Assessing Policies to Create a More Circular Food System

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Abstract: Circular economy solutions aim to keep valuable materials in economic circulation (out of landfills) and to enhance food security and the environmental sustainability of food systems. Existing economic models of circular food systems often fail to endogenize the amount of food that is wasted and sent to landfills at different food supply chain stages. We develop a general equilibrium model of the U.S. Midwest that endogenizes the food waste decisions at each supply chain segment and is calibrated to observed data. We assess the impacts of two circular policy interventions—a waste disposal tax and a waste abatement cost reduction—at the final two stages of the supply chain. Our results identify a food waste tax levied on consumers as the single instrument that would yield the greatest system-wide reductions in greenhouse gas emissions though it would cause less food consumption and consumer spending on taxes and abatement costs to outstrip savings generated from buying less food at lower food prices. The single instrument that generates the greatest reduction in system-wide landfill deposits is a reduction in consumer waste abatement costs, though reductions in greenhouse gas emissions are muted as consumers increase food consumption as they become less wasteful. Policies aimed at food retailers have much smaller impacts. Applying policies to both consumers and retailers has greater impacts than targeting either group alone, but the impacts are often less than the sum of impacts from applying the instruments to each supply chain segment individually.

JEL Codes: C68, Q18, Q58

Key Words: circular food system, food loss, food waste, food supply chain, general equilibrium, waste abatement cost, waste tax

1. Introduction

Food waste is a global issue, as manifested in UN Sustainable Development Goal Target 12.3, and the U.S. also has paid increasing attention to it. In 2015, the USDA and EPA announced the 2030 Food Loss and Waste Reduction goal which aims to reduce food loss and waste (FLW) by half by 2030. The "Draft National Strategy for Reducing Food Loss and Waste and Recycling Organics,"[1] released in 2023 by the Biden Administration, recognizes the significance of preventing wasted food and adopting circular solutions for organic waste in mitigating associated environmental impacts, reducing households' expenses, and building a more circular economy.

According to ReFED,[2] the U.S. food system is estimated to waste 33% of food production, in total 78 million tons in 2022, which is equivalent to about 145 billion meals or $428 billion USD. This is a significant loss as the U.S. observes food insecurity rates reaching 12.8% in 2022 (Rabbitt et al., 2023). In addition, wasting food wastes the resources used in its production and creates significant environmental impacts: 140 million acres of agricultural land, 664 billion kWh of energy, and 170 million metric tons of greenhouse gas (GHG) emissions, among other things (Jaglo et al., 2021). Such factors support the rationale behind the target of halving food waste and loss by 2030, advocated by the UN and the U.S.

An increasing body of literature has investigated the effects of food waste reductions. Theoretical studies on food waste economics discuss food waste as an optimal decision and assess the factors that drive food security and welfare outcomes of food waste reduction strategies (Lusk & Ellison, 2020; Rutten, 2013). Microeconomic household food waste models are proposed to examine a socially optimal food waste tax (Katare et al., 2017), the effects of enhanced food utilization (Hamilton & Richards, 2019), and the impacts of halving household food waste rate (Drabik et al., 2019). Partial or general equilibrium

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[1] Accessed May 2, 2024: https://www.epa.gov/circulareconomy/draft-national-strategy-reducing-food-loss-and-waste-and-recycling-organics

[2] ReFED Food Waste Monitor, Accessed May 2, 2024: https://insights-engine.refed.org/food-waste-monitor

models have also been used to analyze food loss and waste reduction at major stages in a food supply chain or economy-wide impacts. A partial equilibrium model of farmers, intermediaries, and consumers investigates direct and cascading impacts of waste reduction across the supply chain (de Gorter et al., 2021). Partial equilibrium approaches also examine the global-level environmental and food security impacts of food waste reduction (Kuiper & Cui, 2021; Lopez Barrera & Hertel, 2021). Studies adopting general equilibrium models examine the effects of public and private interventions to reduce household or food processor food waste, such as the adoption of a food waste tax (Bartelings & Philippidis, 2024), supply-side compliance cost increases (Philippidis et al., 2019), and agricultural input reductions in food production (Jafari et al., 2020) on the measures of food security, sustainability, and circularity. Lastly, environmentally-extended input-output analyses have been adopted to assess the changes in a range of environmental indicators, including land, energy, and water use and toxic pollutant emissions, associated with food waste reduction or related interventions (Read et al., 2020; Read & Muth, 2021; Salemdeeb et al., 2017). Still, the literature presents ambiguous findings of the impacts of waste reduction and relevant policy interventions and a lack of an established approach to examine them.

The ambiguity in results is often driven by supply and demand elasticity, general equilibrium effects, trade openness, and modeling of waste behavior and waste abatement costs, some of which also contribute to the indeterminacy of the modeling approach. In a series of conceptual analyses of food waste (Lusk & Ellison, 2020; Rutten, 2013), food waste is considered an optimal economic decision resulting from a complex equilibrium and dependent on socioeconomic factors, such as preferences, prices, income, and human capital. In a naïve analysis, reducing loss and waste would benefit both producers, who could sell more products at a lower cost, and consumers, who could save their spending on food and purchase more other goods. However, the effects are ambiguous if waste reduction is relatively costly, thus offsetting the benefits of a price decrease, or if interactions between stages along the food supply chain or with other sectors are significant.

Focused on food waste at the consumer stage, which accounts for the most significant share of food waste and loss in developed countries, theoretical models of household food waste problems have been developed with a basis in consumer theory. An economic analysis of household food waste and its relation with waste disposal taxes and government incentives on food preservation is conducted to investigate socially optimal food waste and government interventions (Katare et al., 2017). In the context of recent policy proposals, adjusting market prices and reducing household food utilization costs are studied using a household food waste model with fresh and processed food products (Hamilton & Richards, 2019). An analytical model is shown to be empirically applicable to the food sector. Drabik et al. (2019) develop a consumer food waste microeconomic model with endogenous waste rate and waste abatement and disposal costs and apply it to the UK poultry sector to examine the impacts of food waste reduction on prices, demand, and supply. All consumer food waste studies highlight the significance of elasticity and market conditions in determining the effects of policy interventions and suggest directions for future empirical analysis on critical consumer elasticities and economic factors.

Food loss and waste from other stages of the food supply chain and its impacts across the broader economy have also been explored. De Gorter et al. (2021) theoretically and empirically examine exogenous food waste reduction from key supply chain actors—consumers, intermediaries, and farmers—using a partial equilibrium model to find that the impacts of reducing waste are dependent on elasticities and trade openness. They also highlight the significance of the cascading effects due to the interactions among actors within the food system. To address broader economic impacts, Bartelings & Philippidis (2024) develop a general equilibrium model incorporating endogenous rational household food waste behavior. They show that the adoption of a food waste tax to incentivize food waste reduction leads to improved food affordability with the falling average food price and to a smaller agri-food industry due to decreased production. Philippidis et al. (2019) instead model household food waste reduction as an exogenous adjustment in the budget share and a consequent reduction in food consumption, accounting for supply-side compliance costs, which also impact household food consumption through the price mechanism. Their findings reveal that agri-food production is unambiguously reduced, whereas price changes are indeterminate and depend on the net effects of demand and supply responses. Both results report improvements in environmental indicators, such as GHG emissions and land use. Jafari et al. (2020) focus on waste reduction in the food processing sector by simulating food waste reduction by substituting agricultural input for non-agricultural inputs under different associated cost scenarios. Their findings reveal that decreased demand by the food processing firm leads to lower agricultural commodity prices and higher food production though the magnitude of such effects is reduced under higher cost assumptions. They report only moderate environmental benefits as reduced food waste is offset by increased use of other goods and services.[3]

Despite previous modeling attempts, the effects of waste reduction remain far from straightforward and depend on modeling assumptions and economic structures. To complement the existing literature, we develop a general equilibrium model that aims to account for major modeling components discussed in the literature. Our contributions are fourfold. First, this study models multiple major stakeholders (farmers, food manufacturers, food suppliers,[4] and consumers) optimally choosing food loss and waste to maximize their utility or profit. Existing studies are limited in either focusing only on the waste of a single actor, ignoring the remining food supply chain (Bartelings & Philippidis, 2024; Drabik et al., 2019; Hamilton & Richards, 2019; Jafari et al., 2020; Katare et al., 2017) or modeling food waste rate as an exogenous variable (de Gorter et al., 2021; Kuiper & Cui, 2021; Lopez Barrera & Hertel, 2021; Philippidis et al., 2019). Thus, our model can be considered as a framework that consistently integrates rational food waste decisions across stages in the food supply chain. This allows for conducting an analysis of interventions in multiple stages simultaneously.

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[3] Such "rebound" effects are reported by other non-simulation-based approaches (Hegwood et al., 2023; Salemdeeb et al., 2017)

[4] The food suppliers include the retailers and foodservice providers, which provide the final food goods purchased and consumed by the consumer. Details are found in Section 3.1.

Second, we incorporate abatement cost functions, formulated as a function of abatement rate and production (or food purchase), uniformly for all actors. Abatement costs are critical in determining the effects of waste reduction, as highlighted in the literature (Bartelings & Philippidis, 2024; Jafari et al., 2020; Philippidis et al., 2019; Rutten, 2013). Despite their inclusion of abatement costs in the model, these previous studies tend to develop an approach unique to a particular actor, unsuitable to other parts of the food supply chain. As an attempt to develop a universally adaptable abatement cost function, thus allowing the examination of simultaneous interventions across sectors, we develop a uniform cost function, calibrated to each stage. This approach is advantageous in interpreting and comparing abatement cost changes under different scenarios. The selected functional form is comparable to those invoked by Katare et al. (2017) and de Gorter et al. (2021).

Third, thanks to the two aforementioned modeling techniques, our work is capable of simulating and comparing the effects of a combination of public (e.g., waste tax) and private (e.g., technology improvement) interventions at different stages of the food supply chain in a single framework. It is made possible by modeling all actors' rational waste behavior and related abatement costs. Using our model, we examine each intervention's direct and indirect impacts up or down the supply chain.

Lastly, amid the dominance of EU-focused studies in the literature, we turn to the U.S. Midwest, which provides a unique setting as an agriculturally intensive and agri-food exporting region and a relevant case study given the release of Federal funding to support circular solutions to food system sustainability. The economic structure of the study region is another critical feature, as stressed in the literature. Our study region can be characterized by inelastic demand, elastic supply, and a higher degree of openness to trade. Our study thus is anticipated to provide relevant insights for this context.

To summarize our findings, first, a food waste tax levied on the consumer and the supplier works differently: a consumer waste tax tends to reduce both the waste ratio and food consumption, whereas a supplier waste tax would impact solely the supplier's waste ratio. Thus, a tax targeted at the consumer consequently may diminish food security. GHG emissions are reduced more in the consumer waste scenario, as it also drives the supplier to produce less, than in the supplier waste tax scenario. Second, scenarios with waste abatement cost reductions reveal that it effectively mitigates waste rates and quantities and would improve food security and resource use efficiency. However, the efficiency gains have relatively minor impacts on GHG emissions from the food supply chain due to tendency to increase food consumption and production at other stages. Lastly, a simultaneous adoption of taxes and abatement cost reductions presents a potential for improving both welfare and GHG emissions with interventions though the impact of applying instruments at both consumer and food supplier segments are less than additive in their impacts on waste and GHG outcomes.

The paper is outlined as follows. The next section describes the data used to calibrate and simulate the model. Section 3 presents the summary of the general equilibrium model with food waste and its abatement and scenarios. Section 4 provides the analysis of policy interventions and their consequences in economic and environmental indicators. Section 5 and 6 provide discussion and conclusions, respectively.

2. Data

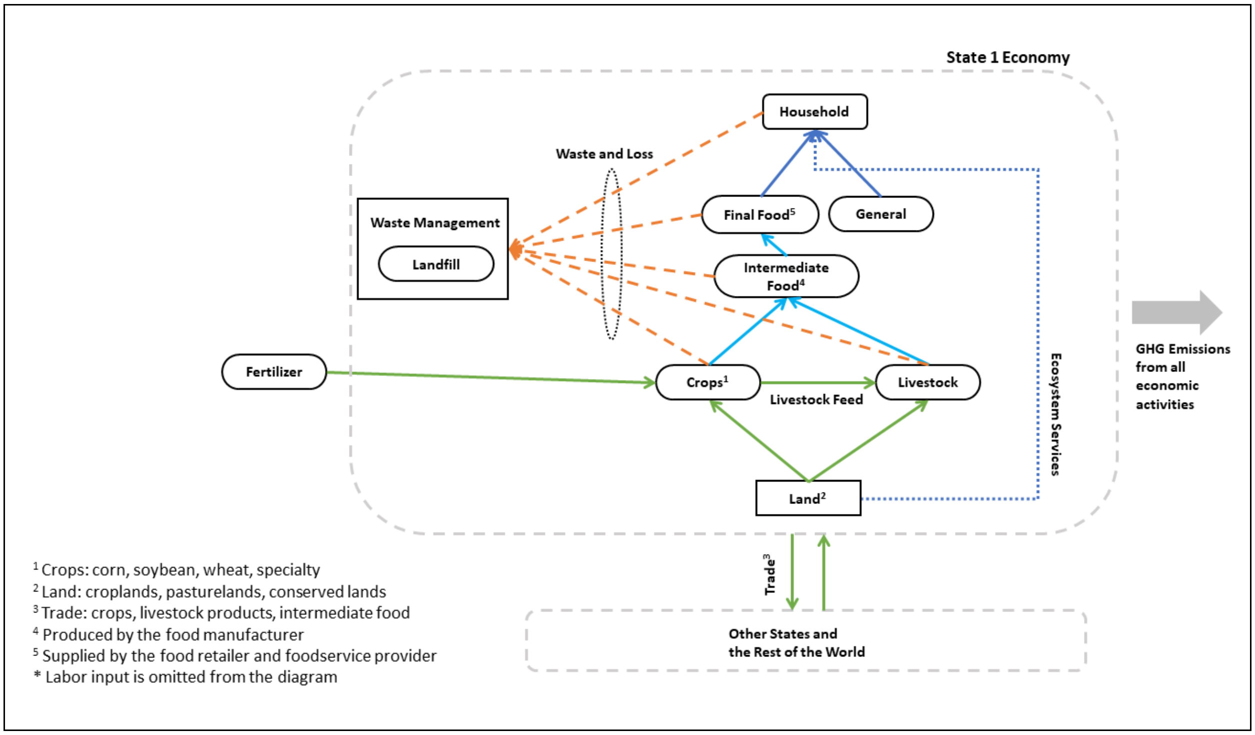
The study obtains data from an extensive set of sources. First, state-level crop production, cropland use, livestock production, pastureland use, and price data are taken from the USDA National Agricultural Statistics Service. The food sector's uses of crop and livestock products are drawn from the USDA Economic Research Service (ERS). The data on corn and soybeans used for non-food (mainly fuel) production is drawn from the U.S. Energy Information Administration and USDA ERS. State-level food trade flows are computed with the data from ReFED. State-level GDP, labor, and capital stock are obtained from the U.S. Bureau of Economic Analysis, U.S. Bureau of Labor Statistics, and IMPLAN.

Food waste estimates for each stage of food systems (farm, food manufacturer, food supplier, and consumer) are collected from the ReFED Food Waste Monitor and used to adjust production quantities. The specification of waste management sectors (e.g., capital investment and operating costs) is based on the literature (Badgett & Milbrandt, 2021; Shahid & Hittinger, 2021). For environmental impact analyses, GHG emissions by sector and waste management practice are calculated using emissions factors from life cycle assessment (LCA) models, including the Department of Energy's Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation Model (GREET), EPA's U.S. Environmentally-Extended Input-Output Models (USEEIO) and Waste Reduction Model (WARM), and other LCA-based literature (Crippa et al., 2021; Poore & Nemecek, 2018).

3. Methods

3.1. Model

In our general equilibrium model, each state economy in our five-state region includes producers of major crops (corn, soybeans, wheat, and specialty crops) and livestock products, a food manufacturer, a food supplier (combining retailer and foodservice provider), a general (non-food) manufacturing and services firm, and a representative household. Each economic agent, except the general sector firm, is assumed to generate a certain level of FLW and bear the costs of reducing their FLW to the current level.



[1] Crops: corn, soybean, wheat, specialty
[2] Land: croplands, pasturelands, conserved lands
[3] Trade: crops, livestock products, intermediate food
[4] Produced by the food manufacturer
[5] Supplied by the food retailer and foodservice provider
* Labor input is omitted from the diagram

Figure 1 Model Schematic Diagram

3.1.1. The Household's Problem

The representative household (HH)[5] in each state, j, maximizes their utility (Eq. 1) given their budget constraint (Eq. 3). The utility function is a function of a consumption bundle, $\boldsymbol{y} = \left(y^{general}, y^{food,final}, l^{conserved}\right)$ of per capita consumption (or purchase) of general goods and services (non-food), $y^{general}$, food products, $y^{food,final}$,[6] and conserved land, $l^{conserved}$, which provides ecosystem services. To incorporate the food waste at the consumer level, the model distinguishes the quantity purchased ($y^{food,final}$) and consumed ($\left(1 - r^{wasted,consumer}\right) \cdot y^{food,final}$) and only the consumed amount contributes to the household's utility level. The utility function is the weighted additive utility function with isoelastic functional forms,

$$U(\mathbf{y}^j) \cdot Pop^j, \tag{1}$$

where

$$\begin{aligned} U(\mathbf{y}^j) = {} & \frac{\left(y^{general,j}\right)^{1-\gamma^{c,general,j}}}{1-\gamma^{c,general,j}} + \omega^{food,j} \frac{\left\{\left(1 - r^{wasted,consumer,j}\right) \cdot y^{food,final,j}\right\}^{1-\gamma^{c,food,j}}}{1-\gamma^{c,food,j}} \\ & + \omega^{conserved,j} \frac{\left(l^{conserved,j}\right)^{1-\gamma^{c,conserved,j}}}{1-\gamma^{c,conserved,j}}. \end{aligned} \tag{2}$$

ω represents the relative weight of each good's contribution to the utility, and γ represents relative risk aversion coefficient associated with each good.

The household's budget constraint is:

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[5] Household and consumer are used interchangeably.

[6] We distinguish two food products: first, food manufactured and used as an intermediate input to the food supplier, and second, food supplied to and consumed by the household. The former one (from the food manufacturer) and its associated sector and stage are indexed with $food, inter$, and the latter one (from the food supplier) and its sector and stage are indexed with $food, final$.

$$
\begin{aligned}
&\Pi^{total,j} + \kappa^j K^{general,j} + \sum_{s_{land}} \iota^j L^{s_{land},j} + \sum_{s_{lab}} w^j N^{s_{lab},j} \\
&+ \tau^{tipping,j} W^{landfill,j} + \tau^{lumpsum,j} \\
&= Pop^j \cdot \left(y^{general,j} + p^{food,final,j} y^{food,final,j} \right) + I^{general,j} \\
&+ \zeta^{landfill,j} + Z^{cost,consumer} + \left(\tau^{tipping,j} + \tau^{tax,consumer} \right) \cdot r^{wasted,consumer} y^{food,final,j} Pop^j .
\end{aligned}
\tag{3}
$$

The left-hand side shows the total income earned, which is the sum of the profits from all firms ($\Pi^{total,j}$), the returns on capital ($\kappa^j K^{general,j}$) and land ($\sum_{s_{land}} \iota^j\ L^{s_{land},j}$), wages ($\sum_{s_{lab}} w^j\ N^{s_{lab},j}$), and tipping fees[7] ($\tau^{tipping,j} W^{landfill,j}$) collected for all food waste sent for landfill disposal ($W^{landfill,j}$), given the assumption that the household owns the firms, land, capital, and waste management facility in the economy. Total land, labor, and capital available for economic activities are given for each state.[8] The last term on the left-hand side is the lumpsum transfer of tax revenue to the household. s_{land} indicates sectors using land as an input, $s_{land} \in \{corn,\ soybean,\ wheat,\ specialty,\ livestock\}$, and s_{lab} indicates three sectors taking labor input, $s_{lab} \in \{food,inter,\ food,final,\ general\}$. κ, ι, and w represent return rates for capital and land, and the wage in each state, respectively.

The right-hand side shows the sum of all household expenses. The first two terms are the spending on the consumption of non-food and food goods ($Pop^j \cdot \left(y^{general,j} + p^{food,final,j} y^{food,final,j}\right)$) and capital investment ($I^{general,j}$). The general good serves as a numeraire, and thus, its price is set to one. $p^{food,final,j}$ is the market price of the food purchased by the household. The third term indicates the annualized costs (capital and operations & management (O&M) costs combined) of landfills ($\zeta^{landfill,j}$). It is assumed in this model that there is only one food waste management approach and that the food waste management facility (i.e., the landfill) is owned by the household, meaning its associated costs are borne by them. $Z^{cost,consumer}$ represents the waste reduction cost borne by the consumer that yields waste rates at the current level. The last term on the right-hand side

---

[7] A tipping fee is a fee charged for a given quantity of disposal. In the model, we adopt the national average tipping fee of $52/ton.

[8] We do not consider flows of primary inputs across the state borders.

is the sum of waste disposal tipping fee and potential tax paid by the household for their wasted food. In the following section, the state index, j, is omitted.

3.1.2. Food Waste Abatement Cost

Waste abatement cost functions at each stage in the supply chain ($stage \in \{corn,\ soybean,\ wheat,\ specialty,\ livestock,\ food,inter,\ food,final,\ consumer\}$) are defined as:

$$Z^{cost,stage} = \theta^{1,stage}\left\{\left(\frac{1}{r^{wasted,stage}}\right)^{\theta^{2,stage}} - 1\right\}Q^{stage}, \tag{4}$$

where $\theta^1, \theta^2 > 0$, and $r^{wasted,stage} \in (0,1]$ is the stage-specific waste rate. The function is strictly convex and increasing as the waste rate decreases. The cost equals zero when all the food at a particular stage (Q^{stage}) is wasted and goes to infinity when the waste rate approaches zero. The infinite cost implies the existence of inedible and unavoidable parts that are wasted at each stage. In our model, the abatement costs estimate the monetary value of any efforts made to reduce FLW. This may include: for consumers, more trips to groceries with fewer bulk food purchases, more time spent on meal preparation and food management, and the purchase and use of kitchen appliances and associated costs (e.g., electricity); for retailers, increased cold chain transport or investment in inventory management; for manufacturers, line optimization; for farmers, inventory management or gleaning.

3.1.3. Food Waste Management

The cost for waste management is

$$\zeta^{landfill} = \theta^{landfill} \cdot W^{landfill}, \tag{5}$$

where $\theta^{landfill}$ is the annualized cost of landfills (e.g., transportation, O&M, capital) and $W^{landfill}$ is the total waste treated in landfills. The total amount of treated waste equals the sum of waste created through all processes in the food supply chain from farm to consumer:

$$
\begin{aligned}
W^{landfill} = & \sum_{crop} r^{wasted,crop} \cdot Q^{crop} + r^{wasted,livestock} \cdot Q^{livestock} \\
& + r^{wasted,food,inter} \cdot Q^{food,inter} + r^{wasted,food,final} \cdot Y^{food,final} \\
& + r^{wasted,consumer} \cdot y^{food,final} \cdot Pop.
\end{aligned} \tag{6}
$$

3.1.4. Crop Producer's Problem

The Q^{crop} amount of a crop is produced using L^{crop} of land and $F^{chem,crop}$ of chemical fertilizer for each crop ($crop \in \{corn, soy, wheat, specialty\}$). $r^{waste,crop} \cdot Q^{crop}$ of produced crop is wasted at the farm level and the rest is sold in the market. Given that, the profit is maximized:

$$
\begin{aligned}
\Pi^{crop} = & p^{crop} \cdot \left(1 - r^{wasted,crop}\right) \cdot Q^{crop} \\
& - p^{fert,chem,crop} F^{chem,crop} - \iota L^{crop} \\
& - Z^{cost,crop} - \left(\tau^{tipping} + \tau^{tax,crop}\right) \cdot r^{wasted,crop} Q^{crop}.
\end{aligned} \tag{7}
$$

$Z^{cost,crop}$ is the waste reduction cost, which is a function of each crop's waste rate, $r^{wasted,crop}$ and production, Q^{crop}. The last term is the sum of any costs (known as tipping fees) associated with depositing waste into landfills ($\tau^{tipping}$) and any tax burden from depositing waste ($\tau^{tax,crop}$). The crop production function is a nested normalized constant elasticity of substitution (CES) function of land and fertilizer inputs,

$$
\frac{Q^{crop}}{Q_0^{crop}} = \left\{ \omega^{crop} \left(\frac{L^{crop}}{L_0^{crop}} \right)^{\rho^{crop}} + \left(1 - \omega^{crop}\right) \left(\frac{F^{chem,crop}}{F_0^{chem,crop}} \right)^{\rho^{crop}} \right\}^{\frac{\alpha^{crop}}{\rho^{crop}}}. \tag{8}
$$

3.1.5. Livestock Producer's Problem

The livestock products, $Q^{livestock}$, are produced with the feed crops of corn, $Q^{corn,feed}$, and soybeans, $Q^{soy,feed}$, and with pasture land $L^{pasture}$. The waste rate at the livestock farm level is indicated with $r^{wasted,livestock}$. The producer's profit is:

$$\begin{aligned}\Pi^{livestock} =& p^{livestock} \cdot \left(1 - r^{wasted,livestock}\right) \cdot Q^{livestock} \\ & - p^{corn} Q^{corn,feed} - p^{soy} Q^{soy,feed} - \iota L^{pasture} \\ & - Z^{cost,livestock} - \left(\tau^{tipping} + \tau^{tax,livestock}\right) \cdot r^{wasted,livestock} Q^{livestock}.\end{aligned} \tag{9}$$

The livestock production function is formulated as a normalized Cobb-Douglas function,

$$\frac{Q^{livestock}}{Q_0^{livestock}} = \left(\frac{Q^{corn,feed}}{Q_0^{corn,feed}}\right)^{\alpha^l} \left(\frac{Q^{soy,feed}}{Q_0^{soy,feed}}\right)^{\beta^l} \left(\frac{L^{pasture}}{L_0^{pasture}}\right)^{\gamma^l}, \tag{10}$$

where α^l, β^l, and γ^l are share parameters and their sum is assumed to be less than one.

3.1.6. Food Manufacturer's Problem

The intermediate food production firm either supplies manufactured food to in-state retailers and foodservice providers or exports outside the state. The $Q^{food,inter}$ amount of food is produced with the $Q^{corn,food}$, $Q^{soy,food}$, $Q^{wheat,food}$, $Q^{speiclaty,food}$, and $Q^{livestock,food}$ of corn, soybeans, wheat, specialty crops, and livestock products, respectively, and the $N^{food,inter}$ amount of labor input. The waste rate at the food manufacturer level is indicated with $r^{wasted,food,inter}$. The profit is

$$\begin{aligned}\Pi^{food,inter} =& p^{food,inter} \cdot \left(1 - r^{wasted,food,inter}\right) \cdot Q^{food,inter} \\ & - p^{corn} Q^{corn,food} - p^{soy} Q^{soy,food} - p^{wheat} Q^{wheat,food} - p^{specialty} Q^{specialty,food} \\ & - p^{livestock} Q^{livestock,food} - w N^{food,inter} \\ & - Z^{cost,food,inter} - \left(\tau^{tipping} + \tau^{tax,food,inter}\right) \cdot r^{wasted,food,inter} Q^{food,inter}.\end{aligned} \tag{11}$$

The intermediate food production function has a nested structure. First, a non-meat food composite and the meat product are combined in a CES function, which then comprises the top-level CES function with labor input:

$$\begin{aligned}\frac{Q^{food,inter}}{Q_0^{food,inter}} = \left\{ \beta^{food} \cdot \left[\left(1-\omega^{f5}\right) \left\{ \left(\frac{Q^{corn,food}}{Q_0^{corn,food}}\right)^{\omega^{f1}} \left(\frac{Q^{soy,food}}{Q_0^{soy,food}}\right)^{\omega^{f2}} \left(\frac{Q^{wheat,food}}{Q_0^{wheat,food}}\right)^{\omega^{f3}} \left(\frac{Q^{specialty,food}}{Q_0^{specialty,food}}\right)^{\omega^{f4}} \right\}^{\alpha^{food}} \right.\right. \\ \left.\left. + \omega^{f5} \left(\frac{Q^{livestock,food}}{Q_0^{livestock,food}}\right)^{\alpha^{food}} \right]^{\frac{\eta^{food}}{\alpha^{food}}} + \left(1-\beta^{food}\right) \left[\frac{N^{food,inter}}{N_0^{food,inter}}\right]^{\eta^{food}} \right\}^{\frac{\gamma^{food}}{\eta^{food}}} .\end{aligned} \tag{12}$$

3.1.7. Food Supplier's Problem

The final food supplier sector includes retailers and foodservice providers. The profit is formulated as

$$\begin{aligned}\Pi^{food,final} = & p^{food,final} \cdot \left(1 - r^{wasted,food,final}\right) \cdot Y^{food,final} \\ & - p^{food,inter} Q^{food,input} - w N^{food,final} \\ & - Z^{cost,food,final} - \left(\tau^{tipping} + \tau^{tax,food,final}\right) \cdot r^{wasted,food,final} Y^{food,final},\end{aligned} \tag{13}$$

where the final food production function is a function of intermediate food input and labor

$$\frac{Y^{food,final}}{Y_0^{food,final}} = \left[\omega^{fianl} \left(\frac{Q^{food,input}}{Q_0^{food,input}}\right)^{\rho^{final}} + \left(1-\omega^{fianl}\right) \left(\frac{N^{food,final}}{N_0^{food,final}}\right)^{\rho^{final}} \right]^{\frac{\alpha^{final}}{\rho^{final}}} . \tag{14}$$

3.1.8. General Goods and Services Firm's Problem

The general goods and services firm's production, equivalent to the state economy GDP net of the proportion of state GDP attributed to the modeled agriculture and food sectors above, takes capital and labor inputs for production. As this product is designated as a numeraire in the model, its price is set to one. The production function is a standard CES function of capital and labor inputs (not shown).

3.1.9. Market Clearing Conditions

As an example of agricultural commodities, produced and imported corn is used for producing food, feeding livestock, generating corn-based ethanol fuel ($Q^{corn,trans}$), and exporting:

$$\left(1 - r^{wasted,corn}\right) \cdot Q^{corn} + Q^{corn,im} = Q^{corn,food} + Q^{corn,feed} + Q^{corn,trans} + Q^{corn,ex} . \tag{15}$$

Manufactured or imported intermediate food products are used as an input in the final food sector (food supplier) or are traded:

$$\left(1 - r^{wasted,food,inter}\right) \cdot Q^{food,inter} + Q^{food,inter,im} = Q^{food,input} + Q^{food,inter,ex}. \qquad (16)$$

We assume that all final food supplied by retailers and foodservice providers is acquired by the household in the state:

$$\left(1 - r^{wasted,food,final}\right) \cdot Y^{food,final} = Pop \cdot y^{food,final}. \qquad (17)$$

Lastly, land and labor markets clear for each state (not shown).

3.2. Scenarios

Each scenario examines a distinct set of two types of interventions: waste disposal tax adoption and abatement cost reduction. We assume that the revenue from the waste tax will be transferred to the household in a lumpsum (as shown in Eq. 3) and abatement cost reduction is costless. Each intervention is separately or simultaneously implemented at the consumer or supplier level. In total, the following seven scenarios are simulated:

No.	Scenarios
S0	Baseline
S1	Consumer Waste Tax
S2	Supplier Waste Tax
S3	Consumer & Supplier Waste Tax
S4	Consumer Abatement Cost Reduction
S5	Supplier Abatement Cost Reduction
S6	Consumer & Supplier Abatement Cost Reduction
S7	Consumer & Supplier Tax and Cost Reduction

Subsections 3.2.1-3.2.3 describe the scenarios in detail.

3.2.1. Baseline

To establish the baseline, the model parameters are calibrated such that the food waste ratios at each stage of the food supply chain are matched closely with data,[9] in addition to all other production and consumption quantities. The data and the calibrated baseline values (at a five-state average) are shown in Table 1.

Table 1 Calibrated Food Waste Ratios

Stages	Data	Calibrated Baseline
Corn Farms	4.7%	3.7%
Soybean Farms	4.5%	4.1%
Wheat Farms	4.5%	3.3%
Specialty Farms	14.76%	11.9%
Livestock Farms	3.5%	3.4%
Food Manufacturer	0.8%	0.8%
Food Supplier	3.76%	4.1%
Consumer	26.78%	25.4%

In calibration of the food waste ratios, one critical model component is the waste abatement cost. The literature has paid limited attention to the current level of abatement costs at each stage and, hence, related data is scarce. Without reference data, the calibration of abatement cost functions is challenging and thus may be considered a limitation of the current study, which needs to be improved when such data is available. Philippidis et al. (2019), based on the literature and expert opinion, model compliance costs (e.g., improved labeling and packaging) associated with consumers' food waste reduction as a 1-5% increase in per unit cost for each agri-food industry. Drabik et al. (2019) formulate the consumer-level food waste cost function for a single food commodity as a function of market price, waste rate, waste

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[9] We use 2016 as our base year.

disposal cost, and consumption. In our calibration, the abatement cost function parameters are chosen as a tuning parameter such that not only does each actor's waste rate match the data, but also all other economic variables closely match the observed state of the economy. To give a perspective, Table 2 shows the regional average unit cost of waste abatement for the baseline, along with food prices for comparison. The baseline price of the final food supplier is calibrated to align with the price of foodservice providers, which is far higher than the food retail price. Our model does not distinguish between food from retailers and foodservice operators, nor does it specify a household food production function. We assume that, in a virtual competitive market of two food goods, the price of retail food, once labor and time costs are accounted for, equals the price of food at restaurants.

Table 2 Calibrated Waste Abatement Costs and Food Prices (2016 USD / Ton)

Stages	Baseline Abatement Cost	Baseline Food Prices
Corn Farm	18	153
Soybean Farm	37	342
Wheat Farm	16	147
Specialty Farm	97	673
Livestock Farm	221	2,473
Food Manufacturer	44	3,789
Food Supplier	285	9,409
Consumer	881	9,409

The calibrated baseline unit costs show that farm-level abatement efforts cost producers around 10% of the market prices of their agricultural commodities. The food manufacturing firm with the lowest food waste rate (<1%) presents the lowest abatement cost relative to its market price (only 1.2%). With the highest food waste rates, the consumer's abatement cost is estimated to be the highest relative to the market price of purchased food, at 9.4%. Looking at the consumer's cost another way, the abatement cost is translated into an annual cost of \$392 per person. Again, it may not be an accurate number and is a limitation of this research.

3.2.2. Waste Tax Scenarios

Food waste taxes have rarely been discussed in the literature or the real world (see South Korea for an exception, Lee (2023)), and thus, a reference number for a policy simulation might not be available. If we consider a food waste tax in the context of Pigouvian tax that aims to internalize negative externalities associated with lost and wasted food, the essential one, among other things, would be GHG emissions due to wasted food and its impact on climate change. We compute GHG emissions generated from production through the food supply chain to disposal to estimate GHG emissions from a particular stage's waste. For example, GHG emissions associated with consumer-level waste is the sum of GHG emissions due to farming, manufacturing, retailing, and cooking. The estimated emissions are 7.80 metric tons and 8.02 metric tons per ton of wasted food for retailers and consumers, respectively. The U.S. EPA announced in 2023 an updated estimate of the social cost of carbon dioxide (SC-CO_2) at \$190 per metric ton in 2020.[10] When using this estimate as a reference, the food waste tax can be \$1,481 and \$1,525, respectively. In our scenario, we simulate the tax rate of \$1,500 per ton of food waste (or \$0.75 per pound of food waste).

3.2.3. Abatement Cost Reduction Scenarios

As an alternative intervention, we consider abatement cost reduction scenarios. As highlighted in Hamilton & Richards (2019), a food waste tax might be politically infeasible in the U.S., and attempts to evade taxation, such as sink disposal, can emerge to compromise the effectiveness of the intervention. The scenarios are specified with a reduction in the per unit marginal abatement costs by half ($\theta^{1,stage,new} = 0.5 \cdot \theta^{1,stage,base}$) at a particular stage (e.g., consumer) without incurring any additional cost. This approach is comparable to exogenous rate reduction in other studies (e.g., de Gorter et al. (2021)). The

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[10] "Report on the Social Cost of Greenhouse Gases: Estimates Incorporating Recent Scientific Advances," accessed from https://www.epa.gov/environmental-economics/scghg

difference is that previous efforts directly change the waste rate (with or without consideration of associated reduction costs), but our change to abatement cost involves an actual reflection of interventions, and indirectly change the waste rate. These scenarios relate to efficiency gains in food systems, for example, through technological improvement for suppliers or education campaigns for consumers.

4. Results

This section presents the results of all scenarios, each of which is characterized by a distinct combination of interventions. All results presented are the regional-level average (e.g., for waste ratio, price, consumption) or region-wide totals (e.g., for the value of waste, greenhouse gas emissions) in one year. State-level results are available upon request. We focus on waste behavior and quantity, the measures of food affordability and security, such as food price, consumption, and production, and GHG emissions.

4.1. Food Waste Disposal Tax Scenarios

With a consumer waste tax introduced, the consumer waste ratio decreases by 0.67 percentage points, or 2.6% (S1 in the second column in Table 3). Despite this relatively small change in the ratio, the quantity of consumer waste decreases by 5.3%. The consumer, faced with a new tax, reduces food purchases, partly substituting with non-food goods. The results are a decline in food purchase (-2.75%) and actual consumption (-1.9%). As both food's market price (-0.2%) and sales (-2.75%) decrease, the supplier's surplus would decrease without any tax imposed on themselves, implying a cascading upstream effect. Suppliers waste 2.7% less food without any increase in abatement costs as total food supply at the supplier level declines by 2.7%. Indeed, across the food system, the amount of food wasted in terms of its total value (price times quantity) declines by 4.9%, which equates to $3.02 billion less waste across this five-state region.

The decrease in food consumption may imply that the tax negatively impacts food security and household resources. In terms of income, the tax requires the household to make the tax payment (161) and to spend more on abatement (32), though the household spends less cash on food (124) for a net additional burden of 69.

In terms of environmental benefits, 2.55 million metric tons of CO_2 equivalent (CO_2e) are avoided along the food supply chain. Most GHG emissions reduction is attributable to the reduction in supplier-level emissions reduction (over 85%) as its production is reduced, and the rest is from reductions from consumers (i.e., cooking) and landfills. The reduced GHG is equivalent to 606,905 gasoline passenger vehicles driven for one year or electricity use by 503,258 homes for one year. [11]

In the second scenario, with a tax on the supplier (S2 in the third column), it can be said that most of the tax burden falls on the supplier. The consumer experience, including consumption, price, and waste, are all largely unchanged (< 0.3%), while total food production declines only modestly (0.45%). The tax incentivizes the suppliers to increase their abatement cost by 9% to reduce their waste ratio by 0.26 percentage points (6%) or their waste quantity by 6.7%. Reduced food supply and waste lead to a slight decrease in GHG emissions (0.19%). While the effects of a tax on consumers propagate up the supply chain, impacting food suppliers, a tax on suppliers causes few ripples elsewhere in the supply chain. GHG emissions reduction in S1 is six times greater than in S2. The results also suggest that a tax on the supplier directly impacts waste rate decision rather than production whereas a tax on the consumer impacts both consumption and the waste ratio.

Thirdly, the scenario that imposes tax on both consumers and suppliers presents results that are essentially additive effects from the first and second scenarios. For example, S1 reduced the consumer waste quantity by 12 pounds per person per year while S2 reduced consumer waste by a single pound per person per year. The effect of imposing both taxes (scenario 3) yielded a 13 pound per person reduction.

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[11] U.S. Environmental Protection Agency. Energy and the Environment: Greenhouse Gas Equivalencies Calculator, accessed from https://www.epa.gov/energy/greenhouse-gas-equivalencies-calculator

An important exception to this is that the reduction in greenhouse gas emissions due to S3 was 16.7% greater than the simple sum of S1 and S2 reductions (3.5 million metric tons vs. 3.0 million metric tons). Hence, taxation of waste at multiple points in the food supply chain generates a nonlinear effect that supports greenhouse gas mitigation.

Table 3 Waste Tax Scenario Results

Variables	Baseline	S1) Tax on Consumer	S2) Tax on Supplier	S3) Tax on Both
Consumer Waste Ratio	25.44%	24.77%	25.43%	24.75%
Consumer Waste Quantity (lbs. per person)	228	216 (-5.33%)	227 (-0.25%)	215 (-5.55%)
Food Purchase (lbs. per person)	890	866 (-2.75%)	888 (-0.19%)	864 (-2.93%)
Food Consumption (lbs. per person)	664	651 (-1.9%)	663 (-0.17%)	650 (-2.0%)
Consumer Abatement Cost (per person)	392	425 (+32.4 / +8.26%)	392 (+0.2 / +0.05%)	425 (+32.5 / +8.30%)
Consumer Tax Payment (per person)	-	161	-	160
Food Expenditure (per person)	4,187	4,063 (-124)	4,193 (+6)	4,069 (-118)
Non-Food Consumption (per person)	46,724	46,810 (+86)	46,731 (+7)	46,816 (+92)
Supplier Waste Ratio	4.054%	4.057%	3.799%	3.802%
Total Supplier Waste Quantity (million short tons)	0.894	0.870 (-2.7%)	0.835 (-6.7%)	0.812 (-9.2%)
Supplier Abatement Cost (per ton)	285	284 (-0.12%)	310 (9.07%)	310 (8.95%)
Total Food Supply (million short tons)	21.95	21.34 (-2.74%)	21.85 (-0.45%)	21.25 (-3.17%)
Total Waste Quantity (million short tons)	14.40	14.08 (-2.2%)	14.32 (-0.51%)	14.01 (-2.7%)
Market Price for Food Purchased (per lb.)	4.70	4.69 (-0.2%)	4.72 (0.3%)	4.71 (0.12%)
Price for Food Consumed[12] (per lb.)	6.31	6.24 (-1.1%)	6.33 (0.3%)	6.26 (-0.8%)
Total Value of Waste (billion USD)	62.37	59.35 (-4.9%)	61.88 (-0.8%)	58.87 (-5.6%)

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[12] We distinguish the market price paid by consumers and the actual price of food consumed by consumers. The latter is higher than the former as the consumers waste a portion of the food they purchased. This real price of food is calculated by $p^{food,consumed} = \frac{p^{food}}{(1-r^{wasted,cosnumer})}$. de Gorter et al. (2021) use the same measure and term it as "effective" price.

Variables	Baseline	S1) Tax on Consumer	S2) Tax on Supplier	S3) Tax on Both
GHG Emissions[13] (million metric ton of CO_2e)	218.9	216.3 (-1.2%)	218.5 (-0.19%)	215.4 (-1.6%)

4.2. Abatement Cost Reduction Scenarios

Compared to tax scenarios, abatement cost reduction scenarios, in general, lead to a greater decrease in both waste ratios and quantities, whereas their impacts on the GHG emissions reduction are less pronounced due to smaller changes in the food supply. At the heart of this is an increase in the efficiency of converting food into calories (at the consumer level) or into food sales (at the supplier level) that is enabled by the reduced waste abatement costs simulated in these scenarios. In the consumer's cost reduction scenario (S4), the second column in Table 4, the consumer waste ratio and quantity decrease by three percentage points and 12.5 percent, respectively. At a similar food price, consumers purchase a smaller amount of food (0.5% less), but their actual consumption is still increased by 3.5% thanks to a higher level of food utilization. Thus, this scenario implies an improvement in food security. In addition, consumer welfare would improve as their consumption of both food and non-food goods increases. This is attributable to the decreased abatement cost and food expenditure savings. In the meantime, the food supplier would experience a modest decrease in its surplus as both the market price and sales are fractionally reduced.

In the fifth scenario (S5) the supplier benefits from cost reduction and is able to reduce waste by 25.6%. This supplier's efficiency gain leads to decreased supplier's production (0.3%), yet increased sales in the market. As a consequence, food price is decreased by 1%. Their profit would increase as their sales revenue loss is smaller than food waste abatement cost and disposal fee savings. The impacts have ripples downstream as the consumer tends to buy more food (0.77%) and waste a greater quantity of food (0.97%). Unlike in S4, where efficiency improvement on the consumer side has a negative impact on the supplier side, in S5, supplier's abatement cost reduction is likely to benefit both actors. Despite reductions

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[13] We only consider GHG emissions from the agricultural and food sectors and food waste treatment facility.

in food suppliers' production and waste sent to landfills, the increased production at other stages and consumption offset the positive environmental benefits, resulting in only a 0.1% decrease in GHG emissions. Scenario S6, similar to S3, combines changes of scenarios S4 and S5. However, unlike the tax setting, where taxation at both points in the supply chain led to a sizeable interaction with respect to GHG emissions reduction, the effect of abatement cost reductions at two points in the supply chain is much smaller (only an 8% ‘bonus’ rather than 16.7% in the tax case).

Table 4 Abatement Cost Reduction Scenario Results

Variables	Baseline	S4) Consumer Cost Reduction	S5) Supplier Cost Reduction	S6) Both Cost Reduction
Consumer Waste Ratio	25.44%	22.38%	25.50%	22.43%
Consumer Waste Quantity (lbs. per person)	228	199 (-12.52%)	230 (0.97%)	201 (-11.67%)
Food Purchase (lb. per person)	890	885 (-0.54%)	897 (0.77%)	892 (0.22%)
Food Consumption (lb. per person)	664	687 (3.5%)	668 (0.7%)	692 (4.3%)
Consumer Abatement Cost (per person)	392	325 (-66.9 / -17.1%)	392 (-0.2 / -0.04%)	325 (-67.1 / -17.1%)
Consumer Tax Payment (per person)	-	-	-	-
Food Expenditure (per person)	4,187	4,163 (-24)	4,173 (-14)	4,149 (-38)
Non-Food Consumption (per person)	46,724	46,814 (+90)	46,771 (+47)	46,861 (+137)
Supplier Waste Ratio	4.054%	4.054%	3.023%	3.024%
Total Supplier Waste Quantity (million short tons)	0.894	0.890 (-0.52%)	0.665 (-25.6%)	0.662 (-26.0%)
Supplier Abatement Cost (per ton)	285	285 (-0.02%)	211 (-25.9%)	211 (-25.9%)
Total Food Supply (million short tons)	21.95	21.83 (-0.54%)	21.88 (-0.31%)	21.76 (-0.85%)
Total Waste Quantity (million short tons)	14.40	13.71 (-4.7%)	14.22 (-1.2%)	13.53 (-6.0%)
Market Price for Food Purchased (per lb.)	4.70	4.70 (-0.04%)	4.65 (-1.1%)	4.65 (-1.1%)
Price for Food Consumed (per lb.)	6.31	6.05 (-4.0%)	6.24 (-1.0%)	5.99 (-5.0%)
Total Value of Waste (billion USD)	62.37	56.01 (-10.2%)	60.09 (-3.7%)	53.74 (-13.8%)

Variables	Baseline	S4) Consumer Cost Reduction	S5) Supplier Cost Reduction	S6) Both Cost Reduction
GHG Emissions (million metric ton of CO_2e)	218.9	218.0 (-0.4%)	218.6 (-0.1%)	217.6 (-0.6%)

4.3. Waste Tax and Abatement Cost Reduction Scenario

In the seventh scenario, we combine two interventions previously examined separately: the introduction of a waste tax and the reduction of abatement costs, all applying both to the consumer and the supplier. The results, presented in Table 5, reveal that the combination of the carrot (abatement cost reductions) and the stick (waste tax) generate larger reductions in key metrics such as total waste and total GHG emissions than either policy suite alone could accomplish, but that the effects are less than additive. For example, GHG emissions are reduced by 1.9% under S7, which is a greater reduction than under either S3 (1.6% reduction) or S6 (0.6% reduction) individually, but less than additive (less than 2.2% = 1.6% + 0.6%). A similar relative pattern of results hold for total system-wide food waste created and for total food production with S7 driving the largest results but less than the sum of S3 and S6 results.

The punitive effects of a tax on key consumer outcomes (i.e., a 2% reduction in food consumption and an 8.3% increase in abatement costs when only taxes are imposed in S3) are offset by the abatement cost reduction such that under S7 total food consumption increases by 2.4% and total abatement costs decline by 9.3%.

Under S7 the GHG emissions across agricultural and food sectors decrease by more than 4 million metric tons. This is largely attributable to the decrease in food supply, then to production and waste disposed of in landfills. This emissions reduction is equivalent to taking one coal-fired power plant out of the grid for one year, whose emissions are close to 1 million gasoline passenger vehicles driven for one year. The scenario suggests that when implementing a tax high enough to address all negative externalities is infeasible, then subsidizing the reduction of abatement costs can help improve consumer welfare, food security, and the environment.

Table 5 Tax and Waste Cost Reduction Scenario Results

Variables	Baseline	S3) Tax on Both	S6) Both Cost Reduction	S7) Waste Tax and Cost Reduction
Consumer Waste Ratio	25.44%	24.75%	22.43%	21.81%
Consumer Waste Quantity (lbs. per person)	228	215 (-5.55%)	201 (-11.67%)	190 (-16.34%)
Food Purchase (lb. per person)	890	864 (-2.93%)	892 (0.22%)	869 (-2.38%)
Food Consumption (lb. per person)	664	650 (-2.0%)	692 (4.3%)	680 (2.38%)
Consumer Abatement Cost (per person)	392.2	425 (+32.5 / +8.30%)	325 (-67.1 / -17.1%)	354.0 (-38.2 / -9.73%)
Consumer Tax Payment (per person)	-	160	-	142
Food Expenditure (per person)	-	4,069 (-118)	4,149 (-38)	4,043 (-144)
Non-Food Consumption (per person)	46,724	46,816 (+92)	46,861 (+137)	46,940 (+216)
Supplier Waste Ratio	4.054%	3.802%	3.024%	2.835%
Total Supplier Waste Quantity (million short tons)	0.894	0.812 (-9.2%)	0.662 (-26.0%)	0.603 (-32.5%)
Supplier Abatement Cost (per ton)	285	310 (8.95%)	211 (-25.9%)	230 (-19.2%)
Total Food Supply (million short tons)	21.95	21.25 (-3.17%)	21.76 (-0.85%)	21.15 (-3.64%)
Total Waste Quantity (million short tons)	14.40	14.01 (-2.7%)	13.53 (-6.0%)	13.21 (-8.23%)
Market Price for Food Purchased (per lb.)	4.70	4.71 (0.12%)	4.65 (-1.1%)	4.65 (-1.08%)
Price for Food Consumed (per lb.)	6.31	6.26 (-0.8%)	5.99 (-5.0%)	5.95 (-5.67%)
Total Value of waste (billion USD)	62.37	58.87 (-5.6%)	53.74 (-13.8%)	50.89 (-18.41%)
GHG emissions (million metric ton of CO_2e)	218.9	215.4 (-1.6%)	217.6 (-0.6%)	214.6 (-1.94%)

5. Discussion

The key innovation of the current study is the creation of a model in which all supply chain actors endogenously select waste rates rather than having waste rates exogenously assigned and then altered. This makes it possible to simulate different policy interventions not only separately but simultaneously at multiple stages. As most literature discusses a single intervention, their results may be comparable to our corresponding scenarios with one intervention. First, Bartelings and Philippidis (2024), who simulate a waste behavior tax to meet the 50% household waste reduction target, predict a fall in household food demand and following decreases in the price index (1.8%) and agricultural (1.9%) and agrifood (2.1%) production and an increase in trade surplus (33%). The results are qualitatively consistent with our study, though to a lesser extent due to our more minor waste reduction. They construct the household demand function as an inelastic CES function of food consumption and waste collection services. Suppose their CES function is close to a Leontief function. In that case, it is speculated that household food consumption, as a complementary good, would also decrease, like our results, as the price of their food and waste service composite increases.[14] In their study, a 50% reduction in the waste level is achievable by a tax, presumably due to their absence of abatement cost. Without abatement costs in their model, price effects can easily drive food waste (and consumption) reduction. In our model, achieving a 50% reduction would require a punitive tax due to the convex-shaped abatement cost function, and an increase in the tax would impact not only the waste ratio but also food purchase and consumption. Whether a tax high enough to reduce waste by half can only impact waste without decreasing consumption remains an empirical question.

Still, a food waste tax is rarely implemented in the world, and there are scarce empirical studies on it. In this context, Lee (2023) may provide a rare reference with his analysis of the adoption of a food waste tax in South Korea. The study reports a 20% reduction in household food waste with a small food waste tax of $54.4 per short ton, substantially smaller than our tax scenario of $1,500 per short ton. An interesting finding from the study is that non-pecuniary effects (e.g., information provision, moral tax) account for 90% of the effects, which may translate to only 2% waste reduction attributable to the tax's pecuniary effect (price effect). The results suggest that the price effect, a focus of most modeling approaches, is limited in reducing food waste, and non-pecuniary effects need to be accounted for.

Contrary to our study, Lee (2023) finds that food intake is maintained while grocery purchases decrease. Again, Lee's tax is considerably smaller. He also highlights the considerable abatement costs

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[14] As they do not disclose the household's consumption change, we are unable to compare our consumption change to theirs.

(time cost) incurred in reducing food waste, estimated at 60 additional hours annually, which may validate the inclusion of abatement costs in the modeling. If non-pecuniary effects are mostly from information provision and can be related to abatement cost reductions, our last scenario can be relevant, where a tax reduces grocery purchases without cutting consumption.

In terms of abatement cost reduction, the comparison across scenarios can provide policy prioritization. Our scenarios S4 and S5 simulate lowering marginal abatement costs by half for the consumer and supplier, respectively. Though they are not precisely comparable, it may still suggest that intervention at the consumer level is more effective in reducing the quantity of food waste, the value of waste, and GHG emissions by reducing food supply, just as in tax scenarios. The effectiveness of interventions at different stages is studied by de Gorter et al. (2021) by adjusting food waste rates exogenously without considering abatement costs, assuming technological improvement. It should be noted that they only exhibit the comparison between waste reductions by consumers and retailers in a closed economy, whereas our model is more comparable to their case of a small open economy with inelastic demand. In terms of consumer and retailer waste quantity, sales, and prices, all signs are in agreement with our results. They also find that consumer-level improvement is more successful in reducing food waste quantities.

The last scenario may shed light on the relationships between two types of interventions in lessening food waste. The modeling literature has paid little attention to a portfolio of interventions.[15] In our results, the adoption of a tax ends up in a partial trade-off between food waste reduction (and associated environmental benefits) and consumer (and producer) welfare. To mitigate the trade-off, waste abatement efforts would need to be made cost-effective, possibly through other interventions. Thus, an optimal suite of various instruments is implemented to achieve a "win-win" by reducing food waste.

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[15] De Gorter et al. (2021) simulate exogenously halving food loss and waste rates at multiple stages and Philippidis et al. (2019) examine a combination of exogenous changes in consumer's food consumption and food manufacturer's associated costs for the waste reduction.

6. Conclusion

Circular food systems are increasingly drawing attention from policymakers and scholars, including economists. We contribute to the discussion of food waste reduction by developing a macroeconomic model that integrates the decisions of critical actors across the food system on food waste and its related environmental impacts as measured by greenhouse gas emissions. In addition, by incorporating different policy interventions, our model enables the simulation of various policy interventions, separately and simultaneously. Our analysis gives perspectives on interventions' effectiveness and tradeoffs and also how we could better implement a policy to achieve circular food systems.

Of the single instruments we simulate, we find that a Pigouvian tax on consumer waste has the largest impact on GHG emissions, delivering 74% of the emissions reductions and 81% of the total waste reduction that are simulated to occur if all four simulated instruments were used simultaneously (consumer waste tax, food supplier waste tax, consumer waste abatement cost reduction, supplier waste abatement cost reduction). Applying pressure to consumers via a waste tax has clear distributional implications as consumers curb their consumption despite facing lower market prices for food while their additional expenditures on abating waste and paying the waste tax outstrip savings achieved by buying less food at lower prices. Consumer taxation effectively drives upstream action as well. Food suppliers waste less (despite spending less to abate waste) and less food is supplied by retailers and foodservice providers simply because consumers are buying less food. In contrast, taxing food supplier waste has relatively little impact on system-wide waste and emissions and negligible effects on consumers. Our simulated reductions in abatement costs, which might arise due to educational efforts or technology development efforts, drove larger impacts on system-wide waste than taxation approaches but smaller effects on GHG emissions compared to taxation efforts as food consumption levels endogenously increased in response to improved system-wide efficiencies (less waste by food suppliers and consumers).

Hence, we conclude that for our simulated system taxation is most effective for driving GHG reductions while reductions in waste abatement costs drive waste reduction.

As a modeling study, our study has several limitations. First, our model is capable of considering waste abatement efforts only in a monetary value and cannot capture other channels of interventions. As the previous studies (Casonato et al., 2023; Lee, 2023; Veselá et al., 2023) highlight, non-pecuniary effects may be significant. To address this shortcoming, we may need to refer to empirical studies or survey-based approaches to elicit consumers' or suppliers' responses to waste taxes or efficiency gains to better explain a complex decision of food waste reduction. Second, though we incorporate waste abatement costs, we do not consider any GHG emissions that may be caused by the associated abatement actions (for consumers, frequent trips to groceries; for suppliers, increased cold chain transportation). As stated in Salemdeeb et al. (2017), environmental benefits are likely to be overestimated without accounting for GHG emissions from abatement efforts. Relatedly, our GHG emissions from other sectors are not presented as all non-food sectors are aggregated into one general goods and services sector, and, with this model structure, it would be difficult to know how the substitution occurs between food goods and non-food goods. It would require further disaggregation of food and non-food sectors. Lastly, we do not explicitly model labor inputs for the agricultural and waste treatment sectors. The inclusion of labor in the model would allow us to discuss the changes in employment in those sectors.

To further improve the model and better understand policy intervention impacts, future studies can disaggregate consumers by socioeconomic groups differentiated by food purchase and waste behaviors and unbundle food consumption by food types, each associated with distinct waste rates and GHG emissions. By segmenting consumers, we can also analyze the effects of different taxation and cost abatement schemes. For example, the collected revenue from a food waste tax can be redistributed to lower-income groups via an assistance program, such as the Supplemental Nutrition Assistance Program (SNAP). Such an analysis would illuminate the incidence and distributive perspective of a food waste tax and food security. In addition, when detailed data on food purchases by different consumer groups, such as the proportion of perishable and non-perishable processed foods, is available, we may be able to discuss dietary intake impacts of policy interventions by consumer groups.

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