Optimal Food Waste: Taxes and Government Incentives

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Abstract

In 2010, 21% of the total U.S. food available for consumption was wasted at the household level. In response to this waste, a number of counties and U.S. localities have instituted policies (disposal taxes) directed toward reducing this waste. However, currently, there is no federal food-waste disposal tax. The aim of this paper is to establish a theoretical foundation for household food waste, and based on this theory, determine an optimal food-waste (disposal) tax along with government incentives. The theory unravels the interrelation between social food insecurity and external environmental costs, not generally considered by households when they waste food. An optimal disposal tax and government incentives involve Pigovian mechanisms and government benefits. For a zero level of food waste, the optimal disposal taxes and government incentives approach infinity.

Key words: Externalities, Food insecurity, Food waste, Social welfare, Sustainability.
JEL codes: D11, D62, H21, H23, I18, I31, Q51.

Food waste is an emerging regional, national, and global issue. In 2010, 21% of the total food available for U.S. consumption was wasted at the household level (Buzby et al. 2011). In response, a number of countries and U.S. localities have instituted incentive mechanisms, directed toward waste reduction. Examples are South Korea and Seattle, Washington employing food-waste disposal taxes in excess of landfill costs (Kravitz 2015; Mazzoni 2013). Currently, there are no federal food disposal taxes or government preservation incentive mechanisms. House bill HR 4184, the Food Recovery Act, currently in committee, would establish grant and loan programs to increase food-waste awareness, expand tax deductions for food donations, and require uniform labeling for "sell-by" dates (H.R. 4184 2015). The bill would aid in achieving the United States and United Nations goals for a 50% reduction in food waste by 2030 (United Nations 2016; USDA 2015).

The objectives of disposal taxes and/or government incentives (government mechanisms) are not always grounded in economics. Some opponents of food waste even have a zero food-waste objective (Riddlestone 2015). This is counter to marginal-economic analysis likely yielding resource efficiency at some optimal positive level. Economic research on food waste is in the preliminary stages of measuring the degree of food waste within regions and documenting household and firm food-waste external costs. Examples are Aschemann-Witzel et al. (2015), Buzby and Hyman (2012), and Love et al. (2015). Food-waste research is just now at the cusp of applying economic theory, which will yield hypotheses for empirical testing. Without this application of theory yielding optimal government mechanisms, the United States and United Nations food-waste goals may be difficult to reach.

As a first attempt at developing a theoretical foundation for household decisions, the household food-waste decision calculus is outlined yielding a number of propositions and associated corollaries. Incorporating a household's external costs associated with social food insecurity, environmental degradation, and government net spending on food-waste mechanisms, a theorem on optimal waste-disposal taxes and government incentives is derived. The theory unravels the interrelation between food insecurity and external environmental costs, not generally considered by households when they waste food. The welfare effects that external costs have on the optimal are then investigated along with the conditions necessary for the optimal yielding zero food waste. Similar to the literature on energy efficiency, a rebound effect is identified for household food waste where an increase in food preservation can lead to increased food waste.

Food Waste Literature

There is no universal definition of food waste. Hodges et al. (2011) and de Lucia and Assennato (1994) consider food waste in the context of post-harvest loss, which represents all quantitative and qualitative losses of food throughout the entire food-supply chain. This includes losses and waste occurring during production (harvesting), processing, transportation, packaging, storage and consumption of food products. According to Buzby and Hyman (2012), food waste can emerge either as a result of natural factors including adverse weather conditions, which lead to changes of physical or chemical qualities of food products, or deliberate decisions to discard food. For instance, retail chains may be instructed to destroy their food stock if it is found to pose a threat to consumer health (Pleitgen, 2011).

There are few studies that attempt to estimate food loss. Due to data scarcity, studies often focus on particular geographical zones or certain stages of the food-supply chain. Buzby and Hyman (2012) estimate U.S. food waste at the retail and consumer level. Building upon their previous research on U.S. food waste, Buzby et al. (2011) aggregate data on more than 200 individual food products. Results indicate in 2008 United States wasted $165.6 billion or roughly one-third of the food supply. Nine percent of available food was wasted at retail while households wasted 22%.

Similarly, Hall et al. (2009) provide an estimation of the energy content of U.S. food waste from 1974 to 2003. They employed an inferential approach based on a mathematical model of human metabolism, which relates human-weight changes to food consumed. Their results suggest household food waste increased from 30% to almost 40% of total food supply. They demonstrate their findings are in contrast with the data published by the USDA, which employed the traditional approach of gleaning information on physical amounts of wasted food from public sources. According to USDA estimates, the proportion of household food waste remained approximately 30% during the same period (Kantor et al. 1997).

Geographically, Gustavsson et al. (2011) estimate the magnitude of food loss for seven geographical areas effectively covering 127 countries. Employing data on production, waste, and losses collected from FAO reports, they estimate that in 2007 approximately 1.3 billion tons of food products were lost or wasted at different stages of the global supply chain (approximately 30% of total production). In developed countries, literature suggests both retailers and households bear the prime responsibility for increased food waste (Buzby and Hyman 2012; Hodges et al. 2011; Gustavsson et al. 2011).

Aschemann-Witzel et al. (2015) explore the factors that govern household behavior regarding food consumption, which might contribute to food waste. They find households often dispose of commodities with minor visual imperfections or expiration dates. Food waste also occurs when households do not plan shopping routines carefully or are subject to impulse purchases. Government incentive mechanisms including information campaigns aimed at educating consumers to develop efficient shopping habits may be crucial to reducing household food waste.

The literature has also addressed disposal taxes, which raise the economic costs associated with waste-generating behavior and improper food disposal (Hodges et al. 2011). Recently, several U.S. and international locations established food disposal taxes in excess of landfill costs (Kravitz 2015; Mazzoni 2013). Taxation of food waste is an important government mechanism to internalize the external costs of environmental degradation and food insecurity.

Available studies on food taxation leave the problem of food waste beyond their focus. Chouinard et al. (2006) investigate the role of taxes in correction of poor nutritional habits. In particular, they explore taxation of milk products with high fat content in the context of the U.S. obesity and heart disease epidemics. Employing a Generalized Almost Ideal Demand System, they estimate elasticities for a variety of milk products to determine their exposure to a commodity tax. Their results suggest a 10% ad valorem tax has almost no effect on fat intake, but instead generates measurable welfare loses.

The theory on optimal taxation provides a framework for derivation of second-best Pareto optimal taxes and government incentives, which explicitly account for negative externalities resulting from food waste. Recently, this theory was primarily employed to explore the environmental impact of the automobile fuel industry. Parry and Small

(2002) derive and compare optimal taxes on gasoline in the United Kingdom and the United States. Vedenov and Wetzstein (2007) and Wu et al. (2012) apply the model developed by Parry and Small (2002) to derive the optimal U.S. ethanol and biodiesel subsidies, respectively. The overall effect of the ethanol subsidy on reduced gasoline consumption is uncertain. There is reduced gasoline consumption from an increased share of ethanol in the blended fuel mix. However, the subsidy reduces the cost of vehicle fuel, which has a rebound effect of increased gasoline consumption.

In any development of the household food-waste problem, possible rebound effects should be considered. Chan and Gillingham (2015) provide the first comprehensive economic development of the rebound effects in the energy sector. Qi and Roe (2016) are first to realize there are rebound effects in the calculus of society's food waste. As developed by Chan and Gillingham, an energy efficiency improvement can reduce the amount of total household energy consumed. However, this improved efficiency can decrease the implicit price of a commodity using energy. The price decline will stimulate an increase in quantity demanded for the energy consuming commodity, which increases energy demand. This is termed the rebound effect where the effect mitigates any energy savings from an efficiency improvement and theoretically can completely offset the savings (called backfire).

In the economics of food waste, an analogous rebound effect is characterized by an increase in the efficiency of food disposal lowering the implicit price of food waste. This price decline will stimulate an increase in food waste. However, the rebound effect is not isolated to this one form. As the theoretical analysis indicates, there are other such rebound effects where market mechanisms play a role in modifying the outcome of a policy to improve efficiency.

Theoretical model

Microeconomic theory of household food waste is developed based on the principles of consumer theory. The main objective is to provide an intuitive treatment of household food-waste economics in a universal setting considering multiple types of waste disposal. With this treatment as a foundation, the goal is to guide empirical investigation in modeling household food waste. Such treatment will direct the development of theoretically sound elasticity estimates and their application to food-waste policy. This will provide the first theoretical development of the welfare policies focused on mediating households' generation of food waste and society's social food-waste costs.

The theory employed for determining the optimal gasoline government mechanisms, such as an optimal tax (Parry and Small, 2005; Vedenov, 2008; Wu, 2012), is modified for developing the theoretical optimal disposal taxes and governmental incentives. This theoretical foundation will be based on household determinants for food purchases along with social costs not considered by households.

Market conditions result in households generally purchasing more food than they will consume. They derive benefits from having excess food and reducing their shopping trips. However, negative external costs, which households do not consider in their calculus, indicate market inefficiencies associated with these food purchases. Food insecurity (hunger); wasted resources in food production, transportation, and disposal along with environmental external costs are the major external costs.[1] Of these, resources employed in food production and transportation are pecuniary externalities, which do not yield market inefficiencies. However, food insecurity and environmental external costs are nonpecuniary externalities, which are not accounted in market derived food prices. Food insecurity results from food resources being directed toward food waste instead of food consumption. Environmental effects are in the forum of resources expended on food items that ultimately are wasted, resulting in air and water pollution, land allocation, and potential greenhouse gas emissions.

The focus is to develop a household model addressing the problem of determining the optimal level of food waste and food preservation capital for reducing waste, along with the costs of food waste external to household decisions. The focus is on a static household decision problem, which embodies the characteristics of actual real-life decisions. For tractability and understanding the major theoretical implications the model is first developed when there is only one type of food waste, say curbside disposal. It is then extended to consider multiple food-waste types.

One Food-Waste Type

Consider first the case of only one type of food waste, a household's consumption of food, C, is then net of food purchases, F, after subtracting food waste, W

$$C = F - W.$$

The generation of food waste is influenced by both the level of food purchases and amount of food preserving capital employed. There are two types of preservation capital, human and physical. Examples of human capital are meal forethought prior to food purchases and knowledge of varied food shelf life. Physical capital includes proper storage facilities including historical root cellars or refrigeration and animal suppression (pets and arthropods). The creation of food waste is then a function of household food purchases and food preserving capital

$$W = W(F, X),$$

where X represents a composite of food education (human capital) and preservation technologies (physical capital). It is assumed $\partial W/\partial F > 0$, $\partial^2 W/\partial F^2 > 0$, $\partial W/\partial X < 0$ and $\partial^2 W/\partial X^2 > 0$. Household consumption of food, C, may include a certain desired level of food waste, beyond the physical human food intake. This may include some level of food loss in preparation (examples are apple cores and vegetable stems), convenience of having food readily available (travel cost and time avoidance), and emergency food stocks with limited shelf life. This desirability of food loss may result in increased food purchases, so $\frac{\partial W}{\partial F} > 0$.

Assume a static model with many households who have in their decision calculus the amount of food to purchase along with determining the level of food preserving capital. Let a representative household's preferences be modeled as a quasi-linear utility function, U, associated with food waste

$$U(F, X) = u[F - W(F, X)] - \delta(P) - \gamma(S) + \rho(G). \quad (1)$$

The other variables are food environmental degradation, P, food insecurity, S, and government net spending on food-waste mechanisms, G. Variables P, S, and G are features of the household's environment, so the household perceives them as exogenous. Functions u and ρ are quasi-concave with δ and γ being weakly convex representing disutility from environmental degradation and food insecurity.

With the presence of externalities, households ignore the effect of their own food waste on food insecurity, environmental degradation, and cost of government mechamisms. A household then attempts to maximize utility (1) subject to a budget constraint

(2) $pF + \tau W(F, X) + rX = I,$

where p and r denote the per-unit price of food and food preservation capital, respectively, τ is a per-unit food-waste disposal tax, and I represents household disposable income allocated to food, food-waste disposal, and waste preventing efforts. Government mechanisms for influencing a household's level of food waste are a disposal tax, τ, and government incentives. Government incentives are possibly in the form of a food-preservation per-unit subsidy, which reduces the cost of food preservation capital. An example is an Extension outreach program reducing the cost of food-preservation educational materials. Alternatively, an Extension program could reduce any information asymmetries with households' food-waste knowledge and practices relative to current food preservation prescriptions. Such reduced asymmetry through government programs would decrease the per-unit cost of household food preservation capital.

Household's Cost

The optimal disposal tax and government incentive are determined from the indirect utility function

(3) $V(\tau, r, p, I) = \max \mathcal{L}(F, X) = \max u[F - W(F, X)] + \lambda[I - pF - \tau W(F, X) - rX],$

obtained by maximizing (1) subject to (2), where λ is the Lagrange multiplier. The variables τ and r then become parameters along with p and I.

The F.O.C.s for (3) are

(4a) $\frac{\partial \mathcal{L}}{\partial F} = \frac{\partial u}{\partial C}\left(1 - \frac{\partial W}{\partial F}\right) - \lambda\left(p + \tau\frac{\partial W}{\partial F}\right) = 0,$

(4b) $\frac{\partial \mathcal{L}}{\partial X} = -\frac{\partial u}{\partial C}\frac{\partial W}{\partial X} - \lambda\left(r + \tau\frac{\partial W}{\partial X}\right) = 0,$

(4c) $\frac{\partial \mathcal{L}}{\partial \lambda} = I - pF - \tau W(F, X) - rX = 0.$

From (4a), the additional monetary value of food consumption minus food waste is equal to its associated price plus the marginal cost of waste disposal, $\frac{1}{\lambda}\frac{\partial u}{\partial C}\left(1 - \frac{\partial W}{\partial F}\right) = \left(p + \tau\frac{\partial W}{\partial F}\right)$. In (4b), the additional monetary value of consumption from preservation, $-\frac{1}{\lambda}\frac{\partial u}{\partial C}\frac{\partial W}{\partial X}$, plus the marginal benefit of reduced waste disposal from preservation, $-\tau\frac{\partial W}{\partial X}$, is equal to the marginal cost of preservation, r. The effective food price, p_f, is the food-market price plus the cost of disposal divided by the change in consumption from food purchases

(5) $p_f = \left[p + \tau\frac{\partial W}{\partial F}\right] / \left[1 - \frac{\partial W}{\partial F}\right].$

From the F.O.C.s (4a and b)

$$\lambda^* = \frac{\partial u}{\partial C}\frac{1}{p_f} = -\frac{\partial u}{\partial C}\frac{\partial W}{\partial X} / \left(r + \tau\frac{\partial W}{\partial X}\right) > 0,$$

given $\frac{\partial u}{\partial C} > 0$ and $p_f > 0$. Rearranging

(6) $r + \tau\frac{\partial W}{\partial X} = -p_f\frac{\partial W}{\partial X}.$

The price of food preservation is composed of the per-unit cost of preservation, r, plus the incremental tax savings from preservation, $\tau\frac{\partial W}{\partial X} < 0$. For household-utility maximization, this price of food preservation must equal the value of the marginal product of food preservation, $-p_f \frac{\partial W}{\partial X} > 0$.

Based on these F.O.C.s, the following proposition results

Proposition 1. The elasticity of food waste to preserving capital is inversely proportional to the negative of the effective food price plus disposal tax

$\varepsilon_{W,X} \propto \frac{-r}{p_f+\tau}$.

The proof follows directly from (6)

The marginal product of preserving capital in reducing food waste, $\frac{\partial W}{\partial X}$, must be equal to the negative of the price of food preserving capital weighted by the effective food price plus disposal tax. Proposition 1 reveals as food prices or disposal taxes increase, the elasticity of food waste to preserving capital, $\varepsilon_{W,X}$, becomes more inelastic. Households are less responsive to reducing food waste given a change in preserving capital. As p_f or τ increase, food purchases and waste decline. This mitigates the utility derived from preserving capital, X, so food waste is less responsive to X. Proposition 1 is consistent with the substitution relationship between taxes and government incentives presented as Corollary 5 in the Welfare Effects section. The reverse occurs for the price of household preservation, *r*. An increase in *r*, results in a more elastic food waste to preserving capital response. For a household willing to purchase food preservation at a higher price, the absolute value response of food waste to preservation capital must be larger. Future empirical investigations will reveal the magnitude of the elasticity, which has direct bearing on optimal taxes and government incentives.

Corollary 1 (inverse elasticity rule or Ramsey taxation). As the elasticity of food waste to preserving capital becomes more inelastic the optimal-household disposal tax and government incentive increase.

Proof:

Solving (6) for the optimal-household tax, τ, and government incentive yields

$$\tau = -\frac{X}{W}\frac{r}{\varepsilon_{W,X}} - p_f,\ r = -\frac{W}{X}\varepsilon_{W,X}(p_f - \tau).$$

Then

$$\frac{\partial\tau}{\partial\varepsilon_{W,X}} = \frac{X}{W}\frac{r}{(\varepsilon_{WX})^2} > 0,\ \ \frac{\partial r}{\partial\varepsilon_{W,X}} = -\frac{W}{X}(p_f - \tau) < 0, \qquad \square$$

Households who are very responsive to reducing food waste given an increase in food preservation capital, only require a relatively low disposal tax and/or limited government incentives for yielding the optimal-household food-waste solution.

Differentiating the F.O.C.s (4) with respect to the parameters τ and r yields the following comparative statics propositions.

Proposition 2. Assuming no backfire effect, the elasticity of food preservation capital to a disposal tax is negatively proportional to the elasticity of food waste to preservation

$$\varepsilon_{X,\tau} \propto -\varepsilon_{W,X}.$$

If the elasticity of food waste with respect to preservation is negative, $\varepsilon_{W,X} < 0$, then the elasticity of food preservation capital to a disposal tax is positive, $\varepsilon_{X,\tau} > 0$.

Proof is provided in Appendix A.

Proposition 2 indicates there is an inverse relation between the response of food preservation to a disposal tax and the response of food waste to preservation. If $\varepsilon_{W,X} <$

0, then $\varepsilon_{X,\tau} > 0$, if households decrease their food waste by employing preservation capital, then a disposal tax will enhance their use of food preservation capital. Further, the more responsiveness households are to reducing food waste through preservation (the more elastic $\varepsilon_{W,X}$) the more responsive they will be to a disposal tax (more elastic is $\varepsilon_{X,\tau}$). However, as addressed in Appendix A, there is a negative rebound effect. An increase in the disposal tax will lead to preservation, but the negative rebound effect can mitigate this increase in preservation. If the second-order partial derivatives are is zero, $\frac{\partial^2 u}{\partial F \partial X} = \frac{\partial^2 W}{\partial F^2} = \frac{\partial^2 u}{\partial F^2} = \frac{\partial^2 W}{\partial F \partial X} = 0$, then the full marginal benefits of a disposal tax, τ, would be realized.

Proposition 3. If $\frac{\partial^2 u}{\partial X \partial F} \geq 0$ and $\frac{\partial^2 W}{\partial X \partial F} \leq 0$, then the elasticity of food purchased to a disposal tax is negative, $\varepsilon_{F,\tau} < 0$.

Proof is provided in Appendix A. An increase in the disposal tax will reduce food purchases without any observed rebound effect. As indicated in (5), the effective food price, p_f, is linearly related to the disposal tax, so Proposition 3 is analogue to the Law of Demand assuming food is a normal good.

Proposition 4. If $\frac{\partial^2 u}{\partial X \partial F} \geq 0$ and $\frac{\partial^2 W}{\partial X \partial F} \leq 0$, then $\varepsilon_{X,r} < 0$. In contrast, $\varepsilon_{F,r} \overset{<}{\underset{>}{=}} 0$.

Proof is provided in Appendix A.

Similar to Proposition 3, Proposition 4 is consistent with the Law of Demand for preservation capital, $\varepsilon_{X,r} < 0$. Further, the indeterminate cross elasticity sign of $\varepsilon_{F,r}$ is a standard microeconomic theory condition. Food could be a neutral, gross complement, or gross substitute commodity for food preservation capital.

Corollary 2. Given Proposition 4, the elasticity of food waste to the preservation price is positive if food preservation reduces waste

$$\varepsilon_{W,r} > 0, \text{ if } \varepsilon_{W,X} < 0.$$

Similar to Proposition 2, if households decrease their food waste by employing preservation capital, then food waste declines with a decrease in the per-unit cost of a government incentive.

In summary, the propositions and associated corollaries yield the standard microeconomic theory results

$\varepsilon_{F,\tau} < 0$, Proposition 3,

$\varepsilon_{X,r} < 0$, Proposition 4,

$\varepsilon_{F,r} \overset{<}{\underset{>}{=}} 0$, Proposition 4.

Complementing the standard results are

$\varepsilon_{X,\tau} > 0$, Proposition 2,

$\varepsilon_{W,r} > 0$, Corollary 2.

As indicated by these proposition and corollaries, it is again the magnitude of $\varepsilon_{W,X}$ that determines how responsive households' food waste is to governmental mechanisms.

Multiple Food-Waste Types

There are a number of household food-waste disposal mechanisms. Examples are disposal through the sewer system, combine with curbside collection of overall residual waste, household food-waste collection centers, and household composting and feeding to animals. Without loss of generality, for modeling multiple types of food-waste disposal, consider two disposal types, say sewer and curbside, denoted $W_1$and W_2 , along with two types of food preservation capital, say human and physical, denoted $X_1$and X_2. For tractability and emphasizing the interaction of these disposal types to disposal taxes and food preservation prices, hold the level of food purchases fixed at F^o.[2] Let $\tau_1$and τ_2 represent a disposal tax for disposal types *1* and *2* and let $r_1$and r_2 represent per-unit cost of food preservation capital, *1* and *2*, respectively. Ignoring household external costs, the household problem is then to

(7) $$V(\bar{\tau}, \bar{r}) = max\ \mathcal{L}(X_1, X_2)$$

$$= max\ u[F^o - W_1(X_1, X_2) - W_2(X_1, X_2)] + \lambda[I - pF^o - \tau_1 W_1 - \tau_2 W_2 - r_1 X_1 - r_2 X_2],$$

where $\bar{\tau} = (\tau_1, \tau_2)$ and $\bar{r} = (r_1, r_2)$ with parameters F^o, p, and I suppressed.

The F.O.C.s for (7) are

(8a) $$\frac{\partial \mathcal{L}}{\partial X_i} = \frac{\partial u}{\partial X_i} - \lambda\left(\tau_1 \frac{\partial W_1}{\partial X_i} + \tau_2 \frac{\partial W_2}{\partial X_i} + r_i\right) = 0, i = 1, 2,$$

(8b) $$\frac{\partial \mathcal{L}}{\partial \lambda} = I - pF^o - \tau_1 W_1 - \tau_2 W_2 - r_1 X_1 - r_2 X_2 = 0,$$

where $\frac{\partial u}{\partial X_i} = -\frac{\partial u}{\partial C}\left(\frac{\partial W_1}{\partial X_i} + \frac{\partial W_2}{\partial X_i}\right)$.

Based on these F.O.C.s (8), Appendix B develops a similar conclusion as Proposition 2, where $\varepsilon_{X_i, \tau_m} > 0,\ i, j, m = 1, 2$.

Considering multiple food-waste disposal types yields the following proposition.

Proposition 5. Assuming no backfire effect, the own-food preservation price response is negative, $\varepsilon_{X_i, r_i} < 0, i = 1, 2$. The associated cross elasticity of food preservation is positive, $\varepsilon_{X_j, r_i} > 0, i, j = 1, 2, i \neq j$.

Proofs are provided in Appendix B.

The result of $\varepsilon_{X_{i},r_{i}} < 0$ is consistent with considering only one preservation type, Proposition 4. The cross-price effect indicates the two types of food-waste disposals are gross substitutes. This substitution relation when considering only two commodities is a standard microeconomics result, given diminishing marginal utilities implies strictly convex indifference curves. With more than two commodities (waste-disposal types), this substitution relation does not necessarily hold.

Propositions 1 through 5 and associated corollaries assume the household does not consider the effect of their own food waste on food insecurity, environmental degradation, and funding waste disposal. Considering the welfare effects associated with these external costs yields the social-optimal taxes and government incentives. Employing these optimal mechanisms will yield the social-optimal level of household food waste.

Welfare Effects

Disposal taxes, τ_1 and τ_2, along with government incentives, denoted as s_1 and s_2, are mechanisms for enhancing food preservation capital. The welfare effects of an incremental change in these government mechanisms may be determined by totally differentiating the indirect utility function

$$(9) \qquad V(\bar{\tau}, \bar{r}) = \max \mathcal{L}(F, X_1, X_2, \lambda)$$

$$= \max u[F - W_1(F, X_1, X_2) - W_2(F, X_1, X_2)] - \delta(P) - \gamma(S) + \rho(G)$$

$$+ \lambda[I - pF - \tau_1 W_1 - \tau_2 W_2 - r_1 X_1 - r_2 X_2].$$

Note that in contrast to (3) and (7), in (9) the household's externalities are now internalized into the calculus. The government incentive mechanisms are intended as incentives for households to implement food preservation capital. They can be considered mechanisms, which reduce the cost of food preservation. In this sense, converting the mechanisms to per-unit prices of preservations, s_1 and s_2, they may be represented as a reduction in household preservation costs, r_1 and r_2. Government disposal-tax revenues minus incentive costs are then represented as

(10) $G = \tau_1\bar{W}_1 + \tau_2\bar{W}_2 - s_1\bar{X}_1 - s_2\bar{X}_2,$

where $\bar{W}_m$ and $\bar{X}_i, i, m = 1, 2$, represent aggregate food waste and preservation, respectively.

Considering food insecurity, it is assumed food-waste insecurity, *S*, is based on the aggregate levels of food preservation capital, $\bar{X}_i$, where $\partial S/\partial \bar{X}_i < 0$, $i = 1, 2$

(11) $S = S(\bar{X}_1, \bar{X}_2)$.

The environmental degradation of food waste, *P*, is decomposed into external costs of food production, *Z*, and disposal, D.

(12) $P = Z(\bar{X}_1, \bar{X}_2) + D(\bar{X}_1, \bar{X}_2)$, $\partial Z/\partial \bar{X}_i < 0$, and $\partial D/\partial \bar{X}_i < 0, i = 1, 2$.

Noting that $\frac{\partial V}{\partial \tau_m} = -\lambda W_m < 0, m = 1, 2,$ $\frac{\partial V}{\partial r_i} = -\lambda X_i < 0, i = 1, 2,$ and $\frac{\partial V}{\partial P} = -\delta' < 0,$ $\frac{\partial V}{\partial S} = -\gamma' < 0,$ and $\frac{\partial V}{\partial G} = \rho' > 0$ yields

(13a) $\frac{dV}{d\tau_m} = -\lambda W_m - \delta' \frac{dP}{d\tau_m} - \gamma' \frac{dS}{d\tau_m} + \rho' \frac{dG}{d\tau_m}, m = 1, 2,$

(13b) $\frac{dV}{dr_i} = -\lambda X_i - \delta' \frac{dP}{dr_i} - \gamma' \frac{dS}{dr_i} + \rho' \frac{dG}{dr_i}, i = 1, 2.$

From the F.O.C.s of (9)

$W_m = [\bar{\tau}, \bar{r}, F(\bar{\tau}, \bar{r}), X_1(\bar{\tau}, \bar{r}), X_2(\bar{\tau}, \bar{r})], m = 1,2.$

Then

$$\frac{dW_n}{d\tau_m} = \frac{\partial W_n}{\partial \tau_m} + \frac{\partial W_n}{\partial F}\frac{\partial F}{\partial \tau_m} + \frac{\partial W_n}{\partial X_1}\frac{\partial X_1}{\partial \tau_m} + \frac{\partial W_n}{\partial X_2}\frac{\partial X_2}{\partial \tau_m}, m, n = 1, 2.$$

From Proposition 2, $\frac{\partial W_m}{\partial \tau_m} < 0$, $\frac{\partial X_i}{\partial \tau_m} > 0, i, m = 1, 2$ and given Proposition 3, $\frac{\partial F}{\partial \tau_m} < 0$, leading to $\frac{dW_m}{d\tau_m} < 0$ and $\frac{dW_n}{d\tau_m} \lesseqgtr 0$, $m \neq n$. The indeterminate sign is the result of $\frac{\partial W_n}{\partial \tau_m}$ being indeterminate.

For r_i

$$\frac{dW_m}{dr_i} = \frac{\partial W_m}{\partial r_i} + \frac{\partial W_m}{\partial F}\frac{\partial F}{\partial r_i} + \frac{\partial W_m}{\partial X_1}\frac{\partial X_1}{\partial r_i} + \frac{\partial W_m}{\partial X_2}\frac{\partial X_2}{\partial r_i} > 0, i, m = 1, 2 \text{ from Corollary 2.}$$

Furthermore, from Proposition 2, $\frac{\partial W_m}{\partial X_i} < 0, i, m = 1, 2,$ Proposition 4, $\frac{\partial F}{\partial r_i} \lesseqgtr 0$, $i = 1, 2$, and Proposition 5, $\frac{\partial X_i}{\partial r_i} < 0$ and $\frac{\partial X_j}{\partial r_i} > 0$, $i, j = 1, 2, i \neq j$.

From the definitions of P, S, and G in (12), (11), and (10), respectively

(14a) $$\frac{dP}{d\tau_m} = \left(\frac{dZ}{dW_1} + \frac{dD}{dW_1}\right)\frac{dW_1}{d\tau_m} + \left(\frac{dZ}{dW_2} + \frac{dD}{dW_2}\right)\frac{dW_2}{d\tau_m} \lesseqgtr 0, m = 1, 2,$$

(14b) $$\frac{dP}{dr_i} = \left(\frac{dZ}{dW_1} + \frac{dD}{dW_1}\right)\frac{dW_1}{dr_i} + \left(\frac{dZ}{dW_2} + \frac{dD}{dW_2}\right)\frac{dW_2}{dr_i} > 0, \ i = 1, 2,$$

(14c) $$\frac{dS}{d\tau_m} = \frac{dS}{dW_1}\frac{dW_1}{d\tau_m} + \frac{dS}{dW_2}\frac{dW_2}{d\tau_m} \lesseqgtr 0, m = 1, 2,$$

(14d) $$\frac{dS}{dr_i} = \frac{dS}{dW_1}\frac{dW_1}{dr_i} + \frac{dS}{dW_2}\frac{dW_2}{dr_i} > 0, i = 1, 2,$$

(14e) $$\frac{dG}{d\tau_m} = W_m + \tau_1\frac{dW_1}{d\tau_m} + \tau_2\frac{dW_2}{d\tau_m} - s_1\frac{\partial X_1}{\partial \tau_m} - s_2\frac{\partial X_2}{\partial \tau_m} \lesseqgtr 0, m = 1, 2,$$

(14f) $$\frac{dG}{ds_i} = -X_i + \tau_1\frac{dW_1}{ds_i} + \tau_2\frac{dW_2}{ds_i} - s_1\frac{\partial X_1}{\partial s_i} - s_2\frac{\partial X_2}{\partial s_i} \lesseqgtr 0, i, j = 1, 2.$$

Note that in (14) the assumption is $r_i = r^o - s_i$, where r^o is the price of preservation prior to a government incentive.

For further analysis and interpretation, define the marginal costs of environmental degradation (external costs of food production and disposal) and insecurity as

$$E^{PW_m} = \frac{\delta'}{\lambda}\left(\frac{dZ}{dW_m} + \frac{dD}{dW_m}\right), m = 1, 2,$$

$$E^{SW_m} = \frac{\gamma'}{\lambda}\frac{dS}{dW_m}, m = 1, 2.$$

The marginal external cost of food waste (MEC) is defined as the sum of the marginal costs of environmental degradation. It is the sum of food insecurity and environmental external costs, which are nonpecuniary externalities.

$$MEC_m = E^{PW_m} + E^{SW_m}, m = 1, 2.$$

In determining (14), aggregate food wastes, $\bar{W}_1$ and $\bar{W}_2$, and preservations, $\bar{X}_1$ and $\bar{X}_2$ are no longer constant.

Substituting (14) into (13) and dividing by λ results in the marginal monetary welfare effect of the disposal tax and preservation mechanism

(15a) $$\frac{1}{\lambda}\frac{dV}{d\tau_m} = -W_m - (E^{PW_1} + E^{SW_1})\frac{dW_1}{d\tau_m} - (E^{PW_2} + E^{SW_2})\frac{dW_2}{d\tau_m} + \frac{\rho'}{\lambda}\left(W_m + \tau_1\frac{dW_1}{d\tau_m} + \tau_2\frac{dW_2}{d\tau_m} - s_1\frac{\partial X_1}{\partial \tau_m} - s_2\frac{\partial X_2}{\partial \tau_m}\right), m = 1, 2,$$

(15b) $$\frac{1}{\lambda}\frac{dV}{ds_i} = X_i - (E^{PW_1} + E^{SW_1})\frac{dW_1}{ds_i} - (E^{PW_2} + E^{SW_2})\frac{dW_2}{ds_i} + \frac{\rho'}{\lambda}\left(-X_i + \tau_1\frac{dW_1}{ds_i} + \tau_2\frac{dW_2}{ds_i} - s_1\frac{\partial X_1}{\partial s_i} - s_2\frac{\partial X_2}{\partial s_i}\right), i = 1, 2.$$

Based on (15) optimal disposal taxes and government incentives are derived.

Theorem 1. The optimal disposal taxes and government incentives are

(16a) $\tau_m^* =$

$$\left[MEC_m\varepsilon_{W_m,\tau_m} + MEC_n\varepsilon_{W_n,\tau_m}\frac{W_n}{W_m} - \frac{\rho'}{\lambda}\left(\frac{\tau_n W_n}{W_m}\varepsilon_{W_n,\tau_m} - \frac{s_1X_1}{W_m}\varepsilon_{X_1,\tau_m} - \frac{s_2X_2}{W_m}\varepsilon_{X_2,\tau_m}\right)\right] \Big/ \left[\frac{\rho'}{\lambda}\left(\varepsilon_{W_m,\tau_m}+1\right) - 1\right],$$

$m, n = 1, 2, m \neq n,$

(16b) $s_i^* =$

$$\left[MEC_1\varepsilon_{W_1,s_i}\frac{W_1}{X_i} + MEC_2\varepsilon_{W_2,s_i}\frac{W_2}{X_i} - \frac{\rho'}{\lambda}\left(\frac{\tau_1W_1}{X_i}\varepsilon_{W_1,s_i} + \frac{\tau_2W_2}{X_i}\varepsilon_{W_2,s_i} - \frac{s_jX_j}{X_i}\varepsilon_{X_j,s_i}\right)\right] \Big/ \left[-\frac{\rho'}{\lambda}\left(\varepsilon_{X_i,s_i}+1\right)+1\right],$$

$i, j = 1, 2, i \neq j.$

Proof:

Setting F.O.C. (15a) to zero and multiplying by $\frac{\tau_m}{W_m}$ yields

$$-\tau_m - MEC_m\varepsilon_{W_m,\tau_m} - MEC_n\varepsilon_{W_n,\tau_m}\frac{W_n}{W_m}$$

$$+\frac{\rho'}{\lambda}\left(\tau_m + \tau_m\varepsilon_{W_m,\tau_m} + \tau_n\varepsilon_{W_n,\tau_m}\frac{W_n}{W_m} - \frac{s_1X_1}{W_m}\varepsilon_{X_1,\tau_m} - \frac{s_2X_2}{W_m}\varepsilon_{X_2\tau_m}\right) = 0,$$

$m, n = 1, 2, m \neq n.$

Solving for τ_m yields the optimal disposal taxes (16a).

Setting F.O.C. (15b) to zero and multiplying by $\frac{s_i}{X_i}$ yields

$$s_i - MEC_1\varepsilon_{W_1,s_i}\frac{W_1}{X_i} - MEC_2\varepsilon_{W_2,s_i}\frac{W_2}{X_i} + \frac{\rho'}{\lambda}\Big(-s_i + \tau_1\varepsilon_{W_1,s_i}\frac{W_1}{X_i} + \tau_2\varepsilon_{W_2,s_i}\frac{W_2}{X_i} -$$

$$s_i\varepsilon_{X_i,s_i} - \frac{s_jX_j}{X_i}\varepsilon_{X_j,s_i}\Big) = 0,$$

$i, j = 1, 2, i \neq j.$

Solving for s_i yields the optimal government incentives (16b). □

As noted by Parry and Small (2005), the optimal disposal taxes and government incentives are only second-best, given Theorem 1 (16) depends on parameter values at the social optimum and any observed values apply to the existing, possibly non-optimal, tax-incentive equilibrium. In particular, as indicated in (16a), the optimal tax τ_m^* is dependent on the level of tax $\tau_n, m \neq n$, and the government incentives $s_i, i = 1, 2$. Similarly, the optimal government incentive s_i^* in (16b) is dependent on the levels of the taxes $\tau_m, m = 1, 2$, and the government incentive $s_j, i \neq j$. For analytical determination of the optimal disposal taxes and government incentives, (16) could be determined by dynamic policy iteration.

In investigating (16), first address the denominator in (16a). The government marginal monetary welfare effect, ρ'/λ, converts the reduction in food waste, W_m, into monetary government benefits. If $\varepsilon_{W_m,\tau_m} = -1$, unitary, then an increase in the disposal tax, τ_m, will yield no net change in government the revenue, $\tau_m W_m$, so there is no marginal government welfare gain or loss. Instead, if ε_{W_m,τ_m} is elastic (inelastic), then a decrease in τ_m will increase (decrease) government revenue, yielding a denominator less (greater) than -1, which decreases (increases) the optimal tax, τ_m^*. For a positive disposal tax, the denominator in (16a) must be negative. This implies

Corollary 3. If $\tau_m^* > 0$ and $\frac{\rho'}{\lambda} > 0$, then $\varepsilon_{W_m,\tau_m} < \frac{1}{\frac{\rho'}{\lambda}} - 1, m = 1, 2$.

This is consistent with revenue seeking institutions (firms and agencies) only operating in the elastic response area. Consistent with Corollary 1, the disposal tax should be increased until its elasticity is in the elastic range. It is theoretically possible for the sign in the denominator of (16a) to be reversed, which would imply a disposal subsidy, $\tau_m^* < 0$, $m = 1, 2$, rather than a tax. However, as indicated in Proposition 2, as $\varepsilon_{W_m,\tau_m} \rightarrow 0$, then $\tau_m^* \rightarrow 0$, so the possibility of a subsidy for producing food waste is just a paradox and not worth further consideration.

Turning to the denominator in (16b), for a positive subsidy the denominator must be negative. Commonly, for food preservation capital, $s_i < 0$. An example is a negative subsidy (commodity tax) where consumers bear a portion of the tax. Even human capital is taxed in the form of taxes on educational materials. However, a reduction in this commodity tax will still reduce food waste. In general and consistent with Corollary 1, the more responsive food preservation is to the subsidy, more elastic ε_{X_i,s_i}, the lower will be the subsidy.

In terms of the numerators in (16), the optimal disposal taxes and government incentives involve a similar Pigovian tax and subsidy, $MEC_m\varepsilon_{W_m,\tau_m} + MEC_n\varepsilon_{W_n,\tau_m}\frac{W_n}{W_m}$ and $MEC_1\varepsilon_{W_1,s_i}\frac{W_1}{X_i} + MEC_2\varepsilon_{W_2,s_i}\frac{W_2}{X_i}$, respectively. The Pigovian tax (subsidy) is the external marginal cost from a per-unit change in food waste, $MEC_m, m = 1, 2$, times the weighted responsiveness of this waste to a change in the tax (subsidy), ε_{W_m,τ_m} ($\varepsilon_{W_m,s_i}\frac{W_m}{X_i}$). The more elastic (inelastic) food waste is to the tax, the higher (lower) the tax. Similarly, the optimal government incentive is also positive. The more elastic (inelastic) food waste is to the incentive, the higher (lower) the mechanism.

In addition to the own elasticity adjustments in the denominators of (16), there are supplementary Pigovian adjustments associated with the cross elasticities, the third terms in the numerators of (16). From Corollary 3, an increase in the disposal tax, τ_m, will reduce government revenue by $\frac{\tau_n W_n}{W_m}\varepsilon_{W_n,\tau_m}$, if $\varepsilon_{W_n,\tau_m} < 0$ and increase revenue if

$\varepsilon_{W_n,\tau_m} > 0$. Similarly, increasing τ_m will increase governmental expenditures by $\frac{s_1 X_1}{W_m}\varepsilon_{X_1,\tau_m} + \frac{s_2 X_2}{W_m}\varepsilon_{X_2,\tau_m}$. If $\varepsilon_{W_n,\tau_m} < 0$, such government fiscal effects will mitigate the magnitude of the optimal disposal taxes, τ_m^*. For the optimal subsidy, s_i^*, Corollary 2 and Proposition 5 indicate a loss in government revenue for both types of food waste, W_1 and W_2, and an associated increase in governmental expenditures. These fiscal effects will decrease the optimal government incentives, s_i^*.

The comparative statics optimal disposal taxes and government incentives Theorem 1 (16) are explored with the following corollaries to Theorem 1.

Corollary 4.

$\varepsilon_{\tau_m,\tau_n} \propto \varepsilon_{W_n,\tau_m}, m, n = 1, 2, m \neq n,$

$\varepsilon_{s_i,s_j} \propto -\varepsilon_{X_j,s_i}, i, j = 1, 2, i \neq j.$

Proof follows from Theorem 1 (16).

If an increase in the disposal tax τ_m reduces food waste W_n, then an increase in τ_n will reduce τ_m. The taxes are then substitutes. In reverse, if an increase in the disposal tax τ_m increases food waste W_n, then an increase in τ_n will increase τ_m. The taxes are complements. In terms of government incentives, given Proposition 5, $\varepsilon_{X_j,s_i} > 0$, so an increase in s_j will reduce s_i, $\varepsilon_{s_i,s_j} < 0$. Government incentives are substitutes.

Corollary 5.

$\varepsilon_{\tau_m,s_i} \propto -\varepsilon_{X_i,\tau_m}, i, m = 1, 2,$

$\varepsilon_{s_i,\tau_m} \propto \varepsilon_{W_m,s_i}, i, m = 1, 2.$

Proof follows from Theorem 1 (16).

From Proposition 2, $\varepsilon_{X_i,\tau_m} > 0$, so $\varepsilon_{\tau_m,s_i} < 0$, an increase in s_i will decrease τ_m. From Corollary 2, $\varepsilon_{W_m,s_i} < 0$, so consistent with $\varepsilon_{\tau_m,s_i} < 0, \varepsilon_{s_i,\tau_m} < 0$, an increase in τ_m will decrease s_i. In both cases, taxes and government incentives are substitutes. This substitution relation is consistent with Proposition 1.

Corollary 6. If $MEC_m = MEC_n = 0$, then

$\tau_m^* = \frac{\rho'}{\lambda}\varepsilon_{G,\tau_m}\frac{G}{W_m} > 0$, given Corollary 3,

$$s_i^* = -\frac{\rho'}{\lambda}\varepsilon_{G,s_i}\frac{G}{X_i} > 0,$$

where ε_{G,τ_m} and ε_{G,s_i} denote the elasticity of government net expenditures on disposal taxes and government incentives with respect to the disposal tax τ_m and government incentive, s_i, respectively.

Proof follows from (15) and given (14e and f). If there are no government benefits, then $\tau_m^* = s_i^* = 0$. Note that if only $MEC_m = 0$, then $\tau_m^*, s_i^* > 0$ are possible given $MEC_n > 0$.

Corollary 7. (zero optimal food waste). If $\frac{\rho'}{\lambda} = 0$, as $\varepsilon_{W_1,\tau_m}$and $\varepsilon_{W_2,\tau_m} \rightarrow -\infty$, perfectly elastic, then $\tau_m^* \rightarrow \infty$, *m = 1, 2*. Similarly, ε_{W_1,s_i} and $\varepsilon_{W_2,s_i} \rightarrow -\infty$, perfectly elastic, $s_i^* \rightarrow \infty, i = 1, 2$.

Proof follows from Theorem 1 (16). Perfectly elastic food-waste responses to the disposal taxes and/or government incentives result in a complete household response, so the optimal taxes or government incentives approach infinitely. This results in zero food waste. Considering the monetary marginal benefits of government, $\frac{\rho'}{\lambda}$, a perfectly elastic food waste response to disposal taxes and/or government incentives would result MEC being mitigated by government's marginal benefits. As indicated by Corollary 3, if $\varepsilon_{W_m,\tau_m} < -1$, elastic, then $\tau_m^* > 0, m = 1, 2$, so government revenue will decline with a rise in a disposal tax. Considering this decline in government revenue for both disposal taxes and government incentives, prevents optimal food waste declining to zero for perfectly elastic responses.

The implication from Corollary 7 is proponents for zero food waste are implicitly implying there are no government effects associated with waste mitigation and the elasticities of food waste response are perfectly elastic. Otherwise, some positive level of food waste is optimal.

Implications

The implication of Theorem 1 (16) has direct bearing on policy and economists' associated response. The optimal government mechanisms, τ_m^* and s_i^*, yield the optimal percentage waste reductions, $\propto_m^*, m = 1, 2$. This provides a rich field for empirical investigation of government mechanisms to mitigate food waste. Empirical comparison of $\propto_m^*, m = 1, 2$ with the U.S. and U.N. current target of a 50% reduction by 2030 would indicate how close the target is to the optimal. Estimating this possible cleavage would offer insights into consideration of possible policy shifts. Such empirical investigations would reveal the magnitude of elasticities required for determining the optimal along with associated U.S./U.N. target government mechanisms. This would aid in comparing alternative sets of government mechanisms for achieving the optimal or target levels of food waste. Without some explicit criteria such as Theorem 1 (16), the likely success in developing the correct set of mechanisms is low.

In determining the optimal set of government mechanisms, Theorem 1 (16) indicates government incentive are substitutes for each other. They will increase all types of household preservation capital. In contrast, disposal taxes may be substitutes or complements of each other depending on the direction of the response of a food-waste type on a tax associated with an alternative food-waste type. Further, Theorem 1 (16) indicates taxes and government incentives are substitutes, although not perfect substitutes. The direction and magnitude of these effects are a subject for empirical investigation.

Conclusions

Investigating the theory underlying household food waste and government mitigation mechanisms reveals the importance of measuring the responsiveness of food waste and household food preservation capital to disposal taxes and government incentives. Determining the optimal level of these government mechanisms is directly dependent on measuring these elasticities. The theoretical development also reveals the importance of considering government revenues derived from disposal taxes and expenditures in developing and implementing government incentives to reduce food waste. If society is serious about reducing food waste to some acceptable targets (50% by 2030), then it is the mission of economists to develop optimal mechanisms for targeting. The presented theoretical analysis is a static foundation for determining the steady-state level of government mechanisms. The implementation of such mechanisms would require theoretical and empirical analysis on the optimal phasing in of these mechanisms. What is the optimal government mechanism-set trajectory to the steady state?

The theoretical results provide the first insights into developing an efficient set of governmental mechanisms, which adjust prices toward an optimal level of social food waste. The simultaneous development of optimal disposal taxes and government incentives yields insights into their substitutability and complementarity characteristics. With this food-waste theory as a foundation, further theoretical and empirical efforts will unravel the complex economic and environmental nature of food waste. Only then will efficient economic solutions be revealed.

Footnotes

[1] Another possible external cost is over-nutrition (obesity), where overeating is considered wasted food. Internalizing this cost could require developing optimal fat taxes, which are tangential to developing optimal disposal taxes and government preservation incentives.

[2] Relaxing the assumption of fixed food purchases increases the complexities of the comparative statics, leading to the same Proposition 5 with no additional insights.

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Appendix A

Proofs of propositions 2, 3, and 4

Substituting the solutions to the F.O.C.s (4)

$F^*(\tau, r, p, I)$,

$X^*(\tau, r, p, I)$,

$\lambda^*(\tau, r, p, I)$,

into (4) and differentiating with respect to τ yields

(A1a) $\frac{\partial^2 u}{\partial F^2}\frac{\partial F}{\partial \tau} + \frac{\partial^2 u}{\partial F \partial X}\frac{\partial X}{\partial \tau} - p\frac{\partial \lambda}{\partial \tau} - \tau\frac{\partial W}{\partial F}\frac{\partial \lambda}{\partial \tau} - \lambda\tau\frac{\partial^2 W}{\partial F \partial X}\frac{\partial X}{\partial \tau} - \lambda\tau\frac{\partial^2 W}{\partial F^2}\frac{\partial F}{\partial \tau} - \lambda\frac{\partial W}{\partial F} = 0,$

(A1b) $\frac{\partial^2 u}{\partial F \partial X}\frac{\partial F}{\partial \tau} + \frac{\partial^2 u}{\partial X^2}\frac{\partial X}{\partial \tau} - r\frac{\partial \lambda}{\partial \tau} - \tau\frac{\partial W}{\partial X}\frac{\partial \lambda}{\partial \tau} - \lambda\tau\frac{\partial^2 W}{\partial F \partial X}\frac{\partial F}{\partial \tau} - \lambda\tau\frac{\partial^2 W}{\partial X^2}\frac{\partial X}{\partial \tau} - \lambda\frac{\partial W}{\partial X} = 0,$

(A1c) $-p\frac{\partial F}{\partial \tau} - \tau\frac{\partial W}{\partial F}\frac{\partial F}{\partial \tau} - W - \tau\frac{\partial W}{\partial X}\frac{\partial X}{\partial \tau} - r\frac{\partial X}{\partial \tau} = 0,$

where

$$\frac{\partial^2 u}{\partial F^2} = \frac{\partial^2 u}{\partial C^2}\left(1 - \frac{\partial W}{\partial F}\right)^2 - \frac{\partial u}{\partial C}\frac{\partial^2 W}{\partial F^2},$$

$$\frac{\partial^2 u}{\partial F \partial X} = -\frac{\partial^2 u}{\partial C^2}\frac{\partial W}{\partial X}\left(1 - \frac{\partial W}{\partial F}\right) - \frac{\partial u}{\partial C}\frac{\partial^2 W}{\partial F \partial X},$$

$$\frac{\partial^2 u}{\partial X^2} = \frac{\partial^2 u}{\partial C^2}\left(\frac{\partial W}{\partial X}\right)^2 - \frac{\partial u}{\partial C}\frac{\partial^2 W}{\partial X^2}.$$

Solve (A1) with Cramer's Rule by denoting

$$a_{11} = \frac{\partial^2 u}{\partial F^2} - \lambda\tau\frac{\partial^2 W}{\partial F^2} < 0, \qquad a_{12} = a_{21} = \frac{\partial^2 u}{\partial F \partial X} - \lambda\tau\frac{\partial^2 W}{\partial F \partial X} \lesseqgtr 0,$$

$$a_{22} = \frac{\partial^2 u}{\partial X^2} - \lambda\tau\frac{\partial^2 W}{\partial X^2} < 0, \qquad a_{13} = a_{31} = -p - \tau\frac{\partial W}{\partial F} < 0,$$

$$a_{23} = a_{32} = -r - \tau\frac{\partial W}{\partial X} < 0,$$

where it is assumed $\frac{\partial^2 u}{\partial F^2}$ and $\frac{\partial^2 u}{\partial X^2} < 0$, diminishing marginal utility.

Proposition 2 Proof

(A2) $$\frac{\partial X}{\partial \tau} = \left[\lambda\frac{\partial W}{\partial F}a_{23}a_{31} + a_{13}a_{21}W - \lambda\frac{\partial W}{\partial X}(a_{13})^2 - a_{11}a_{23}W\right] / |H|,$$

where the bordered Hessian, $|H| > 0$, for a maximum. Assuming $\frac{\partial W}{\partial X} < 0$, the first and third terms in the numerator are positive. The sign of the second term, $\left(-p - \tau\frac{\partial W}{\partial F}\right)\left(\frac{\partial^2 u}{\partial F \partial X} - \lambda\tau\frac{\partial^2 W}{\partial F \partial X}\right)W$, involving the cross commodity effects on utility and waste is unknown. If $\frac{\partial^2 u}{\partial F \partial X} > 0$ and $\frac{\partial^2 W}{\partial F \partial X} < 0$, then this second term is negative along with the last term. The condition of $\frac{\partial^2 u}{\partial F \partial X} > 0$ is the standard microeconomic comparative statics result. For food waste, an additional cross-commodity condition results on how food preservation and purchases interact. These negative terms are the rebound effects and if they offset the first and third positive terms then this yields a backfire effect.

The negative terms represent all the second-order partial derivatives in contrast to the first partials for the positive effects. Considering these second-order derivative reveals the rebound effects. In all cases, these second-order derivatives lead to a reduction in food waste for a decrease in food consumption. This reduction in waste mitigates the required change in food preservation, *X*, from a disposal tax. The associated elasticity response, $\varepsilon_{X,\tau}$, is then reduced (becomes more inelastic). For $\frac{\partial^2 u}{\partial F \partial X} > 0$, preservation, *X*, and marginal utility of food are positively related, so an increase in *X* will reduce food consumption, yielding a reduction in food waste. Similarly, for $\frac{\partial^2 W}{\partial F^2} > 0$, food purchases and marginal waste of food are positively related, so a decrease in food consumption yields a decrease in food waste. For $\frac{\partial^2 W}{\partial F \partial X} < 0$, preservation, *X*, and marginal waste of food are inversely related, so an increase in *X* will then reduce food consumption yielding a reduction in food waste. Also, given $\frac{\partial^2 u}{\partial F^2} < 0$, as food consumption declines , marginal utility of food increases yielding a reduction in food waste.

Converting (A2) to elasticities yields Proposition 2. □

Proposition 3 Proof

From Cramer's Rule

$$\frac{\partial F}{\partial \tau} = \left[\left[a_{12}a_{23}W + a_{13}\lambda\frac{\partial W}{\partial X}a_{32} - a_{13}a_{22}W - \lambda\frac{\partial W}{\partial F}(a_{23})^2\right]\right]/|H| < 0,$$

if $\frac{\partial^2 u}{\partial X \partial F} \geq 0$ and $\frac{\partial^2 W}{\partial X \partial F} \leq 0$.

Converting into elasticity results in Proposition 3, $\varepsilon_{F,\tau} < 0$. □

Differentiating (4) with respect to r yields

(A3a) $\frac{\partial^2 u}{\partial F^2}\frac{\partial F}{\partial r} + \frac{\partial^2 u}{\partial F \partial X}\frac{\partial X}{\partial r} - p\frac{\partial \lambda}{\partial r} - \tau\frac{\partial W}{\partial F}\frac{\partial \lambda}{\partial r} - \lambda\tau\frac{\partial^2 W}{\partial F \partial X}\frac{\partial X}{\partial r} - \lambda\tau\frac{\partial^2 W}{\partial F^2}\frac{\partial F}{\partial r} = 0,$

(A3b) $\frac{\partial^2 u}{\partial F \partial X}\frac{\partial F}{\partial r} + \frac{\partial^2 u}{\partial X^2}\frac{\partial X}{\partial r} - r\frac{\partial \lambda}{\partial r} - \tau\frac{\partial W}{\partial X}\frac{\partial \lambda}{\partial r} - \lambda\tau\frac{\partial^2 W}{\partial F \partial X}\frac{\partial F}{\partial r} - \lambda\tau\frac{\partial^2 W}{\partial X^2}\frac{\partial X}{\partial r} - \lambda = 0,$

(A3c) $-p\frac{\partial \lambda}{\partial r} - \tau\frac{\partial W}{\partial F}\frac{\partial F}{\partial r} - X - \tau\frac{\partial W}{\partial F}\frac{\partial X}{\partial r} - r\frac{\partial X}{\partial r} = 0.$

Proposition 4 Proof

Solving (A3) with Cramer's Rule results in

$$\frac{\partial X}{\partial r} = [a_{13}a_{21}X - (a_{13})^2\lambda - a_{11}a_{23}X]/|H| \ ,$$

If $\frac{\partial^2 u}{\partial X \partial F} \geq 0$ and $\frac{\partial^2 W}{\partial X \partial F} \leq 0$, then $\frac{\partial X}{\partial r} < 0$.

$$\frac{\partial F}{\partial r} = [\, a_{12}a_{23}X + a_{13}\lambda a_{32} - a_{13}a_{22}X]/|H| \, .$$

The sign of the first term is unknown and the signs of the second and third terms are

positive and negative, respectively, leading $\frac{\partial F}{\partial r} \overset{<}{\underset{>}{=}} 0$.

Converting to elasticities yields Proposition 4. □

Appendix B

For demonstrating $\frac{\partial X_i}{\partial \tau_m} > 0$, substitute the solutions to the F.O.C.s (8)

$$X_i^*(\bar{\tau}, \bar{r}), i \ = \ 1, 2,$$

$$\lambda^*(\bar{\tau}, \bar{r}),$$

into (8) and differentiate with respect to τ_m

(B1a) $\frac{\partial^2 u}{\partial X_i^2}\frac{\partial X_i}{\partial \tau_m} + \frac{\partial^2 u}{\partial X_i \partial X_j}\frac{\partial X_j}{\partial \tau_m} - \tau_1 \frac{\partial W_1}{\partial X_i}\frac{\partial \lambda}{\partial \tau_m} - \tau_2 \frac{\partial W_2}{\partial X_i}\frac{\partial \lambda}{\partial \tau_m} - \lambda\tau_1 \frac{\partial^2 W_1}{\partial X_i^2}\frac{\partial X_i}{\partial \tau_m} -$

$\lambda\tau_2 \frac{\partial^2 W_2}{\partial X_i^2}\frac{\partial X_i}{\partial \tau_m} - \lambda\tau_1 \frac{\partial^2 W_1}{\partial X_i \partial X_j}\frac{\partial X_j}{\partial \tau_m} - \lambda\tau_2 \frac{\partial^2 W_2}{\partial X_i \partial X_j}\frac{\partial X_j}{\partial \tau_m} - \lambda \frac{\partial W_m}{\partial X_i} - r_i \frac{\partial \lambda}{\partial \tau_m} = 0,$

(B1b) $\frac{\partial^2 u}{\partial X_j^2}\frac{\partial X_j}{\partial \tau_m} + \frac{\partial^2 u}{\partial X_i \partial X_j}\frac{\partial X_i}{\partial \tau_m} - \tau_1 \frac{\partial W_1}{\partial X_j}\frac{\partial \lambda}{\partial \tau_m} - \tau_2 \frac{\partial W_2}{\partial x_j}\frac{\partial \lambda}{\partial \tau_m} - \lambda\tau_1 \frac{\partial^2 W_1}{\partial X_j^2}\frac{\partial x_j}{\partial \tau_m} -$

$\lambda\tau_2 \frac{\partial^2 W_2}{\partial X_j^2}\frac{\partial X_j}{\partial \tau_m} - \lambda\tau_1 \frac{\partial^2 W_1}{\partial X_i \partial X_j}\frac{\partial X_i}{\partial \tau_m} - \lambda\tau_2 \frac{\partial^2 W_2}{\partial X_i \partial X_j}\frac{\partial X_i}{\partial \tau_m} - \lambda \frac{\partial W_m}{\partial X_i} - r_i \frac{\partial \lambda}{\partial \tau_m} = 0$

(B1c) $-W_m - \tau_1 \frac{\partial W_1}{\partial X_i}\frac{\partial X_i}{\partial \tau_m} - \tau_2 \frac{\partial W_2}{\partial X_i}\frac{\partial X_i}{\partial \tau_m} - \tau_2 \frac{\partial W_2}{\partial X_j}\frac{\partial X_j}{\partial \tau_m} - \tau_1 \frac{\partial W_1}{\partial X_j}\frac{\partial X_j}{\partial \tau_m} - r_i \frac{\partial X_i}{\partial \tau_m} - r_j \frac{\partial X_j}{\partial \tau_m} = 0,$

where $\frac{\partial^2 W_m}{\partial X_i^2} > 0, i, j, m = 1, 2,$ $\frac{\partial^2 u}{\partial X_i^2} = \frac{\partial^2 u}{\partial C^2}\left(\frac{\partial W_1}{\partial X_i} + \frac{\partial W_1}{\partial X_i}\right)^2 - \frac{\partial U}{\partial C}\left(\frac{\partial^2 W_1}{\partial X_i^2} + \frac{\partial^2 W_2}{\partial X_i^2}\right) < 0,$

$\frac{\partial^2 u}{\partial X_i \partial X_j} = \frac{\partial^2 u}{\partial C^2}\left(\frac{\partial W_1}{\partial X_j} + \frac{\partial W_2}{\partial X_j}\right)\left(\frac{\partial W_1}{\partial X_i} + \frac{\partial W_2}{\partial X_i}\right) - \frac{\partial U}{\partial C}\left(\frac{\partial^2 W_1}{\partial X_i \partial X_j} + \frac{\partial^2 W_2}{\partial X_i \partial X_j}\right) \lesseqgtr 0$, depending on $\frac{\partial^2 W_m}{\partial X_i \partial X_j}$,

$i, j, m = 1, 2, i \neq j.$

Solve (B1) with Cramer's Rule by denoting

$$a_{ii} = \frac{\partial^2 u}{\partial X_i^2} - \lambda\tau_1 \frac{\partial^2 W_1}{\partial X_i^2} - \lambda\tau_2 \frac{\partial^2 W_2}{\partial X_i^2} < 0,\ a_{jj} = \frac{\partial^2 u}{\partial X_j^2} - \lambda\tau_1 \frac{\partial^2 W_1}{\partial X_j^2} - \lambda\tau_2 \frac{\partial^2 W_2}{\partial X_j^2} < 0$$

$$a_{ij} = a_{ji} = \frac{\partial^2 u}{\partial X_i \partial X_j} - \lambda\tau_1 \frac{\partial^2 W_1}{\partial X_i \partial X_j} - \lambda\tau_2 \frac{\partial^2 W_2}{\partial X_i \partial X_j} \lesseqgtr 0,$$

$$a_{i3} = a_{3i} = -\tau_1 \frac{\partial W_1}{\partial X_i} - \tau_2 \frac{\partial W_2}{\partial X_i} - r_i < 0,\ i, j = 1, 2,\ i \neq j.$$

$$a_{j3} = a_{3j} = -\tau_1 \frac{\partial W_1}{\partial X_j} - \tau_2 \frac{\partial W_2}{\partial X_j} - r_i < 0,\ i, j = 1, 2,\ i \neq j.$$

(B2) $\frac{\partial X_i}{\partial \tau_m} = \left[a_{ij}a_{j3}W_m + a_{i3}\lambda \frac{\partial W_m}{\partial X_j} a_{3j} - a_{i3}a_{jj}W_m - \lambda \frac{\partial W_m}{\partial X_i}(a_{j3})^2\right] / |H_o|,\ i, j, m = 1, 2, i \neq j,$

where the bordered Hessian, $|H_o| > 0$, for a maximum. The last term in numerator of (B2) is positive. Distributing the other terms reveals a rebound effect

$$a_{ij}a_{j3}W_m + a_{i3}\lambda\frac{\partial W_m}{\partial X_j}a_{3j} - a_{i3}a_{jj}W_m =$$

$$\frac{\partial^2 u}{\partial C^2}\left(\frac{\partial W_1}{\partial X_j} + \frac{\partial W_2}{\partial X_j}\right)\left(\frac{\partial W_1}{\partial X_i} + \frac{\partial W_2}{\partial X_i}\right)a_{j3}W_m +$$

$$\left(\lambda\frac{\partial W_m}{\partial X_j}a_{3j} - a_{jj}W_m\right)\left(-\tau_1\frac{\partial W_1}{\partial X_i} - \tau_2\frac{\partial W_2}{\partial X_i}\right) + \left[-\left(\frac{\partial U}{\partial C} + \lambda\tau_1\right)\frac{\partial^2 W_1}{\partial X_i \partial X_j} - \left(\frac{\partial U}{\partial C} +\right.\right.$$

$$\left.\left.\lambda\tau_2\right)\frac{\partial^2 W_2}{\partial X_i \partial X_j}\right]a_{j3}W_m - \left(\lambda\frac{\partial W_m}{\partial X_j}a_{3j} - a_{jj}W_m\right)r_i.$$

The first and second terms on the right-hand-side are positive, but the last term is a negative rebound effect, $-\left(\lambda\frac{\partial W_m}{\partial X_j}a_{3j} - a_{jj}W_m\right)r_i < 0$. Any increase in preservation X_i from an increase in τ_m will have cost r_i, which has a rebound effect of reducing preservation. The sign of the third term depends on the second cross-partials on food waste, $\frac{\partial^2 W_m}{\partial X_i \partial X_j}$, *m = 1, 2*. If $\frac{\partial^2 W_m}{\partial X_i \partial X_j} > 0$, then increasing the food preservation X_j will result in more effective use of X_i. An example is an increase in food preservation human capital will improve the effectiveness of preservation physical capital. In this case, the cross-partials reinforce $\varepsilon_{X_i,\tau_m} > 0$. If instead $\frac{\partial^2 W_m}{\partial X_i \partial X_j} < 0$, then a cross rebound effect exists. Increasing food preservation X_j will decrease the marginal product of waste reduction for X_i, $\frac{\partial X_i}{\partial \tau_m}$ declines. This reduces X_i, which mitigates ε_{X_i,τ_m}.

Proposition 5 Proof

Differentiating (8) with respect to r_1 yields

(B3a) $$\frac{\partial^2 u}{\partial X_1^2}\frac{\partial X_1}{\partial r_1} + \frac{\partial^2 u}{\partial X_1 \partial X_2}\frac{\partial X_2}{\partial r_1} - \tau_1\frac{\partial W_1}{\partial X_1}\frac{\partial \lambda}{\partial r_1} - \tau_2\frac{\partial W_2}{\partial X_1}\frac{\partial \lambda}{\partial r_1} - \lambda\tau_1\frac{\partial^2 W_1}{\partial X_1^2}\frac{\partial X_1}{\partial r_1} - \lambda\tau_2\frac{\partial^2 W_2}{\partial X_1^2}\frac{\partial X_1}{\partial r_1}$$

$$-\lambda\tau_1\frac{\partial^2 W_1}{\partial X_1 \partial X_2}\frac{\partial X_2}{\partial r_1} - \lambda\tau_2\frac{\partial^2 W_2}{\partial X_1 \partial X_2}\frac{\partial X_2}{\partial r_1} - \lambda - r_1\frac{\partial \lambda}{\partial r_1} = 0,$$

(B3b) $\frac{\partial^2 u}{\partial X_2^2}\frac{\partial X_2}{\partial r_1} + \frac{\partial^2 u}{\partial X_2 \partial X_1}\frac{\partial X_1}{\partial r_1} - \tau_1 \frac{\partial W_1}{\partial X_2}\frac{\partial \lambda}{\partial r_1} - \tau_2 \frac{\partial W_2}{\partial X_2}\frac{\partial \lambda}{\partial r_1} - \lambda\tau_1 \frac{\partial^2 W_1}{\partial X_2^2}\frac{\partial X_2}{\partial r_1} - \lambda\tau_2 \frac{\partial^2 W_2}{\partial X_2^2}\frac{\partial X_2}{\partial r_1} -$

$\lambda\tau_1 \frac{\partial^2 W_1}{\partial X_2 \partial X_1}\frac{\partial X_1}{\partial r_1} - \lambda\tau_2 \frac{\partial^2 W_2}{\partial X_2 \partial X_1}\frac{\partial X_1}{\partial r_1} - r_2 \frac{\partial \lambda}{\partial r_1} = 0,$

(B3c) $-X_1 - \tau_1 \frac{\partial W_1}{\partial X_1}\frac{\partial X_1}{\partial r_1} - \tau_2 \frac{\partial W_2}{\partial X_1}\frac{\partial X_1}{\partial r_1} - \tau_2 \frac{\partial W_2}{\partial X_2}\frac{\partial X_2}{\partial r_1} - \tau_1 \frac{\partial W_1}{\partial X_2}\frac{\partial X_2}{\partial r_1} - r_1 \frac{\partial X_1}{\partial r_1} - r_2 \frac{\partial X_2}{\partial r_1} = 0,$

Solving (B3) with Cramer's Rule results in

$$\frac{\partial X_i}{\partial r_i} = \left[a_{ij}a_{j3}X_i - a_{i3}a_{jj}X_i - \lambda\left(a_{j3}\right)^2\right]/|H_o| \ \substack{<\\-\\>}\ 0, i = 1, 2, i \neq j.$$

The second and third terms in the numerator on the right-hand-side are both negative. However, the first term is indeterminate. Distributing this term

$$a_{ij}a_{j3}X_i = \frac{\partial^2 u}{\partial C^2}\left(\frac{\partial W_1}{\partial X_j} + \frac{\partial W_2}{\partial X_j}\right)\left(\frac{\partial W_1}{\partial X_i} + \frac{\partial W_2}{\partial X_i}\right)\left(-\tau_1 \frac{\partial W_1}{\partial X_1} - \tau_2 \frac{\partial W_2}{\partial X_1}\right)X_i + \left[-\left(\frac{\partial U}{\partial C} + \lambda\tau_1\right)\frac{\partial^2 W_1}{\partial X_i \partial X_j} - \left(\frac{\partial U}{\partial C} + \lambda\tau_2\right)\frac{\partial^2 W_2}{\partial X_i \partial X_j}\right]\left(-\tau_1 \frac{\partial W_1}{\partial X_1} - \tau_2 \frac{\partial W_2}{\partial X_1}\right)X_i - \left[-\left(\frac{\partial U}{\partial C} + \lambda\tau_1\right)\frac{\partial^2 W_1}{\partial X_i \partial X_j} - \left(\frac{\partial U}{\partial C} + \lambda\tau_2\right)\frac{\partial^2 W_2}{\partial X_i \partial X_j}\right] r_i X_i - \frac{\partial^2 u}{\partial C^2}\left(\frac{\partial W_1}{\partial X_j} + \frac{\partial W_2}{\partial X_j}\right)\left(\frac{\partial W_1}{\partial X_i} + \frac{\partial W_2}{\partial X_i}\right) r_i X_i.$$

The first term on the right-hand-side is negative, which reinforces $\varepsilon_{X_i,r_i} < 0$. The last term is positive, representing a rebound effect; mitigating ε_{X_i,r_i}. The signs of the middle two terms depend on the signs of the second cross-partials on food waste, $\frac{\partial^2 W_m}{\partial X_i \partial X_j}$, *m = 1, 2, i* $\neq j$. Alternative cross rebound effects exist depending on their magnitudes and signs.

$$\frac{\partial X_j}{\partial r_i} = \left[\lambda a_{j3}a_{3i} + a_{i3}a_{ji}X_i - a_{ii}a_{j3}X_i\right]/|H_o| \ \substack{<\\-\\>}\ 0, i = 1, 2, i \neq j.$$

The first term in the numerator on the right-hand-side is positive supporting $\frac{\partial X_j}{\partial r_i} > 0$.

Distributing the second and third terms reveals rebound effects

$a_{i3}a_{ji}X_i - a_{ii}a_{j3}X_i$

$$= -\frac{\partial^2 u}{\partial C^2}\left(\frac{\partial W_1}{\partial X_j}+\frac{\partial W_2}{\partial X_j}\right)\left(\frac{\partial W_1}{\partial X_i}+\frac{\partial W_2}{\partial X_i}\right) r_i X_i - a_{ii}\left(-\tau_1\frac{\partial W_1}{\partial X_1}-\tau_2\frac{\partial W_2}{\partial X_1}\right)X_i$$

$$+\frac{\partial^2 u}{\partial C^2}\left(\frac{\partial W_1}{\partial X_j}+\frac{\partial W_2}{\partial X_j}\right)\left(\frac{\partial W_1}{\partial X_i}+\frac{\partial W_2}{\partial X_i}\right)\left(-\tau_1\frac{\partial W_1}{\partial X_1}-\tau_2\frac{\partial W_2}{\partial X_1}\right)X_i + a_{ii}r_iX_i$$

$$+\left[-\left(\frac{\partial U}{\partial C}+\lambda\tau_1\right)\frac{\partial^2 W_1}{\partial X_i\partial X_j}-\left(\frac{\partial U}{\partial C}+\lambda\tau_2\right)\frac{\partial^2 W_2}{\partial X_i\partial X_j}\right]\left(-\tau_1\frac{\partial W_1}{\partial X_1}-\tau_2\frac{\partial W_2}{\partial X_1}\right)X_i$$

$$-\left[-\left(\frac{\partial U}{\partial C}+\lambda\tau_1\right)\frac{\partial^2 W_1}{\partial X_i\partial X_j}-\left(\frac{\partial U}{\partial C}+\lambda\tau_2\right)\frac{\partial^2 W_2}{\partial X_i\partial X_j}\right]r_iX$$

The first and second terms on the right-hand-side are positive, which reinforces $\varepsilon_{X_j,r_i} > 0$. The third and fourth terms are negative, representing rebound effects, The signs of the last two terms depend on the signs of the second cross-partials on food waste, $\frac{\partial^2 W_m}{\partial X_i \partial X_j}$, $m = 1, 2, i \neq j$. Alternative cross rebound effects exist depending on their magnitudes and signs.

Converting into elasticities yields Proposition 5. □