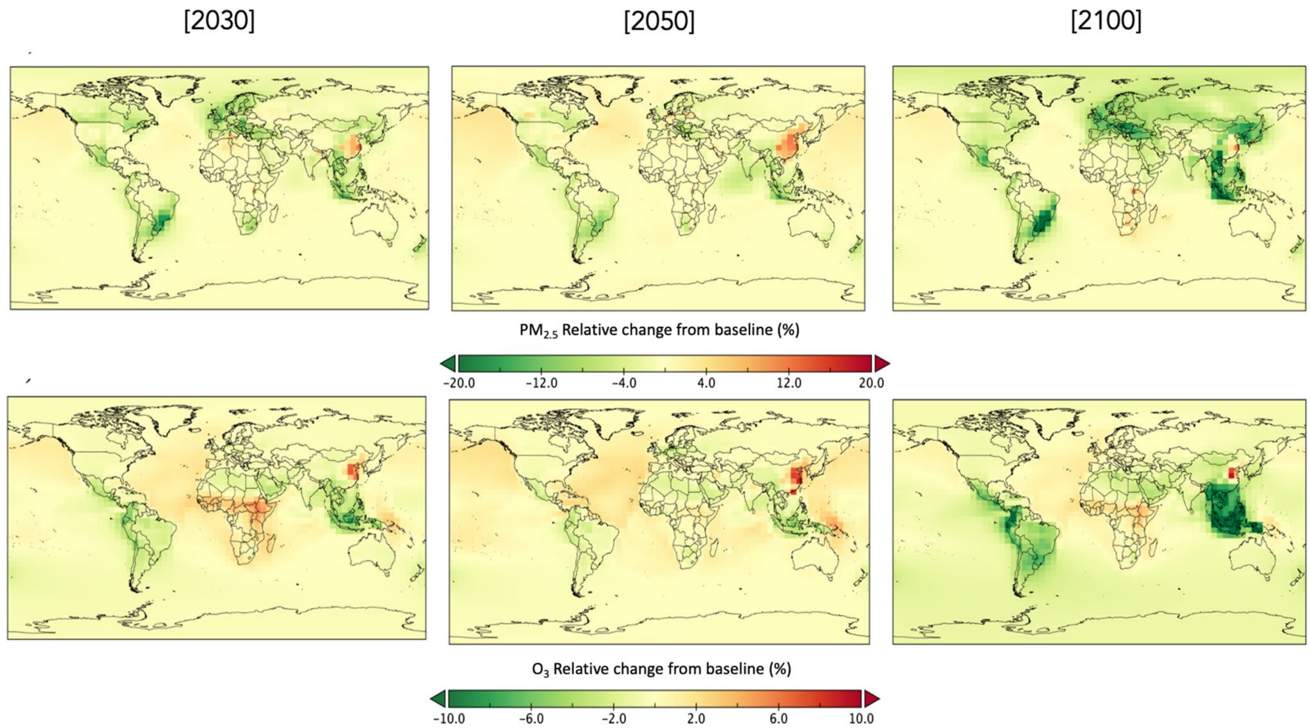

Fig. 5 The relative percentage change of $PM_{2.5}$ in (upper) and O_3 in (lower) 2030, 2050, and 2100 as a result of dietary changes and food loss prevention (SC2) compared with the baseline scenario (SC1). The negative values indicate a reduction in concentration, while positive values signify an increase in concentration resulting from the implementation of dietary change policies

These emissions are expected to decline rapidly from 2030 to 2100. In the European Union, upon comparing our current study with the research conducted by Himics et al. (2022), we observed that implementing a 50% reduction in red meat consumption, as suggested in our study, could lead to an approximate 35.79% reduction in NH_3 emissions. This contrasts with the findings of Himics et al., where a flexitarian approach resulted in a reduction of 30%. The variations in the percentage reductions between our current study (AIM/Hub) and the research conducted by Himics et al. (GLOBIOM) may be attributed to the differences in the uncertainty associated with IAMs as Fujimori et al.'s (2022) study.

To achieve substantial reductions in NH_3 emissions, an integrated policy that combines various strategies will yield better results than standalone dietary change policies. Although dietary changes play a role in reducing NH_3 emissions, their impact was projected to be relatively small under a 1.5 °C climate change mitigation scenario compared to the baseline scenario. Improvements in agricultural practices, including better manure management, optimized feeding regimes, and the use of efficient nitrogen-based fertilizer, have already led to considerable reductions in NH_3 emissions.

While the combined impact on NH_3 emissions from our integrated policies (SC4) may not exhibit a significant reduction compared to climate change measures scenario (SC3), it is crucial to underscore the substantial positive effect on mitigating climate change through the significant reduction in CH_4 and N_2O emissions which are key contributors to global warming (Jones et al. 2023) and our comprehensive approach has proven notably effective in curbing their release. This underscores the importance of addressing multiple GHGs simultaneously for a more comprehensive and impactful climate strategy.

Impacts of emissions reduction on ambient $PM_{2.5}$ and O_3 concentrations

We investigated the impact of NH_3 emissions resulting from the reaction between NH_3 and oxidizing agents, such as sulfuric (H_2SO_4) and nitric (HNO_3) acids. These emissions contribute significantly to the composition of ambient $PM_{2.5}$, which is a form of fine particulate matter that has adverse effects on human health and the environment. Our findings suggest that altering dietary behavior could be a potential strategy to reduce NH_3 emissions in regions where agriculture plays a key role as a significant anthropogenic activity.

By addressing the sources of NH_3, we can effectively mitigate the formation of ammonium, sulfate, and nitrate pollutants, which contribute to $PM_{2.5}$ formation. Our findings highlighted Europe and Asia as the regions with the highest levels of sulfate–nitrate–ammonium (SNA) aerosols,

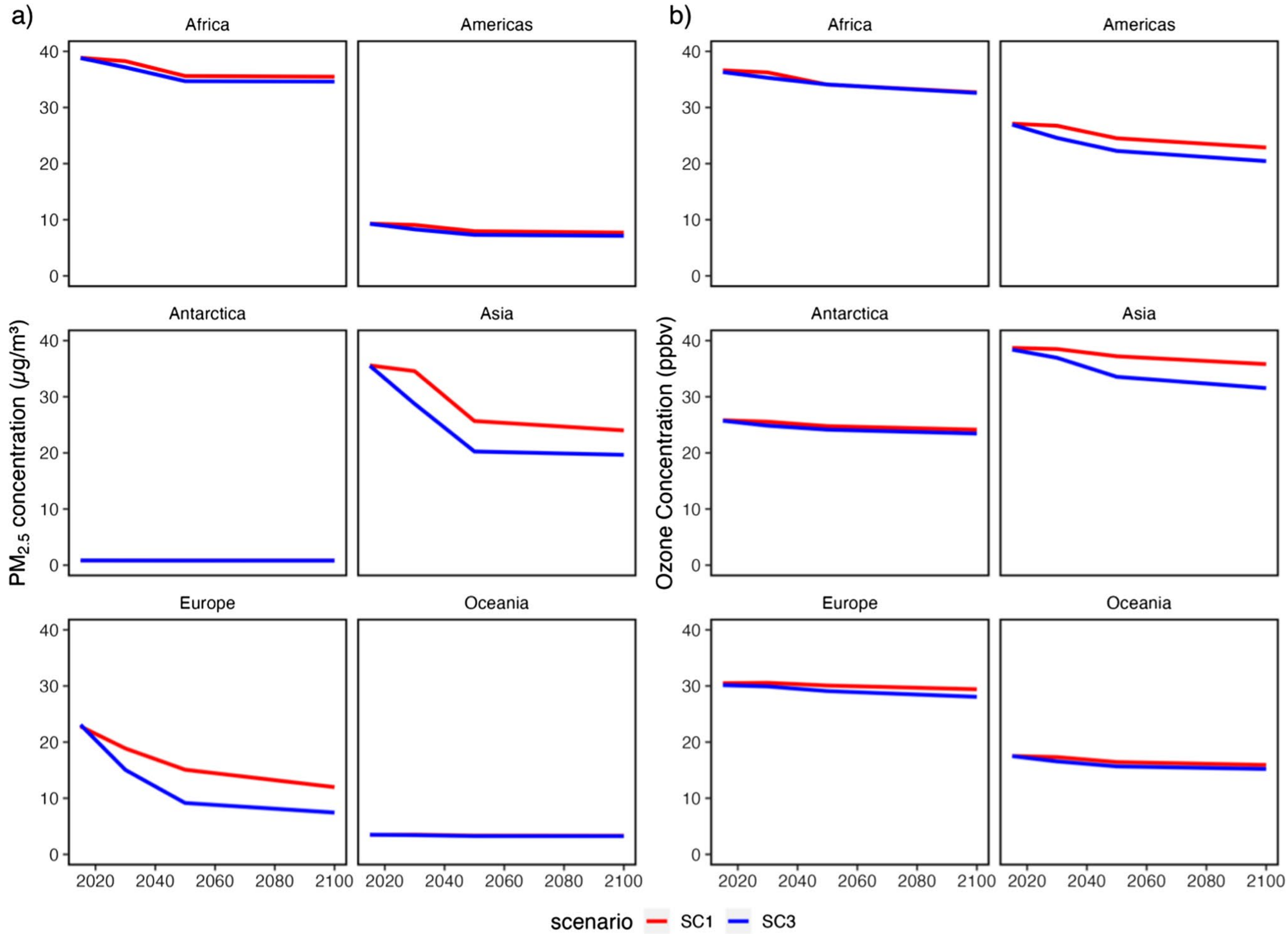

Fig. 6 Temporal resolution $PM_{2.5}$ (**a**) and O_3 (**b**) concentrations comparing between baseline scenario:SC1 (red) and climate change mitigation policy: SC3 (blue) between 2015 and 2100

aligning with the conclusions drawn in the study conducted by Pai et al. (2022) and Himics et al., (2022). In Europe, SNA compounds account for 46.3% of the $PM_{2.5}$ composition. Thus, when NH_3 emissions are reduced through dietary changes and sustainable agricultural practices, there will be a significant decline in $PM_{2.5}$ levels, as also suggested in a previous study (Jonson et al. 2022).

In Africa, however, dietary changes and climate change mitigation policies may not be as effective in controlling $PM_{2.5}$ levels. Our study suggests that the proportion of SNA aerosol components in $PM_{2.5}$ is relatively low in Africa, and that other sources of $PM_{2.5}$ pollution, including dust and biomass burning, may have more significant impacts on pollution levels. This finding aligns with a review by Tahri et al. (2022) and Gaita et al. (2014), who reported that the primary sources of particulate matter in Africa are related to industrial emissions, transportation, and solid fuel burning in buildings.

Our findings in China differed from those of previous studies that investigated the effects of dietary change on $PM_{2.5}$ and O_3 concentrations (Guo et al. 2022; Liu et al. 2021a). We found that dietary change could increase both NH_3 and NO_x emissions from the agricultural sector, particularly as a consequence of soil management activities. This increase in emissions could lead to elevated levels of both $PM_{2.5}$ and O_3 in the atmosphere. Notably, our study focused on a baseline scenario (SC1) where dietary change occurred in the absence of sustainable agricultural practices. Consequently, a reduction in livestock production was associated with a rapid increase in demand for plant-based foods, which in turn intensified soil management activities.

Societal benefits of reducing mortality by improving air quality through dietary change and climate change mitigation

Sustainable eating habits combined with climate change mitigation efforts could have significant positive effects on public health, including a lower probability of illness from air pollution. These methods could help to reduce the

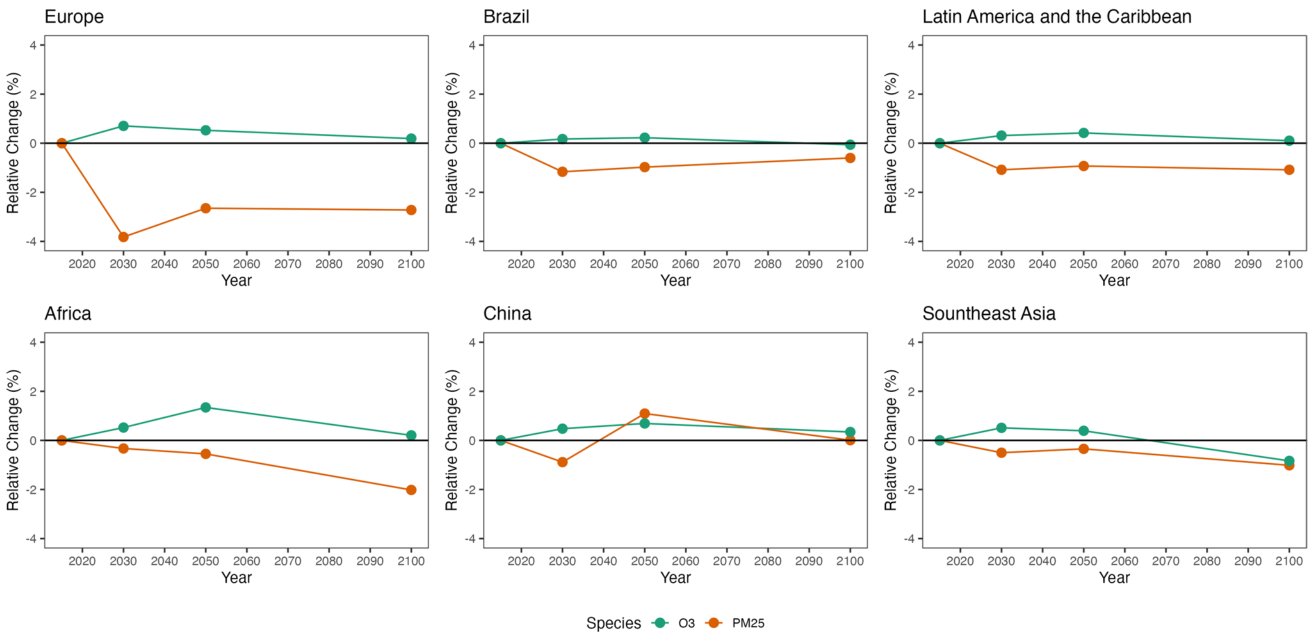

Fig. 7 Regional comparison of concentrations change in $PM_{2.5}$ (triangle) and O_3 (circle) between dietary change and food loss prevention (SC2) with baseline (SC1) as green line ($RC_{SC2}(\%)$) and integrated policy (SC4) with climate change mitigation (SC3) as orange line ($RC_{SC4}(\%) = \frac{SC4-SC3}{SC3} \times 100$)

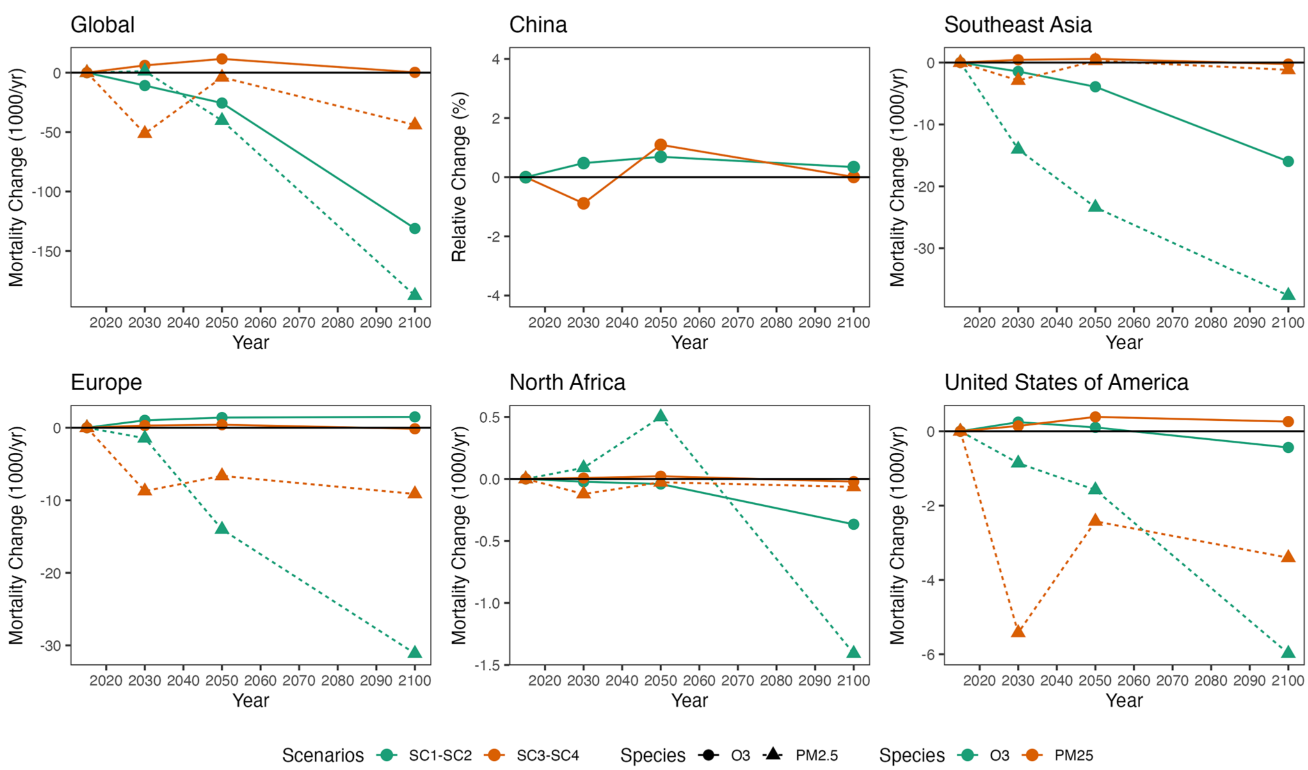

Fig. 8 Global and regional comparison of changes mortality (1000 deaths/year) related-$PM_{2.5}$ (triangle) and O_3 (circle) between dietary change and food loss prevention (SC2) with baseline (SC1) as green line ($RC_{SC2}(\%) = \frac{SC2-SC1}{SC1} \times 100$; RC is relative change) and integrated policy (SC4) with climate change mitigation (SC3) as orange line ($RC_{SC4}(\%) = \frac{SC4-SC3}{SC3} \times 100$). Positive number represents increasing of mortality, while a negative represents decreasing of mortality

production of $PM_{2.5}$ and O_3, which are important contributors to air pollution and poor health. According to a WHO report, climate change is expected to cause approximately 250,000 additional deaths per year between 2030 and 2050 (WHO 2023). Dietary change and climate change mitigation policies could help to reduce this burden of mortality. In our study, we estimated that 171,410 deaths per year could be avoided by 2050 due to air quality improvements brought about by dietary change. There would be an associated reduction in the costs of healthcare. Because healthier people typically have higher work productivity and lower healthcare expenses, this reduction in health spending costs may have economic benefits. However, implementing dietary change as a standalone policy will have little effect on most drivers of climate change. Combining dietary changes with climate change mitigation policies offers a viable solution to simultaneously address climate change and improve low nutrition issues, while also reducing the health impact of ambient air pollution.

The IPCC Special Report on Global Warming of 1.5 °C emphasizes that addressing climate change may involve economic costs, especially when moving toward a low-carbon economy and implementing climate change mitigation initiatives. These efforts could lead to GDP losses of 2.6–4.2% per year by 2050. The integration of policies that combine dietary changes and climate change mitigation could help to offset some of these economic costs. One significant advantage of such integrated policies is the potential for improved health outcomes. By reducing harmful emissions and air pollution, we can promote better public health, resulting in healthier populations. For example, implementing such integrated policies could prevent 55,580 pollution-related deaths per year by 2050 due to reduced exposure to pollutants such as $PM_{2.5}$ and O_3.

In addition, The EAT-Lancet study reveals a substantial potential for averting 10.8–11.6 million deaths annually by adopting recommended dietary changes, resulting in a significant reduction of 19.0–23.6% in mortality attributed to low nutrition. This emphasizes the profound impact that dietary shifts can have on public health. While this section does not directly compare these mortality results with those from other sectors, it underscores the multifaceted benefits of combining policies targeting both dietary habits and environmental factors. By doing so, not only can mortality from air quality-related issues be mitigated, but also mortality stemming from nutritional deficiencies, particularly in developing areas, can be addressed. This dual approach to policy formulation holds the potential to yield comprehensive benefits for both public health and the economic sector.

Further research and comparative studies across various sectors are warranted to provide a more nuanced understanding of the relative impacts and trade-offs associated with different mitigation strategies. Nonetheless, the synergistic effects of combining policies, as highlighted by the EAT-Lancet study, advocate for a holistic approach to address diverse health and environmental challenges.

Uncertainty and limitations

Downscaled grid emissions data were developed using the AIM-DS model. The approach of downscaling emissions from the AIM-Hub model in proportion to total regional emissions in the agricultural sector can introduce uncertainties, particularly when considering long-term impacts on land-cover and land-use change. For example, downscaling emissions based on total regional emissions assumes a proportional connection, which may not effectively capture the spatial distribution of agricultural activity and emissions. This technique may overlook changes in agricultural practices and land-use patterns within the region, thereby introducing uncertainty into GHG emissions estimates.

Additional physical and chemical processes may contribute to model biases in air pollutant simulations via the GEOS-Chem model. For example, it is difficult to capture actual surface wind fields. According to Carvalho (2019), all reanalysis products including MERRA-2 tend to underestimate ocean surface winds, particularly in the tropics, and overestimate inland surface winds. These biases could lead to an underestimation of inland $PM_{2.5}$ concentrations. The potential reasons for overestimation in GEOS-Chem have been explored, focusing on uncertainties related to the heterogeneous uptake coefficient of N_2O_5 and NO_2, dry-deposition velocity of nitric acid, and the nighttime boundary layer. Studies by Miao et al. (2020), Zhai et al. (2021), Travis et al. (2022), and Li et al. (2023) have investigated these uncertainties as contributing factors to the overprediction. Travis et al. (2022) specifically identified a pronounced overprediction of nitrate during the night, emphasizing its potential impact on the overestimate in $PM_{2.5}$.

In our O_3 simulation using the GEOS-Chem model, CH_4 was held constant using data from National Oceanic and Atmospheric Administration Global Monitoring Division flask observations. Thus, although emissions may change under scenario SC4, these policies may not impact O_3 concentrations at the ground level.

Conclusion

This study investigated the impact of dietary changes on future air quality and assessed the associated health implications. Four scenarios were developed: baseline (SC1), dietary change with food loss prevention (SC2), climate change mitigation (SC3), and an integrated dietary change/climate mitigation policy (SC4), all of which operated under the SSP2 scenario. Emissions were quantified using the AIM-Hub model, and then used as input for GEOS-Chem, which was used to estimate $PM_{2.5}$ and O_3 concentrations. We also produced estimates of premature mortality attributable to these pollutants. This analysis provided a comprehensive understanding of the health consequences that could result from the impacts of dietary modifications on air quality.

We concluded that implementing dietary changes could have positive impacts on air quality and associated health outcomes. Europe, Southeast Asia, and China have significant potential for reducing $PM_{2.5}$ levels and preventing premature deaths through dietary modification. However, our results also highlighted the limited impacts that dietary change can have on O_3 concentrations, particularly when dietary change is combined with climate change mitigation. Overall, our findings suggest that a combination of dietary change combining dietary changes with climate change mitigation policies has the potential to simultaneously improve air quality and reduce the health risks associated with $PM_{2.5}$ exposure. Such an integrated approach could provide more comprehensive air quality improvements in specific regions. However, careful consideration is needed to address any potential adverse effects on O_3 concentrations in some areas.

Implementing dietary modifications to improve future air quality could also result in a decrease in healthcare costs. The convergence of climate change mitigation and dietary modification based on the suggestions of the EAT-Lancet Commission offers a viable path to achieving a sustainable and healthier future for both humans and the planet and represents an opportunity to address environmental and health concerns in a complementary manner, which could result in enormous advantages for society as a whole.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s11625-024-01490-w.

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Author contributions Thanapat Jansakoo: writing—original draft preparation, analysis, methodology, and visualization. Satoshi Sekizawa: analysis; Thanapat Jansakoo and Shinichiro Fujimori: conceptualization. All authors: writing—reviewing and editing.

Data availability The scenario data, emission flux, and outcomes from the GEOS-Chem model are available for access via the following link: https://doi.org/10.7910/DVN/PRK7EL.

Code availability GEOS-Chem (GCClassic) version 13.4.0 code is available from https://github.com/geoschem/geos-chem. All code used for data analysis and creating the figures is available at https://github.com/tjansakoo/dietarychange.git.

Declarations

Conflict of interest The authors have no competing interests to declare that are relevant to the content of this article.

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