**Policy solutions for transitioning to healthier and sustainable diets in the United States**

**Maksym Chepeliev, Center for Global Trade Analysis, Purdue University, USA, mchepeli@purdue.edu**
**Alessandro Gatto, Wageningen University and Research, Netherlands, alessandro.gatto@wur.nl**
**Thomas Hertel, Center for Global Trade Analysis, Purdue University, USA, hertel@purdue.edu**
**Thiago Simonato, Center for Global Trade Analysis, Purdue University, USA, tsimonat@purdue.edu**

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# Policy solutions for transitioning to healthier and sustainable diets in the United States

*Maksym Chepeliev, Purdue University, USA*

*Alessandro Gatto, Wageningen University and Research, Netherlands*

*Thomas Hertel, Purdue University, USA*

*and*

*Thiago Simonato, Purdue University, USA*

## Abstract

With growing concerns about multiple burdens of malnutrition and increasing environmental footprints of the U.S. food system, it is important to understand what policy solutions could help transitioning toward healthier and more sustainable diets in the country. In this study, we develop a comprehensive modeling framework for the analysis of consumer behavior and the environment by linking a Global Trade Analysis Project (GTAP) Data Base with the ENVISAGE dynamic computable general equilibrium (CGE) model, greenhouse gas (GHG) emissions and air pollutant modules, nutritional accounts, and global food loss and waste (FLW) database. We explore eight scenarios that incorporate different level of meat taxation – based on the environmental footprints of meat and the level of the Social Cost of Carbon – combined with the provision of subsidies to vegetables, fruits, and nuts producers in the United States. We find that implementing meat taxation shows promise in enhancing dietary healthiness (decreasing per capita meat consumption in a range of 7%-14%) and alleviating environmental impacts (reducing methane emissions by almost 5% by nitrous oxide emissions by over 4%). Combining meat taxation with subsidies to vegetables, fruits, and nuts results in a significant increase in the consumption of these foods (by up to 25%) associated with numerous health and environmental benefits. However, the increase in the production of subsidized fruits, vegetables, and nuts generates a rebound effect for the case of GHGs, partly offsetting the initial benefits observed under standalone meat taxation policies. Even more substantial rebounds are observed for the case of FLW, as the increase in production of fruits, vegetables, and nuts results in higher overall FLW levels. The observed rebounds stress on the importance of taking into account the potential spillover effects outside of the agricultural and food sectors, when designing food policies in the U.S.

## 1. Introduction

Transitioning to a more sustainable food system is central to the Sustainable Development Goals (U.N., 2019). Today, mounting concerns regarding the double- (and triple-) burden of malnutrition, intertwined with public health challenges, food insecurity, and environmental pressures (Lopez Barrera and Hertel, 2023; Gomez et al., 2013), underscore the necessity of shifting towards healthier and more sustainable diets.

In the United States, excessive calorie intake and unbalanced diets, low in fruits, vegetables, nuts, and whole grains, while high in red and processed meat, significantly contribute to health issues (USDA & HHS, 2020). More than 40% of US households struggle with overconsumption and obesity, while the average diet lacks essential micronutrients for a significant portion of the population (Popkin et al., 2020; Lopez Barrera and Hertel, 2023). These challenges are additionally compounded by the overall scale of food loss and waste. Around 62 million tonnes of food in the US and 1.92 billion tonnes worldwide are estimated to be lost or wasted – a figure that is increasing over time (Gatto and Chepeliev, 2024).

Various barriers and disparities hinder the accessibility and availability of foods conducive to healthy dietary patterns, with inadequate income levels being a key factor, particularly, in developing countries. Low-income consumers often rely on affordable and easily accessible foods, which often lack essential nutrients, as fresh fruits, vegetables, and other healthier options tend to be more expensive (French et al., 2019). A healthy diet is estimated to cost approximately 3 US dollars per person per day, regardless of the country where this measurement has been conducted (Bai et al., 2021), a concerning figure given that over one-fifth of the global population lives on less than 3.65 US dollars per day (World Bank, 2023).

Despite this, much of the nutrition shortfall in the United States comes from consumer choice. Altering consumer behavior is challenging, requiring targeted policy interventions and careful consideration of potential spillover effects outside the agricultural and food sectors, both domestically and through international trade channels (Chepeliev, 2023).

Policies targeting consumer choices for reducing health and environmental impacts, including legislation, taxes, labels, and information campaigns are now widespread (Warren, 2018; Creutzig et al., 2018; OECD, 2021). However, there is limited evidence regarding their effectiveness and the resulting impact on environmental outcomes (Abrahamse, 2020; White et al., 2019; Osman et al., 2021). The literature assessing such interventions tends to focus on information-based policy interventions aimed at increasing knowledge and awareness about healthier and more sustainable food choices (Ammann et al., 2023; Ran et al., 2024). However, there is little evidence that such interventions promote long-term sustainability (Ran et al., 2024). Market-based policy interventions, such as taxes, subsidies, or regulatory measures targeting the most polluting products, are deemed more effective in driving enduring changes (Thow et al., 2014; Ammann et al., 2023; Latka et al., 2021). However, the broader impacts and environmental consequences of such instruments remain largely unknown.

In addition, existing studies examining the impacts of fiscal interventions aimed at influencing food consumption primarily focus on the food system in individual countries (Broeks et al., 2020; Abadie et al., 2016; Ejamoud and Smed, 2013), overlooking the implications for the environment and for the global food system. In the United States, research on taxing sugar products (Nuno-Ledesma et al., 2023; Bourquard and Wu, 2020) or red meat (Taillie et al., 2023) confirms the efficacy of such measures but tends to limit its scope to specific products, disregarding broader socio-economic and environmental consequences of shifting demand, trade and production patterns. Additionally, interventions in the United States have centred on single policy instruments (e.g., taxes or subsidies), neglecting the analysis of a more comprehensive set of combined policies, such as (red) meat taxation alongside simultaneous subsidies for healthier foods like fruits and vegetables (Broeks et al., 2020).

This study aims to address these limitations by developing a comprehensive modeling framework to analyze consumer behavior and environmental impacts related to the implementation of policy solutions for promoting healthier diets in the United States.

We link the Global Trade Analysis Project (GTAP) Data Base (Aguiar et al., 2019) with the ENVISAGE dynamic computable general equilibrium (CGE) model (van der Mensbrugghe, 2024), incorporating greenhouse gas (GHG) emissions and air pollutant modules (Chepeliev, 2020; 2021; 2022b), GTAP nutritional accounts (Chepeliev, 2022a), and a global food loss and waste database (Gatto and Chepeliev, 2024).

The main strength of the global CGE modeling framework is the consistent representation of inter-dependencies between different sectors, agents, and markets in the economy. By capturing both the supply and demand sides, the model captures adjustments in quantities and prices following the implementation of a policy. For instance, if taxes on the consumption of red meat are implemented in the model, prices of corresponding products will increase, reducing overall red meat supply and demand, and stimulating the production of meat substitutes, as well as other food items that consumers might consider substituting for meat. Because the model is global, it also captures the impact on trade and related environmental impacts.

When considering alternative policy solutions for transitioning to healthier diets, it is important to consider the true cost of food, factoring in the full scope of health, environmental, biodiversity, and socio-economic implications. A recent study by the Rockefeller Foundation (2021) found that the true cost of the U.S. food system is around $3.2 trillion per year - at least three times more than what consumers actually spend on food. The proposed economy-wide (dynamic CGE) modeling framework is well suited for assessing the economic externalities of the food system, taking into account the potential for resource allocation and technological progress to either alleviate or exacerbate these costs.

Using the developed approach, we analyze two sets of forward-looking scenarios till 2050 aimed at supporting the sustainable dietary transition in the U.S. First, as suggested by earlier studies, in Denmark (Caro et al., 2017) and Sweden (Sall, 2018), taxes on meat are being explored as a vehicle for promoting dietary changes, reducing the environmental impacts of agri-food systems while improving public health. Recent surveys suggest that the majority (70%) of consumers in Germany, France, and the Netherlands support a meat tax that reflects environmental costs, provided that the tax revenues are recycled via the provision of subsidies to vegetables and fruits (TAPPC, 2020 - https://plantbasednews.org/culture/politics/europeans-support-meat-tax/). In light of these developments, we explore a potential scenario involving the imposition of taxes on meat and while simultaneously reducing taxes on vegetables and fruits in the U.S.

We investigate the implications of these sets of policies for a wide range of indicators, including health- and nutrition-related metrics, greenhouse gas emissions, food loss and waste, food affordability, employment, wages, production competitiveness, trade, prices, and macro indicators. By tracing the flow of food within an economy-wide modeling framework, our study provides valuable insights to policymakers, not only in the United States but also in other countries around the world. The analysis provided in this paper will be of interest to a diverse group of researchers and decision-makers who are involved in the development of policies toward transitioning to a healthier and more sustainable food system in the U.S. Results presented in this study will provide valuable insights into the socio-economic, environmental, and nutritional implications of the dietary transition in the U.S., facilitating the design of better-informed policy solutions.

# 2. Data and Methods

## 2.1 Global Trade Analysis Project (GTAP) Data Base

The core data input for the development of the modeling framework be a global trade analysis project (GTAP) Data Base (Aguiar et al., 2019). GTAP is a global dataset that describes bilateral trade patterns, production, consumption and intermediate use of commodities and services in the countries/regions around the world. The 10th release of the GTAP Data Base, utilized in this study, has multiple reference years, with 2014 being the most recent one, covers 141 regions and disaggregates an economy in each region into 65 activities. Agricultural and food activities in the database are represented by 20 sectors, including 12 primary agricultural sectors and 8 food-processing sectors (Aguiar et al., 2019). The database reports emissions of $CO_2$ greenhouse gases (GHGs) (Chepeliev, 2022b), non-$CO_2$ GHGs (Chepeliev, 2020) and air pollutants (Chepeliev, 2021).

The GTAP Data Base is a core input into virtually all global computable generation equilibrium (CGE) models and thus is an essential database for tracing the food supply from farm to fork in an economy-wide modeling framework. The version of the GTAP Data Base used in the current study is extended by the addition of nutritional accounts as well as estimates of global food losses and waste as further discussed below.

## 2.2 Nutritional Accounts and Food Loss and Waste Data

For the proper representation of preference shifts and dietary changes it is vital to embed the nutritional accounts within the general equilibrium assessment framework, merging food and nutrient supplies. To accomplish this, we rely on a method developed in Chepeliev (2022a). The approach builds on the Food and Agricultural Organization (FAO) Food Balance Sheets (FBS) data and nutritive factors to estimate nutritional content of primary commodities and derived commodities represented in primary commodity equivalent within FBS. Calories, fats, proteins and carbohydrates are estimated and reported. Use categories that account for food, feed, seed, losses and other uses are identified. Food supply is distinguished across GTAP primary commodity sectors, food processing sectors and service sectors that supply food (e.g., restaurants). In order to account for the complete supply chain through which foodstuffs are delivered to final demand, it is necessary to take account of both direct, and indirect sources of demand. For example, the consumption of pasta in a restaurant requires the processed product (pasta), but also the crop (e.g., wheat) that was used to make this pasta. Capturing the full set of input requirements to deliver the pasta to the customer's plate requires us to compute what is termed the 'Leontief inverse matrix'. These inverse matrices are constructed separately for distinct sources of final demand (e.g., domestic consumption vs. imports). Estimates of food supplied by service sectors (food out of home) are further cross-checked with available country-specific data.

A critical piece of the puzzle for linking food purchases to production as well as health outcomes is the quantification of food losses and waste (FLW). By definition, food that is wasted is not consumed and therefore will not contribute to obesity. However, this wasted food does require resources to be produced and mitigation food losses can improve environmental outcomes. Thus estimating FLW generated across global food supply chains is another important dimension for assessing sustainability solutions of dietary policies (Parfitt et al., 2010). Overall, there is a lack of harmonized global FLW estimates that could be readily incorporated in an economy-wide modelling framework, which poses a major challenge for the assessment of circularity measures in the livestock sector (Kuiper and Cui, 2021). To address this point, in the current study we rely on a newly developed methodology toward incorporating FLW flows in an economy-wide modelling framework following Gatto and Chepeliev (2024).

By considering food products in their entirety (i.e., edible and non-edible parts) and excluding non-food biomass flows (i.e., feed, seed, and biomass used for industrial purposes) from FLW, the proposed approach overcomes broadly debated methodological inconsistencies of available FLW estimates (Delgado et al., 2021), providing an important alternative to the heavily criticized (Sheahan and Barrett, 2017; Xue et al., 2017) estimates from FAO (2011). We define five stages of the food supply chains (FSC) to quantify FLW at each stage of the global FSC: Agricultural Production, Post-Harvest Handling & Storage, Manufacturing, Distribution & Retail, and Consumption. At the global level, our data collection covers eight commodity groups including cereal crops, horticulture, and animal-sourced foods. Incorporation of the FLW tracing into the analytical framework allows us to estimate both food supply and net intakes at the level of final consumers.

### 2.3 Global Computable General Equilibrium Model ENVISAGE

To provide an assessment of alternative policy scenarios, which are discussed in more detail in the Scenario Framework section below, we rely on a multi-region multi-sector CGE model. The Environmental Impact and Sustainability Applied General Equilibrium (ENVISAGE) Model is a recursive dynamic and global CGE model (van der Mensbrugghe, 2024). The model follows a modular set up, where different modules of the framework can be turned on or off depending on the purpose of simulations. ENVISAGE is solved as a sequence of comparative static equilibria wherein the factors of production accumulate, as well as depreciate, over time. A more detailed description of the ENVISAGE model is available in van der Mensbrugghe (2024).

For the current analysis, we have extended the modelling framework by incorporating the nutritional, as well as food loss and waste modules as discussed above. For the representation of final demand, the model uses a Constant Difference of Elasticities *(*CDE*)* demand system, which has been further re-parametrized for the purposes of the current study to better capture the long-term patterns in food demand (Valin et al., 2014).

For the purposes of the current study, a specific sectoral and regional aggregation has been developed, which covers 36 activities (with a particular focus on primary agricultural sectors and food processing) and 18 regions, with the United States being represented as a separate country. Details on the sectoral and regional aggregation are provided in the Appendix A.

A developed modelling framework reports a wide range of economic, environmental and nutritional indicators (Figure 1). The core strength of a global CGE models, like ENVISAGE, is a consistent representation of inter-dependencies between sectors, agents and markets within the economy. By capturing both the supply and demand sides, the model represents adjustments in quantities and prices reacting to the policy shock. For instance, if a tax of meat consumption is imposed, this would lead to increasing meat prices, reduction in meat demand and substitution toward alternative food commodities, such as other grains, dairy products or vegetables and fruits.


**Figure 1. Selected indicators reported by the developed modelling framework**
*Notes:* 'WIP' stands for work in progress and indicates modules under development.

### 2.4 Scenario Framework

To assess the alternative policies aimed at transitioning to healthier and more sustainable diets, we explore a set of alternative scenarios (Figure 2). First, the baseline scenario till 2050 is developed. This scenario is based on the projected macroeconomic and demographic patterns from the Shared Socioeconomic Pathways (SSP) database – SSP2 middle of the road scenario (IIASA, 2024). This reference scenario assumes a continuation of historical dietary patterns and reflects moderate shifts in consumption patterns as a consequence of  growing incomes.

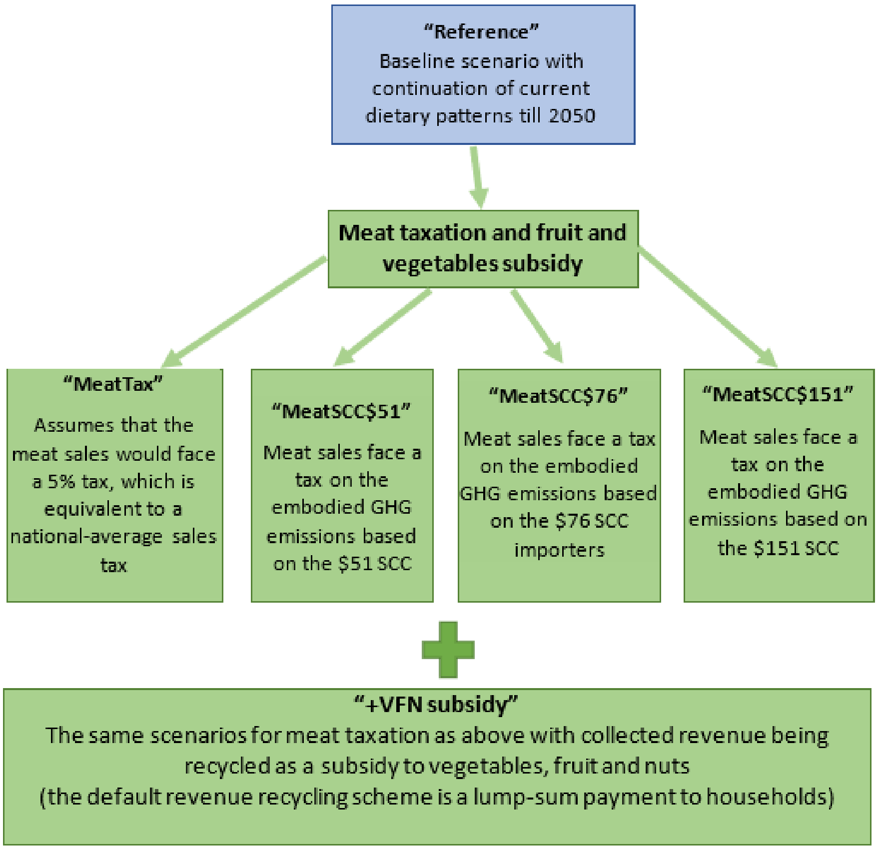


**Figure 2. Scenario framework**

*Source:* Developed by authors.

Policy scenarios are imposed on top of the baseline scenario and include two elements/dimensions: (a) Taxation of meat (sales taxes on cattle meat and other meat) and (b) Subsidies to vegetables, fruits and nuts (implemented as a subsidy to value added of the corresponding sector in the US). Four levels of meat taxes are considered in the study. First, we consider an option whereby meat consumption faces a uniform (across cattle meat and other meat) tax rate of 5%. This is broadly equivalent to the US national-average sales tax from which food products are typically exempted. (In the reference case meat faces a "0%" sales tax in the US). Subsequently, alternative levels of meat taxation are estimated based on the environmental footprints of meat and the level of the Social Cost of Carbon (SCC).

We consider three additional meat taxation scenarios – each corresponding to a different social cost of carbon: $US 51, 76 and 152 per tCO2e, covering a range of values reflecting the underlying uncertainty in the appropriate social discount rate as well as in the science of climate impacts (U.S. Interagency Working Group, 2021). To estimate the sales taxes equivalent to the considered SCC, we first estimate the GHG emissions footprint of each type of meat (in kg $CO_2$eq. per 1USD), covering $CO_2$ emissions, methane, nitrous oxide and fluorinated gases embodied into processed meat (cattle and other meat) consumed by households in the U.S. The method uses the Leontief inverse approach and covers emissions through the entire value chain. We then apply each level of SCC to the estimated GHG emission footprints to estimate the corresponding ad valorem equivalent tax on meat. Meat consumption and emission intensities are based on the data incorporated to the developed assessment framework and discussed above. Figure 3 provides estimates of the GHG emission footprints and corresponding ad valorem tax equivalents across SCC levels. Tax on cattle meat ranges between around 9% and 27% across the range of SCC estimates, while the tax on other meat is in a range from 4% to 9% depending on the SCC level.

In addition to the four meat taxation scenarios, we consider four scenarios where revenue collected form meat taxation is recycled in the form of subsidies to value added in the U.S. vegetables, fruits and nuts production activities aimed at increasing the affordability of healthier foods and stimulating positive dietary shifts.

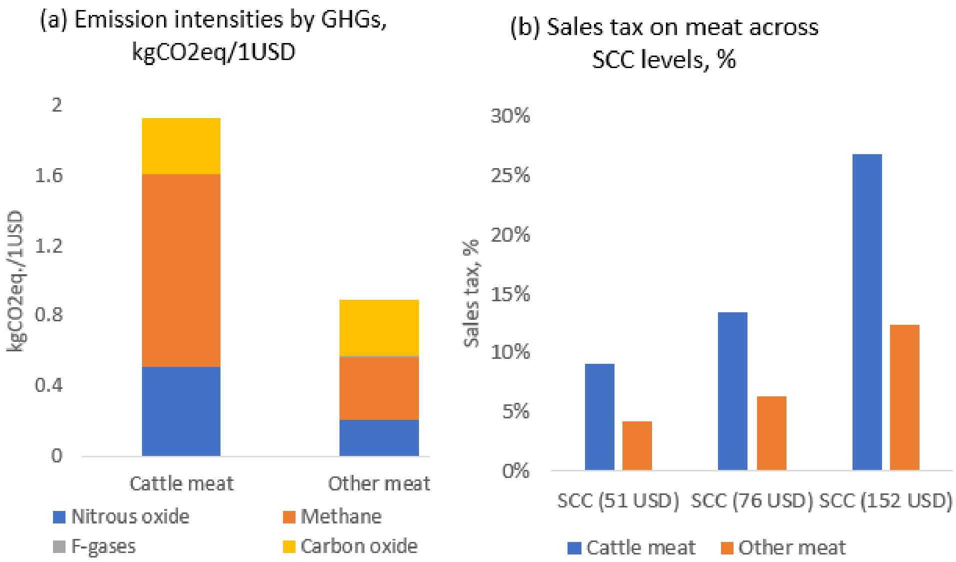


**Figure 3. Emission intensities (a) and meat sales taxes corresponding to different SCC (b)**
*Source:* Developed by authors based on the GTAP Data Base and GTAP environmental accounts.
*Notes:* Emission intensities reported on panel (a) are estimates across all three emission scopes using the Leontief inverse approach and represent emission intensities in the reference year (i.e. 2014). Sales taxes reported on panel (b) are derived by the multiplication of the corresponding Social Cost of Carbon by the emission intensity in the reference year (reported on panel 'a') for each type of meat.

## 3. Results

### 3.1 Household food consumption trends, prices, and changes in dietary composition

Dietary trends in the United States in the Business as Usual (BAU) scenario show an increase in meat consumption by an average +16% by 2050. Expenditures on meat products for an average household in the United States represent around 23% of the total direct food expenditures, a share that is expected to increase to 25% by 2050. In contrast, the share of expenditures on fruits and vegetables is estimated to be much lower, around 6%, as per capita consumption of these products is projected to remain stable or even slightly decrease by 2050.

The introduction of taxes on meat products aimed at decreasing current overconsumption trends has the potential to improve the healthiness of diets while also exerting positive synergies on the environment. Depending on the magnitude of the tax, meat consumption in the United States is projected to decline by an average of -2.8% in the "Meat Tax" scenario, where a 5% tax is imposed, and up to an average of -10.5% in the more stringent "Meat SCC $152" scenario (Panel A – Figure 4). Particularly, ruminant meat consumption is significantly impacted, decreasing from -3.3% up to -14.4% by 2050, according to the size of the intervention.

From Figure 4 it is possible to notice that standalone interventions aimed at decreasing consumption of meat products exert a rather weak effect on fruit and vegetables intakes, requiring ad-hoc subsidies to stimulate their consumption (Panel A). As the size of the subsidy is determined by the revenue collected from the imposition of meat taxes, the most significant increase in fruit and vegetables consumption is observed under the “Meat SCC $152 + VFN scenario” where provided subsidies are highest. This scenario leads to an average decrease of 12.1% in meat consumption, while also increasing consumption of fruit and vegetables by 24.6% by 2050.

Changes in demand resulting from policies are primarily driven by the price effects induced by the analysed interventions (Panel B - Figure 4). By 2050, standalone meat-related policies lead to an increase in meat product prices, ranging from an average of 5% in the "Meat tax 5%” scenario to +21.1% in the more stringent "Meat SCC $152" scenario. In parallel, the price of fruits, vegetables, and nuts stays relatively steady under standalone meat taxation policies, requiring specific subsidies for reducing average prices and encouraging healthier consumption. As a result, subsidies facilitate the reduction of average prices for fruits, vegetables, and nuts, ranging from -13.2% in the "Meat Tax 5% + VFN subsidy" scenario to -34.3% in the "Meat

SCC $152 + VFN scenario," thereby justifying the increase in consumption of fruits, vegetables, and nuts observed in Panel A.

Following changes in demand, the average daily per capita calorie intake in the United States reaches 2875 kcal in 2050 in the BAU baseline scenario (Panel C – Figure 4). Under standalone meat taxes, daily calorie intakes of meat products decrease by -9 calories per capita per day with a 5% tax (“Meat tax 5%” scenario) reaching -34 calories per capita per day in the “Meat SCC $152” scenario, compared to BAU in 2050. In contrast, when meat taxes are combined with subsidies on fruit, vegetables, and nuts, combined calorie intake from these two groups of food slightly increase. This is due to the rise in calories linked to a higher consumption of fruits, vegetables, and nuts. In the “Meat Tax 5% + VFN subsidy” scenario, calories per capita per day obtained from the intake of fruits, vegetables, and nuts, increase by 17 kcal, a figure that reaches 63 kcal per capita per day under the more stringent “Meat SCC $152 + VFN subsidy” scenario (Panel C – Figure 4). Nonetheless, while meat-related calories are substituted by plant-based calories, the overall intakes across scenarios are lower than the BAU trends in 2050. This is driven by a lower intake of cereals and grains across scenarios, which are partially substituted by the higher consumption of fruits, vegetables, and nuts.

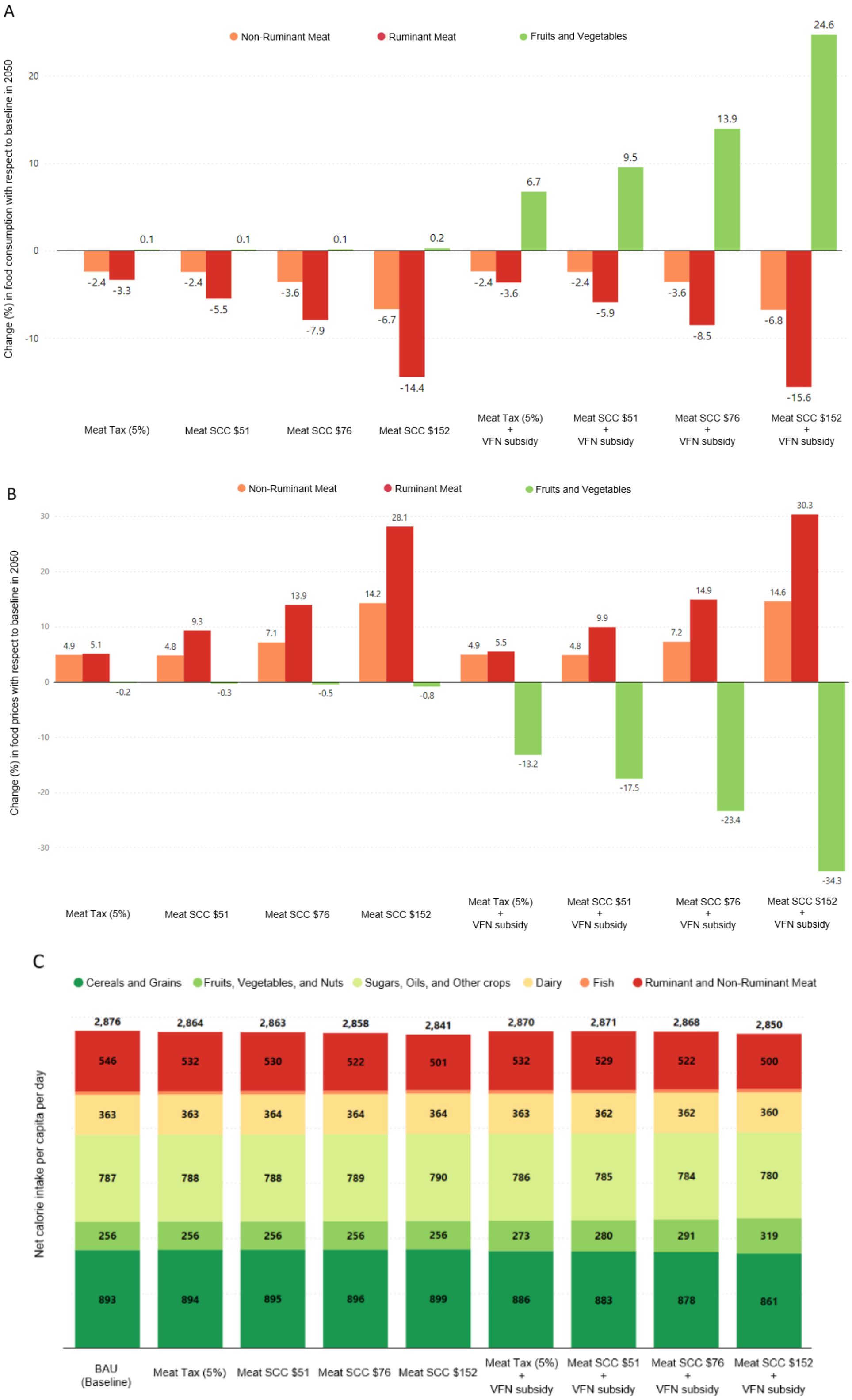


**Figure 4. Changes (%) in consumption and prices of targeted food items, as well as changes in dietary composition (calories per capita per day) in the United States relative to the baseline in 2050**. Panel A showcases the changes (%) in demand for food commodities targeted by policy interventions, including ruminant and non-ruminant meat, and fruits, vegetables, and nuts, compared to the Business-as-Usual (BAU) scenario in 2050. Panel B illustrates the changes (%) in prices of ruminant and non-ruminant meat, as well as fruits, vegetables, and nuts, compared to the BAU scenario in 2050. Lastly, Panel C presents the average dietary intake (net of food loss and waste) in calories per capita per day across baseline and investigated policy scenarios in 2050.

### 3.2 Production changes, trade, dietary affordability, and welfare

The changes in demand patterns observed across the different scenarios have direct consequences for food producers. In our baseline scenario, meat production in the United States increases by an average +44.6% or 24.5 million tonnes by 2050 (Table 1). While most of the meat consumed in the United States is supplied from domestic sources, a higher meat demand results in increased imports of meat products (73.2% or 0.4 million tonnes), principally from Australia and New Zealand (+4.3%). This drives a simultaneous rise in animal feed production, particularly grains, which increase by 21.9% or 30.6 million tonnes in 2050.

**Table 1. Change (million tonnes and %) in production of food and feed biomass across scenarios in 2050.**

| | **With respect to base year (2014)** | **With respect to Baseline (BAU) scenario in 2050** | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | BAU (2050) | Meat Tax 5% | Meat SCC $51 | Meat SCC $76 | Meat SCC $152 | Meat Tax 5% + VFN subsidy | Meat SCC $51 + VFN subsidy | Meat SCC $76 + VFN subsidy | Meat SCC $152 + VFN subsidy |
| **Fruits, Vegetables and Nuts** | **6.2 (+7.4%)** | **0.1 (+0.1%)** | **0.2 (+0.2%)** | **0.2 (+0.3%)** | **0.5 (+0.6%)** | **12.6 (+13.9%)** | **17.6 (+19.3%)** | **25.2 (+27.7%)** | **43.1 (+47.2%)** |
| Cereals and Grains | 101.8 (+24.4%) | -4.4 (-0.8%) | -6.9 (-1.3%) | -10.0 (-1.9%) | -18.2 (-3.5%) | -6.8 (-1.3%) | -10.5 (-2.0%) | -15.4 (-3.0%) | -29.5 (-3.2%) |
| Oils, Sugars, and Other crops | 0.023 (+0.1%) | 0.1 (+0.1%) | 0.3 (+0.2%) | 0.4 (+0.2%) | 0.7 (+0.4%) | -1.1 (-0.7%) | -1.6 (-1.0%) | -2.5 (-1.5%) | -5.3 (+0.2%) |
| Dairy | 28.5 (+31.1%) | 0.09 (+0.1%) | 0.1 (+0.1%) | 0.2 (+0.2%) | 0.3 (+0.3%) | -0.2 (-0.2%) | -0.3 (-0.3%) | -0.5 (-0.4%) | -1.1 (-1.0%) |
| Fish | 2.1 (+37.7%) | -0.007 (-0.1%) | -0.010 (-0.1%) | -15.1 (-0.2%) | -27.3 (-0.3%) | -3.4 (-0.1%) | -5.2 (-0.1%) | -8.5 (-0.1%) | -20.1 (-0.2%) |
| **Ruminant and Non-Ruminant Meat** | **24.5 (+44.6%)** | **-1.8 (-2.3%)** | **-2.2 (-2.8%)** | **-3.2 (-4.1%)** | **-6.1 (-7.7%)** | **-1.8 (-2.4%)** | **-2.3 (-2.9%)** | **-3.4 (-4.3%)** | **-6.4 (-8.1%)** |
| Animal Feed | 32.7 (+21.5%) | -3.7 (-2.1%) | -5.8 (-3.2%) | -8.5 (-4.6%) | -15.4 (-8.4%) | -4.2 (-2.3%) | -6.6 (-3.6%) | -9.6 (-5.2%) | -17.8 (-9.7%) |

Compared to the 2050 BAU scenario, standalone meat taxation policies lead to a reduction in production, ranging from -2.3% (or 1.8 million tonnes) in the "Meat tax 5%" scenario to -7.7% (or 6.1 million tonnes) in the "Meat SCC $152" scenario. The decline in meat demand primarily impacts domestic production, while imports of meat products remain close to baseline levels in 2050 (Panel A - Figure 5). Differently, the implementation of subsidies to fruits, vegetables, and nuts alongside meat taxation policies significantly boosts the production of the former group of products, with an increase of +13.9% (or 12.1 million tonnes) in the "Meat Tax 5% + VFN subsidy" scenario, and a more substantial +47.2% (or 43.1 million tonnes) growth in the more stringent "Meat SCC $152 + VFN subsidy" scenario. The increase in domestic production of fruits, vegetables, and nuts, combined with the reduction in feed demand due to declining meat production, leads to a simultaneous decrease in cereals and grains production, ranging from -1.3% (or 6.8 million tonnes) in the "Meat tax 5% + VFN subsidy scenario" to -5.7% (or 29.5 million tonnes) in the "Meat SCC $152 + VFN subsidy" scenario by 2050 (Table 1).

While standalone taxes on meat products exert rather weak effect on trade, the application of subsidies on fruits, vegetables, and nuts decreases imports of meat from -9.1% (or 3.1 million tonnes) in the "Meat Tax 5% + VFN subsidy" scenario, up to -23.1% (or 7.8 million tonnes) in the "Meat SCC $152 + VFN subsidy" scenario (Panel A – figure 5), mainly from Europe and Canada (average decrease from -18.1% up to -45.1% across scenarios). At the same time, the observed rise in domestic production of fruit, vegetables, and nuts drives exports of such products from the United States (from 1.2 to 6.5 million tons across meat tax + subsidy scenarios). Parallelly, changes in meat demand have simultaneous effects on meat imports, decreasing across the analysed scenarios (from -3.1 up to -7.8 million tonnes), particularly from Europe (from -1.8% up to -5.0% across scenarios) and South America (from -1.2% up to -4.6% across scenarios).

Following the decrease in production, exports of cereals and grains parallelly shrink from a -0.9 million tonnes up to -4.1 million tonnes across scenarios in 2050. On the other hand, the reduction in domestic meat consumption leads to an increase in exports of meat products from the United States, ranging from a +1.2 million tonnes in the "Meat tax 5% + VFN subsidy" scenario up to a +4.7 in the "Meat SCC $152 + VFN subsidy" scenario.

Changes in food demand resulting in shifting trade patterns have direct consequences on the sourcing of the average diet in the United States. However, these changes in food sourcing are relatively moderate (Panel B – Figure 5). Standalone meat policies have stronger effects on domestic meat production compared to imports, decreasing the domestic-import ratio of meat supply from -0.03% in the "Meat Tax 5%" scenario up to -0.13% in the "Meat SCC $152" scenario compared to BAU in 2050. Differently, when subsidies are combined with meat taxes, the increase in domestic production of fruits, vegetables, and nuts, coupled with a decrease in imports across scenarios results in a higher share of domestic sourcing of such products from +1.3% in the "Meat Tax 5% + VFN subsidy" scenario up to +3.3% in the "Meat SCC $152 + VFN subsidy" scenario compared to BAU in 2050. This affects the overall share of domestically sourced food supply in the United States, which increases under combined policies (up to +0.65%) due to a rise in domestic demand. In contrast, standalone meat interventions result in a more pronounced impact on domestic food demand compared to imports, reducing the share of food supply from domestic sources in 2050 compared to BAU (Panel B - Figure 5).

The observed changes in food production and trade have direct consequences on agricultural wages in 2050. Given that livestock sectors are relatively more capital intensive compared to the fruit, vegetables, and nuts sectors, the decrease in meat production has a relatively small effect on wages, which overall benefit from the analysed policy interventions. In comparison to the BAU scenario in 2050, positive effects on agricultural wages are observed across standalone meat tax scenarios (ranging from an average of +0.03% in the "Meat Tax 5%" scenario to an average of +0.11% in the "Meat SCC $152" scenario), as well as when subsidies are combined with taxes (from an average of +0.04% in the "Meat Tax 5% + VFN" scenario to an average of +0.10% in the "Meat SCC $152 + VFN subsidy" scenario). This, coupled with a decrease in average prices of fruit, vegetables, and nuts, generated by policy interventions (Panel B of Figure 4), results in a higher affordability of a healthy diet for agricultural workers in the United States in 2050.

Finally, despite the introduction of policies allows to increase the affordability of a healthier diet, by changing its composition towards a healthier food basket (Panel C – Figure 4), the implementation of such policies has rather minimal costs (Panel C – Figure 5). Up to 2050, aggregate welfare in the United States is projected to slightly increase under standalone meat taxation policies, ranging from an increase of +0.01% in the “Meat Tax 5%” scenario, up to a +0.03% in the “Meat SCC $152” scenario. In per-capita terms, such increase ranges from a +7.8 to +22.1 US dollars per capita. Differently, when subsidies are introduced in combination to meat taxes, welfare trends are reversed due to the higher costs for financing the policies. In the “Meat Tax 5% + VFN subsidy” scenario, aggregate welfare moderately decreases by -0.01%, a figure that further decreases up to -0.03% in the “Meat SCC $152 + VFN subsidy” scenario in 2050. This translates in a decrease in per capita aggregate welfare, ranging from -2.7 to -30.1 US dollars per capita.

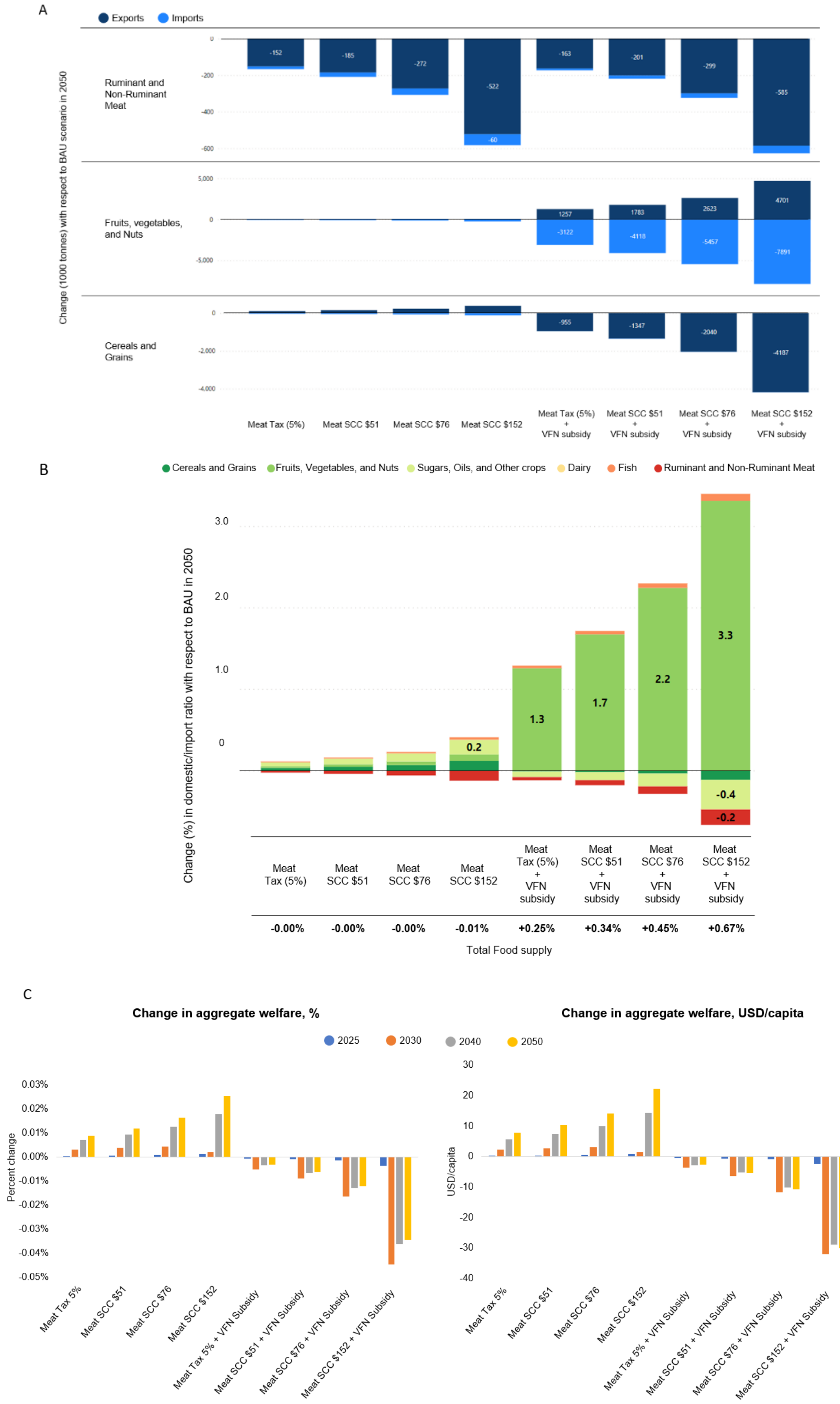


**Figure 5. Change in trade, dietary sourcing, and aggregate welfare with respect to Baseline (BAU) scenario in 2050.** Panel A displays the changes (in 1000 tonnes) in imports and exports of major food commodities influenced by policy interventions, as compared to the Business-as-Usual (BAU) scenario in 2050. Panel B depicts the percentage changes in the domestic-import ratio, which is calculated by dividing domestic food supply by imported food supply, for individual commodities and total food supply in the United States across the examined policy scenarios compared to the Business-as-Usual (BAU) scenario in 2050. Finally, panel C illustrates percentage changes and in USD per capita in aggregate welfare across the examined policy scenarios compared to the Business-as-Usual (BAU) scenario in 2050.

### 3.3 Environmental impacts of changing dietary trends

Implementing meat taxation policies in the United States has the potential to progressively decrease greenhouse gas (GHG) emissions from 2025 to 2050 (Panel A - Figure 6). Under standalone meat taxation policies, the reduction in meat consumption leads to a decrease in methane (CH4) emissions ranging from -1.1% (or -7.3 million tons of $CO_2$ equivalents) in the "Meat tax 5%" scenario to -4.6% (or -30.7 million tons of $CO_2$ equivalents) in the "Meat SCC $152" scenario by 2050. Additionally, a reduction in emissions is observed for levels of nitrous oxide ($N_2O$), progressively decreasing from 2025 to 2050 (Panel A - Figure 6). In 2050, standalone meat policies result in a decrease in $N_2O$ pollution by -1.0% (or -4.1 million tons of $CO_2$ equivalents) in the "Meat tax 5%" scenario to -4.1% (or -13.9 million tons of $CO_2$ equivalents) in the "Meat SCC $152" scenario.

However, less beneficial effects on emissions are observed when subsidies for fruits, vegetables, and nuts are combined with meat taxation policies (Panel B - Figure 6). Although combined policies decrease total GHG emissions levels compared to baseline levels in 2050, the increase in the production of subsidized fruits, vegetables, and nuts generates a rebound effect, partly offsetting the initial benefits observed under standalone meat taxation policies. The benefits achieved on methane emissions remain preserved and are further increased up to -5.6% in the more severe "Meat SCC $152 + VFN subsidy" scenario. Conversely, a rebound effect occurs in the case of $N_2O$ emissions. In 2050, combined policies result in a lower reduction of $N_2O$ pollution levels, which, compared to the achieved reduction observed under standalone meat taxation policies, are relatively higher (+0.4% in the "Meat tax 5% + VFN subsidy" scenario to +1.0% in the "Meat SCC $152 + VFN subsidy" scenario, Panel B - Figure 6).

Changes in dietary trends have direct consequences on the generation of food loss and waste (FLW) (Panel C – figure 6). In the BAU scenario, FLW in the United States increases by 17.14% (or 17.1 million tonnes), principally driven by the increase in meat and dairy demand. While in BAU, meat-related FLW increase by 43.6% (or 3.1 million tonnes) compared to the base year, the imposition of taxes primarily impacts such flows, with reduction ranging from -3.1% (or 0.3 million tonnes) in the “Meat tax 5%” scenario, up to -8.5% (or 0.8 million tonnes) in the "Meat SCC $152”, compared to the BaU in 2050. More severe effects of FLW generation are observed when subsidies are applied in combination with meat-related taxes. In 2050, FLW generated from production and consumption of fruits, vegetables, and nuts, increases from

+6.7% (or 2.5 million tonnes) in the "Meat tax 5% + VFN subsidy" scenario up to +24.6% (or 9.2 million tonnes) compared to BAU. Such increase results determinant for the overall levels of FLW which, despite an observed decrease in meat-related FLW across combined policy scenarios (from -2.7% up to -8.8%), result higher (from +1.9% or 2.1 million tonnes to 6.7% or 7.7 million tonnes) compared to BAU in 2050.

In terms of nutritional losses, changes are linked to the type of policy implemented. Under standalone meat taxation policies, the decrease in meat FLW, often presenting high caloric content, results in a lower loss of calories per capita per day (Panel C - Figure 6). Conversely, when subsidies complement meat-related taxes, the increase in FLW from fruits, vegetables, and nuts offsets the decrease in meat-related FLW, resulting in a higher loss of calories (ranging from +5 to +15 calories per capita per day) compared to the BAU scenario in 2050. However, this increase is relatively less severe than the increase observed in absolute weight levels, as the reduction in highly caloric meat-related FLW under combined policies (ranging from -3 to -9 calories per capita per day) mitigates the overall rise in nutritional losses in 2050.

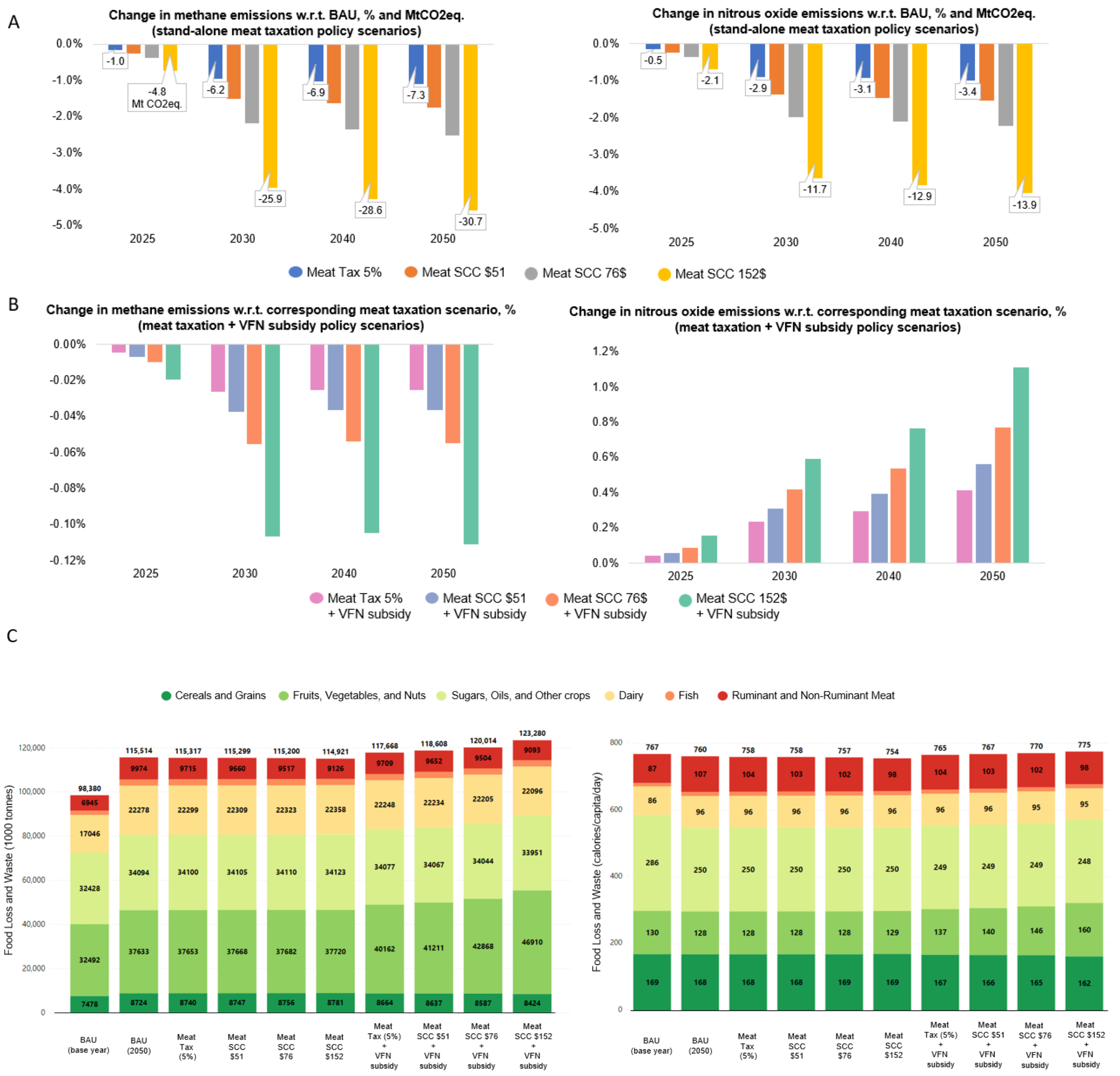


**Figure 6. Changes in Methane emission, Nitrogen Oxide emission, and food loss and waste generation across policy scenarios.** Panel A showcases the changes in Methane emissions (percentage and in CO2 equivalents) and Nitrogen Oxide emissions (percentage and in CO2 equivalents) in scenarios where standalone meat-related taxes are implemented, compared to the Business-as-Usual scenario in 2050. Panel B illustrates changes in Methane emissions (percentage and in CO2 equivalents) and Nitrogen Oxide emissions (percentage and in CO2 equivalents) in combined policy scenarios (meat-related tax + subsidy on fruits, vegetables, and nuts), relative to the standalone meat-related tax scenarios reported in panel A. Lastly, Panel C presents the magnitude and nutritional content of food loss and waste generated (1000 tonnes and calories per capita per day) by the production and consumption of food commodities in the United States in the base year (2014) and across investigated scenarios in 2050.

## 4. Discussion and Conclusion

As dietary patterns in the United States continue to evolve, projections suggest that meat demand will further increase by 2050. This upward trend raises concerns regarding both public health and environmental sustainability, highlighting the pressing need to align food consumption with the global Sustainable Development Goals (SDGs). The findings of this study provide valuable insights into the intricate relationship between policy interventions fostering dietary transitions, nutritional and environmental impacts, and socio-economic changes. They underscore the complexity of transitioning toward healthier and more sustainable diets in the United States, emphasizing the multifaceted nature of this endeavour.

We use a global economic computable general equilibrium model (CGE) that incorporates nutritional and environmental accounts to explore the potential effects of various policy options on economic welfare, health, and environmental conservation in the United States. The model, calibrated using national statistics, captures the dynamics of the global economy, considering factors like trade barriers, regional trade patterns, and volumes of global food trade. It accounts for how producers and consumers respond to changes in prices when policies are applied. By tracing physical and nutritional flows, along with various environmental factors such as emissions, air pollutants, and food loss and waste, the model offers a comprehensive analysis beyond the monetary values typical of CGE models. This approach enhances the multidisciplinary relevance of our analysis, addressing a key weakness of these economic models (Pyka et al., 2022). By providing estimates of food intake in both grams and calories, we additionally assess how policies directly affect nutritional availability in 2050, allowing a comparison of our results with global sustainable dietary guidelines.

The use of a CGE model, in contrast to the partial-equilibrium (PE) models utilized in previous studies assessing dietary shifts (Springmann et al., 2018; 2021), enables us to directly measure the impacts on economic welfare and wages, elements that are key for food affordability but often overlooked by PE models. Additionally, by examining specific policy scenarios aimed at promoting dietary changes, we grasp the potential costs and benefits of transitioning to a healthier diet in the United States. By analysing dietary transition costs, we expand previous macroeconomic studies on the impact of sustainable diets (Gatto et al., 2023), in which dietary shifts are assumed to occur with no additional costs.

Our analysis highlights the necessity for substantial adjustments in food consumption for transitioning towards healthier diets in the United States. We find that implementing meat taxation policies, specifically targeting the reduction of meat overconsumption, shows promise in enhancing dietary healthiness and alleviating environmental impacts. The results suggest that standalone meat taxation policies could significantly decrease meat consumption, leading to a lower calorie intake from meat products, which is often associated with favourable health outcomes (Willett et al., 2019). Moreover, these policies contribute to reducing greenhouse gas emissions, particularly methane and nitrous oxide, thereby aligning with efforts to combat environmental pollution and climate change. These findings confirm the beneficial effects of meat taxation on both health and environmental quality (Caro et al., 2017; Sall, 2018) additionally providing a quantitative macro-level policy assessment for the United States, previously available only at a consumer level (Tallie et al., 2023).

While decreasing meat consumption represents a first step to improve the sustainability of diets in the United States, sustaining healthy nutritional levels requires encouraging the consumption of healthier and more sustainable alternatives such as fruits, vegetables, and nuts. Our analysis underscores that combining meat taxation with subsidies for these plant-based foods offers a holistic strategy for fostering healthier dietary habits. The synergistic effects of these policies result in a significant increase in the consumption of plant-based foods associated with numerous health and environmental benefits (Springmann et al., 2016; Willet et al., 2019). However, an important finding of our analysis lies in the fact that substantial policy interventions are necessary to drive changes in dietary patterns. We find that moderate policy measures, such as those explored in the "Meat Tax 5%" scenario, yield limited impacts on food consumption patterns, necessitating more severe interventions. While more severe policies show promise in steering consumption towards a healthier food basket, they may fall short of achieving sustainable dietary goals (HHS/USDA, 2015; Willett et al., 2019; Mapes et al., 2022). Comparing dietary intakes from our most stringent policy scenario (Meat SCC $152 + VFN subsidy) with projected dietary guidelines for 2050,[1] it becomes evident that significant reductions in meat consumption are imperative to align with sustainable dietary patterns. Ruminant meat intakes (grams per capita per day) would need to decrease by an additional -70%, while non-ruminant meat intakes would require a further decrease of -78%. This underscores the need for complementary policy measures, as the monetary policies investigated offer a pathway for changing consumption but may not suffice to meet dietary targets in the United States by 2050.

[1] Implemented dietary guidelines are based on the preliminary estimates obtained within the EAT-Lancet study and are subject to further refinements and revisions.

In this regard, our study emphasizes the importance of carefully considering broader socio-economic implications alongside ensuring the adequate magnitude of interventions. While meat taxation policies show minimal negative effects on agricultural wages and overall welfare, the introduction of subsidies alongside taxes may result in potential rebound effects, compromising environmental targets. Consequently, the adoption of more severe monetary interventions to influence consumer choices could impose additional strains on aggregate welfare, placing significant burdens on government budgets. Nonetheless, the observed increase in the affordability of healthy diets for low-income agricultural workers and the higher share of domestically sourced food products highlight the importance of implementing targeted policies to address disparities in access to nutritious foods. In this, selecting the appropriate combination and magnitude of policies remains crucial, as the resulting environmental impacts alongside socioeconomic changes can vary significantly.

While implementation of meat taxation policies in the United States appears to offer a promising avenue for progressively reducing greenhouse gas (GHG) emissions over the period from 2025 to 2050, the integration of subsidies for fruits, vegetables, and nuts alongside meat taxation policies complicates the emissions landscape. Although total GHG emissions still decrease compared to the baseline scenario by 2050, the increase in production of subsidized plant-based foods triggers a rebound effect, partially counteracting the initial benefits observed under standalone meat taxation. Notably, methane emissions continue to decrease and even amplify under combined policies, indicating a positive impact on reducing emissions associated with livestock farming. On the other hand, the rebound effect is more pronounced for nitrous oxide emissions, resulting in a smaller reduction or even a slight increase compared to standalone meat taxation scenarios.

Changes in dietary trends induced by policy interventions additionally influence the generation of food loss and waste (FLW). While the baseline scenario shows a considerable increase in FLW, particularly driven by rising meat and dairy demand, the imposition of meat taxes leads to notable reductions in meat-related FLW. However, when subsidies are introduced alongside meat taxation, the overall impacts on FLW may lead to additional rebounds. Despite decreases in meat-related FLW, the increase in FLW from fruits, vegetables, and nuts outweighs these reductions, resulting in higher overall FLW levels compared to the baseline scenario. On a positive note, the increase in nutritional losses, while concerning, it is relatively less severe compared to the absolute weight levels, as the reduction in highly caloric meat-related FLW under combined policies helps mitigate the overall rise in nutritional losses.

It is important to acknowledge the uncertainties and limitations inherent in this study. One key factor influencing our findings is the calibration of food demand price elasticities. Since changes in demand in response to price effects from policy interventions depend on these elasticities, the ongoing debate about the magnitude of these elasticities (Andreyeva et al., 2010), coupled with gaps in research on substitutions between healthy and unhealthy foods, leaves room for discussion regarding the appropriate magnitude of policy interventions aimed at moderating the consumption of animal food products.

Another potential limitation is the representation of a single household type and income level across the United States. Considering different income levels could lead to diverse food purchasing choices across policy scenarios. This coupled with heterogeneous household types could provide additional insights into how dietary transitions may affect various income classes in 2050.

Additionally, our analysis primarily focuses on calories to address adequate intake levels, but considering additional micronutrients could enhance the estimation of nutritional adequacy achieved by policy interventions. A more detailed representation of nutrients, along with the inclusion of heterogeneous household types, could facilitate a deeper analysis of undernutrition and obesity cases, allowing for tailored policy interventions for specific income groups in the United States.

Lastly, in our scenario design, our model does not include certain products like sugar-sweetened beverages, which are often at the heart of debates on healthier dietary transitions in the United States. Including these products in the model could enable the design of corresponding policy scenarios to address nutrition-related health issues through monetary instruments.

In conclusion, our findings underscore the importance of adopting a holistic approach to policy-making that considers the interconnectedness of dietary patterns, environmental sustainability, and socio-economic factors. By combining taxes, subsidies, and regulatory measures, policymakers can effectively incentivize consumers to make healthier and more sustainable food choices while mitigating potential trade-offs. Future research should focus on refining policy interventions, investigating more complex policy packages for assessing long-term impacts on public health, environmental sustainability, and socio-economic development. Finally, efforts to strengthen international collaboration and knowledge-sharing on food consumption and related health and environmental impacts will be crucial for advancing global efforts towards achieving healthier and more sustainable diets for all.

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## Appendix A. Sectoral and regional aggregations used in the study

### Table A.1. Sectoral coverage

| No. | Sectoral description |
|---|---|
| 1 | Rice |
| 2 | Wheat |
| 3 | Other cereals |
| 4 | Vegetables, fruit, nuts |
| 5 | Oil seeds |
| 6 | Sugar |
| 7 | Other crops |
| 8 | Bovine cattle, sheep and goats, horses |
| 9 | Animal products nec |
| 10 | Raw milk |
| 11 | Forestry |
| 12 | Fishing |
| 13 | Coal |
| 14 | Oil |
| 15 | Gas |
| 16 | Other extraction |
| 17 | Bovine meat products |
| 18 | Meat products nec |
| 19 | Vegetable oils and fats |
| 20 | Dairy products |
| 21 | Other food |
| 22 | Energy intensive manufacturing |
| 23 | Refined petroleum |
| 24 | Other manufacturing |
| 25 | Electricity transmission & distribution |
| 26 | Coal and oil electricity |
| 27 | Gas electricity |
| 28 | Nuclear electricity |
| 29 | Hydro electricity |
| 30 | Solar electricity |
| 31 | Wind electricity |
| 32 | Other renewable electricity |
| 33 | Construction |
| 34 | Accommodation, Food and service activities |
| 35 | Transport services |
| 36 | Other services |

## Table A.2. Regional coverage

| No. | Description of the region |
|---|---|
| 1 | Canada |
| 2 | United States of America |
| 3 | Brazil |
| 4 | Other South, Central America & Caribbean (incl. Mexico) |
| 5 | Former Soviet Union (European and Asian) |
| 6 | Europe (excl. Turkey) |
| 7 | Middle-East / North Africa (incl. Turkey) |
| 8 | Sub-Saharan Africa |
| 9 | China (incl Hong-Kong, Macao) |
| 10 | India |
| 11 | High-income Asia |
| 12 | South-East Asia (excl High-income Asia) |
| 13 | Other Asia (incl. Other Oceania) |
| 14 | Australia/New Zealand |
| 15 | Burkina Faso |
| 16 | Ethiopia |
| 17 | Pakistan |
| 18 | Malawi |