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Analyzing the Economics of Food Loss and Waste Reductions in a Food Supply Chain

1. Introduction

The food supply chain is complex and interlinked with a large number of producers, processors, retailers and consumers, each interacting with many other actors in the chain. The economics of food loss and waste becomes more intertwined and complicated as a result. This is because in equilibrium, agents at each stage of the value chain require compensation for any effort and inputs expended—including those that are wasted. For firms to remain in business, the sales price has to be higher than the purchase price regardless of all other factors (including any costs of disposing of the waste via landfill fees and the like). At each phase of the supply chain, added costs will influence both input demand and output supply. Therefore, food loss and waste up and down the supply chain impact both the quantity available and the prices required to clear the market. This is the case independent of the regular costs of doing business for farmers, costs of processing for food manufactures, or costs of marketing services for retailers that are central in standard models of food and agricultural commodity markets.

The purpose of this paper is to contribute to the existing literature by outlining a general analytical framework to analyze food waste along an entire food supply chain. We do so by linking models of three distinct players in the market: consumers (see Drabik et al. 2019), intermediaries and farmers. We develop a tractable theoretical framework including these stages of the supply chain. We then calibrate the overall model to market and waste data for two commodities for the UK—chicken and fruit—using data collected by WRAP (2019). In the simulation exercise, we also increase the realism of the market structure by allowing for a larger number of distinct intermediaries (see Figure 1). In addition to direct individual effects of a change in the rate of food waste, our empirical results also account for indirect effects. We identify conditions under which the ambiguous outcomes occur.

The issue of food loss and waste often focuses solely on absolute quantities: how much is lost and wasted and where. The focus has been justified by the argument that, the greater the loss, the greater the possibility of social costs. However, *where* food is lost or wasted also matters for determining the eventual welfare implications. Moreover, if we are to determine effective interventions to curb waste, we must be able to determine the indirect effects an intervention might have on other parts of the supply chain. A wide range of interventions (public or private initiatives) have been proposed to reduce food loss and waste. The key to analyzing the impact of interventions or other shocks to waste is found in three broad categories of factors: the structure of the market, the underlying policy objectives, and the source (and effectiveness) of the interventions. We briefly summarize the key factors in each category before presenting our conceptual framework and empirical analysis of reducing food loss and waste.

The paper is outlined as follows. The next section describes the key features of the structure of the model that have various impacts on food waste in the supply chain. Section 3 summarizes the data and key parameters analyzing food waste for four food sectors in the UK. Section 4 provides the theory of direct versus indirect (cascading) effects of reducing the rate of food waste in different parts of the food supply chain. Section 5 presents the empirical results from our calibrated model, and Section 6 provides concluding remarks.

2. Structure of the Market

The length and structure of the food supply chain under consideration has key implications for the ability to manage food waste. The simulation partial equilibrium model of competitive markets in this paper captures six stages in the food supply chain (see Figure 1). These include waste from produced post-harvest at the farm, transportation, handling and storage (THS), processing, retailing, hotels, restaurants and institutions (HRI), and at-home vs. away-from home consumption. Intuitively, the level and distribution of the rates of food loss and waste along the supply chain are fundamental in determining the economic impacts of food waste.[1] For example, if consumers waste the vast majority of food, reducing their waste rate could reduce their effective demand for food, which in turn may reduce prices and production up the supply chain.[2] Interventions that directly impact one level of the chain (such as the banning of landfill waste from restaurants) could have complicated implications that impact production and demand up and down the chain indirectly.

The interaction of supply and demand elasticities at each level of the chain in this model shapes how improvements in waste at one level can transmit to production and consumption amounts as well as realized producer, consumer, and retail prices. Assumptions regarding international trade are also critical. Hence, we present three models: a closed economy, a small open economy and a large open economy. For the latter, the elasticity of export supply (import demand) facing the country[3] versus the elasticity of import demand (export supply) of the country is found to be of particular importance as it impacts the effective demand elasticities along the supply chain.[4]

In typical models of the food supply chain, intermediary margins play a large role in determining price transmission. As we will show, the level and distribution of these margins are also important in determining how waste rates impact prices and eventual consumption levels. Specifically, the level of margins demanded by intermediaries determines the *farm share of the final consumer dollar* (defined as the farm sales price divided by the consumer purchase price) as well as the effective demand elasticities at each stage. Margins vary across products, but generally increase as you move downstream in both developed and developing country food supply chains.

To understand how policy interventions aimed at reducing food waste impact the final market equilibrium, we model exogenous changes in the rates of food loss and waste at each stage of the food supply chain. de Gorter et al. (2018) instead model the rates of loss and waste as endogenous with pre-specified abatement cost functions. Their results show that not only is the rate of waste endogenous at the stage where the rate of food waste is directly affected, but there are also indirect effects up and down the supply chain on other rates of food waste. However, result using

[1] FAO (2011) estimates 33 percent of worldwide food production is wasted.
[2] These rates of food waste vary along the food chain, generally increasing going downstream in developed countries and declining going downstream in developing countries.
[3] The country's share of the world market is a major factor determining the size of the trade elasticity facing a country.
[4] The ratio of domestic production (consumption) to imports (exports) is a major factor determining the size of the trade elasticity of a country.

endogenous changes in waste rates are quantitatively similar to the results based on exogenous changes outlined below. We therefore refer interested readers to de Gorter et al. (2018) for a more detailed exposition of such a model.
Several aspects of the structure of the food supply chain that we do not model (but could be very important if our model were extended) include the marginal cost of each intermediaries' supply of services, and the marginal cost of dispositions (for food recovered, in landfill/sewage or donated). We also do not model pre-existing policy interventions like production and consumption subsidies or taxes on disposition.

To motivate the discussion, consider a simplified food supply chain with farmers (F), transportation, handling and storage providers (THS), food manufactures or processors (P), food marketers or retailers (R), and final consumers (C). Table 1 gives a hypothetical example (the rates of loss and waste are the simple average for the four UK products—chicken, fruit, bread and milk). As we go downstream, the quantities available decline due to loss and waste.[5] Production or purchases at each stage are necessarily greater than sales (or consumption). The last column of Table 1 presents the waste at each stage of the supply chain. Notice the total waste is 36.8% of total farm production (in quantity terms), using average rates of food waste for the four UK products studied.

3. Overview of the Economic Structure for four UK Products

Table 2 summarizes four key market indicators which affect the effectiveness of policy interventions aimed at reducing food waste. In addition to the two UK products for which we provide simulation results (chicken and fruit), Table 2 also summarizes these indicators for milk and bread. Simulation results based on these two commodities reveal quantitatively similar patterns to the example of chicken, which is why we omit them from the simulation results for brevity of exposition. However, we include this data to allow the reader to form a better idea of how existing market structures compare across different product categories. The first row gives the share of domestic production imported. The shares are quite low (the UK is a net exporter of milk) except for fruit. As we will show, a high share of imports means a more price inelastic import demand in the UK for fruit. This will mean the impact of a reduction in waste rates will differ markedly for fruit compared to the other three commodities under study.[6]

The second row in Table 2 gives the farm share of the final consumer dollar, ranging from a low of 11 percent for bread to a high of 57 percent for fruit. This share, which depends on both margins and waste rates along the supply chain, affects the effective demand elasticity faced by the farmer. The third row in Table 2 gives the share of at-home food consumption (relative to food consumed in restaurants or other public settings). For all commodities, these at-home shares are quite high, ranging from a low of 0.65 for chicken to a high of 0.93 for milk.

The final row defines a new variable q_F* which scales domestic production q_F up for imports and

[5] The analysis can be reversed for a typical developing country where rates of waste are high at the farm level and decline downstream.
[6] See Box 1 for the distinction between the trade elasticity <u>of</u> a country (*versus* the trade elasticity <u>facing</u> a country), and why the share of domestic production imported can be a key factor in the analysis.

down for exports.[7] The reason we do this is to accurately capture the amount of waste attributable to domestic consumption. In particular, we calculate waste as if all consumption were produced in the UK with the corresponding prevailing rates of waste along the supply chain. We therefore increase domestic food production by the implied production of imports (and hence down for exports). We do this so that comparisons across commodities (and between open and closed economies) are consistent in our policy simulations, as trade shares vary widely as the first row of Table 2 indicates. Most notably, the quantity of fruit wasted in the UK is 3.5 times the actual domestic production of fruit so an adjustment has to be made to allow for sensible comparisons across food categories. The share of "production" wasted ranges from a low of 21 percent for milk to a high of 50 percent for fruit.

The next important perspective on food waste and loss are the levels and distribution of three critical variables across the various stages of the food supply chain: (*i*) rates of waste, (*ii*) margins for intermediaries and (*iii*) greenhouse gas emissions (GHGE) per unit product. Table 3 summarizes the data. Generally, waste and margins increase as food moves downstream (we would expect the opposite for developing countries). Clearly, the outcomes of interventions or market shocks on food loss and waste will depend on the level and distribution of these parameters across the supply chain. In our discussion of the empirical results, we will highlight some important implications.

Table 4 summarizes the level and value of food waste at the farm, intermediary (aggregate) and consumption (at-home and away-from-home). Line 5 summarizes the total share of food wasted for each category: in total, 44 percent of fruit is wasted while milk is second at 22 percent. The last line in Table 4 shows that the share of the value of waste for fruit and bread roughly matches their share of the total quantity of waste. This is, however, not true for the case of chicken and milk: the waste share for chicken is higher in value terms due to the combination of high retail margins and high waste rates at the consumer level, while it is lower for milk since margins are highest further up the supply chain (see Table 3).

The last column in Table 4 compares the aggregate shares of the quantity of waste (and the value of waste) among farmers, intermediaries (i.e., THS, processing and retailing) and consumers across the four different product categories. In terms of the quantity of waste, farm production accounts for 18 percent of total quantity of waste (the shares vary significantly by commodity) while intermediaries and consumers each have 41 percent of the total quantity of waste. In terms of the share of the total value of waste, the farm share drops to 10 percent, the intermediaries drop to 28 percent and the consumer shares shoots up to 61 percent (last column, bottom half of table).

To get a further perspective on the four UK products studied, the quantities and values of production and consumption are given in Table 5. Fruit and milk have the highest production/consumption shares while chicken and bread have the highest shares of intermediary waste. The values of production and consumption are not directly correlated with the quantity of waste down the supply chain or across commodities.

[7] This requires using UK rates of waste and loss from the stage of the supply chain waste where imports occur (retail and processing in our examples) back to the farm level.

Interventions that may influence the drivers of food loss and waste along the stages in the food supply chain are varied. There have been many studies recommending ways to reduce rates of loss and waste (e.g., see ReFed (2016a,b), WRI (2019), Reynolds et al. (2019)).[8] We simply model these as an exogenous change in the rate of waste (for a discussion of endogenous waste rates see de Gorter et al. (2018)).

Our empirical analysis considers four main policy performance measures:

1. Improved food security
   a. Reduce effective prices borne by consumers[9] and increase final consumption quantities
   b. Improve farm welfare (this is especially important in developing countries to improve rural livelihoods; however political power of farmers makes this an important objective in developed countries as well, as made evident by the multi-billion subsidy packages for farmers in the United States in the last two years alone)
2. Reduced farm production (to reduce stress on natural resources like land or water)
3. Increased value of trade (i.e., reduce the value of imports or increase the value of exports; this is particularly important for developing countries, but the trade deficit is also frequently a political concern in developed countries—see, for example, the trade policies of the current U.S. administration in response to trade deficits)
4. Reduced value of waste (reflecting the social costs of resources wasted)

An additional policy measure of relevance is the total level of greenhouse gas emissions (GHGEs). However, we defer this issue to future research due to the complicated nature of generating accurate GHGE calculations in the presence of indirect effects up and down the supply chain in response to policy interventions.

Notice that the *quantity* of food waste is never a policy goal per se (nor should it be – see de Gorter 2014; 2017). It is also important to note that the policy goals outlined above often directly conflict with one another. For example, we will show that reducing the value of waste and loss or increasing the value of trade in some cases comes at the expense of increases in food prices and reduced farm welfare. Similarly, a cut in food waste rates can have opposite effects on farm welfare and consumer prices while in other cases, reducing farm production can occur without sacrificing the goal of improving food security.

The ability to achieve policy goals and the degree of conflicts depends critically on several of the factors listed in Section 2 above. The goal of this paper is to isolate the key drivers and describe under what conditions they matter and why.

Table 6 gives the baseline values for key variables in the simulation runs to follow for UK chicken and fruit.[10] Recall that we adjust domestic production as if all imports were produced domestically

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[8] Although not studied in this paper, our framework can easily be extended to include the effects of market shocks like increase in prices due to world market conditions, increases in demand or increases in costs of production. An increase in prices will reduce rates of waste as agents at each stage of the food supply chain now find it more economical to reduce waste as the opportunity costs have risen.

[9] "Effective" prices to consumers are higher than purchase prices because the consumer wastes part of their purchases.

[10] We present overall data on four UK products but present only simulation results on two commodities for illustrative purposes.

(we calculate the implied rates of waste in the chain from the stage the product is imported by going backwards: the retail level for chicken and the processor level for fruit). This is the primary source of differences in the two baselines for each product (the boxes in Table 6 highlight the variables that differ significantly between closed and open economy). The interested reader can refer to Table 6 to understand magnitudes for our simulation results which we express in percentage changes for comparability.

4. Direct versus Indirect (Cascading) Effects in the Food Supply Chain: The Theory

For tractability, our theoretical model focuses on three unique economic models of food waste, representing the behavior of agents at the beginning of the food supply chain (farm production), at the end of the supply chain (final consumption) and in the middle, that is, a collective representation of intermediaries (e.g., processing or retailing).

The question we address is what happens to quantities up and down the supply chain when there is an exogenous reduction in the rate of loss or waste (we once again refer interested readers to de Gorter et al. (2018) for a treatment of endogenous changes). We begin by presenting the three separate models governing the behavior of producers, intermediaries and consumers. To provide intuition, we first present these models assuming waste at only one level at a time. The numerical simulations that follow allow for full interaction between all stages of the supply chain, expand the model from a single aggregate intermediary to several distinct types of agents (see Figure 1), and consider simultaneous waste at all levels.

Theory of Post-harvest Food Loss by Farmers

Food production (including harvest and pre-harvest losses) by a representative competitive farmer is denoted by q_F. An exogenous portion α_F of the food produced is lost after harvest before it is sold to the consumer at price P. The farmer incurs loss of product because the marginal abatement costs for losses are high or technology may not allow for direct control. Therefore, the farmer's sales are $q = (1-\alpha_F)q_F$ and revenues equal $P(1-\alpha_F)q_F$.

The food supply function depends on the market price the producer receives from the consumer (we assume no intermediary for the moment for simplicity). In the absence of food loss (and transportation cost), the consumer and producer price of food would be the same. However, with farm loss, the *effective* (but unobservable) farm price received per quantity produced, P_F, is lower than the price paid by the consumer, P. In order to spread the total revenue across total production, it must be the case that $P_F = (1-\alpha_F)P$.

We now present a simplified model with comparative static results to show the conditions under which cutting losses at the farm level results in a cut in farm production and welfare.

The food supply curve after preharvest and harvest loss is derived from the farmer's optimization problem

$$\max_{q_F} Pq - C(q_F) \equiv P(1-\alpha_F)q_F - C(q_F). \quad [1]$$

Assuming a convex and monotonically increasing cost curve $C(q_F)$, this is solved where

$$(1-\alpha_F)P = C'(q_F) \quad [2]$$

Equation [2] reveals that—for a given food price[11]—as the rate of farm loss declines, both the post-harvest production and sales increase (i.e., $\partial q_F / \partial \alpha_F = -P/C'' < 0$ and $\frac{\partial q}{\partial \alpha_F} = -q_F - (1-\alpha_F)P/C'' < 0$).[12]

Figure 2 shows the equilibrium prices and quantities for an individual farmer who cannot affect the sales price P (the farmer is a price taker). As outlined above, the effective farm price received per quantity produced after accounting for food loss, P_F, is [$P_F = (1-\alpha_F)P$]. The farmer responds to this lower marginal incentive by producing along the curve $S_F(P_F)$. Moreover, the total farm production q_F has to be higher than farm sales q by the amount of the loss. Only a part of production will result in sales, which we can represent by an implied sales supply curve $S(P) = (1-\alpha_F)S_F(P_F)$ which depends on the transacted market price P.[13] The value of P_F is not observable (the sales price P is the only price reported), but represents the effective production incentive of the farmer.

If farm loss is eliminated at no cost (say through some exogenous technological advance), production increases and farm welfare improves by area $a + d + e + f + g$. However, the situation depicted in Figure 2 presumes there is no change in prices as a result of the change in marketable goods (which might be the case for one price taking farmer cutting losses and market prices not changing as a result). However, if many or all farmers cut losses, then there will be market equilibrium effects with a downward sloping demand curve (unless the country is a small open economy totally integrated with the world markets with 100 percent price transmission between domestic and international markets, in which case Figure 2 prevails for the industry as a whole).

Figure 3 depicts a more general scenario where the farm industry faces a downward sloping demand curve $D(P)$ and the farm sector faces an upward sloping supply curve $S_F(P_F)$.

Notice that the demand curve depends on the market price of food P, but the farmer's behavior (food supply) depends on the effective P_F price she receives. This price is linked to the market price, but also takes into account the rate of food loss α_F. The transacted quantity (i.e., food sales) is $q = (1-\alpha_F)S_F(P_F)$. Market equilibrium requires that

[11] The case of a given food price holds for an individual farmer but also a small open economy.
[12] The first result becomes ambiguous when the food price is endogenous with a downward-sloping food demand curve—a case documented numerically in the very first cell in Table 7.
[13] The fact that the curve S does not have a subscript means that S and S_F represent different functions.

$$D(P) = (1-\alpha_F) S_F(P_F). \quad [3]$$

Furthermore, assuming zero transaction costs and production margin implies that the consumers' spending be equal to producers' revenues, that is,

$$PD(P) = P_F S_F(P_F).^{14} \quad [4]$$

Note that the relationship $P_F = (1-\alpha_F)P$ follows directly from combining equations [3] and [4]. Totally differentiating the market equilibrium conditions [3] and [4], we obtain the following comparative statics results:

$$\frac{dP_F}{d\alpha_F} = \frac{(1+\eta_D)P}{\eta_S - \eta_D} > 0 \text{ for } 0 \geq \eta_D \geq -1 \text{ and } \frac{dP_F}{d\alpha_F} < 0 \text{ for } \eta_D < -1 \quad [5]$$

and

$$\frac{dP}{d\alpha_F} = \frac{(1+\eta_S)P}{(1-\alpha_F)(\eta_S - \eta_D)} \geq 0, \quad [6]$$

where η_S denotes elasticity of food supply and η_D elasticity of consumer food demand. The denominator for both comparative statics is always positive because $\eta_S > \eta_D$ for all well-behaved supply and demand curves.

As equation [5] highlights, the effect on effective *production* prices is ambiguous. An individual farmer or a small exporter face perfectly elastic demand ($\eta_D \to -\infty$) which would correspond to an exogenous consumer price as was depicted in Figure 2. In that case $dP_F / d\alpha_F \to -P < 0$ and so a reduction in food waste results in an increase in the producer price equal to the market price of food multiplied by the initial rate of food waste. On the other hand, an industry facing a downward sloping demand curve with elastic demand would see effective production prices decrease in response to a cut in waste rates. The effect on *sales* prices, however, is unambiguous as shown in equation [6]: sales prices always decrease in response to a cut in waste rates.

Following a comment of an anonymous reviewer, we would like to note that the results of our simplifying assumption that there are only two actors in this part of our theoretical model might over-emphasize the impact of a reduction at one end (waste) or the other (farm losses) of the supply chain. It is because the price effects are transmitted in full from the farmer to the consumer (and vice versa). The elasticity of demand at the farm level is not same as at consumer level because of margins. We relax this assumption in the empirical section.

Column 1 of Table 7 summarizes the sign of the corresponding comparative static results with

[14] That is, area $a + b$ is equal to area $P_F(q_F - q)$ in Figure 3.

respect to quantities. The highlighted cells in Table 7 represent the direct effects of a reduction in the respective rate of waste at a given level of the supply chain. All other cells represent indirect effects – which we refer to as *cascading effects*. The direct effect in column 1 is an unambiguous increase in farm *sales*, regardless of all the market parameters listed in Section 2.[15] In addition, a reduction in the rate of post-harvest food waste at farm level is always to reduce the price paid by consumers, thus improving consumers' welfare. This happens because with farm loss, the individual farmer needs a higher sales price to compensate for wasted production expenditures. As the rate of farm loss declines, these costs decline, reducing the burden on consumers.

The net effect on farm *production* is ambiguous as shown in the first row of the first column of Table 7: As in the case of prices, the effect on producers depends on the elasticity of consumer demand. As equation [5] shows, a reduction in food waste reduces the effective price received by the farmer, and hence producer welfare, when food demand is inelastic. The reverse holds for elastic demand. It is as though producers benefited from loss in case of inelastic demand by being able to move up to a more elastic part of the demand curve to P_F in Figure 3, gaining more revenues (akin to monopolistic pricing). We are assuming no cost of disposing of loss here but the costs of production are accounted for in the area under the supply curves $S_F(P_F)$ in Figures 2 and 3.

The second half of table 7 summarizes equilibrium impacts on quantities of waste at each stage. Farm waste always goes down with a cut in α_F, regardless of whether farm production increases or decreases. At the same time, the cascading effect of a cut in farm loss partly offsets this waste reduction as the quantity of waste downstream increases.[16] This is the result of the unambiguously lower *sales* prices cascading down the supply chain while holding downstream waste rates constant.

Theory of Food Waste by Intermediaries

Suppose an intermediary purchases product from farmers and sells to consumers at a local market. Assume there are no costs of marketing.[17] Furthermore, for the sake of intuition, assume no food waste by the consumer or farmer. By making these simplifying assumptions, the model becomes identical to the case of the producer presented previously.[18]

The intermediary selects an amount to purchase from farmers q_P at a market price P_P corresponding to a point on the farmer's supply curve, $S\left(P_P\right)$. However, before the intermediary sells to consumers, a share (α_P) of the product is wasted, and thus only $q=\left(1-\alpha_P\right)q_P$ is sold to consumers. Consumer demand is represented by $D\left(P\right)$, where P is the price paid by consumers. Thus, the equilibrium in the intermediary market can be represented by

[15] Costs of disposing farm waste for example may reverse this result.
[16] Notice the only indicator we are using to deem a cascading beneficial or not is the quantity of waste, a very arbitrary indicator, as we will show later, because more supply downstream with a cut in the rate of farm loss helps consumers and therefore improves food security, for example.
[17] Adding marketing costs with either constant or decreasing returns to scale does not change the results.
[18] This is only true if we abstract from harvest and pre-harvest losses. Their inclusion would make the models differ.

$$D(P) = (1-\alpha_P)S(P_P) \quad [7]$$

and a zero margin by the intermediary implies

$$PD(P) = P_P S(P_P). \quad [8]$$

The graphical depiction of this equilibrium is similar to Figure 3.[19] The comparative statics corresponding to equilibrium conditions [7] and [8] with respect to a reduction in the rate of food waste are given by [9] and [10]

$$\frac{dP_P}{d\alpha_P} = \frac{(1+\eta_D)P}{\eta_S - \eta_D} > 0 \text{ for } 0 \geq \eta_D \geq -1 \text{ and } \frac{dP_P}{d\alpha_P} < 0 \text{ for } \eta_D < -1 \quad [9]$$

$$\frac{dP}{d\alpha_P} = \frac{(1+\eta_S)P}{(1-\alpha_P)(\eta_S - \eta_D)} > 0. \quad [10]$$

Functionally, [9] and [10] are equivalent to [5] and [6]. Therefore, the previous conclusions about the signs of the derivatives conditional on the elasticity of consumer demand apply as well. Following [9], reducing food waste by the intermediary will not necessarily reduce farm production and in some cases will increase it. Hence, in either case, reducing α_P or α_F does not guarantee the double dividend of an improved environment (saving scarce resources or reduce GHG emissions in farm production) and food security.

If we allow simultaneous waste on the part of the farmer and the intermediary, the intermediary will purchase based upon the farmers market supply curve $(1-\alpha_F)S_F((1-\alpha_F)P_P)$. The results become somewhat more complicated analytically (compounding farmer loss by intermediary loss), though the same intuition holds at each level of the market. The traded quantity increases with a reduction in waste, but the change in the amount produced is ambiguous. Column 2 of Table 7 highlights the ambiguity of outcomes for stages above the processor level.

Theory of Food Waste by Consumers

The consumer is the last segment of the food supply chain. The consumer obtains utility from food consumed at home (q_C) but not from food purchases (q). The consumer solves the utility maximization problem

$$\max_{q_C, x} U(q_C, x)$$

subject to the budget constraint $P_U q + P_x x \leq Y$ and the restriction that the amount of food consumed

[19] To represent the case of the intermediary, substitute α_P for α_F in Figure 3.

is a fraction of food purchases: $q_C = (1-\alpha_C)q$, where P_U is the observable market price for a unit of food; *x* is other consumption, P_x is the price of other consumption, and *Y* is income. We present the results of this general model set-up together with their derivations in Appendix 1.

We define P_C as the *effective price of food*, that is, a price that a consumer would be charged for food consumption free of food waste such that she would spend as much money as for the food purchased (i.e., including the food wastes): $P_C q_C = P_U q$ or $P_C(1-\alpha_C)q = P_U q$, from which, $P_C = P_U/(1-\alpha_C)$. Notice that the higher the share of wasted food, the higher the (unobserved) effective price.

The interpretation of the effective price also follows from the consumer utility maximization problem upon eliminating the term q in the budget constraint by substituting it with the term $q_C/(1-\alpha_C)$ and setting $P_C = P_U/(1-\alpha_C)$. These manipulations convert the original problem into one without food waste being explicitly included. The ensuing Marshallian demand function will thus depend solely on P_C. Let us denote that function by $D_C(P_C)$ (Figure 4).

We are now interested in the effect of a reduction in the rate of consumer food waste on the market price P_U. For the sake of intuition, we will consider the simplified case in which the consumer wastes food, but no food is wasted by the producer. A result in Appendix 1 shows that the sign of the derivative $dq/d\alpha_C$ is ambiguous and so food purchases can either increase or decrease with a reduction in the rate of food waste. This unexpected result can be explained as follows. Consider a fixed retail price of food (P_U). A reduction in α_C has two effects: direct and indirect. The direct effect is to reduce food purchases because of reduced food waste. The indirect effect occurs because the reduced α_C reduces the effective price of food P_C [$= P_U/(1-\alpha_C)$]. When the demand curve for food consumption $D_C(P_C)$ is price elastic, the ensuing increase in food consumption outweighs the reduction in food waste (i.e., direct effect) and food purchases increase. On the other hand, when the demand curve for food consumption is price inelastic, the increase in food consumption is not enough to overcome the reduction in food purchases due to lower food waste, and food purchases decrease overall. For an alternative explanation of this result, please see the final part of Appendix 1.

If the food supply curve is upward sloping, then this means that the market price of food P_U can also go up or down, thus $dP_U/d\alpha_C$ is also ambiguous. We can use the demand function $D_C(P_C)$ to determine under what conditions P_U increases or decreases.

Market equilibrium requires that the demand for food consumption (free of food waste) be equal to the food supply facing the consumer, adjusted for the rate of food waste

$$D_C(P_C) = (1-\alpha_C)S(P_U). \qquad [11]$$

The consumer expenditure has to equal the revenue received by the farmer (we omit the presence of any intermediary for simplicity)

$$P_C D_C\left(P_C\right) = P_U S\left(P_U\right). \qquad [12]$$

The structure of equations [11] and [12] is equivalent to [7] and [8]. Totally differentiating [11] and [12] yields

$$\frac{dP_U}{d\alpha_C} = \frac{\left(1+\eta_C\right)P_C}{\eta_S - \eta_C} > 0 \text{ for } 0 \geq \eta_C \geq -1 \text{ and } \frac{dP_U}{d\alpha_F} < 0 \text{ for } \eta_C < -1 \qquad [13]$$

$$\frac{dP_C}{d\alpha_C} = \frac{\left(1+\eta_S\right)P_C}{\left(1-\alpha_C\right)\left(\eta_S - \eta_C\right)} > 0. \qquad [14]$$

Because equations [11] and [12] include demand function $D_C\left(P_C\right)$, elasticity η_C in derivatives [13] and [14] corresponds to that demand curve. It represents the percentage change in effective consumption (i.e., post-waste) in response to a percentage change in the effective price P_C (i.e., retail price adjusted for waste). In Appendix 2 we show that when the rate of consumer food waste is exogenous, this elasticity equals the elasticity of the demand function for food purchases (η_D), which can be obtained empirically. While a reduction in the rate of consumer food waste always causes a decrease in the *effective* food price to consumers, the same reduction will reduce the *market* price of food when demand for food is price inelastic and will increase it in the case of elastic demand. We illustrate these results graphically in Figure 4.

Underlying Figure 4 is a quasi-linear utility function $u = aq_C - 1/2\, bq_C^2 + x$, where $a > 0$ and $b > 0$ are parameters describing consumer's behavior.[20] This utility function gives rise to a linear inverse demand function for consumption

$$P_U = \left(1-\alpha_C\right)a - \left(1-\alpha_C\right)bq_C \qquad [15]$$

and for purchases

$$P_U = \left(1-\alpha_C\right)a - \left(1-\alpha_C\right)^2 bq. \qquad [16]$$

Substituting $P_U = \left(1-\alpha_C\right)P_C$ into equation [15] and rearranging, we obtain the inverse demand curve for food consumed

$$P_C = a - bq_C. \qquad [17]$$

[20] The results derived in Appendix 1 hold for a general utility function, and the quasi-linear specification (and the resulting linear demand functions) is only used for convenience.

A comparison of [15] and [16] shows that the inverse demand curve for food consumption always lies below the inverse curve for food purchases since both curves share the same intercept but the curve for food consumption is steeper (since $0 < \alpha_C < 1$). The three inverse demand curves are depicted in Figure 4 in solid lines.

A decrease in the rate of consumer food waste increases the vertical intercept of both inverse demand curves [15] and [16] by the same amount (depicted by the dashed lines in Figure 4). The amount by which these intercepts increase depends on the cut in α_C and the initial value of the parameter *a*. This means that for a given food market price P_U, consumers are willing to consume more.

However, a decline in α_C has no effect on the horizontal intercept of the inverse demand curve [15] which is fixed at *a*/*b*. This means food consumption always increases with a cut in α_C. On the other hand, the purchase demand curve's horizontal intercept moves to the left. Therefore, depending on the relative magnitudes of the vertical and horizontal shifts of the intercepts of the purchase demand curve, the market price of food may either increase or decrease.[21] Note that both demand curves become steeper after the cut in α_C.

All three models combined

In a model with all three market agents—producer, intermediary, and consumer—there is only one supply and one demand curve. The intermediary transacts food in such a way that farmer's production equals consumer's consumption (not purchases), after considering food loss and waste along the supply chain

$$D_C\left(P_C\right) = \left(1-\alpha_C\right)\left(1-\alpha_P\right)\left(1-\alpha_F\right) S_F\left(P_F\right). \qquad [18]$$

With our simplifying assumption of zero margins, the intermediary also sets the market price so that the consumer's expenditures equal the revenue of the producer

$$P_C D_C\left(P_C\right) = P_F S_F\left(P_F\right). \qquad [18]$$

Totally differentiating the two equilibrium conditions, we obtain

$$\begin{aligned} D_C' dP_C &= -\left(1-\alpha_P\right)\left(1-\alpha_F\right) S_F d\alpha_C - \left(1-\alpha_C\right)\left(1-\alpha_F\right) S_F d\alpha_P \\ &- \left(1-\alpha_C\right)\left(1-\alpha_P\right) S_F d\alpha_F + \left(1-\alpha_C\right)\left(1-\alpha_P\right)\left(1-\alpha_F\right) S_F' dP_F \quad , \\ \left(D_C + P_C D_C'\right) dP_C &= \left(S_F + P_F S_F'\right) dP_F \end{aligned}$$

from which

[21] The food market price is determined by the quantity purchased (not consumed), which includes (future) waste by the consumer.

$$\frac{dP_F}{d\alpha_F} = \frac{(1-\alpha_C)(1-\alpha_P)(1+\eta_D)P_C}{\eta_S - \eta_D} \tag{19}$$

$$\frac{dP_F}{d\alpha_P} = \frac{(1-\alpha_C)(1-\alpha_F)(1+\eta_D)P_C}{\eta_S - \eta_D}. \tag{20}$$

Notice that if we set $\alpha_C = \alpha_P = 0$ (to focus on the producer waste only), the derivative $dP_F/d\alpha_F$ reduces to derivative [5] above. Because $0 \le \alpha_C, \alpha_P \le 1$, the value of the derivative $dP_F/d\alpha_F$ in the full model is always less than in the stand-alone model with the producer and consumer. However, the conclusions about the effect of different demand elasticities do not change. Further extensions of this model could allow for multiple sources of food by the consumer (e.g., at home or away from home), positive margins by the intermediary, or even multiple producer and intermediary sectors.

Simulation

To take the above model to the data and highlight the empirical significance of the indirect (cascading) effects we highlight above, we provide simulation results which allow for simultaneous waste by producers, several distinct intermediaries who can charge positive margins, and consumers. The model is calibrated to the two respective UK commodities assuming constant elasticity supply curves and linear demand curves. We define the supply relationship supposing a representative cost curve for producers that follows

$$C_F(q_F) = Aq_F^{\varepsilon_F}.$$

Thus [2] becomes

$$(1-\alpha_F)P = P_F = C_F'(q_F) = \varepsilon_F A q_F^{\varepsilon_F - 1}$$

which results in the total supply curve

$$q_F = \left(\frac{1}{\varepsilon_F A}\right)^{\eta_F} P_F^{\eta_F} \equiv BP_F^{\eta_F} = S_F(P_F),$$

where $\eta_F = 1/(\varepsilon_F - 1)$ is the elasticity of supply, yielding a standard constant elasticity form. The supply of traded product by the farmer is thus given by

$$q = (1-\alpha_F)q_F = (1-\alpha_F)B(1-\alpha_F)^{\eta_F} P^{\eta_F} = S(P).$$

We specify the demand for consumption as

$$q_C = a - bP_C = D_C\left(P_C\right),$$

which results in the total demand for food purchases of

$$q_U = \frac{a}{1-\alpha_C} - \frac{b}{1-\alpha_C} P_C = \frac{a}{1-\alpha_C} - \frac{b}{\left(1-\alpha_C\right)^2} P_U = D_C\left(P_C\right) / \left(1-\alpha_C\right).$$

After calibrating the supply and demand parameters to the observed market data for the UK, we simulate the model by imposing exogenous changes to waste rates and solving for the effective farm price P_F which ensures that markets at each stage of the supply chain (including trade) clear. Since the price and quantity relationships along the supply chain are directly governed by the respective waste rates and margins (see Table 8 for the corresponding functional relationships), this means that we need to ensure that effective demand at the implied consumption price matches the total quantity that reaches the consumer.

5. Direct versus Indirect (Cascading) Effects in the Food Supply Chain: Empirical Results

We simulate the effects of an exogenous reduction in food waste at various stages of the supply chain for two UK commodities (chicken and fruit) in the case of a closed economy, small open economy and large open economy. In addition, we vary the governing supply and demand elasticities. Comparing results across these scenarios allows us to (i) re-emphasize the importance of key market parameters such as elasticities, waste rates, and margins in determining both the sign and magnitude of the change in key outcome measures of interest; (ii) highlight the important impacts of cascading effects along the supply chain; and (iii) stress the important tradeoffs among the various potential outcome measures of interest a policy-maker or regulator might consider. Recall that all relevant baseline market parameters for UK chicken and fruit are given in Tables 3-6 for reference.

There are two possible representations of changes in waste: a reduction in waste rates or a quantity reduction relative to the baseline quantity of waste. For consistency with the theoretical model, as well as to simulate the case of a technological change that fundamentally alters when or how waste is generated, we here consider exogenous changes to *rates of waste*. In particular, we assume that waste rates at a given stage of the supply chain are cut in half. One downside of this choice is that the magnitude of results will in part depend on the initial level of waste rates (i.e., cutting a waste rate in half that is higher to begin with will lead to larger changes in outcome variables of interest). On the other hand, a given reduction in waste rates is the most natural change in the context of our model since waste rates are assumed to be exogenous in this analysis while quantities are endogenous. A given change in the *quantity* of waste would therefore already be confounded by the indirect effects we aim to highlight, while a change in waste *rates* is not.

For tractability, we restrict our analysis to the two UK commodities. An interesting extension of our framework would be to apply it to the context of developing country settings where the distribution of waste rates along the supply chain is decreasing rather than increasing (i.e., consumers in developing countries waste relatively less, while farmers waste relatively more). This analysis is left for future work.

To provide intuition, we begin by analyzing the case of UK chicken in the case of a closed economy. Table 8 provides detailed results of percent changes in various prices and quantities along the supply chain in response to cutting waste rates in half at the farm level (column 1), the THS level (column 2), the processor level (column 3), the retailer level (column 4), and the consumer level (columns 5 and 6).[22] The last column of Table 8 shows percentage changes for a simultaneous halving of waste rates at each stage of the supply chain. As before, direct effects are highlighted in color.

The sign of the direct and indirect effects in Table 8 is in line with the theoretical comparative statics results summarized in Table 7. Direct effects and effects cascading 'downstream' from the location of the waste rate reduction are unambiguously positive, while indirect effects 'upstream' depend on demand elasticities.

Line 25 of Table 8 highlights the reduction in total waste. An easy way to showcase the importance of indirect effects is to compare the results to a reduction in consumer waste rates between the elastic and inelastic demand scenarios (columns 5 and 6). The total reduction in the quantity of waste is substantially larger in the case of inelastic demand at 23 percent since the indirect effects in this case result in reduced farm production and hence lower waste at all other stages of the supply chain. The reverse is true in the case of elastic demand, which results in a total waste reduction of only 16 percent instead.

It is conceptually more challenging to compare the total reduction in the quantity of waste across the other columns. As outlined above, this is in part due to the fact that the initial levels of waste rates differ substantially between the stages of the supply chain. For example, cutting farm waste in half leads to a 3 percent reduction in waste (column 1) versus the 23 percent reduction in response to halving consumer waste (column 5). However, as shown in column 1 of Table 3, the initial level of farm waste for UK chicken is roughly 4 percent compared to a 38 percent waste rate at the consumer level.

Table 9 details the corresponding absolute changes in the *quantity* of waste at each stage of the supply chain. In particular, line 7 breaks out the ratio of direct versus indirect effects (calculated as the total change in the quantity of waste in line 5 divided by the direct effect highlighted in color). Note that this ratio is larger than one only in the case of a reduction in consumer waste rates in the case of inelastic demand, which benefits most strongly from reinforcing cascading effects upstream.

While it is frequently suggested that policy-makers should prioritize cutting waste at the consumer level due to the upstream waste 'embodied' in each unit that reaches the consumer level, we caution that (i) the effectiveness of such a cut may be muted by cascading upstream effects in the case of elastic demand; (ii) quantities upstream always exceed downstream quantities due to waste,

[22] The baseline demand elasticity for chicken in the UK is at -0.67 (column 4). To highlight the ambiguity in outcomes as a function of the elasticity of demand, we also consider an alternative scenario in which demand is elastic at -1.5 (column 5).

which suggests that cuts in waste rates further upstream benefit from applying to a larger base; and (iii) the optimal place to cut will not only depend on how much waste is reduced, but also on the relative costs of achieving the reduction in the first place. The optimal intervention is therefore likely to be country- and commodity-specific. The simple heuristic that cuts downstream benefit from some sort of multiplier effect upstream is therefore arguably too simplistic given the complex and interconnected nature of food supply chains.

It is also interesting to note that the farmer share of consumer dollar plays an important role above and beyond the total waste share in driving this ratio. Recall that this measure depends on both waste shares and the margins imposed by intermediaries, which means that differences in the farmer share of consumer dollar partly reflect differences in the effective demand faced by the producer, and hence the importance of cascading effects.

Having analyzed in detail how cuts in waste rates affect the equilibrium for the example of UK chicken, we now turn to analyzing impacts on the list of policy goals outlined in Section 3. Tables 10a-c show percent changes in key outcome variables of interest for cuts in farm and consumer waste rates for both chicken and fruit across three trade scenarios (closed economy, small open economy, and large open economy). Table 10a represents the case in which both domestic supply and demand are inelastic as in the baseline scenario (see data in Box 1); Table 10b instead considers the case of doubling the domestic demand elasticity to make it elastic (while keeping the same supply elasticity as in Table 10a); and Table 10c shows results under elastic supply (where the initial supply elasticity is similarly doubled relative to the baseline in Table 10a). Note that the first two columns in Table 10a correspond exactly to the results shown in columns 1 and 5 in Table 8, while column 2 of Table 10b corresponds to the results in column 6 of Table 8.

The first thing to note is the obvious conflict between a reduction in resource stress (which can be approximated by the total production level q_F as this will determine the required land, fertilizer and water needs) and farm welfare. Farm welfare by construction always moves in line with farm production, meaning that any improvement along one dimension always comes at the expense of the other.

Another aspect that stands out in Tables 10a-c is that both the total *quantity* and the *value* of waste always decrease far more for cuts at the consumer level than at the farm level, with a larger differential in value terms than quantity terms (see rows 7 vs 11 of Table 10a). These results hold true across all elasticity scenarios and all assumptions regarding trade. The result with respect to quantities is unsurprising since the base rate of waste is significantly higher at the consumer level than the producer or intermediary level for both chicken and fruit (see Table 3). This finding should not be misinterpreted as suggesting that cuts in consumer waste rates are always preferable to reductions at the producer level. The reason that this finding is magnified in terms of the change in the value of waste is predicated upon the fact that prices rise as the product is transformed and value is added along the supply chain.

In comparing the results for chicken and fruit, it is important to note that due to the higher intermediary waste rates for chicken, driven by waste at the processor level (see top half of Table 3), as well as the substantially higher intermediary margins (see bottom half of Table 3), the farmer share of consumer dollar for chicken is substantially lower than for fruit at 0.24 compared to 0.57

(see row 2 of Table 2). This suggests that the *effective* demand faced by chicken producers is more inelastic although the demand elasticities for the two commodities at the consumer level are assumed to be equal in the UK (see Box 1). This in turn suggests that the cascading effects should be more muted in the case of chicken. One way to see this effect in our simulations is by analyzing the indirect effect on consumer purchases (row 8 of Table 10a) to the effect on farm production (row 1 of Table 10a). As expected, this ratio is far low for chicken in column 1 than for fruit in column 3. This difference in effective demand elasticities also explains why the percentage change in fruit production is only roughly twice as high as that for chicken (row 1 of column 3 versus column 1, Table 10a) while the initial farm-level waste and loss rate for fruit is more than three times as high as that for chicken (row 1 of column 2 vs column 1, Table 3).

Another important result emerges when comparing the effectiveness of waste cuts under alternative trade regimes in the case of inelastic demand supply (Table 10a). In a small open economy, the country effectively acts as a price taker on international markets, meaning that producers face a relatively elastic *effective* demand even when demand by domestic consumers is inelastic. This explains the change in sign of the effects of cuts in farm waste rates on farm production between row one of columns 5 versus the equivalent values in columns 1 and 9—a result in line with the comparative statics outlined in Table 7. The same finding is true with respect to farmer welfare. As a result, while cuts in farmer loss rates benefits food security (consumer purchases rise) but hurts producers in a closed or large open economy,[23] the effect of cutting farm waste rates is unambiguously positive for producers and consumers in a small open economy.

Based on this logic, it may be surprising to see that the percentage change in farm production in the large open economy case for fruit (row 1 in column 11) remains positive, unlike in the case of chicken (row 1 in column 9). Box 1 explains that there are always two "trade" curves in an open economy model. One is the export supply facing the UK for fruit; the other is the implicit elasticity of import demand of the UK for fruit. As outlined in Box 1, the most important piece of data that determines the elasticity of import demand is the ratio of imports to domestic production. If it is very high (as it is for fruit in the UK – see line 1 in Table 2), then the import demand is very price inelastic and reducing food waste has minimal impacts on market prices which explains the similarity to the small open economy scenario for fruit.

To highlight the role of domestic demand elasticities, let's compare Tables 10a to Tables 10b and 11c. The cells highlighted in Tables 11b reflect cells that have a different sign than the equivalent cells in Table 10a. Note that there are no differences in sign between Table 10a and 10c, which is why no cells are highlighted in color. In fact, there are few significant changes between Tables 10a and 10c apart from the difference in magnitude for farm-level results in the case of fruit for the small and large open economy. This underscores the fact that demand elasticities play a relatively more important role in driving results than supply elasticities.

Another interesting quantity to calculate at the farm level is the net reduction in resource stress (approximated by farm production q_F) relative to the total reduction in total waste (W_T). The ratio

[23] See discussion in Section 4 noting that producers effectively benefit from loss in case of inelastic demand by being able to move up to a more elastic part of the demand curve to P_F in Figure 3, gaining more revenues (akin to monopolistic pricing).

$\Delta q_F/\Delta W_T$ is shown in the last row of Tables 10a-c, and differs markedly across market structures, elasticities, and the location of the cut (farmer vs consumer). Note that this ratio is a ratio in levels, and therefore does not equal the ratio of rows 1 and 7 in Table 10a which are calculated in percentages. This ratio is a potentially interesting indicator because the food waste community emphasizes the savings in farm production (and the reduced stress on natural resource use and GHGEs) yet rarely is this ratio is 1 (only in the small open economy case) and many times it is negative (food waste declines but farm production increases).

The final performance measure of interest by policymakers we consider is the value of imports. In general, a more elastic domestic demand curve results in lower gain in foreign exchange earnings with a cut in domestic food waste (compare row 10 in Table 10a with Table 10b). Note that the sign of the change in response to waste reductions differs between row 10 of Table 10a and Table 10b in two cases with elastic domestic demand: the value of imports increases with a decline in food waste.

6. Concluding Remarks

This article has analyzed the direct effects of a reduction in rates of food waste at each stage of the food supply chain and indirect (cascading) effects along the food supply chain. The empirical results are a direct application of the theoretical model. Hence, we use empirical examples from UK agriculture to illustrate the properties of the direct effects analyzed in the theoretical model and the indirect or cascading effects that occur in the food supply chain as a whole. The empirical results capture the direct and indirect effects up and down the food supply chain in a comprehensible way. In our simulations, we expand on the theoretical framework by allowing intermediaries to charge margins, which affects the intensity of price transmission from consumer to farmer. We introduce the concept of "farm share of consumer \$" as an approximate measure of the extent of this phenomenon. A lower farm share of consumer \$ reduces the force of the indirect effects we emphasize in this paper. To further increase the realism of the framework, we also present a series of simulation results that showcase how different trade scenarios affect the results.

The primary results of our analysis are as follows:

The amount of food waste always declines at the stage of the supply chain where the rate of waste declines. Because waste exists, producers and intermediaries, such as processors and retailers, must charge a higher price per unit sold to recover their costs incurred on all units, including the units that were wasted. Reducing waste rates, therefore, always translates into higher sales with lower prices for each producer and intermediary. This, in turn, may trigger increased sales and hence more waste at all other stages of the supply chain. Usually, total waste in the food supply nevertheless declines.[24]

Meanwhile, the reverse holds going upstream: reducing waste of the consumer (or, for example, at the retail level) will increase consumption (sales), but purchases will only decline if demand is inelastic. The analysis of our paper shows that an exogenous reduction in the waste rate has both

[24] A cut in an intermediary rate of waste could result in an increase in total waste. In other words, the direct effects are offset by the cascading effects, but this happens rarely and depends on the margins and rates of waste right next the intermediary up- and downstream from it.

a direct quantity impact on how much of the purchased food can be consumed and an indirect quantity impact through the demand elasticity since lower waste rates reduce the effective unit price of food consumed. Our derivations above show that if demand is sufficiently responsive to price, the latter effect may dominate, leading to increased purchases overall. Note, however, that the value of consumption always declines.

If purchases decline, then there is less waste at all other stages going upstream. While indirect effects are rarely large enough to erase the initial reduction in waste, they may dampen the effectiveness of interventions going downstream and strengthen their effects going upstream (provided demand is inelastic in the latter case). Hence, cutting rates of food waste always improves the welfare of the consumer and improves food security.

The model highlights that indirect effects are more severe (i) the more strongly consumers respond to lower prices; (ii) the less an open economy can influence world prices; and (iii) the higher the farm-share of consumer dollars (after margins charged by intermediaries along the supply chain).

Although total waste in the food supply chain generally declines more with a cut in the consumer rate of waste in our UK examples, it is likely because of higher rates of consumer waste to begin with. We show that a cut in consumer waste has beneficial cascading effects upstream if purchases decline, but the cut in waste is on a lower quantity of consumer purchases (relative to sales and production upstream). The net effect is indeterminate a priori and depends on relative parameters in the food supply chain. We provide empirical examples that cutting waste at the consumer level is not always the first best option in order to maximize the total reduction in waste, even if farmers and consumers generate waste at equal rates. But we do not suggest cutting waste at the farm level should be prioritized either. Instead, we explicitly point out that optimal intervention is, therefore, likely to be country- and commodity-specific. The simple heuristic that cuts downstream benefit from some sort of multiplier effect upstream is, therefore, arguably too simplistic given the complex and interconnected nature of food supply chains.

We show farm production goes up with (a) a cut in farm rate of waste if demand (domestic or small trader) is elastic and margins are low, and (b) a cut in consumer rate of waste provided domestic demand is price elastic as a small country does not count as a demand elasticity but affects the magnitude. Farm production goes down with a cut in the consumer rate of waste if domestic demand is inelastic (margins and rates of waste elsewhere do not matter that much). Farm production increases with a cut in consumer waste with elastic demand and increases with a cut in farm waste with an elastic demand are not guaranteed, depending on the level of margins and the degree of demand elasticity.

Farm welfare moves in the same direction as farm production so given the analysis above, farm sales always increase with a cut in farm waste, but the quantity of production required to achieve these sales after waste may go up or down depending on the market structure (in particular, the demand elasticity and the level of margins). Since farm welfare is directly tied to production, the impact of food waste reduction policies on farmer welfare depends on commodity-specific context.

To reduce stress on natural resources (e.g., land and water), farm production needs to decline. Since the effect of reductions in rates of waste at the farm and handling stages of the supply chain on levels of farm production are ambiguous in sign, so is the result on total resource stress. However, whether domestic production increases or not, imports decline with reduced waste rates so any increase in the stress on domestic resources in the cases where domestic production increases is partially offset by reduced production (and hence the stress on resources) outside the country. It is also important to note that this policy goal of reduced farm production stands in direct conflict with the goal of increased farm welfare, which moves with production.

An important result of our model is that the value of food waste (as an indicator of social costs of waste) always declines with cuts in the rate of waste, and declines more with a reduction in waste further downstream (e.g., consumer) so the value of food waste is "embedded" as one goes downstream. Finally, the value of imports (exports) decline (increase) with a cut in food waste, an important result especially for developing countries with foreign exchange earning considerations.

Our theoretical and empirical results underscore the importance of modeling the food supply chain in its entirety to capture the significant cascading effects of changes in waste rates at different stages. By providing a basic model of such an interconnected set of agents, we are able to derive comparative statics results highlighting that while direct effects correspond to unambiguous increases in sales or consumption when waste rates are reduced, the sign and magnitude of indirect effects depends on key aspects of the prevailing market structure such as demand elasticities and the margins imposed by intermediaries.

One important aspect our model highlights are the potential conflicts between different policy goals such a reduction in resource stress, increases in farm welfare, and enhanced food security. We show that whether these outcome measures move together depends in large part on the domestic demand elasticity in combination with the prevailing trade regime. Regulators should, therefore, carefully analyze the given country- and commodity-specific context of interest in making their policy decisions. In addition, we emphasize that it is not clear that cuts in waste at the consumer level are always more beneficial than equivalent cuts at the producer level. The relative effectiveness of cuts will depend on the presence and magnitude of cascading effects, the relative costs of cutting waste rates at the two stages, and the distribution of waste rates along the supply chain.

Our results, therefore, provide important nuance to the existing literature on food waste, which often focuses on separate parts of the supply chain in isolation. However, there are several relevant aspects of the market environment that our partial equilibrium framework does not speak to. We do not allow for differences in initial wealth levels, credit constraints, or heterogeneity in preferences, and do not directly model cost functions of waste abatement to determine the initial rate of the waste. Readers interested in the case of endogenous waste rates are referred to de Gorter et al. (2018) for more information. In addition, we do not consider general equilibrium ramifications, particularly in the presence of pre-existing distortions such as taxes on wages, which might play a first-order role in developing country settings. While there are many papers introducing food waste in computable general equilibrium (CGE) models, we believe that it will be interesting to derive theoretical results regarding the many outcome measures of interest in a general equilibrium setting.

Tables

Table 1: Impact of waste on sales and purchases through the supply chain

Rates of waste					Waste	
		q_F:	100	= gross farm production		
α_F	0.0488	$q_{TS} = (1-\alpha_F)\cdot q_F$:	95.1	= farm sales (= THS purchases)	$W_F = \alpha_F \cdot q_F$	5
α_T	0.0269	$q_T = (1-\alpha_T)\cdot q_{TS}$:	92.6	= THS sales (= processor purchases)	$W_T = \alpha_T \cdot q_{TS}$	2.6
α_P	0.0543	$q_P = (1-\alpha_P)\cdot q_T$:	87.5	= processor sales (= retail purchases)	$W_P = \alpha_P \cdot q_T$	5.0
α_R	0.0741	$q_R = (1-\alpha_R)\cdot q_P$:	81.1	= retail sales (= consumer purchases)	$W_R = \alpha_R \cdot q_P$	6.5
α_C	0.2200	$q_C = (1-\alpha_C)\cdot q_R$:	63.2	= consumption	$W_C = \alpha_C \cdot q_R$	17.8
					Total	**36.8**

Table 2: Important Characteristics of the UK Products Studied

		Chicken	**Fruit**	**Bread**	**Milk**
Share of…					
Production imported	M/q_F	0.33	6.95	0.04	-0.02
Consumer $ to farmer	P_F/P_R	0.24	0.57	0.11	0.47
At-home purchases	q_R/q_P	0.65	0.83	0.74	0.93
Production wasted	W_{total}/q_F*	0.48	0.50	0.38	0.21

Note: q_F* is an adjusted domestic UK production as if all imports are produced domestically. Otherwise, total waste for fruit would be 3.5 times domestic production, a statistic with little meaning.

Table 3: Levels and Distribution of Waste and Margins

		Chicken	Fruit	Bread	Milk
Rates of waste…					
Farm production	α_F	0.043	0.143	0.020	0.029
THS	α_T	0.010	0.045	0.014	0.042
Processor	α_P	0.225	0.053	0.050	0.011
Retail	α_R	0.076	0.070	0.140	0.060
HRI	α_H	0.045	0.084	0.117	0.009
Away-consumptio	α_A	0.023	0.043	0.060	0.005
At-home consumpt	α_C	0.382	0.373	0.293	0.091
Margins…					
THS	m_T	0.003	0.127	0.273	0.103
Processor	m_P	0.964	0.190	0.559	0.087
Retail	m_R	1.850	0.296	0.799	0.071
HRI	m_H	2.384	0.466	1.040	0.163

Table 4: Quantities and Value of Waste by Product (UK)

	Chicken	Fruit	Bread	Milk	Total	Share
Quantities of waste…						
Farm production	0.11	0.87	0.06	0.21	1.2	0.18
Intermediaries	0.67	0.82	0.54	0.74	2.8	0.41
Consumption	0.42	1.32	0.54	0.53	2.8	0.41
Total	1.20	3.02	1.14	1.48	6.8	
Share	0.18	0.44	0.17	0.22		
Values of waste…						
Farm production	0.11	0.86	0.01	0.06	1.04	0.10
Intermediaries	0.90	1.14	0.48	0.30	2.82	0.28
Consumption	1.91	2.68	1.14	0.32	6.05	0.61
Total	2.92	4.68	1.63	0.67	9.90	
Share	0.29	0.47	0.16	0.07		

Table 5: Quantities and Value of UK Product Prodn/Cons

	Chicken	**Fruit**	**Bread**	**Milk**
Quantities of…				
Farm production	2.5	6.1	3.0	7.2
Share of total	0.13	0.32	0.16	0.38
Intermediary waste	0.72	1.05	0.59	0.74
Share of total	0.23	0.34	0.19	0.24
Consumer purchases	1.7	4.2	2.3	6.2
Share of total	0.12	0.29	0.16	0.43
Consumption	1.2	2.9	1.8	5.7
Share of total	0.11	0.25	0.15	0.49
Values of…				
Farm production	2.6	6.0	0.7	2.0
Share of total	0.23	0.53	0.06	0.17
Value added	5.4	7.8	5.2	4.4
Share of total	0.24	0.34	0.23	0.19
Consumer purchases	7.9	8.7	5.2	3.8
Share of total	0.31	0.34	0.20	0.15
Total	**16.0**	**22.5**	**11.1**	**10.2**
Share of total	**0.27**	**0.38**	**0.19**	**0.17**
Consumption	7.8	8.6	5.0	3.8
Share of total	0.31	0.34	0.20	0.15

Table 6: Baseline Values for Key Variables Closed versus Open Economy: UK Chicken and Fruit

			Chicken		Fruit	
			Closed	Open	Closed	Open
1	Farm production	q_F	2.50	1.68	6.09	0.61
2	Farm sales (= THS purchases)	$q_{TS} = (1-\alpha_F)\cdot q_F$	2.39	1.61	5.22	0.52
3	THS sales (= processor purchases)	$q_T = (1-\alpha_T)\cdot q_{TS}$	2.37	1.59	4.99	0.50
4	Processor sales (= retail + HRI Purchases)	$q_P = (1-\alpha_P)\cdot q_T$	1.83	1.79	4.73	4.50
5	Retail sales (= at-home cons purchases)	$q_R = R_{SH}\cdot(1-\alpha_R)\cdot q_P$	1.10	1.07	3.65	3.47
6	At-home consumption	$q_C = (1-\alpha_C)\cdot q_R$	0.68	0.66	2.29	2.18
7	HRI sales (= away-from-home purchases)	$q_H = (1-R_{SH})\cdot(1-\alpha_H)\cdot q_P$	0.61	0.60	0.74	0.70
8	Away-from-home consumption	$q_A = (1-\alpha_A)\cdot q_H$	0.60	0.58	0.70	0.67
9	Effective farm production price	$P_{EF} = (1-\alpha_F)\cdot P_F$	1.10	1.10	0.98	0.98
10	Farm sales price	P_F	1.10	1.10	1.15	1.15
11	THS sales price	$P_T = P_F/(1-\alpha_T) + m_T + DC/(1-\alpha_T)$	1.11	1.11	1.33	1.33
12	Processor sales price	$P_P = P_T/(1-\alpha_P) + m_P + DC/(1-\alpha_P)$	2.43	2.43	1.59	1.59
13	Retail price = at-home purchase price	$P_R = P_P/(1-\alpha_R) + m_R + DC/(1-\alpha_R)$	4.48	4.48	2.01	2.01
14	HRI price = away-from-home purchase price	$P_H = P_P/(1-\alpha_H) + m_H + DC/(1-\alpha_H)$	4.93	4.93	2.20	2.20
15	Effective at-home cons price	$P_C = P_R/(1-\alpha_C)$	7.3	7.3	3.20	3.20
16	Effective away-home cons price	$P_A = P_H/(1-\alpha_A)$	5.0	5.0	2.30	2.30
17	Farm loss	$W_F = \alpha_F\cdot q_F$	0.11	0.11	0.87	0.87
18	THS loss	$W_T = \alpha_T\cdot q_{TS}$	0.02	0.02	0.23	0.23
19	Processor waste	$W_P = \alpha_P\cdot q_T$	0.53	0.53	0.26	0.26
20	Retail waste	$W_R = \alpha_R\cdot q_P\cdot R_{SH}\cdot q_P$	0.09	0.09	0.27	0.26
21	HRI waste	$W_H = \alpha_H\cdot q_P\cdot(1-R_{SH)}\cdot q_P$	0.03	0.03	0.07	0.06
22	At-home consumption waste	$W_C = \alpha_C\cdot Q_R$	0.4	0.4	1.36	1.30
23	Away-from-home consumption waste	$W_A = \alpha_A\cdot Q_H$	0.01	0.01	0.03	0.03
24	**Total waste**	$\mathbf{W_{total}}$	**1.22**	**1.20**	**3.1**	**3.0**
25	Farm welfare		1.74	1.17	3.3	0.3
26	Consumer expenditures	$= P_R\cdot q_C$	7.9	7.8	8.9	8.5
27	Value of Imports		0	2.5	0	6.8
28	Value of total waste		3.0	2.9	4.8	4.7

Note: DC refers to disposition costs of waste and is assumed to be 0.10 £ per kg at all stages in the supply chain.

Table 7: Direct *versus* indirect effects of reductions in rates of waste on quantities and waste

Changes in...		Farm $\downarrow\alpha_F$	Processor $\downarrow\alpha_P$	Final consumer $\downarrow\alpha_C$ inelastic	Final consumer $\downarrow\alpha_C$ elastic
Farm production	Δq_F	– / +	– / +	–	+
Farm sales	Δq_{TS}	+	– / +	–	+
THS sales	Δq_T	+	– / +	–	+
Processor sales	Δq_P	+	+	–	+
Retail sales (= consumer purchases)	Δq_R	+	+	–	+
Consumption	Δq_C	+	+	+	+
Changes in...					
Farm waste	ΔW_F	–	–	–	+
THS waste	ΔW_T	+	–	–	+
Processor waste	ΔW_P	+	–	–	+
Retail waste	ΔW_R	+	+	–	+
Consumer waste	ΔW_C	+	+	–	–

Table 8: Direct *versus* Indirect (Cascading) Effects of Reductions in Rates of Waste: UK Chicken (Closed Economy)

			0.043	0.010	0.225	0.076	0.382	0.382	
			$\downarrow\alpha_F$ 50%	$\downarrow\alpha_T$ 50%	$\downarrow\alpha_P$ 50%	$\downarrow\alpha_R$ 50%	$\downarrow\alpha_C$ 50% Inelastic	$\downarrow\alpha_C$ 50% Elastic	$\downarrow$ all α_F's 50%
			Percent Changes						
1	Farm production	q_F	-1.1	-0.2	-7	-1.1	-5	1.3	-16
2	Farm sales (= THS purchases)	$q_{TS} = (1-\alpha_F)\cdot q_F$	1.2	-0.2	-7	-1.1	-5	1.3	-15
3	THS sales (= processor purchases	$q_T = (1-\alpha_T)\cdot q_{TS}$	1.2	0.3	-7	-1.1	-5	1.3	-14
4	Processor sales (= retail + HRI Pu	$q_P = (1-\alpha_P)\cdot q_T$	1.2	0.3	7	-1.1	-5	1.3	-2
5	Retail sales (= at-home cons purch	$q_R = R_{SH}\cdot(1-\alpha_R)\cdot q_P$	1.0	0.2	6	2	-10	3	-5
6	At-home consumption	$q_C = (1-\alpha_C)\cdot q_R$	1.0	0.2	6	2	18	34	24
7	HRI sales (= away-from-home pur	$q_H = (1-R_{SH})\cdot(1-\alpha_H)\cdot q_P$	1.4	0.3	8	0.7	3	-1.2	14
8	Away-from-home consumption	$q_A = (1-\alpha_A)\cdot q_H$	1.4	0.3	8	0.7	3	-1.2	16
10	Effective farm production price	$P_{EF} = (1-\alpha_F)\cdot P_F$	-2	-0.5	-13	-2	-10	3	-30
11	Farm sales price	P_F	-4	-0.5	-13	-2	-10	3	-32
12	THS sales price	$P_T = P_F/(1-\alpha_T) + m_T$	-4	-1.0	-13	-2	-10	3	-32
13	Processor sales price	$P_P = P_T/(1-\alpha_P) + m_P$	-3	-0.6	-15	-1.3	-6	2	-24
14	Retail price = at-home purchase pr	$P_R = P_P/(1-\alpha_R) + m_R$	-1	-0.3	-9	-3	-4	0.9	-16
15	HRI price = away-from-home purc	$P_H = P_P/(1-\alpha_H) + m_H$	-1.3	-0.3	-7	-0.6	-3	0.8	-13
16	Effective at-home cons price	$P_C = P_R/(1-\alpha_C)$	-1.5	-0.3	-9	-3	-26	-23	-36
17	Effective away-home cons price	$P_A = P_H/(1-\alpha_A)$	-1.3	-0.3	-7	-0.6	-3	0.8	-14
18	Farm loss	$W_F = \alpha_F\cdot q_F$	-51	-0.2	-7	-1.1	-5	1.3	-58
19	THS loss	$W_T = \alpha_T\cdot q_{TS}$	1.2	-50	-7	-1.1	-5	1.3	-57
20	Processor waste	$W_P = \alpha_P\cdot q_T$	1.2	0.3	-53	-1.1	-5	1.3	-57
21	Retail waste	$W_R = \alpha_R\cdot q_P\cdot R_{SH}\cdot q_P$	1.0	0.2	6	-51	-10	3	-55
22	HRI waste	$W_H = \alpha_H\cdot q_P\cdot(1-R_{SH})\cdot q_P$	1.4	0.3	8	0.7	3	-1.2	-44
23	At-home consumption waste	$W_C = \alpha_C\cdot Q_R$	1.0	0.2	6	2	-55	-49	-53
24	Away-from-home consumption wa	$W_A = \alpha_A\cdot Q_H$	1.4	0.3	8	0.7	3	-1.2	-43
25	Total waste	W_{total}	-3	-0.8	-21	-4	-23	-16	-55

Table 9: Direct *versus* Indirect (Cascading) Effects of Reducing Rates of Waste: UK Chicken*

			↓α_F 50%	↓α_P 50%	↓α_R 50%	↓α_C 50% inelastic	↓α_C 50% elastic	↓ all α_F's 50%
			changes in the levels of…					
	Waste (quantity)	Baseline						
1	Farm/THS	0.131	-0.054	-0.009	-0.001	-0.007	0.002	-0.076
2	Processor	0.532	0.006	-0.284	-0.006	-0.028	0.007	-0.304
3	Retailer/HRI	0.120	0.001	0.008	-0.046	-0.008	0.002	-0.062
4	Consumption	0.434	0.004	0.025	0.009	-0.231	-0.205	-0.227
5	Total	1.22	-0.04	-0.26	-0.04	-0.27	-0.19	-0.67
6	Percent change		-3%	-21%	-4%	-23%	-16%	-55%
7	Direct vs indirect effects*		0.78	0.92	0.97	1.19	0.95	
8	% Δ in Total Value of Waste	3.10	-8%	-20%	-10%	-44%	-32%	-65%

* Closed economy
*Line 5 divided by the highlighted cell

Table 10a: 50% cut in rates of waste: Chicken *vs.* Fruit (inelastic domestic supply and demand)

		Closed				Small Open				Large Open			
		Chicken		Fruit		Chicken		Fruit		Chicken		Fruit	
	Percent changes in....	↓α_F	↓α_C	↓α_F	↓α_C	↓α_F	↓α_C	↓α_F	↓α_C	↓α_F	↓α_C	↓α_F	↓α_C
1	Farm production	-1.1	-5	-2.3	-5	0.6	-2	6	-0.7	-0.2	-5	6	-3
2	Farm sales	1.2	-5	6	-5	3	-2	15	-0.7	2	-5	15	-3
3	Farm sales price	-4	-10	-10	-6	-1.0	-3	-0.2	-0.8	-3	-9	-0.9	-4
4	Effective farm production	-2	-10	-3	-6	1.2	-3	8	-0.8	-0.4	-9	7	-4
5	Farm welfare	-3	-15	-5	-10	2	-5	15	-2	-0.6	-13	14	-7
6	Farm waste	-51	-5	-51	-5	-51	-7	-54	-7	-51	-6	-54	-5
7	Total waste	-3	-23	-10	-26	-4	-24	-15	-27	-4	-23	-15	-26
8	Consumer purchases	1.0	-10	6	-6	0.2	-11	0.1	-8	0.6	-10	0.5	-7
9	Consumption	1.0	18	6	21	0.2	16	0.1	19	0.6	17	0.5	21
10	Value of imports	0	0	0	0	-6	-19	-2	-8	-3	-11	-2	-9
11	Value of waste	-3	-41	-11	-35	-2	-39	-9	-34	-3	-40	-9	-34
	Change in level of....												
12	$\Delta q_F/\Delta W_T$	0.63	0.49	0.44	0.36	0.98	0.62	1.00	0.50	0.83	0.52	0.97	0.42

Note 1: Highlighted cells indicate direct policy goals

Table 10b: Impacts of reducing waste rates by 50 percent in Chicken *versus* Fruit (elastic domestic demand)

		Closed				Small Open				Large Open			
		Chicken		Fruit		Chicken		Fruit		Chicken		Fruit	
	Percent changes in...	$\downarrow\alpha_F$	$\downarrow\alpha_C$	$\downarrow\alpha_F$	$\downarrow\alpha_C$	$\downarrow\alpha_F$	$\downarrow\alpha_C$	$\downarrow\alpha_F$	$\downarrow\alpha_C$	$\downarrow\alpha_F$	$\downarrow\alpha_C$	$\downarrow\alpha_F$	$\downarrow\alpha_C$
1	Farm production	-0.6	1.3	-0.3	2	0.7	0.4	6	0.3	0.1	1.1	6	1.2
2	Farm sales	1.7	1.3	8	2	3	0.4	15	0.3	2	1.1	15	1.2
3	Farm sales price	-3	3	-8	2	-0.9	0.9	-0.2	0.3	-2.1	2	-0.7	2
4	Effective farm production pri	-1.1	3	-0.3	2	1.3	0.9	8	0.3	0.1	2	8	2
5	Farm welfare	-1.7	4	-0.6	4	2.0	1.3	15.1	0.6	0.2	3	14.0	3
6	Farm waste	-50	1.3	-50	2	-51	2	-54	3	-51	1.4	-54	2
7	Total waste	-3	-16	-8	-21	-4	-15	-15	-19	-4	-16	-15	-20
8	Consumer purchases	1.7	3	8.2	2	0.5	3	0.18	3	1.1	3	0.7	3
9	Consumption	1.7	34	8	33	0.5	35	0.2	34	1.1	34	0.7	33
10	Value of imports	0	0	0	0	-5	6	-1.7	3	-2.5	3	-1.5	3.28
11	Value of waste	-2	-29	-7	-26	-2	-29	-9	-26	-2	-29	-9	-25
	Change in level of....												
12	$\Delta q_F/\Delta W_T$	0.41	-0.17	0.06	-0.16	0.94	-0.28	1.00	-0.29	0.73	-0.19	0.96	-0.20

Note 1: Highlighted cells indicate direct policy goals

Table 10c: Impacts of a 50% cut in rates of waste: Chicken versus Fruit (elastic domestic supply)

		Closed				Small Open				Large Open			
		Chicken		Fruit		Chicken		Fruit		Chicken		Fruit	
	Percent changes in...	$\downarrow\alpha_F$	$\downarrow\alpha_C$	$\downarrow\alpha_F$	$\downarrow\alpha_C$	$\downarrow\alpha_F$	$\downarrow\alpha_C$	$\downarrow\alpha_F$	$\downarrow\alpha_C$	$\downarrow\alpha_F$	$\downarrow\alpha_C$	$\downarrow\alpha_F$	$\downarrow\alpha_C$
1	Farm production	-1.3	-6	-2.8	-6	1.1	-3	13	-1.3	-0.3	-6	11	-6
2	Farm sales	0.9	-6	5	-6	3	-3	23	-1.3	2	-6	21	-6
3	Farm sales price	-3	-6	-9	-4	-1.1	-3	-0.3	-0.8	-2.5	-6	-1	-4
4	Effective farm production pri	-1.3	-6	-2	-4	1.1	-3	8	-0.8	-0.3	-6	7	-4
5	Farm welfare	-2.6	-12	-5	-9	2.2	-6	22	-2	-0.6	-12	19	-10
6	Farm waste	-51	-6	-51	-6	-51	-7	-54	-7	-51	-6	-54	-5
7	Total waste	-4	-23	-11	-27	-4	-24	-15	-27	-4	-23	-15	-26
8	Consumer purchases	0.8	-11	5.2	-7.3	0.3	-11	0.2	-8.2	0.6	-11	0.7	-7.1
9	Consumption	0.8	17	5	20	0.3	16	0.2	19	0.6	17	0.7	21
10	Value of imports	0	0	0	0	-6.9	-17	-2.7	-7.9	-3	-7.7	-2.6	-8.4
11	Value of waste	-3	-40	-11	-35	-2	-39	-9	-34	-3	-40	-9	-34
	Change in level of....												
12	$\Delta q_F/\Delta W_T$	0.72	0.55	0.51	0.42	0.98	0.62	1.00	0.50	0.84	0.56	0.96	0.42

Note 1: Highlighted cells indicate direct policy goals

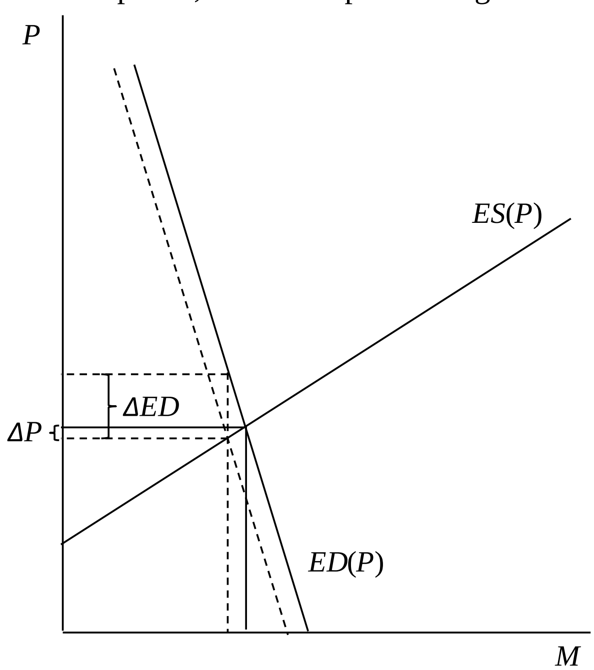
Box 1: The Elasticity of the Trade Curve of a Country versus facing a Country

It is well known that a “small” country importer (exporter) faces a flat (price elasticity = ∞) export supply (import demand) curve. This means any policy actions of this country has no impact on the market price at home or in the world. If on the other hand the country is a large country trader, it faces a trade curve with slope and so any domestic policy actions will influence domestic and hence world market prices.

However, it is also important to understand the elasticity of the trade curve of a country. The standard textbook shows the formula for the elasticity of import demand of a country (the case for chicken, fruit and bread in the UK) to be:

$$\eta^{ED} = \eta^{d}\left(\frac{q^{d}}{M}\right) - \eta^{s}\left(\frac{q^{s}}{M}\right) \qquad [A]$$

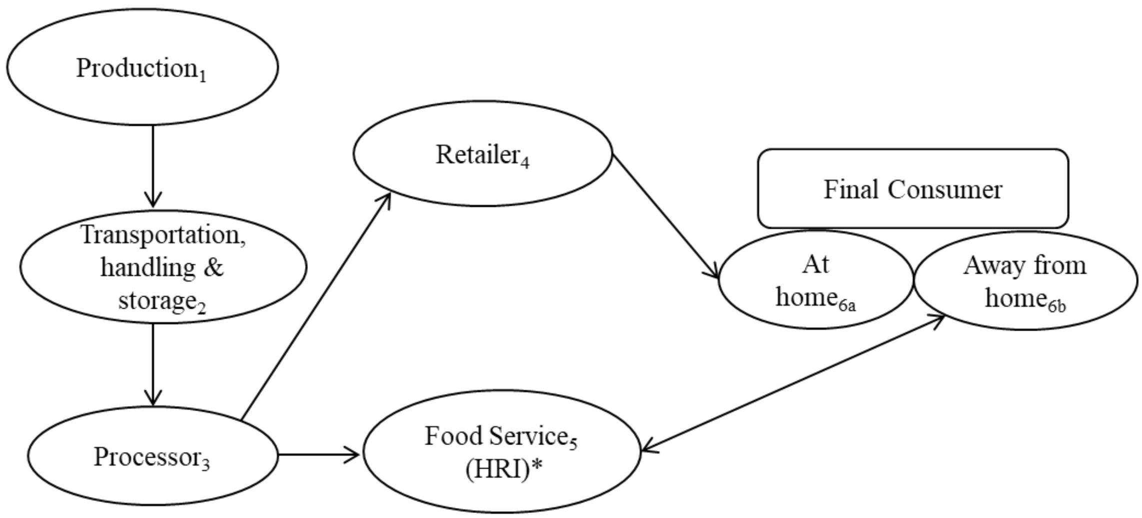
where η^d and η^s are domestic price elasticities demand and supply, q^d and q^s are domestic quantities demanded and supplied, and M represents total level of imports.* The price elasticity of import demand depends critically on the ratios of domestic supply and demand to imports. In the case of fruit, imports are 7 times the domestic production of fruit (see Table 3). This makes the second ratio in the equation above very small (the first ratio is close to 1), resulting in a price inelastic import demand curve of the country. Hence, any domestic policies will have minimal impact on world and hence domestic prices. This is illustrated in the figure below where a very large vertical shift in excess demand (because of a reduction in the rate of food waste) will have a small impact on market prices. The data for the four UK products is given in the table below (milk is a net exporter, so it has a positive sign for its excess supply curve).



	Chicken	Fruit	Bread	Milk
η^{ED}	-4.2	-0.88	-27.2	57.2*
q_D	2.23	4.86	2.90	7.21
q_S	1.68	0.61	2.79	7.38
M	0.55	4.25	0.10	-0.17
η^D	-0.67	-0.67	-0.50	-0.86
η^S	0.50	0.80	0.50	0.50
M/q_S	0.33	6.95	0.04	-0.02

* The elasticity of export supply is simply the negative of equation [A].

Figure 1: Stages of the Vertical Food Supply Chain (i = 1,…,6a,b)



*Food served at hotels, restaurants and institutions (like Universities, hospitals, etc.)

Figure 2: Economics of post-harvest loss for individual farmer (elastic demand)

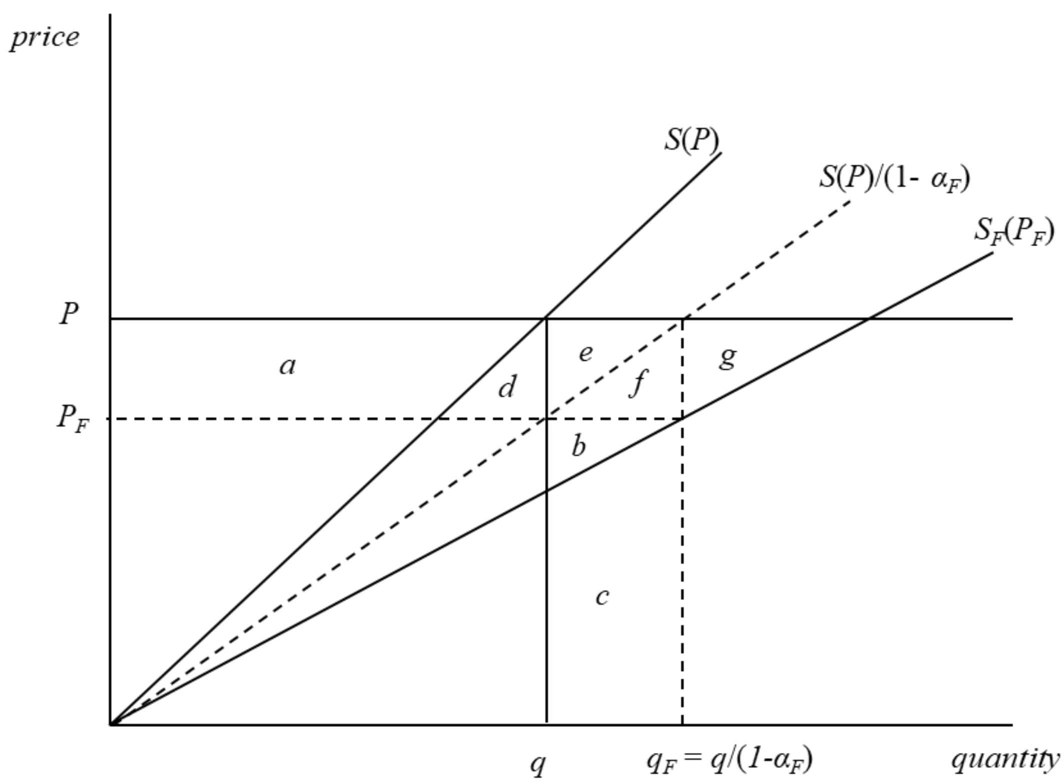


Figure 3: Economics of post-harvest loss at farm sector level (inelastic demand)

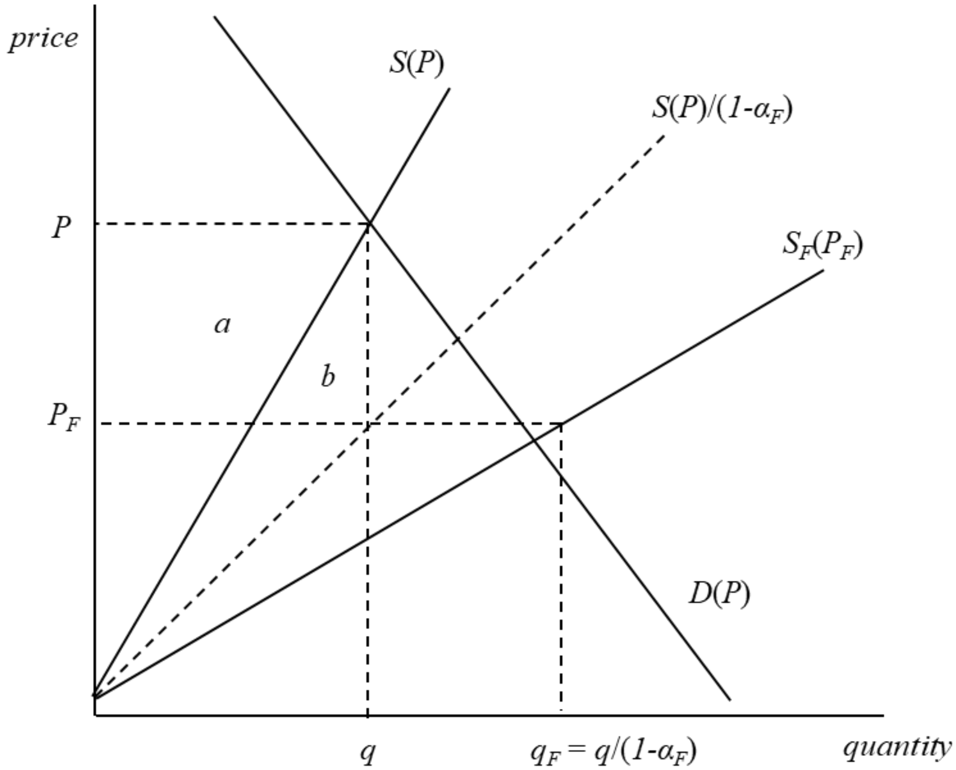
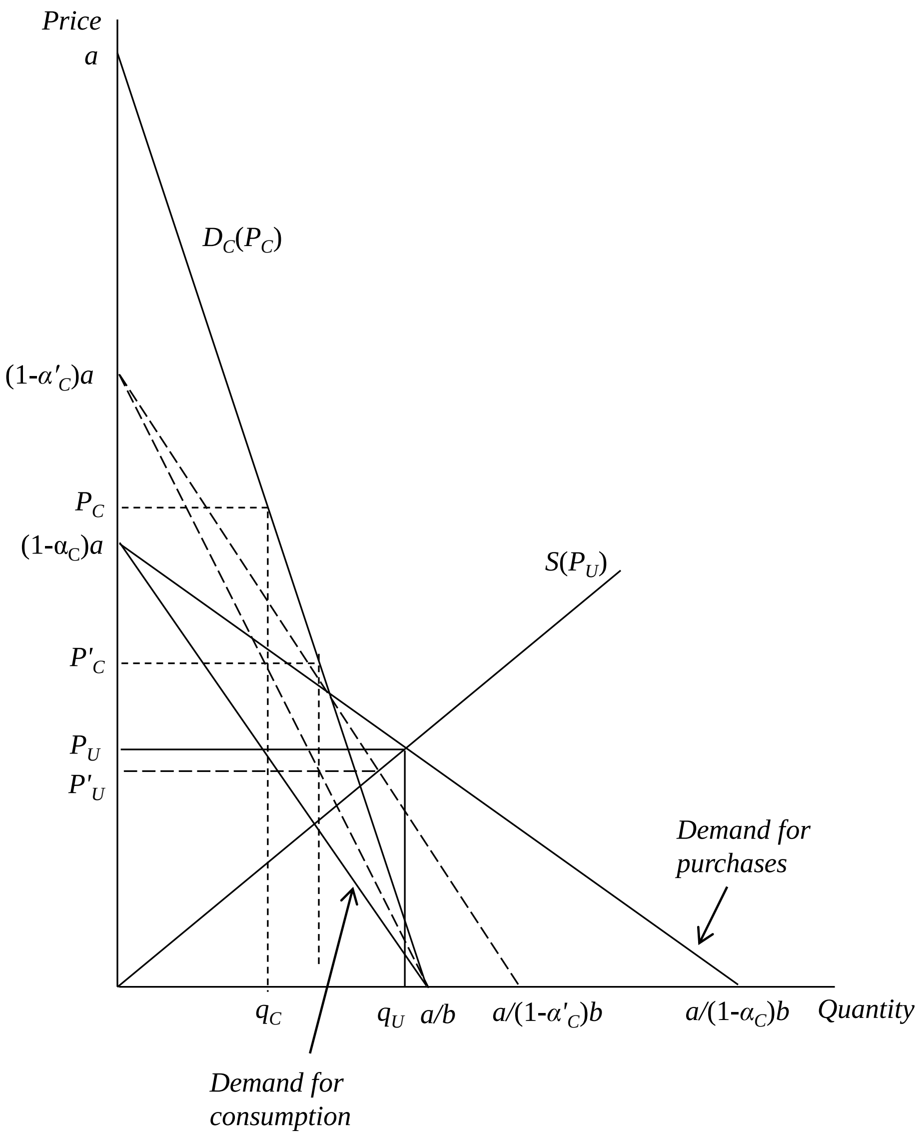


Figure 4: Market Effects of a lower consumer food waste rate



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Appendix 1

Consider a consumer who maximizes her utility by consuming food (q_C) and non-food goods denoted by *x*. The amount q_C is the actual food consumption, that is, what is left from purchases (*q*) after the percentage of consumer waste (α_C) has been accounted for, $q_C = (1-\alpha_C)q$. The utility function is assumed to be concave, and increased consumption of either good increases the consumer's utility. The consumer problem can be formulated as

$$\begin{aligned}&\max_{q_C, x} U(q_C, x)\\&s.t.\\&P_U q + P_x x \le Y\\&q_C = (1-\alpha_C)q\end{aligned},$$

where P_U is the price of food purchases and P_x the price of the aggregated non-food good. Consumer's income is *Y*. Expressing *q* from the last constraint and substituting it into the budget constraint, we can write the Lagrangian of the consumer's problem as

$$L = U(q_C, x) - \lambda\left(\frac{P_U q_C}{1-\alpha_C} + P_x x - Y\right), \quad \text{[A1.1]}$$

where $\lambda > 0$ is the marginal utility of income. The first-order conditions corresponding to the Lagrangian are

$$\begin{aligned}&U_{q_C} - \lambda\frac{P_U}{1-\alpha_C} = 0\\&U_x - \lambda P_x = 0\\&-\left(\frac{P_U q_C}{1-\alpha_C} + P_x x - Y\right) = 0\end{aligned}. \quad \text{[A1.2]}$$

Totally differentiating the system of equations [A1.2], we can derive a comparative statics result for the effect of a change in the rate of food waste on food consumption. The system of total differentials can succinctly be written as

$$\begin{bmatrix} U_{q_C q_C} & U_{q_C x} & -P_U/(1-\alpha_C) \\ U_{x q_C} & U_{xx} & -P_x \\ P_U/(1-\alpha_C) & P_x & 0 \end{bmatrix}\begin{bmatrix} dq_C/d\alpha_C \\ dx/d\alpha_C \\ d\lambda/d\alpha_C \end{bmatrix} = \begin{bmatrix} \lambda P_U/(1-\alpha_C)^2 \\ 0 \\ -P_U q_C/(1-\alpha_C)^2 \end{bmatrix}, \quad \text{[A1.3]}$$

where $U_{q_C q_C} = \partial^2 U / \partial q_C^{\,2}$, $U_{xx} = \partial^2 U / \partial x^2$, $U_{q_C x} = \partial^2 U / \partial q_C \partial x$ and by Young's theorem $U_{x q_C} = U_{q_C x}$. After applying Cramer's rule, we obtain

$$\frac{dq_C}{d\alpha_C} = \frac{\begin{vmatrix} \lambda P_U / (1-\alpha_C)^2 & U_{q_C x} & -P_U/(1-\alpha_C) \\ 0 & U_{xx} & -P_x \\ -P_U q_C / (1-\alpha_C)^2 & P_x & 0 \end{vmatrix}}{\begin{vmatrix} U_{q_C q_C} & U_{q_C x} & -P_U/(1-\alpha_C) \\ U_{x q_C} & U_{xx} & -P_x \\ P_U/(1-\alpha_C) & P_x & 0 \end{vmatrix}} = \frac{\dfrac{P_U}{(1-\alpha_C)^2}\left[\dfrac{q_C}{P_x}\left(U_{q_C x} - \dfrac{P_U U_{xx}}{P_x(1-\alpha_C)}\right) + \lambda\right]}{U_{q_C q_C} - \dfrac{P_U}{P_x(1-\alpha_C)}\left[2U_{q_C x} - \dfrac{P_U U_{xx}}{P_x(1-\alpha_C)}\right]} < 0 .$$

[A1.4]

In determining the sign of derivative [A1.4], we used that $U_{q_C q_C} < 0$ and $U_{xx} < 0$, which follows from the strict concavity assumption about the utility function. The cross partial derivative $U_{q_C x}$ represents the effect of a change in food consumption on the marginal utility of non-food consumption. It is reasonable to assume that this effect is non-negative, thus $U_{q_C x} \geq 0$. Because result [A1.4] holds for a general (well-behaved) utility function, it also holds for any Marshallian demand function describing consumer's food consumption.

The question now is what happens to food purchases, as opposed to food consumption, when the rate of consumer food waste changes. To determine that, we totally differentiate the function transforming food purchases into food consumption, $q_C = (1-\alpha_C)q$, to obtain

$$\frac{dq}{d\alpha_C} = \frac{1}{1-\alpha_C}\left(\frac{dq_C}{d\alpha_C} + q\right) \gtrless 0, \qquad \text{[A1.5]}$$

whose sign is indeterminate because $dq_C / d\alpha_C < 0$ according to [A1.4]. This means that while food consumption always increases with a reduction in food waste, the effect on food purchases is ambiguous.

The ambiguity of [A1.5] can intuitively be explained as follows. The optimal consumption of food and other goods is governed by the budget constraint and the first-order condition

$$(1-\alpha_C)\frac{MU_c}{P_U} = \frac{MU_x}{P_x}, \qquad \text{[A1.6]}$$

which follows from the first two equations in [A1.2]. When food waste is reduced (i.e., α_C decreases), consumption of food (q_C) weakly increases. Following an increase in q_C, marginal utility of food consumption (MU_c) decreases because of the law of diminishing marginal utility. For a given P_U , a change in the left-hand side (LHS) of [A1.6] is ambiguous as $\left(1-\alpha_C\right)$ increases and MU_c decreases. Which effect dominates depends on the utility function representing consumer's preferences. Our threshold for demand elasticity (i.e., elastic or inelastic demand) corresponds to properties of the utility function.

If the LHS of [A1.6] decreases, the right-hand side (RHS) must also decrease, and for a given P_x it means that MU_x decreases which can only happen if *x* increases (because of diminishing marginal utility of good *x*). The implications of these effects for food purchases (*q*) follow from the budget constraint: for a given income and prices, the budget constraint governs that *q* has to decrease. On the other hand, if the LHS of [A1.6] increases, so does MU_x, implying that the consumer consumes less of *x* and more income is available for food purchases.

Appendix 2

In this appendix, we derive the relationship between elasticity of the unobservable demand curve $q_C = D_C\left(P_C\right)$ and the elasticity of the observable demand for food purchases. The relation between the quantity of food consumption free of food waste (q_C) and the price the consumer is willing to pay for this quantity (i.e., the effective price) is governed by the following two equations

$$P_C = \frac{P_U}{1-\alpha_C} \qquad \text{[A2.1]}$$

$$q_C = \left(1-\alpha_C\right)q\,, \qquad \text{[A2.2]}$$

where P_U denotes the price the consumer pays for food purchases (q), and α_C is the rate of food waste. We want to calculate the elasticity of $q_C\left(P_C\right)$; we therefore consider P_U to be exogenous. Corresponding to every P_U, there are related values of q, q_C, P_C, and α_C.

Totally differentiating equations [A2.1] and [A2.2], we obtain

$$dP_C = \frac{1}{1-\alpha_C}dP_U + \frac{P_U}{\left(1-\alpha_C\right)^2}d\alpha_C \qquad \text{[A2.3]}$$

$$dq_C = -qd\alpha_C + \left(1-\alpha_C\right)dq\,. \qquad \text{[A2.4]}$$

The elasticity of $q_C\left(P_C\right)$ is

$$\eta_C = \frac{dq_C}{dP_C}\frac{P_C}{q_C}\,. \qquad \text{[A2.5]}$$

After substituting relationships from [A2.1 – A2.4] into [A2.5], we obtain

$$\eta_C = \frac{\left[-qd\alpha_C + \left(1-\alpha_C\right)dq\right]}{\left[\frac{1}{1-\alpha_C}dP_U + \frac{P_U}{\left(1-\alpha_C\right)^2}d\alpha_C\right]}\frac{\frac{P_U}{1-\alpha_C}}{\left(1-\alpha_C\right)q} = \frac{\left[-qd\alpha_C + \left(1-\alpha_C\right)dq\right]}{\left[\frac{1}{1-\alpha_C}dP_U + \frac{P_U}{\left(1-\alpha_C\right)^2}d\alpha_C\right]}\frac{P_U}{\left(1-\alpha_C\right)^2 q} =$$

$$\frac{\left[\left(1-\alpha_C\right)dq - qd\alpha_C\right]}{\left[\left(1-\alpha_C\right)dP_U + P_U d\alpha_C\right]}\frac{P_U}{q}$$

Multiplying the numerator and denominator of the last expression by $1/dP_U$ and rearranging, we obtain

$$\eta_C = \frac{(1-\alpha_C)\frac{dq}{dP_U}\frac{P_U}{q} - P_U\frac{d\alpha_C}{dP_U}}{(1-\alpha_C) + P_U\frac{d\alpha_C}{dP_U}} = \frac{(1-\alpha_C)\frac{dq}{dP_U}\frac{P_U}{q} - \frac{d\alpha_C}{dP_U}\frac{P_U}{\alpha_C}\alpha_C}{(1-\alpha_C) + \frac{d\alpha_C}{dP_U}\frac{P_U}{\alpha_C}\alpha_C}. \qquad [A2.6]$$

Let's set $\eta_D = \frac{dq}{dP_U}\frac{P_U}{q}$; it is the elasticity of the demand function for purchases. This elasticity is observed in the sense that its estimates can be found in the literature. The term $\rho = \frac{d\alpha_C}{dP_U}\frac{P_U}{\alpha_C}$ represents the elasticity of the food waste rate with respect to the food price. Using the elasticity from above, equation [A2.6] reduces to

$$\eta_C = \frac{(1-\alpha_C)\eta_D - \rho\alpha_C}{(1-\alpha_C) + \rho\alpha_C}. \qquad [A2.7]$$

Equation [A2.7] provides a way to estimate η_C using empirically obtainable η_D and other market parameters. Moreover, it shows that when α_C is exogenous (as is the case in our article), that is, $\rho = 0$, then $\eta_C = \eta_D$, meaning that the elasticity of the unobserved demand function is the same as the elasticity of the "observed" demand function.