Resources, Conservation & Recycling 149 (2019) 500–509

Contents lists available at ScienceDirect

Resources, Conservation & Recycling

journal homepage: www.elsevier.com/locate/resconrec

A conceptual and empirical framework to analyze the economics of consumer food waste

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ARTICLE INFO

Keywords:
Economic model
Food waste
Consumption
Consumer purchases
Effective consumption price
Downstream

ABSTRACT

We develop a microeconomic model to understand food waste of consumers. We capture at-home and away-from home food consumption and distinguish between food purchases and food consumption. We allow the consumer to choose the rate of food waste at home optimally to maximize her utility. We show that consumer purchases can decline or increase with a cut in the rate of consumer waste, depending on the elasticity of food demand. Using the UK data for poultry in 2012, we also show a case where for a price elastic demand food consumption increases with a reduction in the food waste rate, but food purchases (retail sales) increase.

1. Introduction

The 2015 UN Sustainable Development Goal Target 12.3 calls for halving per capita food waste and substantially reducing food losses by 2030. FAO (2011) estimates 30 percent of total food production is lost or wasted. USDA (2018) and ReFED (2016a,b) list a wide ranging and comprehensive portfolio of public and private initiatives to achieve the objective; one of them is the Food Loss and Waste 2030 Champions group established in November 2016 (Champions 12.3, 2017a, 2017b, 2018). The Commission for Environmental Cooperation (CEC, 2018) on FLW stands by the 2015 G20 declaration, reiterated in August 2018 (G20, 2018), that food loss and waste is “a global problem of enormous economic, environmental and societal significance” and all G20 members are encouraged to strengthen their collective efforts to prevent and reduce food loss and waste. Reducing food loss and waste allegedly will improve food security (higher food supplies and lower consumer prices as many in this world struggle with hunger) and the environment (lower GHGEs,[1] degradation of scarce land, water, biodiversity, and the use of polluting inputs like pesticides and fertilizers).[2]

Despite the widespread calls to reduce food loss and waste, there is much controversy regarding the paucity of data as to the extent of the problem, a lack of consensus on why there is food waste, and little evidence on how to reduce food loss and waste successfully across the food supply chain. Food waste can be disposed of using the EPA’s Food Recovery Hierarchy (EPA, 2014): reduce food waste; divert for food use; recover, recycle or compost; and lastly, place in landfills or incinerate. However, the priority ordering among dispositions of food loss and waste is yet to be determined (Galanakis, 2015; Eriksson et al., 2015; Bellemare et al., 2017). Furthermore, the economics of policies affecting the efficacy of such policies has not been derived because no foundational integrated economic model of the vertical and loss and waste disposition markets has been developed at the market level. Policy priorities will depend on multiple and interrelated drivers, the impacts of which can only be determined if such an economic framework has been developed that takes into account all the major interactions.

The issue of food loss and waste often focuses on how much is wasted and where in the supply chain. Moreover, the type of intervention (public or private initiatives) or market shocks that reduce food loss and waste are also discussed. Hence, the impacts of a change in consumer waste depend on the structure of the market (supply/demand elasticities, cross price elasticities in consumption; open vs closed economy), the underlying policy objectives and the interventions/market shocks that induce reductions in food loss and waste. Clearly,

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[1] Gustavsson et al. (2011) and Lipinski et al. (2013) argue that if food waste were a country, it would be the third largest greenhouse gas emitter after China and the United States.

[2] These two goals are not always consistent with one another as improved food security prefers more food supply while the environmental and resource degradation motivation wants lower food production. However, there are also cases where FLW reduction results in both food prices and production to decline.

https://doi.org/10.1016/j.resconrec.2019.06.008
Received 30 November 2018; Received in revised form 1 May 2019; Accepted 7 June 2019
Available online 28 June 2019

the underlying policy objective is not food waste per se but the environmental/resource degradation and implications for food security (de Gorter, 2014, 2017). These objectives can be at odds with each other as food waste declines.

There is a burgeoning literature on food loss and waste, most of which look at micro aspects of behavior. For household food waste (the major focus of this study as most waste in developed countries occurs at the consumer level), WRAP has undertaken the most comprehensive empirical studies (see Appendix 3 for sources of the data used in this study). U.S. studies include Buzby et al. (2011, 2014, 2015), Porata et al. (2018) and Buzby and Hyman (2012). Food waste occurring at the household level has multiple and interrelated drivers (Dou et al., 2016; Koivupuro et al., 2012; Lusk and Ellison, 2017; Aschemann-Witzel et al., 2015; Canali et al., 2017; Parizeau et al., 2015; Stancu et al., 2016; Garrone et al., 2014; Thyberg and Tonjes, 2016; Vittuari et al., 2015; Secondi et al., 2015; O'Donnell, 2016; Waarts et al., 2011). The main body of research on this area has consisted mainly of the identification, through qualitative analyses, of the potential behaviors that can somehow be related to food waste (Bernstad and la Cour, 2011; Bernstad and Anderson, 2015; Parry et al., 2015,Graham-Rowe et al., 2014). Consumers' attitudes towards and awareness of the matter has also been somehow explored by surveys and studies based on the theory of planned behavior (Graham-Rowe et al., 2015; Russel et al., 2017; Neff et al., 2015; Stefan et al., 2016). Many studies have analyzed the effects of labeling (Newsome et al., 2014; Wilson et al., 2017; Petit et al., 2017), packaging (Williams et al., 2012), or the use of large packages and over-buying (Halloran et al., 2014; Heller and Keoleian, 2017), and plate waste (Lorenz et al., 2017). Behavioral studies include Dusoruth and Peterson (2017);,Just and Grabielyan (2016a) Just and Gabrielyan (2016b), Just and Swigert (2016); Visschers et al. (2016); Quinn et al. (2018); Qi and Roe (2016); Refsgaard and Magnussen (2009), and Wansink (2018).

However, the true economic drivers of food waste and economic shifts caused by food waste reduction are not well understood. The current literature around food waste prevention and reduction focuses on the drivers of food waste (Quested et al., 2013; Reynolds et al., 2019), with limited conceptual understandings of the economics of food waste. Segrè et al. (2014) developed a background economic paper though this provided context and had little theory while WRAP (2014a) produced a report econometric modelling approach to understand the influences on food waste and food purchases. In addition, Wilson et al. (2017) have conducted economic experiments with food waste. Our modelling approach here follows that of Rutten (2013); de Gorter (2014, 2017), Katare et al. (2017); Landry et al. (2017); Belavina (2016) and Qi (2018).

There exists no foundational economic model of food loss and waste for consumers, processors, intermediaries and farmers based on first principles. To that end, we develop a micro foundational model of waste for at-home and away-from home food consumption (the latter increasing rather sharply in developed countries), with an abatement cost function that has the rate of waste endogenous, all integrated with the market for the dispositions (diversion, recovery, and landfill/incineration). Interventions affecting dispositions directly will also influence the food supply chain indirectly, and vice-versa. In a comparative statics exercise, we show that consumer purchases decline with a cut in the rate of consumer waste only with price inelastic demand curves. Food waste makes the demand for food more elastic (the demand curve for food purchases is flatter because of food waste and the effective price for food consumption is higher on the demand curve for food consumed, making it more elastic) (de Gorter, 2014).

We empirically apply the model to 2012 UK data in the poultry sector to illustrate the potential use of our model. We present some simulations on various interventions, private or public, that are assumed to reduce the consumer rate of waste. We show the economic impacts of six possible food waste reduction scenarios using our model: 1) a halving of household consumer food waste (with an elastic and inelastic demand curve), 2) an elimination of household consumer food waste, 3) an elimination of out of home consumer food waste (i.e. hospitality and food service industry), 4) an increase in the cost of landfill by a factor of 4, and 5) a reduction in the cost of recycling and recovery by 75%.

2. Analytical framework

The focus of our paper is on consumer food waste. The consumer wastes food at home and away from home. Since the importance of food away from home increases (especially in western countries), we devise an analytical framework that takes the important interactions between food consumption at home and away from home into account.

A representative consumer obtains utility from consumption of three goods: food consumed at home (q_C), away from home (q_A), and the numeraire good (y). Because our objective is to look more closely at the interaction between the two forms of food consumption and to a lesser extent at the interactions with other goods (aggregated in the numeraire good), we consider a quasi-linear utility function

$$U(q_C, q_A, y) = \phi_C q_C + \phi_A q_A - \frac{1}{2}(\lambda_C q_C^2 + \lambda_A q_A^2 + 2\kappa q_C q_A) + y \quad (1)$$

The parameters ϕ_C and ϕ_A represent the intrinsic quality of each good that increases the marginal utility of consuming that good. The parameters λ_C and λ_A measure the rate at which the marginal utility of consumption for a good declines with higher consumption of that good (Choi and Coughlan, 2006). The consumption of food at home and away from home depends on the relative price and the degree of substitutability, $\kappa \in [-1, 1]$. The closer κ is to zero, the more the goods are differentiated. If $\kappa = 1$, goods are perfect substitutes, and if $\kappa = -1$, goods are perfect complements (Häckner, 2000). For the resulting demand functions to be well-behaved, we require $\lambda_C\lambda_A - \kappa^2 > 0$ and $\lambda_A\phi_C - \kappa\phi_A > 0$.

The existence of food waste drives a wedge between the quantity of food purchased and consumed. This discrepancy holds for both food eaten at home and away from home. The amount of food eaten at home is a proportion of food purchased (q_U)

$$q_C = (1 - \alpha_C)q_U \quad (2)$$

where α_C is a proportion of food wasted at home. A similar relationship holds for the consumption (q_A) and purchase (q_H) of food away from home

$$q_A = (1 - \alpha_A)q_H \quad (3)$$

The consumer can avoid (some) food waste at home, but this is costly as the consumer has, among other things, to devote more time to planning food purchases and cooking, better preservation of food ingredients, or watch the expiry dates more closely. We denote the food waste abatement cost function as $C(1 - \alpha_C)$, where the argument $1 - \alpha_C$ represents the proportion of food saved. We assume $C(\cdot)$ is increasing and strictly convex, which means that it is more and more costly for the consumer to reduce food waste.

The consumer disposes of the food waste in two ways. A share (β) of food waste is separated and can be recovered (e.g., recycling or conversion into organic matter) while the rest ($1 - \beta$) ends up in landfill. The cost per ton of waste for recovery is r and the cost of landfill is w. Following the UK prices, we assume that $r < w$, that is, the consumer has an incentive to put an effort in separating food waste (e.g., recycling food waste can be subsidized or taxed less). Yet, in reality not all food waste is recycled despite the relative cost advantage (at least in the data for the UK). A main reason might be the unobservable transactions and opportunity costs for the consumer. To illustrate this, suppose the cost of recycled food waste is four cents per kilo and eight cents for landfill. However, the collection point for recycled waste might be too far from the consumer's home, making it less attractive for her to recycle. If the separation of recyclable and non-recyclable parts of food waste requires efforts exceeding a certain threshold (specific to each consumer), then the consumer is likely to opt for landfill.

These considerations lead us to use the following logistic function to determine the share of food waste that is recovered

$$\beta = \frac{1}{1 + e^{-\theta(x-x_0)}} \quad (4)$$

where θ denotes the steepness of the logistic curve, that is, how sensitive the consumer is to a change in the relative cost of landfill and recycling (x), and x_0 is the relative cost at which 50 percent of food waste is recycled.

The consumer spends her available income (I) on food purchases, the numeraire good (whose price is normalized to one), the cost of abating food waste, and the cost of food disposal. The consumer chooses the amount of food consumed at home, away from home, the rate of food waste at home, and the amount of the numeraire good to maximize her utility, subject to the budget constraint and two constraints linking food consumed and purchased at home and away from home

$$\begin{aligned} &\max_{q_C, q_A, \alpha_C, y} U(q_C, q_A, y) = \phi_C q_C + \phi_A q_A - \frac{1}{2}(\lambda_C q_C^2 + \lambda_A q_A^2 + 2\kappa q_C q_A) + y \\ &s.\ t. \\ &P_U q_U + P_H q_H + y + C(1-\alpha_C) + r\beta\alpha_C q_U + w(1-\beta)\alpha_C q_U = I \\ &q_C = (1-\alpha_C) q_U \\ &q_A = (1-\alpha_A) q_H \end{aligned} \quad (5)$$

By expressing q_U and q_H from the last two constraints and substituting them into the budget constraint, and by expressing y from the budget constraint and substituting it into the utility function, we convert a constrained optimization problem into an unconstrained problem with the following first-order conditions

$$q_C\colon \phi_C - \lambda_C q_C - \kappa q_A - \frac{P_U + \alpha_C z}{1-\alpha_C} = 0 \quad (6)$$

$$q_A\colon \phi_A - \lambda_A q_A - \kappa q_C - \frac{P_H}{1-\alpha_A} = 0 \quad (7)$$

$$\alpha_C\colon -\frac{P_U + z}{(1-\alpha_C)^2} q_C + C' = 0 \quad (8)$$

where $z = r\beta + w(1-\beta)$ denotes the weighted average of the cost of food waste disposal.

To establish the equilibrium on the food market, we require that food purchases for domestic use be equal to supply of food by the retailer[3]

$$q_U = S_R(P_U) \quad (9)$$

and that the demand for food away from home be equal to the supply of food by hotels, restaurants, and institutions (HRI)

$$q_H = S_H(P_H) \quad (10)$$

To operationalize the theoretical model, we assume the food waste abatement cost function is a hyperbola whose value approaches infinity (i.e., extremely high cost) as the share of food waste abated (i.e., $1-\alpha_C$) approaches 1

$$C(1-\alpha_C) = \frac{E}{1-(1-\alpha_C)} - E = E\left(\frac{1-\alpha_C}{\alpha_C}\right) \quad (11)$$

where $E > 0$ is a calibrating constant. This function meets the basic requirements mentioned earlier because its value is zero for no abatement efforts (when $\alpha_C = 1$) and approaches infinity when all food waste is eliminated ($\alpha_C = 0$). Moreover, it is increasing and strictly convex in $(1-\alpha_C)$. We use constant elasticity curves for the retail and HRI food supplies: $S_R(P_U) = B_R P_U^{\mu_R}$, and $S_H(P_H) = B_H P_H^{\mu_H}$, where μ_R and μ_H denote supply elasticities and B_R and B_H are calibrating constants.

[3] Because we focus on the consumer, our working assumption is that the food supply chain is not adjusting to any of scenarios of food waste reduction at the consumer level.

3. A simplified model

We use the analytical model above to run simulations that illustrate the inner workings of the economics of consumer food waste. However, to provide intuition and understand the some unexpected effects of a change in the rate of consumer food waste, we simplify the model to be able to demonstrate the effects graphically. To that end, we consider only food purchased for at-home consumption; the rate of food waste is exogenous as is the consumer price and the split of food waste to recovery and landfills.

Given these simplifying assumptions, we obtain the demand function for food consumption

$$q_C = \frac{(1-\alpha_C)\phi_C - \alpha_C z}{(1-\alpha_C)\lambda_C} - \frac{P_U}{(1-\alpha_C)\lambda_C} \quad (12)$$

The sign of the derivative $\frac{\partial q_C}{\partial \alpha_C} = -\frac{z + P_U}{(1-\alpha_C)^2\lambda_C}$ is negative as long as $z \geq 0$

(because $\lambda_C > 0$). This result suggests that the consumer will consume more with a reduced rate of food waste, provided there is a (positive) net cost to food waste disposal.

Consider, however, a situation in which the consumer does not have to pay for the food waste she recycles but she receives money instead. Suppose also that the amount received per unit of food recovered is sufficiently high relative to the cost of landfill such that $z < 0$. In that case, the sign of $\partial q_C/\partial \alpha_C$ is ambiguous, depending on the relative size of z and P_U. This implies that under certain constellations of the cost of food waste disposal and the market price of food, the food consumption decreases as food waste rate decreases. This effect may occur because the consumer can make money from recycling the food waste and use that money to purchase more of non-food goods.

Combining Eq. (12) with the constraint $q_C = (1-\alpha_C)q_U$, we obtain a derived demand function for food purchased

$$q_U = \frac{(1-\alpha_C)\phi_C - z\alpha_C}{(1-\alpha_C)^2\lambda_C} - \frac{P_U}{(1-\alpha_C)^2\lambda_C} \quad (13)$$

To gain further intuition, let us now also ignore the net cost food waste disposition (i.e., $z = 0$). Then, Eqs. (12and 13) simplify to

$$q_C = \frac{\phi_C}{\lambda_C} - \frac{P_U}{(1-\alpha_C)\lambda_C} = D(P_U) \quad (14)$$

and

$$q_U = \frac{\phi_C}{(1-\alpha_C)\lambda_C} - \frac{P_U}{(1-\alpha_C)^2\lambda_C} = D_U(P_U) \quad (15)$$

We know that under our assumptions $\frac{\partial q_C}{\partial \alpha_C} < 0$; that is, if the rate of food waste decreases, consumption increases (regardless of the demand elasticity).

The effect of a lower food waste rate on food purchases ($\partial q_U/\partial \alpha_C$) is still ambiguous, however.

$$\frac{\partial q_U}{\partial \alpha_C} = \frac{1}{(1-\alpha_C)^2\lambda_C}\left(\phi_C - \frac{2P_U}{1-\alpha_C}\right) \quad (16)$$

The price elasticity of the demand for food purchases can be calculated as

$$\xi_U = -\frac{P_U}{(1-\alpha_C)\phi_C - P_U}$$

from which $\phi_C = \left(1 - \frac{1}{\xi_U}\right)\frac{P_U}{1-\alpha_C}$.

Substituting parameter ϕ_C into derivative [16], we obtain

$$\frac{\partial q_U}{\partial \alpha_C} = -\frac{P_U}{(1-\alpha_C)^3\lambda_C}\left(1 + \frac{1}{\xi_U}\right)$$

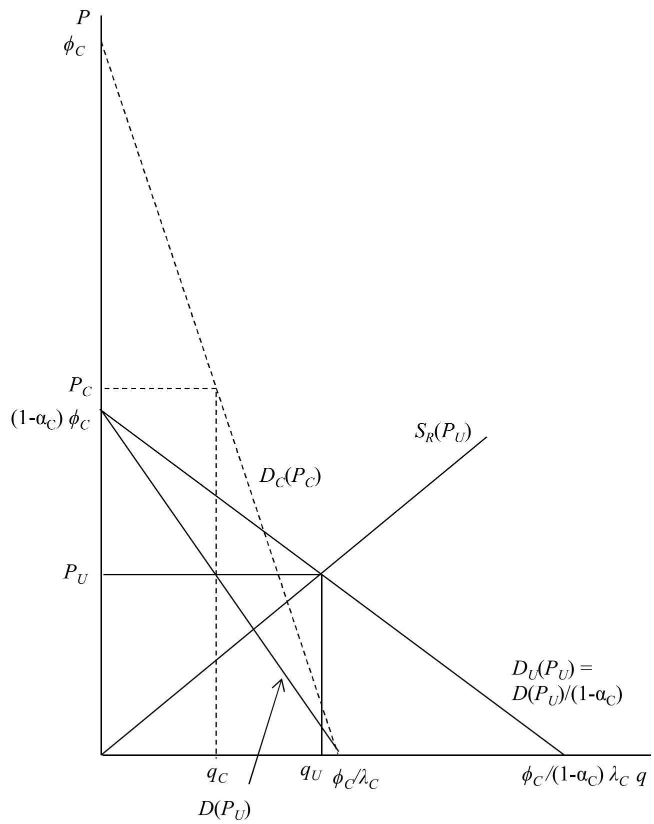

Fig. 1. Economics of food waste by consumers.

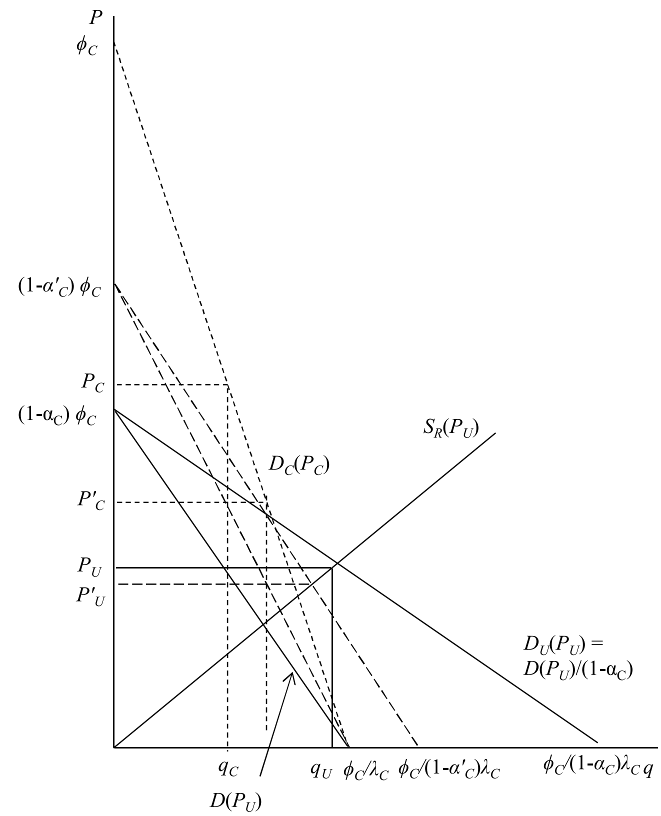

Fig. 2. Market effects of a lower consumer food waste rate.

The derivative $\frac{\partial q_U}{\partial \alpha_C}$ is negative if $\xi_U < -1$, that is, if the demand curve is elastic, and positive if the demand curve is inelastic, that is, $\xi_U > -1$.

To show the intuition for this result, we begin by depicting the initial equilibrium in Fig. 1, and then using Fig. 2, we show how a cut in the rate of food waste causes an increase in food consumption but food purchases could go up or down.

Fig. 1 depicts the inverse demand curves corresponding to Eqs (12 and 13). These are

$$P_U = (1 - \alpha_C)\phi_C - (1 - \alpha_C)\lambda_C q_C \quad (17)$$

$$P_U = (1 - \alpha_C)\phi_C - (1 - \alpha_C)^2\lambda_C q_U \quad (18)$$

A comparison of Eqs. (14 and 15) shows that the inverse demand curve for food consumption always lies below the inverse curve for food purchased (Fig. 1). It is because both curves share the same intercept but the curve for food consumption is steeper (since $0 < \alpha_C < 1$).

Notice that the food consumption demand curve [12] depends on the observed market price of food, P_U and is, therefore, not a proper demand curve. However, we can conceive of an unobserved (internal) price of food consumed (P_C) at which the consumer values the food consumed. Following Fig. 1, such a price has to satisfy

$$P_C D(P_U) = P_U D_U(P_U) \quad (19)$$

which can succinctly be written as $P_C q_C = P_U q_U$. Recalling that $q_U = q_C/(1 - \alpha_C)$,[4] the unobserved consumer price is

$$P_C = \frac{P_U}{1 - \alpha_C} \quad (20)$$

We can think of this price as consumer's willingness to pay for food which would not require any waste. This occurs because there is no utility from food waste in our model.

With the consumer price of food [20], we can derive a proper (albeit unobserved) demand for food consumption. This is done by substituting $P_U = (1 - \alpha_C)P_C$ into Eq. (12), which produces

$$q_C = \frac{\phi_C}{\lambda_C} - \frac{P_C}{\lambda_C} = D_C(P_C) \quad (21)$$

This corresponds to the dashed inverse demand curve depicted in Fig. 1. This demand curve does not change its position as the rate of food waste changes because neither the vertical, nor the horizontal intercept contains α_C. This is in line with our interpretation of this curve as mapping food consumption levels free of waste with corresponding prices.

A decrease in the rate of consumer food waste increases the vertical intercept of both inverse demand curves [17] and [18] by the same amount (Fig. 2). The amount by which these intercepts increase depends on the cut in α_C and the initial value of the parameter ϕ_C. 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 [17] which is fixed at . This means food consumption increases with a cut in α_C. On the other hand, the purchased 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.[5] Note that both demand curves become steeper after the cut in α_C.

To understand this ambiguity intuitively, consider a perfectly inelastic demand for food purchases. In this case the inverse demand curve is perpendicular to the horizontal axis, and a reduction in the rate of food waste shifts the inverse demand curve to the left. Food

[4] Assuming no food donations.

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

Table 1
Summary of simulations results.
Source: Own calculations.

			% change relative to baseline					
		Baseline	α_C halved	α_C close to 0*	$\alpha_A = 0$	Elastic demand and α_C halved **	Cost of landfill 4x higher	Cost of recovery 75% lower
Purchase price (pounds/kilo)	P_U	4.48	−18.6	−41.4	−0.1	3.6	0.3	0.5
Price at HRI (pounds/kilo)	P_H	4.93	−1.4	−2.4	0.0	−1.8	0.0	0.0
Consumer-equiv. price at home (pounds/kilo)	P_C	7.25	−37.8	−63.1	−0.1	−20.9	0.4	0.7
Consumer-equiv. price away from home (pounds/kilo)	P_{HE}	5.05	−1.4	−2.4	−2.3	−1.8	0.0	0.0
Retail supply (million tonnes)	q_R	1.00	−4.0	−10.1	0.0	0.7	0.1	0.1
HRI supply (million tonnes)	q_H	0.56	−0.4	−0.7	0.0	−0.5	0.0	0.0
Consumer food purchases at home (million tonnes)	q_U	1.00	−4.0	−10.1	0.0	0.7	0.1	0.1
Consumption at home (million tonnes)	q_C	0.62	25.6	42.6	0.0	31.8	−0.1	−0.1
Consumption away from home (million tonnes)	q_A	0.54	−0.4	−0.7	2.4	−0.5	0.0	0.0
Proportion of consumer food waste at home	α_C	0.38	−50.0	−95.1	0.0	−50	0.2	0.3
Share of consumer waste going to recovery	β	0.11	0.0	0.0	0.0	0.0	799.1	799.1
Weighted average cost of dispositions (pounds/kilo)	z	0.08	0.0	0.0	0.0	0.0	−45.3	−86.3
Food waste	K	0.39	−50.3	−92.5	−3.3	−48.0	0.2	0.4
…of which recycling	R	0.04	−50.3	−92.5	−3.3	−48.0	801.2	803.1
…of which landfill	L	0.35	−50.3	−92.5	−3.3	−48.0	−98.9	−98.9

* We cannot achieve complete elimination of food waste in our model because of the assumption of a hyperbolic abatement cost function, which yields prohibitively high cost at values of α_C near zero.
** Demand elasticity = -1.5.

purchases therefore decrease. On the other hand, with a perfectly elastic demand curve the inverse demand curve is horizontal. A reduction in the rate of food waste shifts it up because of a change in the vertical intercept. Higher demand increases the price of food and also production, which in equilibrium equals the amount of food purchased. Any other elasticity of the food demand curve lies between these two extreme cases and can, therefore, lead to ambiguous effects, depending on whether the horizontal or the vertical shift dominates.

4. Numerical illustration

To obtain quantitative insights into the economics of the consumer food waste, we have calibrated the theoretical model presented in the earlier section using UK data for 2012 (see Appendix 3 for sources). We include disposition costs, endogenous prices and an endogenous rate of waste for at-home consumption (the away-from home food waste is fixed),

Table 1 presents the results of several simulations we have performed. The third column presents the values of the baseline variables (prices, quantities, and shares). The first scenario is halving the rate of consumer food waste at home (α_C). Since the rate of food waste is endogenous, we achieved the desired reduction in α_C by making it less costly for the consumer to abate food waste by appropriately changing the constant of the abatement cost function. As the proportion of food waste decreases from 38 percent to 19 percent, food purchases go down because the consumer does not need to buy as much food as before. Less purchases result in less production of food which also reduces its market price by about 19 percent for retail and 1.4 percent for away-from home food. The reduction in the purchase price is a reason why the amount of food consumed increases. Notice that the amount of waste goes down by more than half (50.3 percent) because the amount of waste is the product of the waste rate and the quantity purchased, which has also declined. There is therefore a synergy effect between the rate of food waste and its quantity.

When food waste is eliminated by forcing α_C close to zero,[6] the previous results do not change qualitatively but their size is magnified. A comparison of the fourth and the fifth column indicates that the effects of a reduction in α_C are not linear, reflecting the non-linearites in the model. The elimination of the food waste in HRI (column six, α_A) has a negligible effect on the poultry market. There are two reasons for that. First, the waste rate at HRI is low to start with ($\alpha_A = 0.023$) and, second, the amount of food eaten at HRI is less than at home.

Column seven presents results of a simulation in which demand for food at home is assumed to be price elastic (-1.5). The key difference compared to the counterpart simulation with an inelastic demand is that the purchase (retail) price of food increases. The supply of food (food purchases), therefore, increases as well. The implication of this finding (although we do not model it explicitly) is that for given wood loss and waste rates upstream in the supply chain, the amount of food waste increases. Notice also that although the purchase price increases, the consumer-equivalent price at home decreases (as it does with inelastic demand, but less so).

In the two final scenarios, we evaluate two channels of eliminating the food waste going to landfill. Recall that the percentage of waste going to landfill depends on the relative cost of landfill and recovery. In the eighth column, we increase the cost of landfill four times, keeping the cost of recovery at the baseline level. Doing so, we obtain a 99 percent share of waste being recovered and only one percent being disposed of at a landfill.[7] To obtain the same split of the food waste disposal between recovery and landfill, the cost of recovery needs to be reduced by 75 percent (for given model parameters) (the ninth column of Table 1).

Although the two scenarios yield very similar results for a given relative cost of landfill and recovery, there is one key difference: reducing the cost of recovery has a different effect on the total per unit cost of waste disposal (z) from increasing the cost of landfill. This is because the total cost per unit is a share-weighted average of the cost of recovery and landfill, and the shares change depending on the relative cost.

5. Conclusions

In this paper, we developed a microeconomic framework to better understand the economics of consumer food waste. We model at-home

[6] Our model specification does not allow us to eliminate food waste completely because of the hyperbolic abatament cost function, which yields exteremely high cost at very low levels of α_C, and the model does not solve.

[7] This ratio is conditional on the baseline parameters of the logistics curve.

and away-from home food demand (with a cross-price elasticity of substitution), each incurring food waste. Food purchased and consumed are clearly distinguished in our model, with the rates of waste endogenous. We capture the food waste occurring both at home and away from home and let the consumer choose the proportion of food wasted at home to maximize her utility. We find changes in the rate of consumer waste will affect (a) "effective" consumption prices (consumers "pay" for the waste in the form of higher implicit prices for the quantity they end up consuming); and (b) consumer purchases and hence prices up the supply chain.

We find that if there is a reduction in the rate of at-home consumer food waste:

- Purchases and hence purchase prices will decline if demand is price inelastic; will increase otherwise (results can be augmented if there are significant costs of disposition)
- Effective consumer prices always decline, regardless if the quantity and price of food purchases increase or decrease
- Consumption always increases (provided there are no costs of disposition; otherwise it is ambiguous, depending on the cost of disposition and the demand elasticity).

We illustrate our results empirically by using the UK data for poultry in 2012. Our results show that a 50% reduction in at home consumer poultry waste (i.e. achieving SDG 12.3 for at home consumer poultry waste) with an inelastic demand curve for at-home food would lead to a 25% increase in consumption, with only a 4% reduction in retail sales, and 19% reduction in consumer purchase price. However, for a price elastic demand curve (e.g., small open economy although not modeled here), we find that food consumption would increase even more (31%), but at a 0.7% reduction in retail sales.

The implications for achieving SDG 12.3 (and obtaining retail sector engagement) is that there is not a direct linear relationship between reducing consumer food waste and a reduction in retail sales. This only occurs with inelastic demand products – of which poultry is not. Retailers may have previously used this possible linear relationship not to engage fully with food waste reduction activities – as they do not wish to hurt their sales. These results have removed this barrier. However, the price reduction of 19% is an implication that needs further exploration with policy makers, retailers, and other actors in the food system. Likewise, the synergy effect between the rate of food waste and its quantity needs further exploration. In future research all the economic relationships need to be explored further "up" the supply chain (including an understanding of farm-based impacts), and with a greater number of products as there will be food substitution effects that can be important.

Author contribution

Drabik and de Gorter undertook the development of the theory and empirical framework and ran all of the simulations. Reynolds derived all of the data (see Appendix 3) and aided in all aspects of the research, including the writing of this paper.

Acknowledgements

This research was supported by funding from the World Bank. Christian Reynolds is supported from the HEFCE Catalyst-funded N8 AgriFood Resilience Programme and matched funding from the N8 group of Universities. Christian Reynolds has additional funding from NERC to support an Innovation Placement at the Waste and Resources Action Programme (WRAP) (Grant Ref: NE/R007160/1).

Appendix 1 Calibration of the model based on prices, quantities, and assumed elasticities

Using the observed quantities, prices, and assumed elasticities together with the theoretical model equations, we calibrate the unknown constants and prices and quantities as follows

$$z = r\beta + w(1-\beta)$$
$$\theta = -\frac{\ln\left(\frac{1}{\beta}-1\right)}{x-x_0}$$
$$B_R = \frac{q_U}{P_U^{\mu_R}}$$
$$B_H = \frac{q_H}{P_H^{\mu_H}}$$
$$E = \frac{\alpha_C^2(P_U+z)}{(1-\alpha_C)^2}q_C$$
$$q_C = (1-\alpha_C)q_U$$
$$q_A = (1-\alpha_A)q_H$$

The consumer demand functions are implicitly defined by

$$\phi_C - \lambda_C q_C - \kappa q_A - \frac{P_U + \alpha_C z}{1-\alpha_C} = 0$$
$$\phi_A - \lambda_A q_A - \kappa q_C - \frac{P_H}{1-\alpha_A} = 0$$

which after solving yields

$$q_C = \frac{(1-\alpha_C)(\lambda_A\phi_C - \kappa\phi_A) - \lambda_A\alpha_C z}{(1-\alpha_C)(\lambda_C\lambda_A-\kappa^2)} - \frac{\lambda_A P_U}{(1-\alpha_C)(\lambda_C\lambda_A-\kappa^2)} + \frac{\kappa P_H}{(1-\alpha_A)(\lambda_C\lambda_A-\kappa^2)}$$
$$q_A = \frac{(1-\alpha_C)(\lambda_C\phi_A - \kappa\phi_C) + \kappa\alpha_C z}{(1-\alpha_C)(\lambda_C\lambda_A-\kappa^2)} - \frac{\lambda_C P_H}{(1-\alpha_A)(\lambda_C\lambda_A-\kappa^2)} + \frac{\kappa P_U}{(1-\alpha_C)(\lambda_C\lambda_A-\kappa^2)}$$

However, we observe elasticities of the demand for purchased food eaten at home or at a restaurant. We therefore use $q_C = (1-\alpha_C)q_U$ and $q_A = (1-\alpha_A)q_H$ to transform the above system of equations into

$$q_U = \frac{(1-\alpha_C)(\lambda_A\phi_C - \kappa\phi_A) - \lambda_A\alpha_C z}{(1-\alpha_C)^2(\lambda_C\lambda_A - \kappa^2)} - \frac{\lambda_A}{(1-\alpha_C)^2(\lambda_C\lambda_A - \kappa^2)}P_U + \frac{\kappa}{(1-\alpha_A)(1-\alpha_C)(\lambda_C\lambda_A - \kappa^2)}P_H$$
$$q_H = \frac{(1-\alpha_C)(\lambda_C\phi_A - \kappa\phi_C) + \kappa\alpha_C z}{(1-\alpha_A)(1-\alpha_C)(\lambda_C\lambda_A - \kappa^2)} - \frac{\lambda_C}{(1-\alpha_A)^2(\lambda_C\lambda_A - \kappa^2)}P_H + \frac{\kappa}{(1-\alpha_A)(1-\alpha_C)(\lambda_C\lambda_A - \kappa^2)}P_U$$

which can be written as

$$q_U = a - bP_U + cP_H$$
$$q_H = d - eP_H + cP_U$$

where

$$a = \frac{(1-\alpha_C)(\lambda_A\phi_C - \kappa\phi_A) - \lambda_A\alpha_C z}{(1-\alpha_C)^2(\lambda_C\lambda_A - \kappa^2)}$$
$$b = \frac{\lambda_A}{(1-\alpha_C)^2(\lambda_C\lambda_A - \kappa^2)}$$
$$c = \frac{\kappa}{(1-\alpha_A)(1-\alpha_C)(\lambda_C\lambda_A - \kappa^2)}$$
$$d = \frac{(1-\alpha_C)(\lambda_C\phi_A - \kappa\phi_C) + \kappa\alpha_C z}{(1-\alpha_A)(1-\alpha_C)(\lambda_C\lambda_A - \kappa^2)}$$
$$e = \frac{\lambda_C}{(1-\alpha_A)^2(\lambda_C\lambda_A - \kappa^2)}$$

We need to calibrate five parameters of the consumer demand equations: ϕ_C, ϕ_A, λ_C, λ_A, κ. For that, we need five equations.

Own and cross-price elasticities of the demand functions can be written as:

$$\xi_U = -b\frac{P_U}{q_U};\ \xi_H = -e\frac{P_H}{q_H};\ \xi_{UH} = c\frac{P_H}{q_U}$$

from which

$$b = -\frac{\xi_U q_U}{P_U};\ e = -\frac{\xi_H q_H}{P_H};\ c = \frac{\xi_{UH} q_U}{P_H}$$

and the remaining demand parameters come directly from the demand functions

$$a = q_U + bP_U - cP_H,$$
$$d = q_H + eP_H - cP_U$$

We now have the left-hand sides of the following system of equations

$$a = \frac{(1-\alpha_C)(\lambda_A\phi_C - \kappa\phi_A) - \lambda_A\alpha_C z}{(1-\alpha_C)^2(\lambda_C\lambda_A - \kappa^2)}$$
$$b = \frac{\lambda_A}{(1-\alpha_C)^2(\lambda_C\lambda_A - \kappa^2)}$$
$$c = \frac{\kappa}{(1-\alpha_A)(1-\alpha_C)(\lambda_C\lambda_A - \kappa^2)}$$
$$d = \frac{(1-\alpha_C)(\lambda_C\phi_A - \kappa\phi_C) + \kappa\alpha_C z}{(1-\alpha_A)(1-\alpha_C)(\lambda_C\lambda_A - \kappa^2)}$$
$$e = \frac{\lambda_C}{(1-\alpha_A)^2(\lambda_C\lambda_A - \kappa^2)}$$

which can be solved for the unknown parameters ϕ_C, ϕ_A, λ_C, λ_A, κ. Noting that the three equations for b, c, and e can be solved separately, we obtain

$$\lambda_A = \frac{b}{(1-\alpha_A)^2(be - c^2)};\ \lambda_C = \frac{e}{(1-\alpha_C)^2(be - c^2)}$$
$$\kappa = \frac{c}{(1-\alpha_A)(1-\alpha_C)(be - c^2)}$$
$$\phi_C = (1-\alpha_C)\lambda_C a + (1-\alpha_A)\kappa d + \frac{\alpha_C}{1-\alpha_C}z$$
$$\phi_A = (1-\alpha_C)a\kappa + (1-\alpha_A)d\lambda_A$$

Appendix 2 Parameters assumed to calibrate the empirical model

		2012	Unit
Elasticities			
Own price elasticity of consumer demand for home food consumption	ξ_U	−0.670	unit free
Own price elasticity of consumer demand for HRI food consumption	ξ_H	−1.020	unit free
Cross price elasticity of consumer demand for home food consumption with respect to HRI price	ξ_{UH}	0.031	unit free
Elasticity of retail food supply	μ_R	0.200	unit free
Elasticity of HRI food supply	μ_H	0.300	unit free
Shares			
Proportion of consumer food waste at HRI (exogenous)	α_A	0.023	share
Proportion of consumer food waste at home (endogenous)	α_C	0.382	share
Share of consumer waste going to recycling	β	0.110	share
Quantities			
Retail supply of food	q_R	0.999	million tonnes
HRI supply of food	q_H	0.556	million tonnes
Prices			
Purchase price of food (=retail price)	P_U	4.483	£/kg
Price of food at HRI (10% more than P_U in baseline)	P_H	4.931	£/kg
Cost of recycling	r	0.041	£/kg
Cost of landfill	w	0.085	£/kg
CALCULATED VALUES BASED ON THE MODEL EQUATIONS			
Consumer food purchases at home	q_U	0.999	million tonnes
Food consumption at home	q_C	0.618	million tonnes
Consumption of food away from home	q_A	0.543	million tonnes
Food waste at home	waste	0.381	million tonnes
Recycling	R	0.042	million tonnes
Landfill	L	0.339	million tonnes
Weighted average cost of dispositions	z	0.080	£/kg
Relative cost of landfill and recycling in the baseline	x	2.073	unit free
Relative cost of landfill and recycling to a achieve β	x_0	4	unit free

Appendix 3 Data Sources

This paper focuses on the example of consumer poultry food waste in UK for the year 2012. The reason for this year and product selection is the availability of high quality and granular data for the UK for that year. If data gaps are present, additional data has been sourced from other years between 2007 and 2015. Due to the estimation of data gap, the values presented in this paper should be treated as rounded estimations, and should not be used for other applications other than the modelling purpose intended in this publication.

Poultry

Production, Post farm, Imports and exports

The total UK production, imports, exports and changes in stocks of poultry were sourced from the Agriculture and Horticulture Development Board (AHDB) (various years) with the post-harvest/transportation waste calculated multiple sources (Gustavsson et al., 2011; Hartikainen et al., 2018; Redlingshöfer et al., 2017; Tesco PLC, 2018b). Additional imports and exports data for poultry were gathered from the UK government customs service (HMRC, 2018).

HRI

Hospitality and food service sales/purchases were sourced from Living Cost and Food survey (DEFRA and ONS, 2017), with hospitality and food service consumption from the National Diet and Nutrition survey (Bates et al., 2014). WRAP (2011a, 2013a, 2013b, 2013c, 2013d, 2013e) provide tonnages of hospitality Meat and Fish waste for the subsectors of Restaurants, Pubs, Education, Healthcare, Hotels, QSRs, Services, Leisure, and Staff catering. Tonnages of poultry waste were extracted from Meat and Fish waste, assuming a similar percentage of Poultry waste to Meat and Fish waste as found in UK households (i.e., 53% Poultry waste), this percentage was sourced from WRAP (2014b). A generic proportional split bet between plate and preparation waste was supplied by WRAP (2013c) and applied to the tonnages of hospitality poultry waste.

Retail

Retailer purchased data was sourced from Living Cost and Food survey (DEFRA and ONS, 2017), with household consumption from the National Diet and Nutrition survey (Bates et al., 2014). Retail waste figures were sourced from WRAP (2016), with cross validation with Tesco's food waste reporting (2018a, 2018b) and Moult et al. (2018).

Household

Household food waste was supplied from WRAP (2014b). Poultry waste was disaggregated from total Meat & Fish waste using the ratio (53%) of household poultry to total Meat & Fish waste as found in the UK household (WRAP, 2018a), and validataed with additional WRAP data found in other WRAP reports WRAP, 2008, 2009, 2011b, 2013f, 2014b).

Prices

Average yearly wholesale poultry prices were supplied from AHDB (AHDB, 2018, 2016, 2015a, 2015b, 2014, 2012), with average poultry production, import and export prices from HMRC (HMRC, 2018). Average Purchase prices were estimated using the Living Cost and Food survey (DEFRA and ONS, 2017) and cross validated with data from AHDB (AHDB, 2018, 2016, 2015a, 2015b, 2014, 2012). Retailer markups were estimated from discussions with industry experts (22%). Hospitality markups were estimated as a minimum of 10% higher price than retail price due to margins and value added taxes being currently at 10%. This means that prices for consumption of a sit down meal out of home are a minimum of 10% higher than that of the same food consumed in home. In practice the markup prices are higher, and vary considerably across the HRI sector. Due to the lack of a single margin, the minimum (10%) has been selected.

Waste Treatment costs

Waste treatment costs in Appendix 2 were sourced from WRAP (2012, 2013g, 2017, 2018b). Costs for donations were sourced from Fareshare (Tatum, 2018), however, as there was no comprehensive quantification of donations as a treatment method for food waste until post 2014 this will not affect our example (WRAP, 2016). For simplicity we assume that anaerobic digestion is the only form of recycling available, though other (such as animal feed) are also available in the modeled time period. Appendix 2 provides the waste treatment costs.

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