THREE ESSAYS ON CONSUMPTION AND FOOD WASTE

by

Dmytro Serebrennikov

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STATEMENT OF COMMITTEE APPROVAL

Dr. Michael Wetzstein, Co-chair

Department of Agricultural Economics

Dr. Bhagyashree Katare, Co-chair

Department of Agricultural Economics

Dr. H. Holly Wang

Department of Agricultural Economics

Dr. Jiong Sun

Department of Consumer Science

Approved by:

Dr. Nicole J. Olynk Widmar

Head of the Graduate Program

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ABSTRACT

Author: Serebrennikov, Dmytro. PhD
Institution: Purdue University
Degree Received: August 2019
Title: Three Essays on Consumption and Food Waste
Committee Chair: Michael Wetzstein

Population growth and increasing life standards contributed to a high demand for food worldwide. Simultaneously, there is growing evidence that more food is being lost or wasted through the different stages of the supply chain. In the developed world, including the United States, consumer waste often constitutes more than 60% of all food losses.

This dissertation explores the problem of consumer waste from three different perspectives. In the first essay, a game-theoretic model of a direct interaction between consumers and a retailer with monopoly power is developed to capture the effects of dynamic pricing on the transfer of perishable inventory to consumers. The retailer chooses its optimal price taking into account both retailer and consumer preservation. As long as the retailer's inventory is well preserved, its price will be low inducing consumers to stockpile and waste more food. Consumers may also waste more if their own preservation level is relatively high. The second essay focuses on governmental policies aimed at reducing consumer waste, such as a tax and a subsidy. Using microeconomic analysis, closed-form solutions for a social-optimal food waste tax and subsidy are derived. The government may impose this tax to increase the cost of waste disposal for households while using tax revenue to sponsor food preservation efforts. It is shown that the tax might not be an effective instrument if the responsiveness of food waste to this tax is low. Finally, the third essay investigates the impact of a nutrition education program on school-cafeteria waste. This program was implemented to promote the health benefits of consuming fruits and vegetables among elementary

school children. Comparing food waste data in the treatment and control groups, we found no statistically significant evidence of either increased selection or consumption of fruits and vegetables in the treatment group.

CHAPTER 1. INTRODUCTION

Population growth coupled with increasing life standards contributed to a high demand for food worldwide. Parallel to this trend was a substantial increase in the amount of food that is lost of wasted across different stages of food-supply chain. The current literature provides often conflicting perspectives on the definition of food waste (Bellemare 2017). In general terms, food waste (or loss) can be interpreted as dry of liquid substance originally intended for use in human consumption, but ultimately lost or discarded during the production, processing, transportation, storage, and consumption. One empirical study of food waste found the amount of annual food traffic never used to feed people may amount to 30% globally (Gustavsson et al. 2011). The patterns of food waste are however different in developing and developed countries. In the former, food waste primarily occurs in the form of post-harvest losses (raw unprocessed material such as grain or beets) due to poor transportation and storage infrastructure as well as lack of management skills. In the latter, food waste mostly consists of food prepared for immediate consumption, which originates in the retail and household sector.

The focus of this dissertation is on consumer waste, which is essentially the waste that originates in the dinner table. The USDA estimates show that this type of waste is most prevalent in the United States and may range from as little as 9% to as much as 37% of the produced food stock depending upon the type of food (Buzby and Hyman 2012). For example, meat, fish, and poultry as well as fruits and vegetables are discarded most often, which might be partially explained by their natural perishability. Perishability can be characterized as an increased sensitivity of food to environmental factors, such as humidity, temperature, and mechanical pressure. While these factors contribute to increased waste, it is possible to substantially reduce their impact by using ventilated storage or refrigeration. However, consumers can also waste food from changing tastes and preferences. For example, they often stockpile food to save time from multiple shopping trips or in anticipation of future events, which might disrupt food supply (for example, hurricanes). While these stockpiles might be well preserved, consumers still can discard some food in the future due to a change in their preferred diet levels caused by a change in mood, health or social circumstances.

The economic argument explaining the increased food waste on the consumer's side is consumers do not pay the full price for waste disposal. This price does not consider the negative non-pecuniary externalities associated with the traditional methods of waste disposal such as landfilling or incineration. These negative externalities include contaminated land, water, and increased greenhouse gas emissions, whose indirect impact on society is hard to measure in monetary terms. Apart from the low cost of waste disposal, a higher household income may also be a decisive factor contributing to more waste. As consumers earn more, the share of food in their budget shrinks making them much more selective about food products and therefore less concerned about waste in general (Hodges et al. 2012).

To incentivize consumers waste less, different interventions can be implemented. For example, government may potentially increase the direct cost of consumer waste by imposing a disposal tax on every unit of organic household garbage and use proceeds from tax collection to improve food preservation through, for example, sponsorship of information and/or education campaigns. Education campaigns are often implemented in schools and colleges to internalize externalities associated with knowledge dissemination. While the government's tax has a direct impact on consumers' budget, the objective of many education campaigns is to instill healthy nutrition habits without affecting their income constraint.

In this dissertation, we look at food waste from three different perspectives. In Essay 1 (Chapter 2), we develop a dynamic two-period model of direct interaction between consumers and a retailer with monopoly power to study the effects of transfer of a perishable inventory (food) from the retailer to consumers. Both consumers and the retailer can carry their inventories in time subject to exogenous preservations. Using price as a principal incentive mechanism, the retailer can induce consumers to stockpile food early provided its own rate of food preservation is high. Consumers also buy more food in advance if it can be preserved. We introduce a measure of consumer food waste as a difference between the food purchased and the expected level of consumer diet in the second period. We show that consumer waste increases when the retailer sells more food.

Essay 2 (Chapter 3) focuses on food-waste reducing policies such as a tax and a subsidy as applied to consumers (households). The tax is a levy on a unit of food waste, which the government can impose to increase the cost of waste disposal to consumers and reduce the negative external effects of waste on the environment and society. When the government imposes a tax, its revenue increases. The government then can use this revenue to implement the subsidy, compensating consumers the cost of food preservation. We contribute to microeconomic theory by deriving closed-form solutions for both social-optimal tax and subsidy. Employing welfare analysis, we show that the government's decision to impose a tax depends on the elasticity of food waste to this tax. Additionally, it was found that the objective of zero waste will be hard to achieve if the government is in charge of waste mitigation efforts.

The essay 3 (Chapter 4) is empirical and concerns the effects of a special nutrition education program on consumption behavior of elementary school students in the state of Indiana. The nutrition education program consisted of special lessons promoting healthy nutrition habits, which complemented and enhanced the regular class curriculum. These lessons were delivered to a group of selected students (treatment group). To study the impact of the program on students, we compare both selection and consumption of fruits and vegetables in the treatment group to those in the control group. Our results show the implemented program has no statistically significant effect on either selection or consumption of fruits and vegetables.

CHAPTER 2. THE EFFECTS OF DYNAMIC PRICING ON THE TRANSFER OF PERISHABLE INVENTORY FROM A RETAILER TO CONSUMERS

2.1 Introduction

Consumers often tend to purchase more food than they usually demand for immediate satisfaction. For example, strategic stockpiles are created in anticipation of severe weather events threatening to disrupt regular food supply (Mattheis 2017). Purchasing food above some norm is also common under less dramatic circumstances. For example, during a typical holiday season, households may buy food well in excess of their regular requirements to accommodate family members and friends. Retailers can also stimulate advance purchasing even in the absence of special dates or events. For example, quantity discounts are often introduced to increase sales of bulk food (Dhar and Hoch 1996).

When stockpiling food for future consumption, consumers increasingly rely on their current diet, tastes, and preferences. However, when consumption is sufficiently delayed in time, tastes and preferences may change depending on health, mood or social circumstances. This might be especially true for households with children whose consumption needs may be notoriously hard to predict even in the near-term future (Goldenberg 2016). Another factor that might affect consumption of stockpiled food is the availability of storage space and preservation technology. In the absence of reliable refrigeration, perishable food is subject to spoilage and might become undesirable for consumption (Netherlands Nutrition Centre, 2018). Due to uncertainty over future consumption demands, some food might be discarded or wasted. According to USDA, consumer-level food waste in 2010 amounted to 90 billion pounds or 21% of American food traffic (Buzby et al. 2014).

Retailers may derive economic benefits from encouraging consumers to stockpile food. These benefits include increased sales and reduction in waste disposal (ReFED 2018). To encourage stockpiling behavior, retailers often use dynamic pricing and markdowns. Dynamic pricing implies that prices can be adjusted in time to manage uncertain demand. Different industries use dynamic pricing to stimulate advanced selling. For example, hotels may set reduced prices to increase early booking rates (Xie and Shugan 2001). Selling in advance is based on the idea of buyer's uncertainty over future consumption. When the future is uncertain, buyers might be tempted to purchase a product or order a service in advance of actual consumption to increase savings and/or compensate for possible supply interruptions (Xie and Shugan 2001). Sellers, on the other hand, may use advanced selling to better deal with the imminent perishability of their product or service. Ferguson and Koenigsberg (2007) argue that any good/service is essentially perishable, but the rate of market value erosion reflects the underlying nature of the product in question. For example, airline tickets and hotel rooms don't deteriorate in time, but perish instantly once time is up for service delivery. In contrast, many fresh food products deteriorate and lose market value gradually.

The objective of this essay is to establish a dynamic model of direct interaction between consumers and a retailer in the presence of demand (consumption) uncertainty. The retailer sells food and behaves as a firm with monopoly power. The assumption of local monopoly power holds if the retailer is one of the major suppliers within a localized region or neighborhood. Employing non-cooperative game theory as a basis for analysis (Moorthy 1985), the interaction between the retailer and consumers is formalized as a two-stage game with the retailer playing the role of a Stackelberg leader. The retailer begins the game by setting a price for food in the first stage, while consumers respond to this price by expressing their demand in the second stage. The consumer demand is a function of both the retailer's price and consumer preferences (diet). The game is solved employing backward induction, when the first step is to determine consumers' reaction function (demand) followed by the retailer's price.

It is important to realize that in reality consumers and retailers often interact more than once. This is especially true when consumers prefer regular shopping with their local retailer. In this case, consumers may form expectations or develop strategic behavior among shopping trips. Stockpiling is an example of such behavior (Guo and Villas-Boas 2007). Retailers, on the other hand, can also use different strategies to sell their inventory such as setting prices dynamically. If inventory is not selling, a retailer may carry leftovers further in anticipation of consumers' next visit. This combination of stockpiling and inventory carryover establishes a ground for dynamic interaction between consumers and a retail firm.

It is common in the game theoretic literature to separate multiple interactions in time (Aviv and Pazgal 2008; Cachon and Swinney 2009; Mersereau and Zhang 2012). In such a case, the initial one-period game is repeated again in the next period to capture important dynamic effects between the periods. To preserve tractability and derive closed-form solutions, a two-period game is a typical design choice. In compliance with this tradition, we repeat our two-stage game twice assuming demand uncertainty in the second period. In the first period, demand is certain, but consumers can buy more food than they currently require to stockpile and carryover the excess to the next period. Immediately before the start of the second period, consumers are not sure how much food they would consume in future. We will show analytically that if the retailer's price in period 1 is low enough, consumers will stockpile more food in period 1 and purchase less in period 2. If the amount of combined inventory will exceed the expected consumption level in period 2, consumers are going to waste food.

2.2 Literature review

Several recent studies in marketing literature focus on a single retailer’s economic interactions with consumers. Specifically, Aviv and Pazgal (2008), Cachon and Swinney (2009), and Mersereau and Zhang (2012) investigate retailer’s realization strategies in the presence of a segmented consumer market. They all show that market segmentation in both strategic and myopic consumers may shed a considerable light on the nature of interactions between a retailer and consumers. For example, Cachon and Swinney (2009) explore retailer’s pricing and inventory decisions in a two-period dynamic model with strategic consumers. The retailer chooses initial stocking quantity in the first period and a sale (markdown) price in the second. There is also a possibility of stockout in the second period. Given this information, strategic consumers have to decide whether to buy immediately at a high price or wait and face the risk of stockout. They find that consumers sufficiently optimistic about future product availability postpone purchasing. Mersereau and Zhang (2012) explore the effect of periodic clearance sales on the seller’s revenue in a two-period dynamic model, which involves strategic consumers. In contrast to Cachon and Swinney (2009), they assume that a true proportion of strategic consumers might be unknown to the retailer. Comparing this situation to the fully deterministic case (when the number of consumers is certain), they find that the retailer’s optimal revenue might be slightly greater in the absence of uncertainty. Aviv and Pazgal (2008) consider two types of seller’s pricing policies to incorporate a wide variety of consumer purchasing behavior. Assuming a two-period model, they show that a seller’s second period price might be contingent on the past inventory level. As an alternative, the seller can choose to introduce a preannounced future discount price, which does not depend on inventory at all. Comparing the two approaches, they find the seller is better off with contingent pricing if consumers are fully myopic (they never delay purchasing).

While we don’t explicitly segregate market in several consumer groups, we assume that all consumers buying food products can act strategically if they stockpile for future consumption. Furthermore, in our case the retailer never commits to a future price, as its pricing strategy reflects consumer’s actions in both periods. This assumption is different from the above literature with the exception of Aviv and Pazgal (2008). Finally, our study is unique in terms of how market uncertainty is incorporated. In Mersereau and Zhang (2012), the uncertainty assumption specifically relates to the size of a strategic market segment, which might be hidden from the retailer’s view in both time periods. In our case, this uncertainty concerns the level of consumption (not the market size) in the second period only.

A related relevant stream of literature concerns dynamic pricing and inventory management of perishable goods with carryover and replenishment. Hu et al. (2016) develop a joint inventory and markdown model for perishable goods in the context of optimal control theory. Initially, a firm only sells fresh food at a full price. Subsequently, it can carryover all the unsold inventory to the next period and sell it with a markdown alongside a full priced fresh product. On the consumer side, strategic consumers may buy forward by taking advantage of regular price discounts. Hu et al. (2016) conclude that the seller’s optimal strategy leads to a bang-bang solution. According to this strategy, the leftover inventory has to be either discarded or sold at a discount to ensure the cannibalization effect is small. In the context of a supply chain consisting of a single supplier and buyer, Jia and Hu (2010) explore a similar problem of joint pricing and ordering of a perishable good with carryover. In addition to procuring a fresh product from the supplier, the buyer can carryover the old product from the past to the next period. Applying a two-period dynamic game model, they find that the optimal price at which the carryover can be sold to consumers only depends on its inventory in the second period. Compared to these two studies, we are not considering inventory replenishment, implying the product that the retailer can sell in the future is not technically "fresh." Instead, we allow for a gradual decay of the retailer's inventory stock. Similarly, the consumer's amount of stockpiled inventory also decays gradually.

Similar to our study, Ferguson and Koenigsberg (2007) consider a two-period dynamic game, which describes interaction between consumers and a single retailer selling deteriorating inventory. Specifically, they explore the price and stocking decisions made by the retailer, who faces uncertain demand in period one and can replenish its stock in period two. The demand uncertainty may lead to a possible carryover, which determines the composition of the retailer's inventory in the later period. Depending upon consumer demand, price, and quality of the carryover, the firm can choose to carry all, some or zero inventory to the future period. If at least a portion of the product is carried over, the firm has to price it lower compared to the new product to ensure consumers can discriminate between the two. Ferguson and Koenigsberg (2007) find that a partial carryover can bring the highest benefit to the retailer when the demand uncertainty in period one is high. However, when the quality difference between the carryover and fresh products is negligible, the firm might be willing to put only carryover on sale. Our study is distinct from Ferguson and Koenigsberg's in that we assume demand uncertainty later in the game (in period two). As a result, the retailer in our study does not face the problem of whether to carry over or not between the two periods. Furthermore, consumers in Ferguson and Koenigsberg's study are passive in that they do not stockpile or carryover food, which results in no consumer food waste.

Conceptually, studies by Keskinocak et al. (2008) and Erhun et al. (2008) are most closely related to our research. Both studies focus on the economic relationship between a supplier and a retailer (buyer) under the circumstances of capacitated supply. Keskinocak et al. (2008) develop a dynamic two-period model, where the supplier's first-period available capacity (supply) is limited. At the beginning of each period, the supplier announces a wholesale price and the retailer responds by choosing how much capacity to procure and the price at which the procured capacity will be sold to consumers. They find the level of supplier's capacity has a profound effect on both agents' pricing and quantity decisions across time. As long as the initial capacity is high, the wholesale price is low, inducing the retailer to accumulate inventory in excess of the current period demand. In such a situation, the retailer carries extra inventory to the next period. Otherwise, when the capacity is low, the retailer procures just as much as to meet the immediate demand. Keskinocak et al. (2008) show the second-period wholesale price is lower the greater the level of inventory that the retailer carries from period one. Erhun et al. (2008) develop a similar supplier-buyer interaction model, which also includes an assumption of stochastic (two-state) consumer demand in period two. Also, the supplier has a limited capacity allocated over both periods (not just over period one as in Keskinocak et al. (2008)). They show demand uncertainty has a crucial impact on both agents' projected profits. Specifically, when the probability of consumer demand reaching a high state is close to one, both supplier and buyer increase their profits. However, the ratio of the supplier's profit to the buyer's profit shows a supplier earns more. Regarding prices, it is shown that the expected wholesale price in period two is always below that in period one, reflecting the buyer's tendency to procure more of the product earlier in the game in order to induce supplier to decrease the price later.

In contrast to the previous two papers, we assume no supplier in the game, but instead focus on the direct interaction between a single retailer and consumers. The retailer in our model supplies goods purchased by (procured to) consumers. Because of this difference, we initially derive consumer demand from first principles by specifying a utility function to incorporate consumer preferences (diet). Both Keskinocak et al. (2008) and Erhun et al. (2008) omit this step and directly assign an arbitrary form to consumer demand. Furthermore, both papers implicitly treat the tradeable capacity as infinitely durable. We relax this assumption by assuming that the capacity can deteriorate in time.

2.3 Contribution

In summary, this study has three important contributions to the existing literature. First, we establish a model of direct interaction between a retailer and consumers, assuming a continuous product quantity. Earlier studies on consumer-seller interactions are predominantly unit-based. In unit-based studies, consumers are limited to purchasing a unit of a product. While this assumption might be feasible for the market of durable goods, it makes it hard to justify when dealing with perishable goods such as food. Second, we explicitly incorporate perishability in the model by assuming only a portion of initial food stock might be saved for future realization and consumption. Third, it is also explicit in our model that all consumers exhibit strategic behavior when stockpiling food for future consumption. Because of this behavior, consumers may incur food waste if the amount of stockpiled inventory exceeds their future consumption needs.

2.4 Model

2.4.1 Consumer preferences and utility

Consumers derive utility from consuming food q_i in two periods ($i = 1,2$). By definition, they buy at least some food during the first period, but may limit their purchases in the second period. This may happen if consumers stockpile food in the first period to carryover in response to a low retail price. The level of individual consumption in the respective period i is denoted as K_i. This exogenous parameter is sometimes treated in the literature as a level of diet or the desired consumption quantity (Haagsma 2012). Consumers may self-impose this diet on themselves to avoid disutility. Alternatively, they can follow nutritionist's prescriptions to mitigate the negative effects of overconsumption on health, for example, obesity. Table 2.1 contains the full list of the variables and parameters employed in the model.

Table 2.1. Summary of model notation

Symbol	Description
q_i	Quantity of food to purchase (in period *i=1,2)*
K_i	Level of consumer diet (in period *i=1,2*)
M	Hicksian aggregate good (money)
Y	Consumer disposable income
D_i	Consumer aggregate demand (in period *i=1,2*)
W	Amount of consumer food waste
N	Population coefficient
Q	Initial capacity (supply) level
$\alpha \in [0,1]$	Proportion of saved food stock on the retailer side
$\beta \in [0,1]$	Proportion of saved food stock on the consumer side
γ	Discount rate
ρ	Probability of high consumption state in Period 2

We assume that consumers buy more food than their diet level in period 1 if they are incentivized to stockpile for future consumption. The amount of purchases in period 2 is inversely related to the amount of carryover, since consumers buy less again provided their inventory is full. In total, the amount of food stock on the consumer side in the end of period 2 may be above or below the expected consumption level, K_2, resulting in either waste or temporary undernourishment. The latter might happen, for example, if the retailer's stock is depleted or spoiled because of poor refrigeration. In the context of a two-period model, it follows that consumers can exceed their individual consumption level in period 1 to form excess inventory by responding to a low retail price. Formally, this excess inventory can be expressed as a positive difference between the food purchased, q_1, and the consumer diet level, K_1

$$q_2^0 = \beta(q_1 - K_1)^+. \tag{1}$$

With the perishability of food, it is explicitly assumed that in period 2 only a certain portion of the saved inventory will become available in future. The parameter $\beta \epsilon [0,1]$ is the proportion of consumer inventory available in period 2. This parameter can measure the effect of consumer food preservation. A higher β reflects enhanced food preservation. Assuming $\beta > 0$, some inventory enters the consumer's utility function in period 2. Formally, a consumer's utility function is the same in both periods with one key distinction: utility in period 2 has inventory from period 1. Thus, it makes sense to characterize preferences of an individual consumer by looking at the second-period utility function first.

$$U_2(q_2) = M_2 - \frac{\left(K_2^j - q_2^0 - q_2\right)^2}{2}, \tag{2}$$

where q_2 and K_2^j are the amount of purchased food and the individual consumption level (diet) in period 2, respectively. Note the superscript j = H, L, which denotes the binary state of the consumer diet in period 2, where H and L are for high and low consumption levels, respectively. Furthermore, M_2 is the Hicksian aggregate good (money). The above utility function is of quadratic form, which guarantees the existence of a well-defined demand function (Amir et al. 2017).

To derive the optimal level of individual demand in period 2, a consumer maximizes (2) subject to the income constraint $p_2 q_2 + M_2 = Y$, where p_2 is the period 2 food price and Y is the level of disposable income. Assuming the income constraint always binds at an optimum, it can be substituted for M_2 in (2). The resulting unconstrained problem, when optimized for q_2, yields the expression (3) below.

$$q_2 = K_2^j - q_2^0 - p_2. \tag{3}$$

The individual consumer demand in period 2 is a decreasing function of price and past period inventory, but an increasing function of the current period level of diet. If the food is distributed for free ($p_2 = 0$), consumers would buy as much as to cover the gap between what they have and what they demand.

2.4.2 Market demand

It is assumed that the utility function in (2) describes consumer preferences of a representative consumer in the retail firm's entire market. This assumption is based on the quasi-linear nature of utility, where *M* has zero income effect. Consistent with this quasi-linear utility is (3) indicating that consumers' food demand is independent of income, *Y*.

When the income effect is absent, we implicitly assume the population is homogenous with households' income at a level where food purchases are essentially independent of how much household members combined earn. While this might not be a good representation of the entire U.S. population, it certainly accounts for the population of individual communities/neighborhoods with median to high income. Miller (2006) notes that food is often a small portion of a consumer's budget, so the income effect of changes in its price should be small or even zero. When this is the case, we can aggregate consumer demand by multiplying the individual demand function in (3) with an arbitrary population size, *N*. This results in a consumer market's reaction function to the price set by the retailer in period 2

$$D_2 = N\left(K_2^j - q_2^0 - p_2\right). \tag{4}$$

2.4.3 Retailer's problem

With monopoly power, a retailer maximizes its revenue by choosing a price according to market demand (4) subject to a capacity (supply) constraint. This capacity constraint is what the retailer has in total stock covering the two time periods. It assumes no replenishment between the periods nor in period 2. In reality, retail food stores often face short-run supply constraints. For example, supply of fruits, vegetables, dairy, and meats might not be delivered daily especially over weekends or holidays. Longer disruptions are possible as well because of bad weather and transportation delays (Titelius 2016). In our model, the retailer enters the first period fully stocked. The size of initial capacity, Q, is exogenously given. The retailer cannot sell more than this amount even if period 1 demand is over Q. If period 1 demand is lower than Q, the retailer has unsold inventory left. By the design of this problem, the retailor will carryover this inventory to the next period. Formally, the amount of leftover inventory is a positive difference between the initial stocking quantity, Q, and the consumer demand in period 1, D_1

$$\alpha(Q - D_1)^+. \tag{5}$$

Similar to the consumer case, the retailer's stock is perishable. This implies that a portion of the carryover inventory might be available in the next period: $\alpha \in [0,1]$. As a result, in period 2, the retailer's problem is to maximize revenue subject to the leftover inventory constraint.

$$Max_{p_2}\, \Pi_2 = p_2 D_2 \quad s.t. \quad D_2 \leq \alpha(Q - D_1) \tag{6}$$

As in period 1, consumer demand might exceed the level of available capacity. With this high demand, the retailer will raise the price to make sure demand is within the constraint. Otherwise, if demand is already below the constraint, the retailer is going to solve the unconstrained problem. We assume that all the unsold inventory in the end of period 2 will become waste. Also, following a similar approach in supply chain literature (Erhun et al. 2008), the retailer's purchasing cost as well as cost of disposal is normalized to zero.

2.4.4 Sequence of events

A single retailer and consumers interact twice over a two-period game. The stages in each period are similar: the retailer, as a game leader, chooses the price, and consumers follow by responding to this price. However, the decisions made in the second period are conditional on the outcome in the first period. Figure 2.1 illustrates the timeline of events. In total, this game includes four decisions. For analytical reasons, these decisions are presented backwards starting from the end of the game in period 2.

Decision 1. Consumers' response in period 2. Consumers form their aggregate demand for food, D_2, given the retailer's price, p_2, the amount of carryover inventory, q_2^0, and the current consumption level, K_2^j.

Decision 2. Retailer's price in period 2. The retailer chooses its current price, p_2, given its current capacity level, $\alpha(Q - D_1)^+$, and consumers' reaction function (aggregate demand in period 2).

Decision 3. Consumers' response in period 1. Consumers form their aggregate demand for food, D_1, given the retailer's price p_1, the current consumption level, K_1, and taking into account both the consumers' response in period 2 and the retailer's price in period 2.

Decision 4. Retailer's price in period 1. The retailer chooses its current price, p_1, given its current capacity level, Q, the consumers' reaction function (aggregate demand in period 1), and taking into account its own price in period 2.

As can be noticed, a critical difference between the first and second periods is that in period 1 consumers don't know their consumption level in period 2, K_2^j. For simplicity, it is assumed that period 2 consumption may be in either a high (H) or low (L) state, and the probability of reaching the high state is $\rho \in [0,1]$. This information is revealed simultaneously to all market agents between the two periods after consumers make their purchases in period 1 but before the retailer chooses its price in period 2. Because of this uncertainty, consumers may incur a lot of waste at the end of the game if their inventory from period 1 exceeds their consumption.

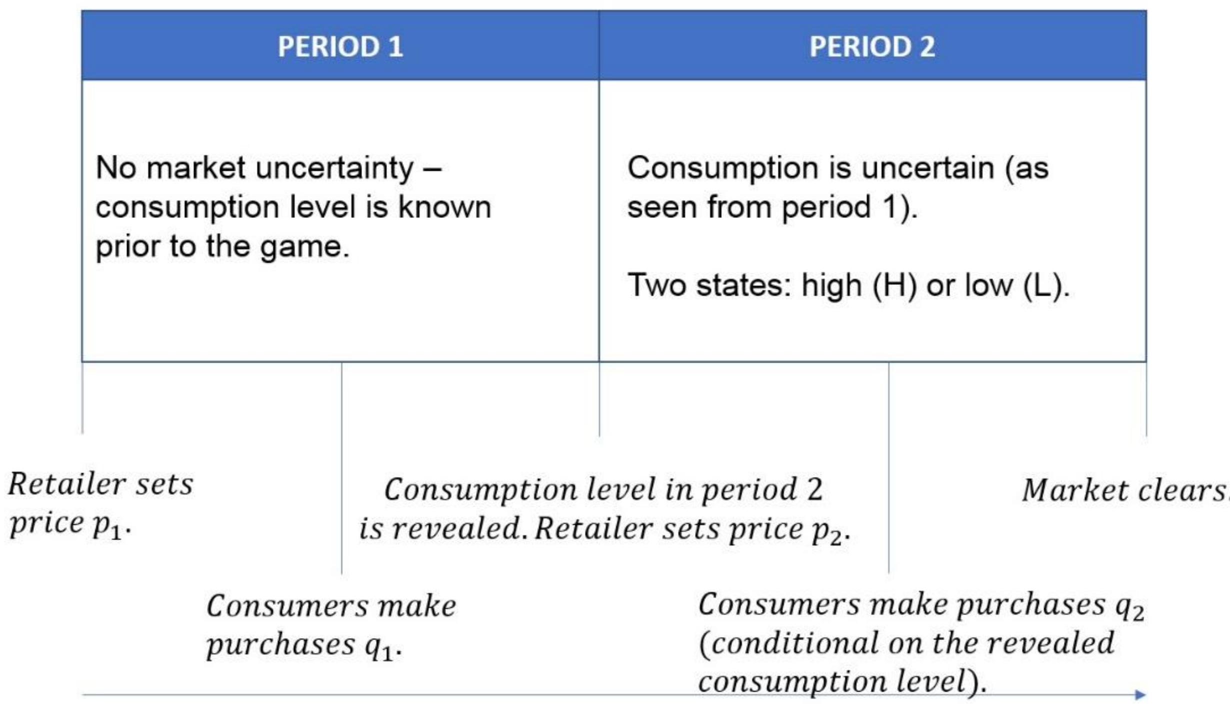

Figure 2.1. Sequence of events in a two-period game.

2.5 Research questions and hypothesis

In this study, we aim to address the following three research questions:

1) What is the optimal price of a forward-looking retailer in period 1?
2) How does the retailer's optimal price in period 1 react to changes in the levels of consumer and retailer preservation, the discount factor, and the probability of a high-consumption state in period 2?
3) What is a measure of consumer waste in period 2?

Using numerical study, we are going to show that the amount of consumer waste in the end of period 2 might be sensitive to a change in the rate of retailer preservation. Specifically, we are going to test the following research hypothesis: *if the retailer preserves more food in-between the two periods, consumers will generate more waste in the end of period 2*.

This hypothesis reflects a retailer's strategy to maximize total sales over a two-period trade regime. As long as its own food preservation is high, the retailer's first-period price will be low resulting in higher immediate sales (since consumers increase demand by stockpiling more). In period 2, the retailer will sell the rest of its inventory due to a high demand. Because this inventory is well preserved, the overall amount of sales over two periods will be high. In contrast, if the retailer's preservation level is low, it can't carryover much inventory between the two periods. Thus, by definition, the second-period sales level will be also low. In period 1, the retailer's price will be high due to the fact that the retailer acts more like a one-period monopoly. Thus, consumers will not buy much in period 1 either.

2.6 Results

Assuming some stockpiling in period 1, we can specify two different trade regimes. Under the first trade regime, the retailer's first-period capacity exceeds demand ($Q > D_1$), which results in more trade in the second period. Under the alternative regime, the retailer liquidates its entire stock in period 1 ($Q = D_1$) and does not proceed further. We will show that in both scenarios, consumers may waste some food as long as the amount of the ending stock exceeds their expected consumption level.

2.6.1 Scenario 1: two-period trade

We start by presenting analytical results for the case involving trade in both periods. The main objective of this section is to derive the retailer's optimal price in period 1 that takes into account immediate consumer demand in period 1 as well as the expected consumer demand and the retailer's price in period 2. To investigate the reaction of the retailer's optimal price to a change in model parameters, numerical analysis will be performed. Following our sequence of events, we first formulate and solve the problems for the representative consumer and the retailer in period 2.

2.6.1.1 Analysis of period 2

The aggregate demand is a consumers' reaction function to the retailer's price (see the equation 4). To determine the optimal price in period 2, the retailer has to solve the following problem

$$Max_{p_2}\, \Pi_2 = p_2 * \min\{D_2,\ \alpha(Q - D_1)^+\} \tag{7}$$

The retailer's optimal solution in period 2 is the price that reflects the binary state of the market, where the consumer demand can be above or below the available supply:

$$p_2 = \begin{cases} p_2^A = \frac{\left(K_2^j - q_2^0\right)N - \alpha(Q - D_1)}{N} & , if \;\; D_2 \geq \alpha(Q - D_1) \\ p_2^B = \frac{K_2^j - q_2^0}{2}, & if \;\; D_2 < \alpha(Q - D_1)\,. \end{cases} \tag{8}$$

As long as demand exceeds supply, the capacity (supply) constraint is binding; the retailer cannot sell more than the available supply. In this case, the retailer has to increase its price to make sure that the consumers with a high willingness to pay purchase first. If demand is below supply, the supply constraint doesn't bind, and the retailer determines its price as a revenue maximizer.

The optimal price in the constrained case, p_2^A, differs markedly from the price in the unconstrained case, p_2^B. The important difference is that the former depends on the amount of the available supply in period 2, which itself is the product of two components: the carryover inventory, $Q - D_1$, and the rate of retailer preservation, α. Due to its dependence on the first-period demand, the retailer's leftover inventory underscores the dynamic character of a retailer-consumer relationship: if the demand in period 1 is high, the retailer has less capacity left for a sale in period 2, resulting in higher price p_2. This effect of abundant inventory will be further enhanced or alleviated if retailer preservation is high or low respectively. As a result, a combination of these two factors determines whether p_2^A will be above or below p_2^B. In the extreme case of zero α, implying an emergency such as storage fire that destroys inventory, $p_2^A > p_2^B$ as consumers faced with the acute deficit are ready to pay their highest price. On the other hand, it is possible to have $p_2^A < p_2^B$ if the amount of retailer preserved inventory is at maximum level. In general, p_2^B should not be treated separately from p_2^A, but rather as a special case of the latter when the market is in the state of abundant supply (which is more likely when α is high). When the market is in the state of extreme deficit (α=0), p_2^B loses analytical value because of the contradiction $D_2 < 0$. However, it is true that $D_2 \geq 0$, in which case $p_2^A = K_2^j - q_2^0$, which is the highest price consumers would pay in period 2. Finally, note that regardless of α, the optimal price in period 2 is conditional on consumers stockpiling in period 1. If consumers preserve more food in-between the two periods, the less will be demanded in period 2, resulting in lower price.

By plugging the optimal price back into the demand function in (3), we can derive the optimal demand function of an individual consumer, where q_2^B is a special case of a more general situation q_2^A:

$$q_2 = \begin{cases} q_2^A = \frac{\alpha(Q-D_1)}{N}, & if \;\; D_2 \geq \alpha(Q-D_1) \\ q_2^B = \frac{K_2^j - q_2^0}{2}, & if \; D_2 < \alpha(Q-D_1). \end{cases} \tag{9}$$

If no inventory survives by period 2 (α=0), consumers purchase nothing as $q_2^A = 0$. Under these circumstances, q_2^B is also useless for reasons discussed earlier (demand should not be negative). In contrast, if the retailer's inventory is fully preserved (α=1), a consumer will buy $q_2^A = \frac{(Q-D_1)}{N}$ as long as demand in period 2 is big enough or $q_2^B = \frac{K_2^j - q_2^0}{2}$ if it is low. Note, that with α=1, a retailer's preserving technology is so reliable that both consumers and the retailer do not take it into account, since the level of available inventory is solely a function of the first-period demand and original supply.

2.6.1.2 Analysis of period 1

Given the level of carryover inventory depends on D_1, it is obvious that the optimal solutions in period 2 are also a direct result of the retailer's price chosen in period 1. Using backward induction, we are going to consider two special cases of the retailer's first-period pricing strategy that impact the amount of carryover available in period 2, $(Q - D_1)^+$. In the first case (referred to as case A), the price chosen in period 1 can be sufficiently low, inducing consumers to stockpile more food in period 1. As a result, in the absence of replenishment, the amount of carryover inventory available for exchange in period 2 will be low, while the effective demand will exceed supply no matter how high the level of retailer preservation is. Alternatively (case B), if the retailer's price in period 1 is sufficiently high, consumers are going to buy less leaving the retailer with more inventory to carry over. This will subsequently lead to enhanced supply exceeding demand in period 2 at any level of retailer preservation. In terms of backward induction, cases A and B in period 1 originate from their respective cases in period 2. That is, the constrained case in period 2 ($D_2 \geq \alpha(Q - D_1)$) will be used to derive the retailer's optimal price in period 1 corresponding to case A. By analogy, the unconstrained problem in period 2 (($D_2 < \alpha(Q - D_1)$) gives a way to the retailer's optimal price in period 1 corresponding to case B. Later, using numerical study, we will show that the optimal first-period price associated with case A can be in fact high or low depending upon how much inventory on the retailer's side is preserved.

2.6.1.2.1 Case A (from the constrained case in period 2)

As in period 2, we analyze a two-stage game by solving first the problem for a representative consumer. With consumers forward-looking, they have to take into account the impact of their future actions on present utility. In period 1, the consumer's problem is then to maximize expected utility subject to a budget constraint

$$Max_{q_1}\, E(U_1) = M_1 - \frac{(K_1 - q_1)^2}{2} + \gamma[\rho U_2^*(K_2^H) + (1-\rho)U_2^*(K_2^L)] \quad s.t. \;\; p_1 q_1 + M_1 = Y \qquad (10)$$

The utility function above effectively consists of two parts. The first is the direct utility function from period 1 and the second is the expected indirect utility function from period 2. Period 2 indirect utility incorporates consumer's optimal consumption achieved in Period 2 in the constrained case, q_2^A, along with the amount of carryover inventory, q_2^0, which links consumer's actions across time. Given uncertainty over future diet, this indirect utility reflects either a low- or high-consumption state in period 2 with probability ρ. Shown in detail below the indirect utility function in period 2 is a result of a purchasing decision made in period 1, q_1 :

$$U_2^*(q_2^*) = M_2 - \frac{1}{2}\left(K_2^j - q_2^0 - q_2^A\right)^2 = M_2 - \frac{1}{2}\left(K_2^j - \beta(q_1 - K_1)^+ - \frac{\alpha(Q-D_1)}{N}\right)^2. \tag{11}$$

When a consumer optimizes the utility function in (10) with respect to q_1, his/her present choice will also affect period 2 consumption and purchasing decisions. The individual period 1 demand can be derived by solving a constrained optimization problem in (10) with respect to q_1

$$q_1^A = \frac{K_1 N(1+\gamma\beta^2) - p_1 N + N\gamma\beta[\rho K_2^H + (1-\rho)K_2^L] - \gamma\beta\alpha(Q-D_1)}{N(1+\gamma\beta^2)}. \tag{12}$$

We assume consumers maintain their preferences over time, so their period 1 utility function is also quasi-linear in the aggregate good, *M*. Again, we can disregard income effects to derive market demand as a product of individual demand and the static parameter, *N,* describing the size of consumer population. For simplicity, we assume the size of consumer market is time-invariant. This leads to the following market demand

$$D_1^A = Nq_1 = \frac{K_1 N(1+\gamma\beta^2) - p_1 N + N\gamma\beta[\rho K_2^H + (1-\rho)K_2^L] - \gamma\beta\alpha Q}{1+\gamma\beta(\beta-\alpha)}. \tag{13}$$

This market demand is the consumer's first-period reaction function to the retailer's price. To find this price, a retailer has to solve its revenue maximization problem in the presence of non-binding capacity constraint ($D_1 < Q$). This assumption is important to ensure that the retailer has some leftover capacity to carry into period 2. If everything is sold yet in Period 1, there is no market interaction in Period 2. Formally, the retailer's period 1 problem is

$$Max_{p_1}\ E(\Pi_1) = p_1 D_1 +\ \gamma[\rho \Pi_2^*(K_2^H) + (1-\rho)\Pi_2^*(K_2^L)] \quad s.t. \quad D_1 < Q. \tag{14}$$

Similar to consumers, the retailer considers the effect of its current pricing strategy on period 2 optimal profits. Hence, the profit function above is then the sum of the direct profit from a period 1 sale and the expected indirect profit to be earned in period 2 in the market case A. This indirect profit is the maximized future profit when accounting for uncertainty over consumer diet, K_2^j:

$$\Pi_2^A(p_2^*) = \left[K_2^j - \beta(q_1 - K_1)^+ - \frac{\alpha(Q-D_1)}{N}\right]\alpha(Q - D_1) \tag{15}$$

Furthermore, this function contains direct references to the first-period individual demand and market demand functions, which both depend on the price in Period 1. By adjusting this price, a retailer can affect its profit in period 2. Thus, by solving the problem (14), the retailer derives an optimal price, which maximizes its expected profit over the two periods

$$p_1^A = \frac{(1+3\gamma\beta^2-2\alpha\gamma\beta+3\gamma^2\beta^4-4\alpha\gamma^2\beta^3+\gamma^3\beta^6-2\alpha\beta^5\gamma^3+3(\alpha\beta\gamma)^2+\alpha^2\beta^4\gamma^3+2\alpha^2\gamma)}{[2+4\gamma\beta^2-4\alpha\gamma\beta+2\gamma^2\beta^4-4\alpha\gamma^2\beta^3+2\gamma\alpha^2+2(\alpha\beta\gamma)^2]}K_1$$

$$+\ \frac{\left(\gamma b+\alpha\gamma+2\gamma^2\beta^3-\alpha(\gamma\beta)^2+\gamma^3\beta^5-2\alpha\gamma^3\beta^4+\alpha^2(\gamma\beta)^3+\beta(\alpha\gamma)\right)^2)}{[2+4\gamma\beta^2-4\alpha\gamma\beta+2\gamma^2\beta^4-4\alpha\gamma^2\beta^3+2\gamma\alpha^2+2(\alpha\beta\gamma)^2]}(\rho K_2^H + (1-\rho)K_2^L)$$

$$-\ \frac{[2(\alpha\beta\gamma)^2+2\alpha^2\gamma](Q/N)}{[2+4\gamma\beta^2-4\alpha\gamma\beta+2\gamma^2\beta^4-4\alpha\gamma^2\beta^3+2\gamma\alpha^2+2(\alpha\beta\gamma)^2]}. \tag{16}$$

The above result reveals a retailer's optimal decision reflecting its anticipation of consumer diet. By assumption, the retailer knows the exact level of consumer diet in period 1, K_1, while the true information about period 2 diet is hidden. Instead, it is known that this diet level is uniformly distributed: $K_2^j \sim U[K_2^H, K_2^L]$. Furthermore, the optimal price is a function of the ratio of the original capacity, Q, to the population factor, N. All three big terms in (16) involve multiple interactions between model parameters both in the numerator and denominator. This nonlinearity yields the inability to characterize the ultimate signs of each term. Comparative statics and numerical analysis will aid in this characterization for demonstrating how the optimal price evolves in response to changes in parameters.

2.6.1.2.2 Case B (from the unconstrained case in period 2)

A similar logic applies to deriving the solution for the case B when the retailer has abundant supply in period 2 and the consumer demand is below this supply level. A consumer's problem is equivalent to that in (10), but the indirect utility function is different from the result in (11), given the new optimum achieved in period 2:

$$U_2^*(q_2^*) = M_2 - \frac{1}{2}\left(K_2^j - q_2^0 - \frac{K_2^j - q_2^0}{2}\right)^2 = M_2 - \frac{1}{2}\left(\frac{K_2^j - q_2^0}{2}\right)^2. \tag{17}$$

As before, we derive the first-period individual and market demand functions by solving the problem (10) and taking into account the population, *N*

$$q_1^B = \frac{4(K_1 - p_1) + \gamma\beta\left[\rho K_2^H + (1-\rho)K_2^L\right] + \gamma\beta^2 K_1}{4 + \gamma\beta^2}, \tag{18}$$

$$D_1^B = Nq_1 = \frac{4N(K_1 - p_1) + \gamma\beta N\left[\rho K_2^H + (1-\rho)K_2^L\right] + \gamma\beta^2 N K_1}{4 + \gamma\beta^2}. \tag{19}$$

Regarding a firm's problem, it is identical to (14) with the indirect profit function reflecting the respective state of the market in period 2

$$\Pi_2^B(p_2^*) = \frac{N\left[K_2^j - \beta(q_1 - k_1)\right]^2}{4}. \tag{20}$$

A solution to (14) is the optimal price that maximizes the retailer's profits over two periods under the condition of abundant supply in period 2

$$p_1^B = \frac{16K_1+8\gamma\beta^2K_1+(12\gamma\beta+\gamma^2\beta^3)[\rho K_2^H+(1-\rho)K_2^L]+\gamma^2\beta^4K_1}{32} \quad (27)$$

Again, it is worth emphasizing here that p_1^B should not be treated separately, but rather as a special case of p_1^A under the conditions associated with poor preservation on the retailer's side (in the low range of α). When it is expected that little inventory will be preserved in period 2, p_1^A will be higher and even can exceed p_1^B. With better preservation, the opposite will happen. We will use a numerical example later to further elaborate on this point and show the consequences for consumer waste.

2.6.1.3 Numerical analysis

We present the results of numerical study, starting from the retailer's optimal pricing policy in period 1 resulting in case A. Subsequently, we will analyze the second price in period 1 resulting in case B. Figures 2, 3 and 4 show the evolution of the retailer's optimal price in period 1, p_1^A, over the entire range of *retailer* food preservation, α, for three different levels of consumer's first-period diet, K_1, market discount rate, γ, and the probability of a high-consumption state in period 2, ρ, respectively. Figure 5 shows how the retailer's price in period 1, p_1^A, changes over the entire range of *consumer* preservation, considering various levels of α, γ and ρ. As for the second price, Figure 6 shows the price p_1^B as a function of consumer preservation (β) for various levels of γ and ρ. Additionally, Figure 7 and Table 2 contain the results of numerical comparison of the two cases.

2.6.1.3.1 Optimal price p_1^A

Figure 2.2 shows that the retailer's optimal price in period 1 resulting in the constrained case in period 2, p_1^A, is higher the higher the level of consumer diet in period 1. This is a direct effect of an increase in K_1 on the consumers' first-period demand, D_1, which can be derived from (13). This price also increases in response to more preservation efforts on the consumer's side. Further investigation of Figure 2 shows that the price in period 1 is a decreasing function of retailer preservation: it quickly reaches maximum when $\alpha = 0.1$, but goes down as the retailer preserves more inventory between the two periods.

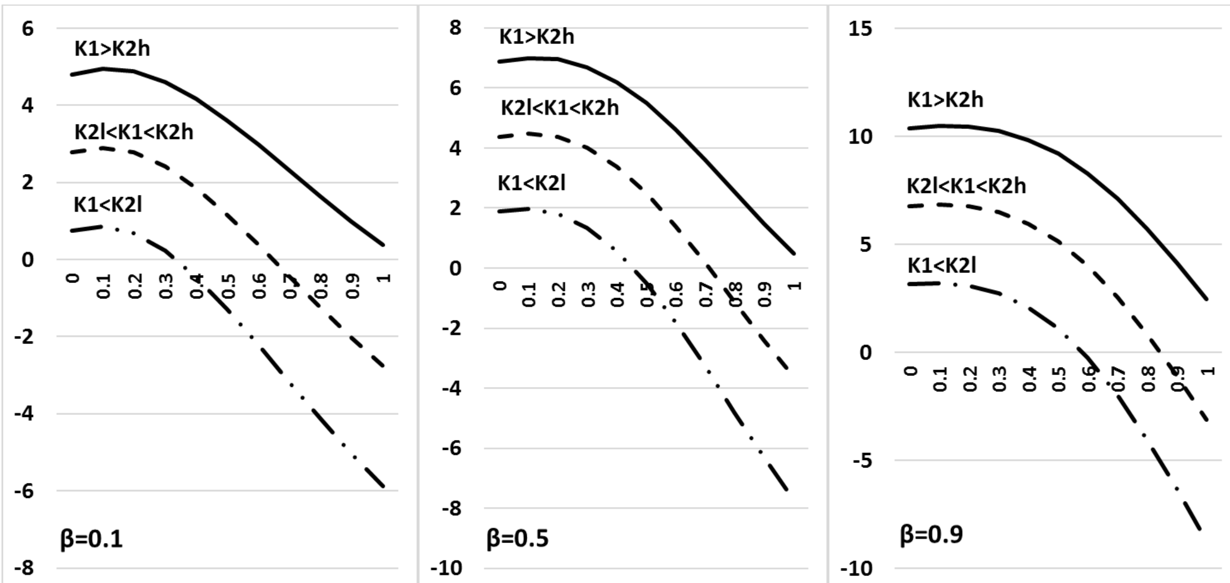

Figure 2.2. Price p_1^A as a function of retailer preservation (α) for various K_1 (consumer diet in period 1). Fixed primitives include: K1={1,5,9}, Q=150, K2l=2, K2h=8, N=10, γ=1, ρ=0.5.

There are several economic insights based on the above observations. It is shown that the retailer's optimal price p_1^A increases in the consumption level K_1 regardless of the consumer preservation level. This finding reflects a retailer's first-period pricing strategy that takes into account the immediate effect of an increase in consumer diet on the current period demand, D_1. If K_1 is high, then D_1 is also high, which results in a vertical shift up in the price function in Figure 2.2. In addition, the delayed effect of its own preservation on carryover inventory, $\alpha(Q - D_1)^+$, in period 2 is considered. As preservation improves, the retailer reduces its first-period price to boost the immediate demand, D_1, and induce consumers to stockpile. As a result of this strategy, the amount of carryover inventory in period 2 will shrink, but it will be well-preserved and sold in the end due to the fact that demand exceeds supply. This outcome reflects a winning strategy for the retailer who can sell more in both periods by pricing low in period 1 if its own preservation is high. As Figure 2.2 also shows, the first-period optimal price tends to be higher for a higher rate of consumer preservation. This observation reflects an impact of consumer preservation efforts on demand in period 1. Consumers decide to stockpile if they can save more inventory between the two periods.

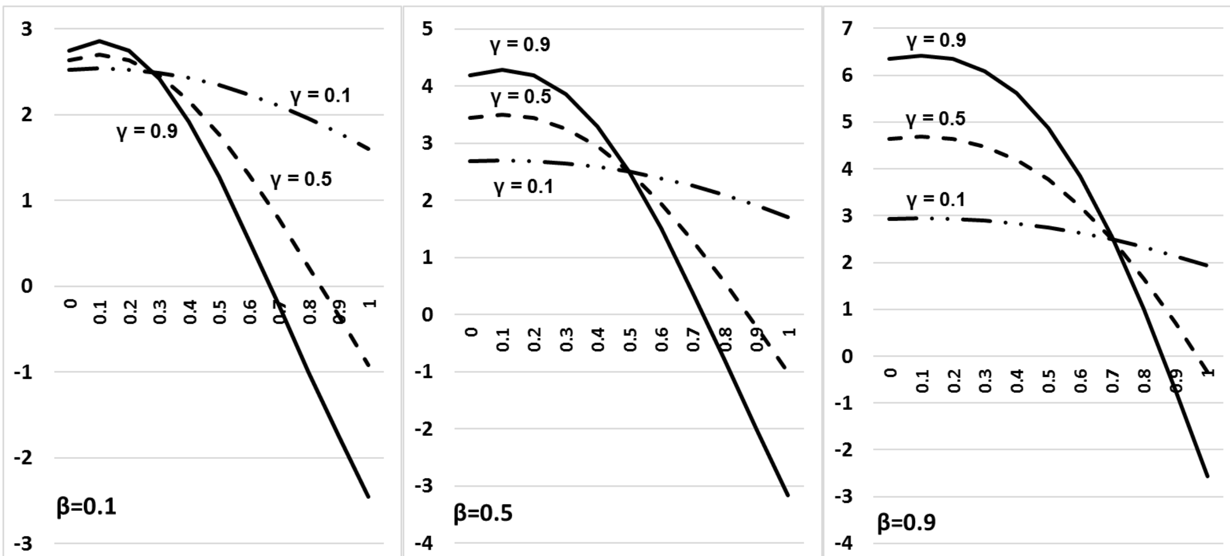

Figure 2.3. Price p_1^A as a function of retailer preservation (α) for various γ (discount factor). Fixed primitives include: K1=5, Q=150, K2l=2, K2h=8, N=10, ρ=0.5.

Figure 2.3 shows the change in the retailer's first-period price, p_1^A, over the whole range of its preservation rate for three different levels of the discount factor, γ. Similar to Figure 2.2, this result is reproduced for several levels of consumer preservation, β. Figure 2.3 yields important observations characterizing the retailer's pricing strategy under various degrees of impatience about future rewards. A highly impatient retailer heavily discounts future while putting more emphasis on the immediate proceeds from trade in period 1. As a result, its first-period price becomes naturally less responsive to changes in the rate of retailer preservation. For example, at *γ=0.1,* the retailer's preference for future is very low, which translates in a relatively flat first-period price curve (because future does not matter much, it is also largely irrelevant how much inventory will be saved between the two periods). On the other hand, if the discount factor is relatively high, the retailer acts more like a forward-looking agent who takes into account his/her future preservation efforts. For example, at *γ=0.9*, given the limited preservation effort on the consumer's side ($\beta = 0.1$), the retailer's price in period 1 quickly drops below the other two prices as long as $\alpha > 0.3$. With consumers investing more in preservation efforts, the retailer's price increases at every given level of the discount factor. However, the difference between the three prices is larger the more consumer inventory is preserved. As consumers improve preservation, they purchase more in period 1 in anticipation of stockpiling for future consumption. Responding to an increased demand, the retailer increases its period 1 price. However, this price ultimately also depends on the retailer preservation level: the numerical results show that in all the three cases the price reaches its peak at $\alpha = 0.1$, after which it exclusively declines.

Figure 2.4 illustrates the change in the retailer's first-period optimal price, p_1^A, over the whole range of its preservation rate as the probability of a high-consumption state in period 2 varies. To incorporate the impact of consumer preservation on this price, this result is reproduced for various levels of β in the spirit of Figures 2.2 and 2.3. It turns out that the uncertainty surrounding the state of consumption in period 2 has a noticeable impact on the retailer's optimal price in period 1. In general, the retailer's optimal price is higher following the indications of a growing consumer sentiment in future. This effect has its origin in the consumer's demand in period 1. When consumers fully account for the future (γ=1) and the probability of a high-consumption state increases, their first-period demand also increases. Algebraically, it can be shown, using (13), that the market demand in period 1 is linearly positively related to ρ: $\frac{dD_1}{d\rho} =$

$N\gamma\beta[K_2^H - K_2^L]$. An increase in β amplifies the positive effect of an increase in ρ on price: with improved preservation, consumers can save more between the periods to prop up the increased probability of a high diet in period 2, thus pushing the price in period 1 further up. As a result, in the presence of a better preservation technology, consumers can plan ahead to avoid being caught during the deficit in period 2. However, this comfort comes at a cost since the retailer will increase its period 1 price up.

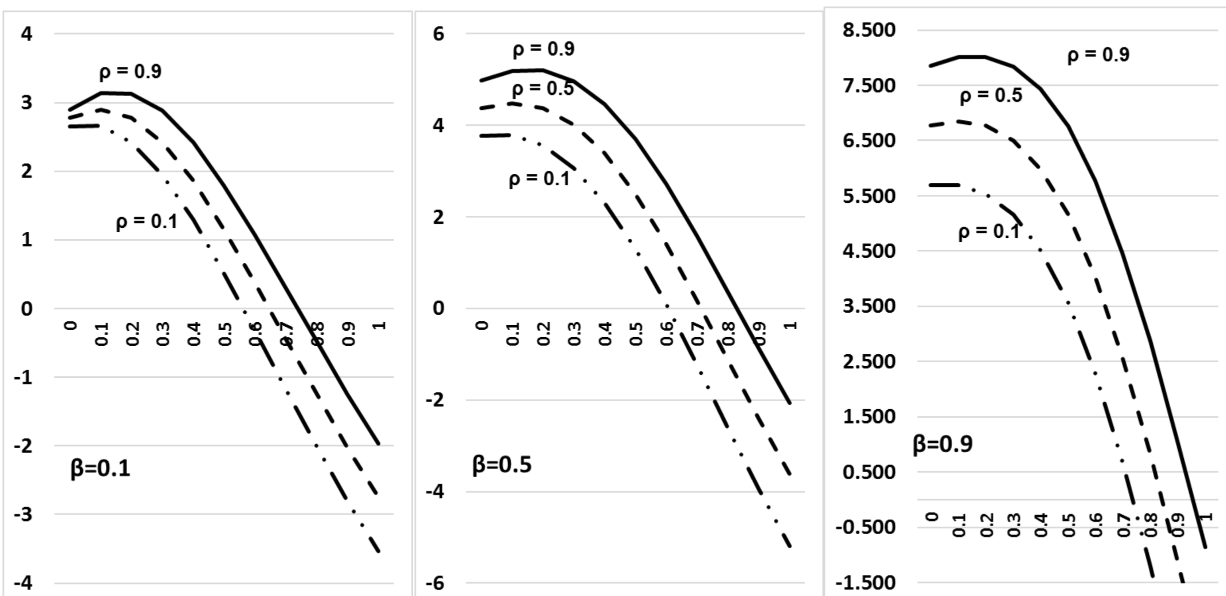

Figure 2.4. Price p_1^A as a function of retailer preservation (α) for various ρ (the probability of a high consumption state). Fixed primitives include: K1=5, Q=150, K2l=2, K2h=8, N=10, γ=1.

It follows from Figure 2.4 that the retailer's price is a concave function of its own preservation, which quickly reaches the maximum when α is relatively low but goes down in the higher range of preservation values. This effect is similar to that one observed in Figures 2.2 and 2.3. The retailer increases its period 1 optimal price taking into account the current period demand and the resulting supply in period 2. As long as the probability of a high-consumption state in period 2 is high, the demand in period 1 will be strong and less inventory will be left for sale in period 2.

Under these circumstances, the retailer can increase its period 1 price even if its preservation is relatively high. Otherwise, the price will reach its peak at a lower preservation level. The numerical results show if the high-consumption state in period 2 is highly probable (*ρ=0.9*), the retailer's optimal price in Period 1 should be at its peak level when $\alpha = 0.2$ ($for\ \beta \geq 0.5$).

Figure 2.5 briefly summarizes the effects of consumer preservation on the retailer's first-period optimal price, p_1^A, for various levels of retailer's preservation technology (α), discount factor (γ) and the probability of a high-consumption state (ρ) respectively. In general, consumer preservation has a positive effect on the retailer's optimal price in period 1. Consumers consider purchasing more in period 1 in anticipation of better preservation, which translates in a higher demand and price in period 1. The retailer will also charge a higher price if its own preservation level is low, while the discount factor and the probability of a high-consumption state are high.

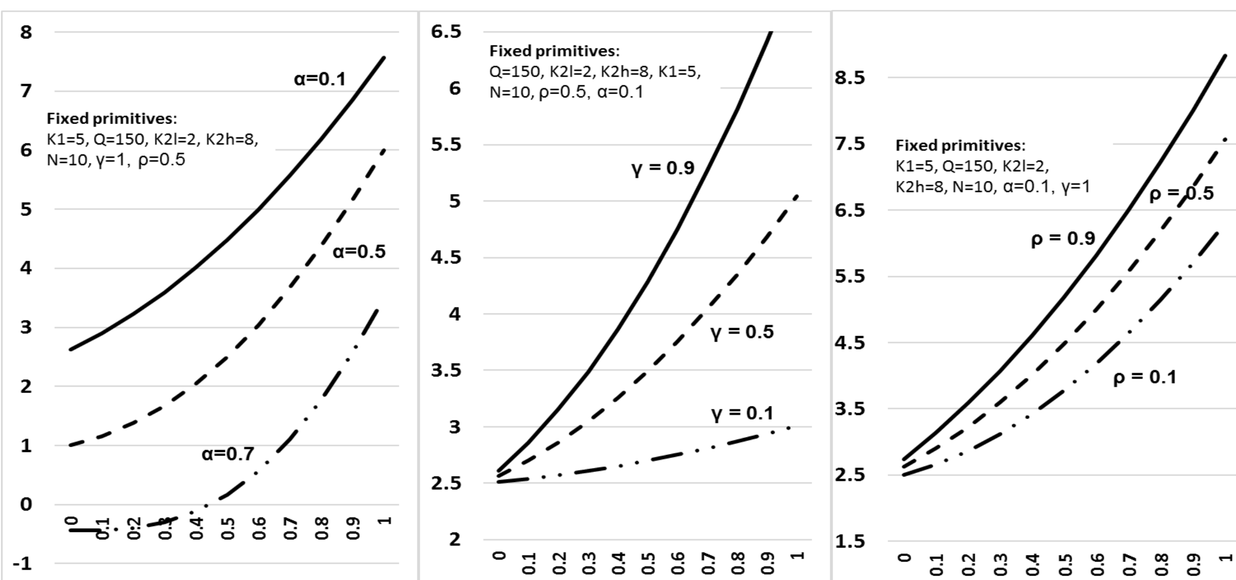

Figure 2.5. Price p_1^A as a function of consumer preservation (β) for various α (retailer preservation), γ (discount factor) and ρ (the probability of a high-consumption state).

2.6.1.3.2 Optimal price p_1^B

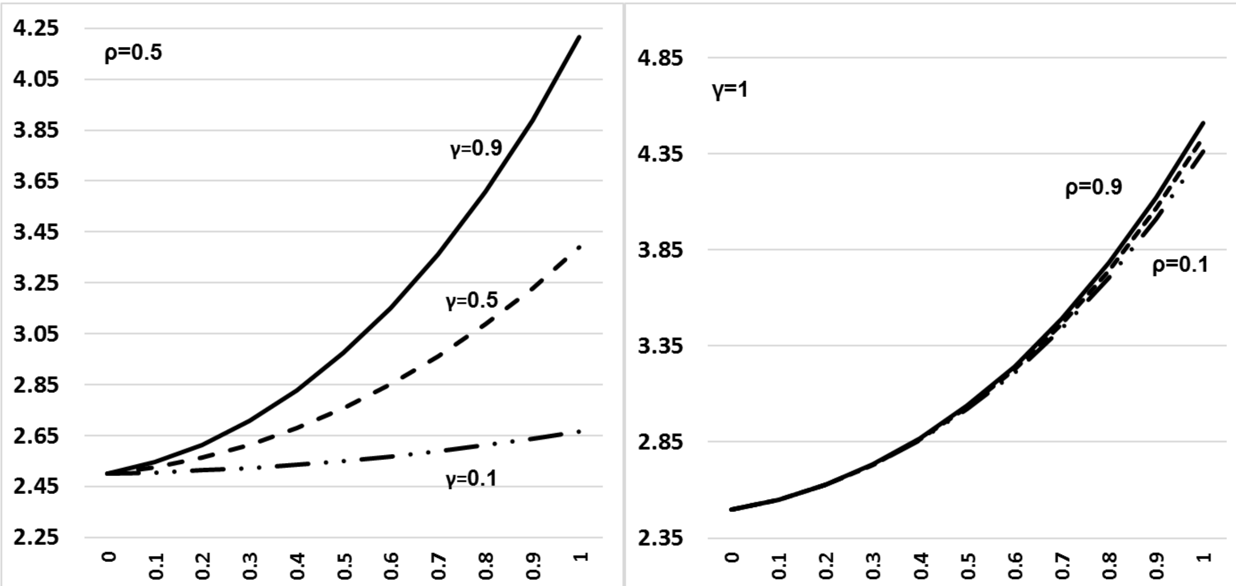

Figure 2.6. Price p_1^B as a function of consumer preservation (β) for various γ (discount factor) and ρ (the probability of a high-consumption state). Other fixed primitives include: K1=5, K2l=2, K2h=8.

Figure 2.6 illustrates the change in the retailer's first-period optimal price, p_1^B, over the whole range of consumer preservation for various levels of the discount factor, γ, and the probability of a high-consumption state in period 2, ρ. Because this price leads to the unconstrained case in period 2, it does not depend on the retailer preservation rate, α, as well as on the initial capacity level, Q, or the population size, N. Similar to the case A, the retailer's price in period 1, p_1^B, increases in β as long as γ>0. When γ=0, the price is solely a positive function of K_1 (no future is considered). For higher levels of the discount factor, the price grows bigger reflecting the retailer's patience for future rewards. An impatient retailer never charges a high price even for high levels of consumer preservation in hope of liquidating its stock within one period. With more patience, the retailer can also charge a higher price reacting to an increased demand from consumers in period 1. Similarly, the retailer's price in period 1, p_1^B, increases in β when the probability of a high-consumption state, *ρ,* varies. In fact, this price is quite similar for three different levels of *ρ,* which differs slightly from the retailer's price in case A.

2.6.1.3.3 Comparison of optimal prices

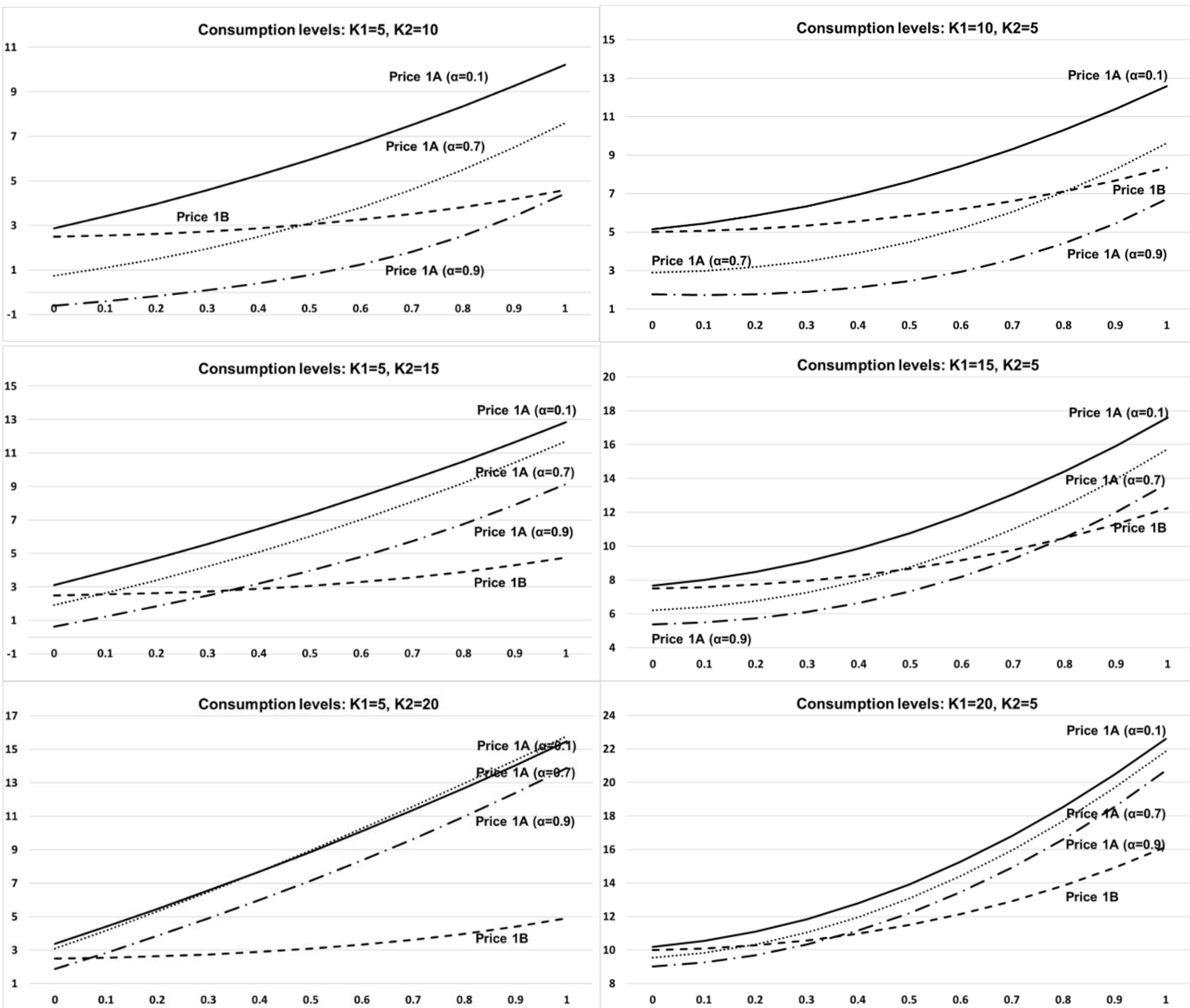

Figure 2.7. Prices p_1^A and p_1^B as functions of consumer preservation for different levels of K1 and K2. Other fixed primitives include: Q=150, N=10, γ=1, ρ=1.

Figure 2.7 compares the evolution of the two prices over the whole range of consumer preservation. This result is reproduced for different levels of consumer diet in periods 1 and 2, assuming no uncertainty in consumption (ρ=1). Visual inspection yields several observations about the price behavior. First, it follows that in general p_1^A grows faster than p_1^B over β for any level of retailer preservation, α. This observation might stem from the fact that the two prices represent different marketing situations in period 2. p_1^A represents a situation resulting in demand exceeding supply (for any α), while p_1^B leads to the opposite case. When the inventory will be in deficit due to high demand, the retailer can raise its first-period price higher in response to a higher β. Second, in the presence of low-level α, p_1^A tends to exceed p_1^B as consumer preservation improves. Table 2.2 complements this visual observation with a numerical example. It is shown that p_1^A never exceeds p_1^B if the retailer preserves ≥ 90% of its inventory between the periods regardless of the consumer preservation rate. However, this situation changes gradually as soon as the level of α goes down. This observation reflects the retailer's strategy to sell as much inventory as possible in both periods. At a high preservation level, this objective will be achieved by setting the first-period price low enough to stimulate consumer stockpiling. In period 2, because of the high demand, the retailer will sell the rest of the stock.

Table 2.2. Optimal prices and profits over different levels of consumer and retailer preservation. Other fixed primitives include: Q=150, N=10, γ=1, ρ=1, K1=10, K2=5.

	β=0.1			***β=0.5***			***β=0.9***		
α	$\boldsymbol{p_1^A\ vs\ p_1^B}$	**Num**	$\boldsymbol{\Pi_1^A\ vs\ \Pi_1^B}$	$\boldsymbol{p_1^A\ vs\ p_1^B}$	**Num.**	$\boldsymbol{\Pi_1^A\ vs\ \Pi_1^B}$	$\boldsymbol{p_1^A\ vs\ p_1^B}$	**Num.**	$\boldsymbol{\Pi_1^A\ vs\ \Pi_1^B}$
0.9	$p_1^A < p_1^B$	2<5	80<330	$p_1^A < p_1^B$	2<6	132<391	$p_1^A < p_1^B$	5<7	315<508
0.7	$p_1^A < p_1^B$	3<5	191<330	$p_1^A < p_1^B$	4<6	302<391	$p_1^A > p_1^B$	8>7	545>508
0.5	$p_1^A < p_1^B$	4<5	285<330	$p_1^A = p_1^B$	6=6	436>330	$p_1^A > p_1^B$	10>7	686>508
0.3	$p_1^A = p_1^B$	5=5	337>330	$p_1^A > p_1^B$	7>6	497>391	$p_1^A > p_1^B$	11>7	738>508
0.1	$p_1^A = p_1^B$	5=5	315<330	$p_1^A > p_1^B$	8>6	479>391	$p_1^A > p_1^B$	12>7	724>508

Please, note that the differences in prices illustrated above are sensitive to changes in the levels of individual consumption in both periods. In general, p_1^A tends to exceed p_1^B even at high levels of retailer preservation if K_1 or K_2 are also high enough. For example, with $K_1 = 5$ and $K_2 = 20$, price p_1^A is above p_1^B almost over entire range of consumer preservation. A similar tendency is noticeable for a high K_1 (while K_2 is fixed at 5). In both cases, p_1^A positively responds to a higher demand stemming from an increased diet level. However, the character of this response varies depending upon whether K_1 or K_2 changes. With an increase in K_2 (the three graphs on the left-hand side of Figure 2.7), p_1^A becomes almost a linear function of consumer preservation. In contrast, when K_1 increases, p_1^A is profoundly convex as consumers preserve more food. This effect might be attributed to the fact that with a change in K_1, consumers can increase their immediate demand in period 1 while taking into account their future preservation technology. If consumers know they can preserve more, this has an additional positive effect on price. Similar to p_1^A, the price p_1^B also increases more over β in response to a change in K_1 compared to a change in K_2.

2.6.2 Scenario 2: one-period trade

An abundant supply in period 1 ($Q > D_1$) was a precondition for a two-period trade regime in the first scenario. Under the alternative scenario ($D_1 \geq Q$), a retailer's stock is instantly liquidated resulting in no trade in period 2 (because of no replenishment assumption). While consumers do not purchase more food in period 2, they still can consume inventory preserved in-between the two periods. If the amount of carryover exceeds a future diet level, consumers can generate waste. This waste may occur principally due to the uncertainty surrounding future consumption. To illustrate this mechanism, we formulate and solve the problems for a representative consumer and a retailer to analyze their interaction in period 1.

Similar to the scenario with a two-period trade, a consumer maximizes the expected utility function as in (10). Because consumers do not buy more food in future, $q_2^A = q_2^B = 0$, and the “indirect” utility part from period 2 only contains the amount of carryover inventory:

$$U_2^*(q_1) = M_2 - \frac{1}{2}\left(K_2^j - q_2^0\right)^2 = M_2 - \frac{1}{2}\left(K_2^j - \beta(q_1 - K_1)^+\right)^2 \quad (28)$$

Thus, optimizing (10) with respect to q_1 yields the following individual and market demand functions respectively:

$$q_1 = \frac{K_1(1+\gamma\beta^2) - p_1 + \gamma\beta\left[\rho K_2^H + (1-\rho)K_2^L\right]}{(1+\gamma\beta^2)}. \quad (29)$$

$$D_1 = Nq_1 = \frac{K_1 N(1+\gamma\beta^2) - p_1 N + N\gamma\beta\left[\rho K_2^H + (1-\rho)K_2^L\right]}{(1+\gamma\beta^2)}. \quad (30)$$

Due to the condition that $D_1 \geq Q$, the retailer only has to solve a one-period problem below

$$Max_{p_1}\, \Pi_1 = p_1 D_1 \quad s.t. \quad D_1 \geq Q. \quad (31)$$

Because the market demand can exceed its supply, the retailer has to set up a price at which both exactly match each other:

$$p_1^* = K_1(1+\gamma\beta^2) + \gamma\beta[\rho K_2^H + (1-\rho)K_2^L] - \frac{Q}{N}(1+\gamma\beta^2) \quad (32)$$

While the retailer does not sell anything in period 2, its optimal price takes into account an effect of an increase in consumption in period 2 as well as a consumer preservation rate. By plugging this price back into (29) and (30), we can derive optimal demands in period 1 under the condition of fully exhausted supply: $q_1^* = \frac{Q}{N}$ and $D_1^* = Q$. Taking the optimal demand into account, we specify food waste at an individual consumer level as a difference between the carryover inventory and the level of consumer diet in period 2, given the probability of a high-consumption state ρ:

$$W = \rho(q_2^0 - K_2^H) + (1-\rho)(q_2^0 - K_2^L) = \rho[\beta(q_1 - K_1) - K_2^H] + (1-\rho)[\beta(q_1 - K_1) - K_2^L]$$

$$= \beta(q_1^* - K_1) - [\rho K_2^H + (1-\rho)K_2^L] = \beta\left(\frac{Q}{N} - K_1\right) - [\rho K_2^H + (1-\rho)K_2^L] \quad (33)$$

It follows from the above formula that waste is an increasing function of both consumer preservation, β, and the amount of initial food supply, Q. On the other hand, an increase in a diet level in either period leads to a reduction in waste. Figure 2.8 illustrates a change in consumer waste over the entire range of consumer preservation and for three different levels of ρ. It is shown that under certain conditions (low preservation and/or the increased probability of a high consumption state in period 2), waste can be negative, implying that consumers might not fully satisfy their future diet requirements. This situation might happen, for example, during short-term deficits caused by supply disruptions in the aftermath of holidays or due to weather events.

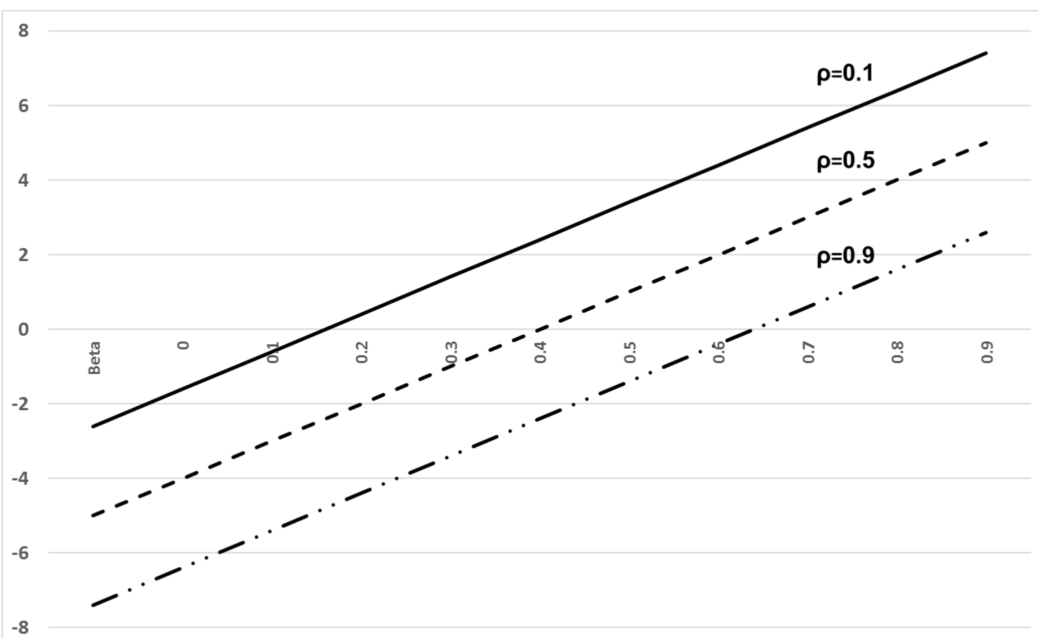

Figure 2.8. Consumer waste as a function of consumer preservation for different levels of ρ. Other fixed primitives include: Q=150, N=10, K1=5, K2l=2, K2h=8.

2.6.3 Food waste: an alternative specification

Consumers can also waste food as a result of a two-period trade scenario. To illustrate this possibility, we introduce a new measure of consumer waste that incorporates both the amount of preserved inventory, q_2^0, and the amount of food purchased in period 2, q_2. Using case A as a basis for analysis, we can specify the optimal amount of food waste in the following manner:

$$W^A = \rho(q_2^A + q_2^0 - K_2^H) + (1-\rho)(q_2^A + q_2^0 - K_2^L)$$

$$= \rho\left[\frac{\alpha(Q - D_1^A)}{N} + \beta(q_1^A - K_1) - K_2^H\right] + (1-\rho)\left[\frac{\alpha(Q - D_1^A)}{N} + \beta(q_1^A - K_1) - K_2^L\right]. \quad (34)$$

Where q_1^A and D_1^A are the optimal individual and market demands from period 1 respectively. Analyzing this equation, it is important to notice an intertemporal effect of a change in price on consumer's purchasing decisions. When the price p_1^A is relatively low, D_1^A goes up leading to a reduction in q_2^A. In other words, consumers stockpile more food now at the expense of limiting their purchases in future. Conversely, when the first-period price is high, consumers delay their purchases, which results in an increased demand in period 2.

The left side of Figure 2.9 illustrates that the amount of food waste may depend on both the retailer and consumer preservation efforts. As long as retailer preservation is high, consumers incur a lot of waste as a result of a two-period trade. This happens primarily for two reasons. First, at this preservation level, a retailer keeps its optimal price p_1^A low as the numerical analysis previously demonstrated. As previously noticed, consumers tend to stockpile a lot of food in response to such a price. Second, the optimal demand in period 2 is also higher at a high-level α. Combined together, these purchases ultimately lead to waste in the end of period 2 if the expected level of consumer diet is low. At a low level of retailer preservation, the reverse happens. Because a retailer's first-period price is higher, consumers don't stockpile a lot of food initially. However, consumers will not buy much in period 2 either due to harsher deficit caused by a low α. As a result, they might not be able to fully cover their consumption needs in period 2.

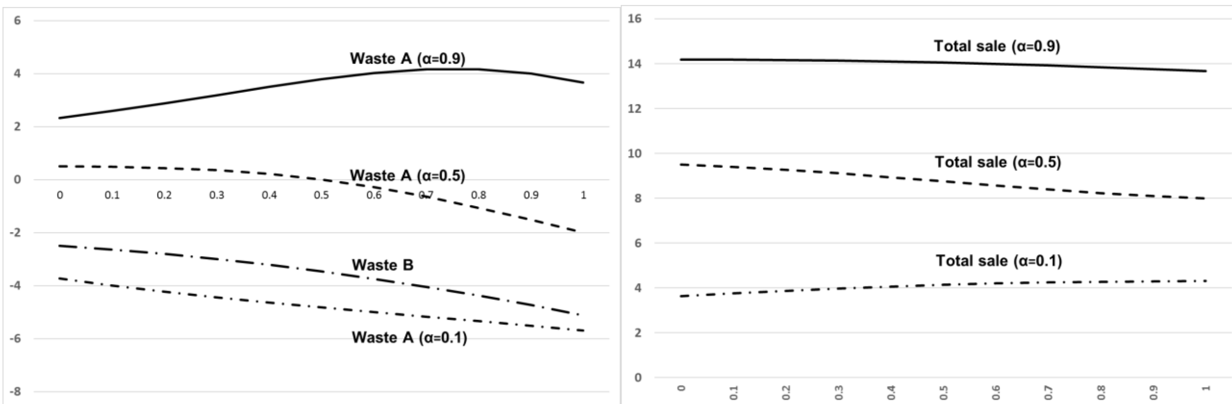

Figure 2.9. Consumer waste (on the left) and total sale (on the right) as functions of consumer preservation for different levels of α. Other fixed primitives include: Q=150, N=10, K1=5, K2l=2, K2h=8, γ=1, ρ=0.5.

The situation with consumer waste reflects the retailer's strategy aimed at increasing total sale of food in both periods. As shown previously, a forward-looking retailer (γ=1) takes into account the effect of its own preservation on the optimal price in period 1, which in turn affects consumers' purchases. As a preservation level improves, the retailer reduces its first-period price to stimulate consumers' stockpiling and increase first-period sales. While the resulting supply in period 2 will decrease, it will be well-preserved. In addition, under the assumption of case A ($D_2 \geq \alpha(Q - D_1)$), the retailer will fully sell the rest of its stock in period 2, resulting in a greater overall sale compared to the situation with a low α (Figure 2.9 on the right). When the preservation is poor, the retailer does not carryover much inventory to period 2, while charging a higher price in period 1 thus preventing consumers from making stockpiles.

Note that in case B, the amount of food waste in the end of period 2 totally depends on the consumer inventory preserved in-between the two periods, which ultimately leads to negative waste or undernourishment:

$$W^B = \rho(q_2^B + q_2^0 - K_2^H) + (1-\rho)(q_2^B + q_2^0 - K_2^L)$$

$$= \rho\left[\frac{K_2^H - \beta(q_1^B - K_1)}{2} + \beta(q_1^B - K_1) - K_2^H\right] + (1-\rho)\left[\frac{K_2^L - \beta(q_1^B - K_1)}{2} + \beta(q_1^B - K_1) - K_2^L\right]$$

$$= \frac{\beta(q_1^B - K_1)}{2} - \frac{[\rho K_2^H + (1-\rho)K_2^L]}{2}. \qquad (35)$$

As pointed out earlier, case B should be considered similar to case A with α in the low range resulting in the outcome with negative waste (Figure 2.9). It is assumed in case B that the first-period price p_1^B is high inducing low D_1^B, which further translates in high $(Q - D_1^B)$ as consumers refuse to stockpile at such a price. By design of this problem in period 2, $q_2^B = (K_2^j - q_2^0)/2$ under the condition that $D_2 < \alpha(Q - D_1)$ for any α. If α is low enough, q_2^B can't be high, which makes it equivalent to $q_2^A = \alpha(Q - D_1^A)/N$ for a low α.

Regarding the impact of consumer preservation on food waste, it follows from Figure 2.9 that consumer waste increases in β (except for in the very high range) in the situation when the retailer carryover is well preserved. This primarily happens because of a low price in period 1 stimulating consumers to stockpile inventory in excess of their diet level. However, an increase in β also leads to a reduction in demand for food in period 2, which translates in less waste in the high range of consumer preservation (for $\beta > 0.8$). The lower levels of retailer preservation are associated with a higher price in period 1, preventing consumers from making large stockpiles, and, as a result, generating less waste.

2.7 Extension

When deriving the retailer's optimal price in period 1, we concentrated on two special cases of the problem that stem from different marketing scenarios in period 2. In the special case A, the optimal price in period 1 reflects the scenario of high demand exceeding supply in period 2 for any level of retailer preservation. In the special case B, the optimal price in period 1 is a result of the opposite: low demand which is below supply for any level of retailer preservation.

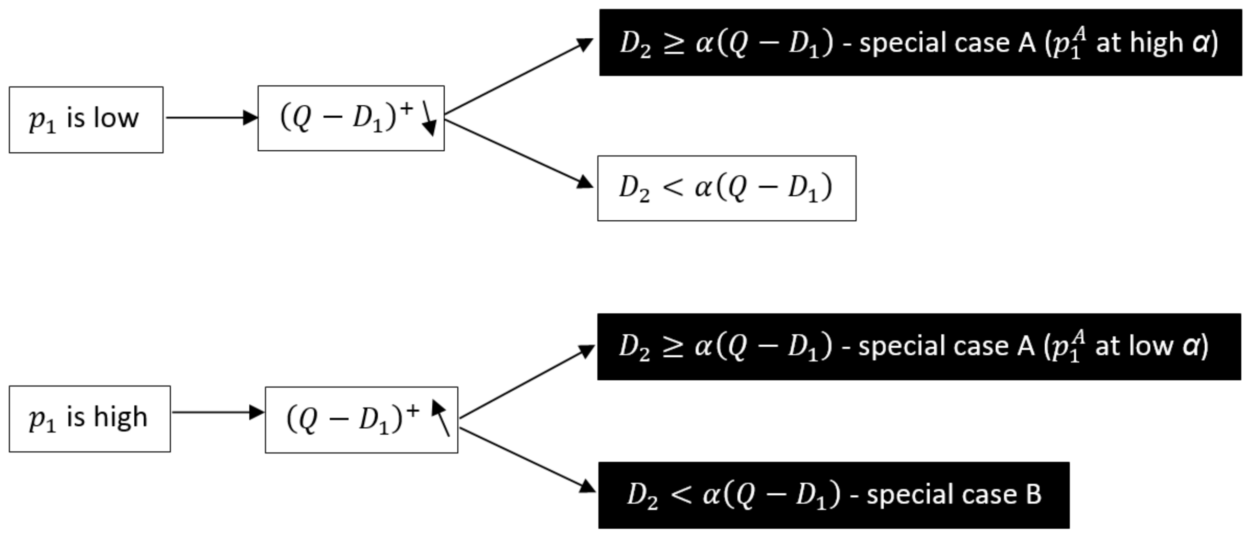

Figure 2.10. Flow chart of analytical cases.

While both scenarios are possible, separating them presents a challenge for economic analysis. The major problem is that the price in case B does not depend on the coefficient of retailer preservation α, which leads to the paradoxical conclusion that the retailer ignores this factor in its strategic calculus when the demand in period 2 is low. At the same time, the retailer's price may vary depending upon α as the case A with high demand clearly demonstrated. Briefly, it was found that the first-period price p_1^A is low given high α, but it is high when α is low. In fact, the flow chart in Figure 2.10 shows that the special case A covers both situations with high demand in period 2 stemming either from a low or high price in period 1.

To cover the rest of the problem, it would be necessary to derive an intermediate optimal price in period 1. At this price, the optimal demands as well as prices in period 2 should be equal: $q_2^A = q_2^B$ and $p_1^A = p_1^B$. Having this price would help in derivation of a threshold level of α, at which cases A and B switch.

2.8 Conclusions

We constructed a dynamic model of a direct interaction between consumers and a monopolistic retailer under the condition of stochastic demand. The retailer has a stock of perishable goods (food), which lasts for two relatively short but equal periods. Depending upon the initial demand in period 1, the retailer may sell all or just a part of its initial inventory in period 1. In the latter case, the retailer may carryover the leftovers to period 2. The amount of carryover inventory available for sale in period 2 depends exogenously on retailer preservation. The retailer's pricing strategy in period 1 determines consumer response. If the initial price is sufficiently low, consumers buy more in period 1 at the expense of limiting their purchases in period 2. As a result, consumers can form stockpiles of food to carry over to the next period. Similar to the retailer, consumers' inventory is subject to a preservation technology, which is also exogenously imposed.

In the context of a two-period trade regime, we analyze two special marketing scenarios, which depend upon both the retailer's first-period price and the configuration of supply and demand in period 2. In the first scenario (case A), the retailer's price in period 1 can be high or low, while the demand in period 2 might exceed the supply. In the second scenario (case B), the retailer's price in period 1 is high, while the demand in period 2 is below the supply.

It was found that the retailer's first-period pricing strategy depends upon both the retailer and consumer preservation technologies. The retailer will reduce its first-period price if its own inventory in period 2 is well preserved in an attempt to boost consumer stockpiling in period 1 and increase total sales over two periods. The retailer's price in period 1 will also increase in response to a better preservation on the consumer's side as consumers will demand more if they can anticipate saving more. The retailer's price response is also conditional on the size of a discount factor that shows how much the retailer cares about future. The higher the discount factor, the more retailer cares about future acting like a forward-looking agent, whose first-period price is sensitive to a change in its own preservation level (i.e., it is decreasing fast as preservation improves). However, as the discount factor becomes low, the retailer's price is also less responsive to the change in preservation.

We specified two measures of consumer waste depending upon an existing trade regime. Under the one-period trade regime, the retailer liquidates its stock in period 1 and does not trade in period 2, while consumers can stockpile some food for future consumption. Food waste occurs as a result of previously stockpiled inventory exceeding the consumer expected diet level in period 2. In this rather trivial case, consumer waste is a linear function positively related to the state of a consumer preservation technology. It also increases if the probability of a high consumption is low. Alternative specification concerns the amount of consumer waste emerging as a result of a two-period trade regime. In this situation, consumers may purchase more food in period 2 if their inventory from period 1 is too low. Consumers respond to the retailer's first-period pricing strategy upon deciding when and how much food to buy. If the first-period price is low enough, they will stockpile initially and then reduce purchases in the next period. This will happen as long as the retailer's level of preservation is high enough. If the retailer does not preserve much food in-between the two periods, its price in period 1 will be higher, resulting in lower sales. The results show that the amount of consumer waste will be higher in the former case (high retailer preservation) consistent with more sales on the retailer's side. These results confirm our research hypothesis that more preservation on the retailer's side is associated with more waste generated by consumers.

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CHAPTER 3. CONSUMER FOOD WASTE REDUCTION POLICIES: TAX AND SUBSIDY

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3.1 Introduction

Food waste is a critical issue that both undermines food security and leads to environmental degradation across the globe. A recent analysis of data on food production, waste and losses, collected from FAO reports, shows that in 2007 on average 30% of total food production was lost or wasted at different stages of supply chain worldwide (Gustavsson et al. 2011). While developing countries lose a bulk of their food supply between farms and retailing sector, it is consumers who bear the prime responsibility for food waste in the developed world (*Ibid*). Buzby and Hyman (2012) estimate that in 2008 the U.S. consumers threw away about 22% of available food compared to 9% thrown by retailers. The estimated monetary value of the total food loss from that study amounts to $165.6 billion annually.

Apart from financial consequences, there are two primary effects of food being directed towards waste: environmental degradation and food insecurity (Hawthorne 2017). Environmental degradation represents a complex effect, which includes depletion and contamination of natural resources used in production, distribution and storage of food. In fact, the environment is affected twice as a result of food consumption. First, when food is produced and supplied to the dinner table, and second, when leftovers are dumped as waste. Food insecurity implies that certain territories or population groups have limited access to food and might be subject to the risk of malnutrition or even hunger. For example, in the U.S. 41.2 million people were found to live in food-insecure households in 2016 (USDA, 2017 (1)).

In economic terms, the effects of food waste are external to a market agent's decision-making. This means that producers or consumers may not pay the full price of food items if they end up as waste and must be recycled or dumped. To reduce the negative impact of food waste on society and the environment, a government might intervene by implementing various behavior-correcting policies and incentives, such as a tax or subsidy. These policies are widely explored in academic literature in the context of other externalities. For example, Parry, Williams and Goulder (1998) and Boehringer and Rutherford (1996) study policy instruments aimed at tackling carbon dioxide emissions at an industrial level. Parry and Small (2002), Vedenov and Wetzstein (2007) and Wu et al. (2012) derive optimal (second-best) taxes and subsidies to regulate consumption of automobile fuels. However, to the best of our knowledge, there are no studies of governmental interventions that address the problem of food waste.

This study represents a formal theoretical introduction into the problem of food waste at a consumer level. In the literature review section, a general definition of food waste is formulated followed by a discussion of empirical studies devoted to the problem of food waste measurement across the supply chain. A geographical review of existing waste reduction policies concludes the section. A new theoretical model to explore the impact of household food waste on society is introduced next. First, the optimal conditions in the absence of external costs of food waste are derived. Subsequently, welfare analysis is carried out to derive the formal definitions of a waste-disposal tax and governmental incentive. Major implications of welfare analysis are discussed followed by conclusions.

3.2 Literature review

3.2.1 The nature of food waste

Academic literature provides various definitions of food waste, which often depend on the context and the objectives of a particular study. In the context of an entire supply chain, food waste should be considered a part of post-harvest loss, which includes quantitative and qualitative losses during production, processing, transportation, packaging, storage and consumption of food products (Hodges, Buzby, and Bennett, 2011; DeLucia and Assennato, 1994). Buzby and Hyman (2012) argue that both natural factors (such as bad weather) and human behavior (one example is purchasing more food than necessary) can contribute to food spoilage with a concurrent change of its physical and chemical qualities. Bellemare et al. (2017) argue that the variety of definitions of food waste adopted in the literature contributes to the problem of food waste measurement.

3.2.2 Food waste measurement

Measuring food waste at an industrial level is often a challenge due to a shortage of relevant data. Many studies limit their focus to certain geographical areas or stages of the food supply chain. For example, Buzby and Hyman (2012) estimate food waste at the retail and consumer levels in the United States, using USDA's data on more than 200 individual food products. Their study found that in 2008 consumers and retailers wasted 22% and 9% of food produced respectively, causing financial losses worth $165.6 billion.

Similarly, Hall et al. (2009) study the energy content of food waste by comparing the total U.S. food supply to the estimated amount of food consumed, applying a mathematical model of human metabolism. Their results suggest that between 1974 and 2003 the share of food waste generated at the consumer level increased from 30% to almost 40% of the total food supply in America.

In constrast, investigation by Kantor et al. (1997) found no change in the proportion of consumer food waste estimated over the same time period. They conclude that consumers contribute on average 30% of the total food waste in the U.S. However, their analysis is based on the summary of physical amounts of food waste collected from public sources.

Internationally, the estimated proportions of food waste and loss are quite similar to those in the U.S. Gustavsson et al. (2011) use FAO reports to estimate the magnitude of food loss across 127 countries. Their findings show that around 30% of global food production was lost or wasted at different stages of supply chain. Developed countries, according to their study, have the highest annual rates of food loss (280-300 kg/capita), while South and South-East Asia generate less loss than any other geographical territory (120 kg/capita).

As suggested by many studies (Buzby and Hyman, 2012; Hodges et al.,2011; Gustavsson et al., 2011), both retailers and final consumers bear the primary responsibility for the increasing volumes of food waste in developed countries. At the same time, the food waste footprint left by manufacturers is still quite noticeable in absolute terms. A recent survey of 15 manufacturers, whose production accounts for 17% of the total projected food sales in the U.S., shows that the amount of food waste generated by them in 2013 exceeded 7.1 billion pounds or 3.2 million tons (BSR, 2014).

3.2.3 Food waste policies worldwide

Comprehensive policies directed at reducing food waste at a consumer level are quite rare. As noted above, this is primarily related to the problem of measuring food waste generated by households. Because it remains challenging to reliably estimate each household's contribution to waste, policies based on an individual’s liability are hard to implement. Furthermore, raising the marginal cost of wasting through taxes or fines might be insufficient if the consumer elasticity of food waste to such instruments is low. This is often the case when the household’s subjective estimate of disutility from wasting food is low. As long as utility itself is a subjective concept to capture benefits of eating food, each household will be placing its own weight on disutility originating from waste. In this section, a review of waste reduction policies in selected countries is presented.

South Korea. South Korea is an example of the country that shows real progress with implementation of policies to reduce consumer food waste. In 2010 the Korean government published the Master Plan for Food Waste Reduction that ties reducing generation of food waste with the national goals of sustainability and green growth. Under this regulation, an obligatory fee was imposed on waste dischargers across all urban localities in the country. The size of the fee varies depending upon the volume of waste. Government introduced several systems of food waste measurement. The most advanced system uses the radio frequency identification (RFID) to both identify the discharger by electronic card or tag and measure the amount of waste generated to set up the fee. By 2012, 20% of local governments were covered with this system (Bagherzadeh, Inamura and Jeong, 2014).

The United States. While there is no federal policy to regulate food waste generation, there are attempts to introduce food waste controls among local governments. For example, the city of Seattle began charging homeowners a fee for putting food into trash cans emptied by the municipal trash service since 2015. This fee was introduced on top of the cost of landfilling. Single households are expected to pay $1 as soon as the share of food in their trash cans exceeds 10%. The fines imposed on apartments, condos and commercial buildings may amount to $50 (Kravitz, 2015). In 2015, USDA launched the Food Waste Challenge to partner with local governments, the private sector and charitable organizations with the goal of achieving a 50% reduction in food waste by 2030 (USDA, 2017(2)).

The United Kingdom. The nation's legislation system contains a fiscal stimulation mechanism to divert food waste produced by municipalities from landfilling. For this purpose, the differentiating rate of landfill tax was introduced for various categories of waste going to landfill. For active waste, which includes all biodegradable matter and food waste, the tax rate is much higher compared to that for inactive waste (64 versus 2.5 pounds/ton). This measure has an indirect impact on households, inducing them to recycle rather than dump food leftovers. However, households have no incentive to prevent food waste generation in first place (Watson, 2013).

3.2.4 Economic theory of food waste

A background study by de Gorter (2014) provides a formal foundation for economic research on the problem of food waste. He describes food waste as an unavoidable consequence of the functioning of a market system, which often incentivizes economic agents to overspend resources to reduce the marginal costs of their activities. For example, consumers might be tempted to purchase more food to reduce the number of their shopping trips. While achieving a zero-waste goal might be unrealistic due to high opportunity costs, it should still be feasible to restrain the generation of food waste by implementing public interventions that take into account divergencies between private and social optimality. According to De Gorter (2014), these divergencies primarily concern negative externalities, imperfect information and non-optimizing agents with psychological biases.

The literature seems to recognize the importance of different policy measures to deal with food waste. For example, Hodges, Buzby, and Bennett (2011) suggest several strategies to reduce post-harvest losses aimed at both consumers and producers of food. While the generation of waste at the producer level might be primarily addressed with taxation, education campaigns are prescribed to increase knowledge and correct wasting habits of consumers. A similar conclusion follows from the paper of Aschemann-Witzel *et al.* (2015) who find that consumers often ignore food products on the basis of minor visual imperfections or expiration dates, while retailers should dispose of the unclaimed goods to free shelf space. Food waste may also accrue if consumers do not plan shopping routines carefully or are subject to shopping “on-impulse”. In such a situation, the authors suggest, consumers should be educated to help them develop correct habits.

While the potential of waste-reducing interventions might be high, it is easy to send a wrong signal to market agents if no proper economic theory underlies those interventions. To provide a proper basis for the estimation of an optimal value of food waste (disposal) tax and government incentive, a rigorous model should be devised, which explicitly incorporates external costs of food waste into a decision maker’s calculus. The theory of optimal taxation provides guidelines for the derivation of such a model. Recently, this theory was primarily used to study the influence of automobile fuel consumption on environment. For example, Parry and Small (2005) derive and compare optimal taxes on gasoline in the United Kingdom and the United States. Following their approach, Vedenov and Wetzstein (2007) derive the optimal ethanol and biodiesel subsidies for the U.S. market. Building upon their ideas in those two papers, a brand-new model for both consumer and producer food waste is constructed.

3.3 Social-optimal household food waste policies: tax and subsidy

Theoretical arguments for food waste reduction are based on the assumption that food waste is in fact food purchased in excess. This excess emerges as a result of improper planning or due to lack of knowledge and relates to the problem of human capital. Once created, food excess should be either consumed or stored somewhere. If storage capacity (e.g., a refrigerator) is absent or insufficient, there is a risk that food would degrade to the point when consumption might render harm to the consumer's health. In this case, poor physical capital would magnify the human error. Thus, it should be noted that improvements in both human and physical capital could serve as a contributor to reduced waste. For this study, human and physical capital are combined under the rubric of *food-preserving capital*.

When the quality of food-preserving capital falls, more food is wasted. This food waste should be recognized as an externality associated with a myriad of negative effects for both the environment and society. The implications for the environment arise in the form of depletion and contamination of natural resources used in production, distribution and storage of food. The risks attributed to society include, above all, food insecurity (hunger and malnutrition). Due to market inefficiencies, these effects of food waste are nonpecuniary and therefore cannot be internalized by a neoclassic utility-maximizer. The absence of an efficient market provides an opportunity for the government to intervene with an alternative pricing mechanism, based on both taxes and incentives (subsidies).

The objective of this study is to derive a comprehensive analytical model for a utility-maximizing household in the presence of food waste externalities and two governmental intervention measures: a tax and a subsidy. The former is introduced in the form of waste-disposal tax to increase the cost of generating externality, while the latter is used as an incentive to enhance food-preserving capital. Based on this framework, closed-form solutions to the optimal values of tax and subsidy will be derived.

3.3.1 Basic model assumptions

A household's food consumption level can be found as a difference between food purchased (F) and food waste (W): $C = F–W$. It is assumed that waste is a function of two variable factors: food purchases and food-preserving capital:

$W = W(F,X)$

Waste is expected to increase in levels of food purchased ($dW/dF > 0, d^2W/dF^2 > 0$), but decrease as a result of food-preserving capital being exercised ($dW/dX < 0, d^2W/dX^2 > 0$). Households will employ food-preserving capital as long as the marginal increment to their utility equals the marginal cost of food-preservation. At this point, the household's utility will be at the maximum level, given all other elements influencing utility.

A utility function that represents household's preferences is assumed to be quasi-concave to guarantee the existence of a unique solution. It should increase in both food consumption and food preservation. However, food preservation does not enter the utility function directly, but only through waste:

$$U(F,X) = u[F - W(F,X)] \tag{1}$$

A representative household tries to maximize the above utility function subject to the following income constraint:

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

Where p and r are the per-unit prices of food and preservation capital respectively, while τ is the per-unit waste disposal tax. Available income, I, is allocated between food, waste and preservation capital. The following Lagrangean equation is set up to formulate the household's problem:

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

Note that no external effects of food waste enter the household decision model above. To solve this problem, the household chooses food consumption and preservation capital to maximize utility but takes prices and the tax as given. This yields the following first-order conditions below:

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

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

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

The interpretation of the first-order conditions is standard. From (4a), the marginal benefit of food consumption net of food waste equals the marginal cost of food, plus the marginal cost of waste disposal. From (4b), it follows that the marginal benefits of food preservation (the benefit from food consumption complemented with tax savings from reduced waste) equal the marginal price of food preservation. Also, condition (4a) yields the effective food price:

$$p_f = \frac{\partial u}{\partial C}\frac{1}{\lambda} = \left[p + \tau\frac{\partial W}{\partial F}\right] \Big/ \left[1 - \frac{\partial W}{\partial F}\right] \tag{5}$$

Combining (4b) and (5) gives the condition for the price of food preservation:

$$r + \tau\frac{\partial W}{\partial X} = -p_f\frac{\partial W}{\partial X} \tag{6}$$

The price of food preservation is the sum of the marginal cost of food-preserving capital and related tax savings. This should be equal to the marginal product of food preservation. Because the first-order effect of food preservation on waste is negative ($dW/dX < 0$), the term on the right-hand side is positive.

3.3.2 An extended model with welfare effects

The previous version of the household's problem yields optimal solutions in the form of household demands for food and food-preserving capital: $F^{*}(\tau, r, p, I)$ *and* $X^{*}(\tau, r, p, I)$. However, this outcome is achieved with no regard for the external effects of food waste that reduce welfare for society as a whole. To determine the social-optimal level of waste-reduction policies, the original indirect utility function should be extended to include the effects of environmental degradation and food insecurity:

$$V(\tau, r, p, I) = \max L(F, X, \lambda) \ = \max u[F - W(F, X)] - \delta(P) - \gamma(S) + \rho(G) \ + \lambda[I - pF - \tau W(F, X) - rX] \quad (7)$$

The above equation differs from (3) by three additive components: environmental degradation, P, food insecurity, S, and government's net gain from intervention G. While ρ *is quasi-concave* implying a positive impact of the government intervention on welfare, δ and γ are *weekly convex* representing disutility from food waste.

The government can stimulate waste reduction behavior by providing a subsidy, s, to reduce the per-unit cost of food preservation. By subsidizing food preservation, government suffers a monetary loss, which can be fully or partially compensated with revenue coming from the tax on waste τ. The net effect of government intervention is estimated as follows:

$$G = \tau\overline{W} - s\overline{X} \quad (8)$$

Where $\bar{W}$ and $\bar{X}$ are the aggregate amounts of food waste and preservation, respectively. As a function of the aggregate amount of food waste, food insecurity increases in response to more waste. This is formally defined below.

$$S = S(\bar{W}), \frac{\partial S}{\partial \bar{W}} > 0 \tag{9}$$

Environmental degradation can be defined as a sum of external costs of food production, *Z*, and disposal, *D*. These costs increase following an increase in the aggregate amount of food waste:

$$P = Z(\bar{W}) + D(\bar{W}),\ \partial Z/\partial \bar{W} > 0, \text{ and } \partial D/\partial \bar{W} > 0 \tag{10}$$

The effect of a change in both tax and the price of food preservation can be obtained by applying the Envelope theorem to the equation (7). The total differentiation of the indirect utility function yields the household's response to the selected intervention measures. Based on the results of the differentiation process, available in detail in Appendix A, the closed-form solutions to the social-optimal household disposal tax and subsidy are respectively derived:

$$\tau^* = \left[MEC\varepsilon_{W,\tau} - \frac{\rho\prime'}{\lambda}\left(-\frac{sX}{W}\varepsilon_{X,\tau}\right)\right] / \left[\frac{\rho\prime'}{\lambda}\left(\varepsilon_{W,\tau} + 1\right) - 1\right] \tag{11}$$

$$s^* = \left[MEC\varepsilon_{W,s}\frac{W}{X} - \frac{\rho\prime'}{\lambda}\left(-\frac{\tau W}{X}\varepsilon_{W,s}\right)\right] / \left[\frac{\rho\prime'}{\lambda}\left(\varepsilon_{X,s} + 1\right) + 1\right] \tag{12}$$

Where MEC is an abbreviation for the marginal external costs of food waste represented by a sum of the marginal costs of environmental degradation and insecurity (details are given in Appendix B):

$$MEC = E^{PW} + E^{SW} = \frac{\delta'}{\lambda}\left(\frac{dZ}{dW} + \frac{dD}{dW}\right) + \frac{\gamma'}{\lambda}\frac{dS}{dW} \tag{13}$$

Other elements contained in (11) and (12) include the elasticity of food waste to tax, $\varepsilon_{W,\tau}$, the elasticity of food waste to subsidy $\varepsilon_{W,s}$, the elasticity of food preservation capital to tax, $\varepsilon_{X,\tau}$, and the elasticity of food preservation capital to subsidy $\varepsilon_{X,s}$. Table 3.1 contains these and other important elasticities used in the analysis.

Table 3.1. Summary of key elasticities

Formal notation	Interpretation	Proof
$\varepsilon_{F,\tau} < 0$	A higher disposal tax => less food purchased.	Proposition 3
$\varepsilon_{X,r} < 0$	More expensive food preservation => less preservation adopted.	Proposition 4
$\varepsilon_{F,r} \lesseqgtr 0$	More expensive food preservation has a dubious effect on the amount of food purchased.	Proposition 4
$\varepsilon_{X,\tau} > 0$	A higher disposal tax => more preservation adopted	Proposition 1
$\varepsilon_{W,r} > 0$	More expensive food preservation => more waste	Corollary 1 (app)
$\varepsilon_{W,X} > 0$	More food preservation => less waste	Proposition 1
$\varepsilon_{W,\tau} < 0$	A higher disposal tax => less waste	Assumption
$\varepsilon_{W,s} < 0$	A higher subsidy => less waste	Corollary 1 (app)
$\varepsilon_{X,\tau} > 0$	A higher disposal tax => more food preservation exercised	Proposition 2
$\varepsilon_{X,s} > 0$	A higher subsidy => more food preservation exercised	Assumption

The derived social-optimal tax and subsidy should be regarded as second-best in light of their dependence on parameter values at the social optimum. If the existing equilibrium in the presence of intervention mechanisms does not allow for an optimal resource allocation, then the calculation of social-optimal tax and subsidy will be subject to an error.

3.4 Implications of welfare analysis

There are four important implications flowing out from the derivation of the social-optimal intervention mechanisms.

Corollary 1: If $\tau^* > 0$ and $\frac{\rho'}{\lambda} > 0$, then $\varepsilon_{W,\tau} < \frac{1}{\frac{\rho'}{\lambda}} - 1$

This corollary results from a closer investigation into the denominator of (11). When food waste gets reduced, the government receives a monetary benefit through ρ'/λ (the marginal monetary welfare effect). It turns out that government gains or loses nothing from an increase in the disposal tax as long as $\varepsilon_{W,\tau} = -1$. However, governmental revenue should rise (fall) following a decrease in tax if the response of waste to tax is elastic (inelastic). Thus, if government acts as a revenue-seeker, it should only increase the value of disposal tax if its elasticity is in the elastic range.

Regarding government incentive, the optimal subsidy in (12) is considered a positive compensation. However, negative subsidies are also possible in practice in the form, for example, of a commodity tax. When the commodity tax is levied, consumers bear a portion of the tax on consumption.

Further investigation of (11) and (12) yields interesting economic insights. It follows that $MEC\varepsilon_{W,\tau}$ and $MEC\varepsilon_{W,s}\frac{W}{X}$ can be considered Pigovian tax and subsidy respectively. This Pigovian tax (subsidy) represents a product of the external marginal cost from a per-unit change in food waste and the weighted elasticity of this waste to a change in the tax (subsidy). It is easy to show that a higher elasticity of food waste to the tax will lead to a higher tax rate. In a similar way, a higher rate of government subsidy is a direct result of a higher elasticity of food waste to the subsidy.

Corollary 2: $\varepsilon_{\tau,s} \propto -\varepsilon_{X,\tau}$; $\varepsilon_{s,\tau} \propto -\varepsilon_{W,s}$

As the level of a disposal tax increases, households want to increase the level of food-preserving capital: $\varepsilon_{X,\tau} > 0$. Then $\varepsilon_{\tau,s} < 0$, and an increase in s will decrease τ. These results flow from Proposition 2 in Appendix A. Furthermore, an increase in subsidy results in less waste $\varepsilon_{W,s} < 0$, which is consistent with the negative elasticity of subsidy to tax, as well as the negative elasticity of tax to subsidy. This allows for substitution between taxes and incentives.

Corollary 3: If $MEC = 0$, $\tau^* = \frac{\rho'}{\lambda}\varepsilon_{G,\tau}\frac{G}{W} > 0$ and $s^* = -\frac{\rho'}{\lambda}\varepsilon_{G,s}\frac{G}{X_i} > 0$

The statement above is applicable in the situation of zero external costs. When this happens, the solution to both optimal tax and subsidy collapses to a simpler form. $\varepsilon_{G,\tau}$ and $\varepsilon_{G,s}$ are the elasticities of government net expenditures on a disposal tax and government incentive, respectively.

Corollary 4: If $\frac{\rho'}{\lambda} = 0$, $\varepsilon_{W,\tau} \to -\infty$, perfectly elastic, then $\tau^* \to \infty$. Similarly, $\varepsilon_{W,s} \to -\infty$, perfectly elastic, $s^* \to \infty$.

The above conditions are necessary for zero food waste. As the elasticities of food waste to tax and subsidy approach negative infinity, the levels of subsidy and tax become infinitely large. A zero-waste equilibrium, though, should not last long. As the level of tax increases, the food waste externality gets effectively eradicated and that lowers governmental revenue. Therefore, for perfectly elastic responses, food waste never declines to zero.

3.5 Conclusions

This study provides a theoretical foundation for measuring the social-optimal levels of governmental tax and incentive (subsidy) in the presence of food waste externality. The governmental policies are designed specifically to address the issue of environmental degradation and food insecurity emanating from wasted food.

The derived closed-form solutions to the socio-optimal tax and subsidy depend upon a range of elasticities, namely the elasticities of waste to tax and subsidy, as well as the elasticities of food-preserving capital to tax and subsidy. Apart from them, there are other elasticities that might be crucial to analysis. Therefore, the empirical analysis aimed at quantification of the optimal values of tax and subsidies might be subject to data constraints.

This study provides several insights for both economic researchers and policy-makers. First, any government seeking to generate revenue from the imposition of tax on waste should be confident that the elasticity of waste to tax is below minus one (in the elastic range). Second, food waste tax and subsidy are found to be substitutes, but not perfect substitutes. This knowledge can be used when the choice of the policy instrument is decisive. Finally, it was determined that as long as the government leads the waste mitigation efforts, the objective of zero waste will be hard to achieve.

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CHAPTER 4. THE IMPACT OF NUTRITION EDUCATION ON SELECTION AND WASTE OF FRUITS AND VEGETABLES IN ELEMENTARY SCHOOLS

4.1 Introduction

The National School Lunch Program (NSLP) is a large federal food and nutrition assistance program that provides low-cost or free lunches in schools (USDA 2017). The estimated cost of the program totaled $12.7 billion in 2014 (U.S. Congress 2015). Since 2012, the federal government mandates schools to serve a certain amount of fruits and vegetables (FV) as a condition for meal reimbursement (USDA 2013). While the new guidelines were designed to increase FV consumption, recent studies show that the regulation rather results in a higher selection, but not necessarily consumption among students (Cohen et al. 2014; Amin et al. 2015). Moreover, high rates of school food waste originating from fruits and vegetables continue to persist (Byker et al. 2014).

Despite the fact that regulations can be effective to increase FV selection in schools, it is much harder to stimulate students to actually eat what is prescribed by government. To promote FV consumption and reduce waste, different interventions were recently implemented across schools in America (Blom-Hoffman et al. 2004; Just and Price 2013; Scherr et al. 2017). Special nutrition education lessons that complement other activities inside and beyond the classroom are an important part of those interventions.

The objective of this study is to quantitatively estimate the effect of a nutrition education intervention program on both selection (choice) and consumption[1] of fruits and vegetables among

[1] Consumption in this study is interpreted through changes in food waste. As a function of waste, consumption increases if the amount of waste goes down and vice versa.

second-grade students from three elementary schools in Indiana. We statistically test two research hypotheses:

1) Under the impact of intervention, the treatment group students increase *selection* of fruits and vegetables compared to those from the control group.
2) Under the impact of intervention, the treatment group students increase *consumption* (alternatively, reduce waste) of fruits and vegetables compared to those from the control group.

The study's focus on food selection in addition to consumption is a contribution to the previous research on school-based nutrition education interventions in the U.S. The literature review shows that the primary interest of many studies lies in consumption while the impact of interventions on food choice is largely disregarded (Perry et al. 1998; Auld et al.1998; Prelip et al.2002; Perry et al. 2004). Estimating selection might be important for two reasons. First, it allows to investigate the impact of intervention on students in a broader context, by considering possible changes at different stages of a meal process. Second, selection can be used to crosscheck the results of consumption measurement and avoid computational errors.

To further differentiate our study from the rest of the literature, we randomly assigned participating students to the treatment and control group. The treatment group students were subject to a special education curriculum unavailable to the control group. Because students were randomly allocated between their groups, the chance of selection bias was minimized, which makes the results of this study valid and generalizable. Many similar studies, in contrast, are based on non-experimental or quasi-experimental designs, naturally inhibiting the generalizability of results.

Another important contribution of our study comes in terms of the method used to collect and measure food waste data. We use digital photography as a primary tool of collection of school-based cafeteria data. Several studies broadly validated digital photography against other methods of data collection, citing its accuracy, reliability and usefulness for low-cost research (Williamson et al. 2003; Taylor et al. 2014; Christoph et al. 2017). However, our study is the first one that explicitly uses digital photography in the context of school-based intervention.

4.2 Literature review

This study contributes to the growing literature on school-based nutrition education intervention programs in the United States that promote selection and consumption of fruits and vegetables (FV) in school cafeterias. Given our focus on elementary school students, we review recently published articles and reports covering subjects of similar age (kindergarten through sixth grade). As shown below, many school-based education intervention studies are based on multi-component designs involving a mixture of treatment procedures and diversity of participants representing various stakeholder groups. While the primary focus of intervention may still be on students, other groups directly related to study objects (mostly, parents and significant others) might also be covered with intervention activities.

For example, Perry et al. (1998) study the effect of *the 5-a-day Power Plus* program on fourth- and fifth-grade students in St. Paul, Minnesota. Their intervention design includes special behavioral in-class curricula complemented with education for parents, changes to school food service as well as industry involvement and support. Relying on the direct observation cafeteria data and 24-hour recall records, Perry *et al.* (1998) construct 46 different indicators that capture a wide variety of student dietary intake information. Using mixed-model regression analysis, they find a significant positive effect of the education intervention program on levels of fruits and vegetables consumed by girls.

Similarly, Hoffman et al. (2010) explore the impact of a multi-component nutrition promotion program on kindergarten and first-grade students in the northeast by implementing different interactive activities in the classroom and school cafeteria. Based on directly measured plate waste data, they estimate student FV intake during two separate intervention periods applying hierarchical linear modelling and simultaneously controlling for pre-intervention intake, body-mass index and socio-demographic characteristics. Their results show that the treatment group students consume more fruits and vegetables in both periods compared to students from the control group.

While the intervention programs based on a two-group randomized design are common, they are not well suited to study the influence of individual components on students. To isolate the effect of different environments and intervention procedures on nutrition, some researchers experiment with separate treatment groups. For example, Prelip et al. (2002) explore the impact of a multicomponent nutrition education program on FV consumption among third- to fifth-grade students in Los Angeles using two intervention designs. One treatment group received traditional and new nutrition curricula, teacher training and parent nutrition education, while the other treatment group's exposure was limited to traditional nutrition and teacher training. Comparing student questionnaire data completed at baseline and post-intervention and analyzed with linear mixed regressions, authors find no effect of either study design on FV consumption.

In a similar vein, several studies implement gardening practices in addition to classroom education. For example, McAleese and Rankin (2007) combine in-class lessons and gardening for one treatment group, while providing just lessons to the second treatment group to study their effects on sixth-grade students in Idaho. Using data from 24-hour food recall workbooks, authors apply ANOVA to estimate the program effect. The results indicate that students with access to both nutrition education and gardening increase their FV intake compared to the control group students. Compared to this research, Parmer et al. (2009) implement similar intervention design, but use heterogenous data collected from surveys, questionnaires and through a direct lunch room observation of second-grade students in the southeast. Employing mixed model ANOVA, they find that students who received lessons in combination with gardening ate significantly more vegetables post-intervention than before.

These studies are of a special interest, because they show that in the absence of experience-enhancing practices that complement classroom-based education, the impact of nutrition education interventions on school students may be statistically insignificant. In our study, based on a single-component intervention model, we found that the students' response to the special nutrition curriculum is not statistically different from their response to the traditional curriculum.

Recently, Jones, Madden and Wengreen (2014) published preliminary results of the effects of the classroom-based FIT game on FV consumption among first- to fifth-grade students from an elementary school in Utah. To the best of our knowledge, this is the only school-based nutrition education study conducted in the U.S. with a single-component intervention design. Using directly measured plate waste data and the conservative dual-criterion for evaluation, authors compare consumption at baseline with the periods when the game was implemented. Their results show that following the game sessions students increased their intake of fruits and vegetables by 38.7% and 33.3% respectively.

Although our study is also based on a single-component design, we do not compare consumption in time, but instead estimate the average treatment effect to find out if the classroom-based intervention has any impact on students. In addition, we incorporate several socio-demographic factors to study their impact on consumption including gender, race and family income.

4.3 Experimental setup

4.3.1 Recruitment of participants and assisting personnel

Several elementary schools in the state of Indiana were randomly contacted by email to recruit participants. As a result, officials from three schools replied to confirm their interest in the study. We received active parental consents for 135 second-grade students from three schools, who were registered as participants and randomly assigned to either control or treatment group. Table 4.1 contains general characteristics of participating schools.

Table 4.1. Characteristics of participating schools

	School 1	**School 2**	**School 3**
Type of school *	KG-6	PreKG-6	KG-2
Student population **	343	209	548
Race/ethnicity (%)			
White/Caucasian	95.3	67.9	89.1
Others	4.7	22.1	10.9
Student/teacher ratio	16/1	15/1	24/1
NSLP participation rate *** (%)	40.2	-	38.9
Study participants (original sample)	33	22	80
Treatment	17	15	52
Control	16	7	28

* KG-2: kindergarten through second grade, KG-6: kindergarten through sixth grade
** Population as of 2016-2017 school year
*** NSLP = National School Lunch Program
All information is our own or from startclass.com

Several people across campus were hired to assist with collection of school cafeteria data. Their primary responsibility was taking photographs of students' trays and home lunch bags during the lunch time. On several occasions, assistants were also asked to collect samples of school cafeteria food and send them to the laboratory for weighting. Separately, two undergraduate students were hired to assist the principal investigator with extraction and processing of the photograph data.

4.3.2 Intervention modules

Education intervention was comprised of 20-minute long in-class modules conducted twice a week by regular teachers from participating schools. In total, twelve special nutrition-oriented modules were implemented during the intervention phase in October and November 2016. Only students from the treatment group received them, while the regular education curriculum was taught to the control group. These modules focused on health benefits resulting from consumption of fruits and vegetables. The curriculum was developed based on four existing programs: MyPlate Levels 1 and 2, Two-Bite Club, and Put a Rainbow on Your Plate. Teachers conducted their lessons by asking so-called "essential questions" to highlight the importance of balanced and nutritious diets. For example, some questions were phrased "What does it mean to be healthy?" or "Why should we eat fruits and vegetables?". The details of the curriculum content are given in Table 4.2. Introductory lessons, initially built around verbal discussions, were followed by tasting sessions, during which children were allowed to choose one item from a group of vegetables and fruits to eat. For these sessions, fruits and vegetables were purchased from the supermarket and sorted out into several groups according to their color (red, orange, green, blue and purple). Students' feedback was based on answers to teachers' questions, completed worksheets, writings on the board etc.

Table 4.2. Nutrition education curriculum content

Week	Overarching (essential) Question	Activity
1	What does it mean to be healthy? What does it mean to eat healthy?	Students labeled a blank copy of the MyPlate diagram after learning the components of healthy meals during both lessons of this week.
2	Why is it important to eat a variety of foods from all food groups?	The concept of nutrients was introduced, and the book, *Two-Bite Club*, was read.
3	What should I eat less of and why? What can I eat instead?	1. This week was focused on teaching children strategies for replacing sweet or salty snacks with healthy choices. 2. ‘Put a rainbow on my Plate’ framework was introduced, as it was incorporated for the rest of the curriculum.
4	Why should we eat fruits and vegetables?	Children learned the nutritional benefits of orange foods and sampled fruits and vegetables that are orange. Final project introduced.
5 and 6	Why should we eat fruits and vegetables?	The nutritional value and tasting of green and blue/purple foods respectively was emphasized. Final project presentation.

4.4 Food consumption data

4.4.1 Digital photographs of food

Digital photography was used as a primary method to collect food consumption data in school cafeterias. Additionally, photographs served as a basis for conversion of the visual images of food into numeric values that can be readily used in econometric analysis. Digital photographs of food students brought in cafeteria were taken with compact pocket cameras equipped with in-built lens, autofocus and flashlight. It was intended that all photographs should contain images of food as well as identification numbers provided to every participating student before the beginning of the study. After every session, all photographs were sorted and stored in their respective designated folders on the PC hard-drive.

4.4.2 Collection of school lunch data

Several assistants were hired and trained to take photographs of food brought to the lunchroom by students. To clearly distinguish between different students, they were provided with plastic place mats carrying their identification numbers. Students were instructed to keep their mats throughout the time of the study and bring them to the lunchroom as often as photographers come to school. Photographs of trays and home lunch bags were taken twice during the lunch time at the places where students chose to sit. Photographs of whole portions were taken at the beginning of lunch to capture the original contents of students' meals. These were followed by photographs of food leftovers after students finish eating. Cafeteria officers helped to ensure that students did not leave their places before the final round of photographs is over. After that, students could dispose of the contents of their lunch trays on their own.

Separately, samples of tray food were collected on several days to complement the photograph data. These samples were later used as a basis for derivation of numerical values of cafeteria food waste. To collect leftovers, randomly selected students were asked to leave their trays on the table at the end of lunch without cleaning them. In addition, whole portions of lunch similar to those selected by students were purchased directly from cafeterias. The collected food was then packed in plastic bags, signed and supplied to the laboratory for weighting.

Data collection took place twice a week during the fall 2016. Time and periodicity of visits were agreed with administrations of the participating schools prior to the beginning of the study. The calendar of visits was regularly updated to account for holidays and school events that disturb normal lunch hours.

4.4.3 Extraction of tray waste data

To convert the photographic information into numeric values, proportions of different items of food waste were derived by comparing the photographs of full lunch with those that contain leftovers. Two undergraduate students were hired and provided with basic training to read the photograph data from a computer screen. They were accompanied by the principal investigator on a regular basis to make sure that each food item has three individual numerical estimates. All three parties simultaneously observed the photographs displayed on the screen and provided the values for proportions of food waste using a quarter-based method. Following this approach, proportions were quantified on a 5-point scale that yields five possible values of waste: zero, quarter, half, three quarters and one (entire meal is thrown away). The results of the extraction process were typed down and stored in Excel spreadsheets. The derived proportions were further multiplied by the actual weights of food either provided by schools or measured independently by research assistants to convert them in grams.

4.4.4 Outcome variables

Three outcome variables are constructed using the results of extraction and processing of school lunch data. The first two variables are *total waste* and fruit and vegetable waste (*FV waste*). Total waste measures the aggregate amount of food that students left unconsumed at the end of lunch. FV waste is a subset of total waste. The values of each variable reflect the average of three estimates given by observers who extracted data. The third variable is fruits and vegetables ordered (*FV order*) that gives the total amount of fruits and vegetables selected by students before the start of lunch.

MyPlate USDA guidelines were used to classify separate food items as fruits or vegetables and to clearly distinguish them from other food groups. Clearly, classification was more challenging for complex meals involving an inseparable combination of several food categories (for example, pizza or tacos). In such a case, if the correct proportion of fruits or vegetables in the food mix could not be determined, they were not treated as part of the fruits or vegetables group.

4.4.5 Treatment of incomplete data

It should be noted that waste estimates were only derived for those meals photographed at two points in time: before and after lunch. In case either photograph was found missing, a special note in the spreadsheet cell was left to indicate which photograph is absent. Similarly, if the photograph was found to contain visual imperfections that seriously obstruct data reading (e.g., body parts covering the food), no numeric value was derived and instead it was specified that the photograph contains insufficient information. For econometric analysis, these observations were treated as missing values and were discarded.

4.4.6 Data exclusion

All packaged food was excluded from the data extraction process. This includes all liquid substances, except for soup in open containers, as well as dry food if served in sealed plastic or paper bags. Likewise, we didn’t make extraction of data from food brought in home lunch bags. This is because that food was not served in cafeteria and there is great uncertainty if students were free to select food themselves or their lunch was prepared by parents.

4.5 Econometric model

To estimate the effect of nutrition education intervention on students, a three-level linear panel model of student consumption with mixed effects was built. Derived values of outcome variables at every time point were sorted by student and school and stacked together to create a long hierarchical structure. This structure has repeated measures at the basic level nested within students (level 2) who are in turn nested within classes (level 3). Two separate models were estimated. The first one is used to measure the average treatment effect over the entire intervention period:

$$y_{dij} = \beta_{000} + \beta_{010}\, Treat_{dij} + B_{020}X_{dij} + B_{100}Day_{dij} + \delta_{00j} + e_{0ij} + u_{dij} \quad (1)$$

Where y_{dij} is the outcome of consumption for student *i* from class *j* in day d, β_{000} is the population average consumption (grand mean) over the entire intervention period, $Treat_{dij}$ defines the treatment dummy (=1 if the student is in the treatment group), X_{dij} is the vector of student-level demographic control variables, which also includes the classroom fixed effects to control for time-invariant classroom characteristics (teaching characteristics). Day_{dij} is day fixed effects to control for common shocks that affect all the students on a given day (e.g., bad tasting food). The random portion of the model includes the class-specific deviation from the grand mean, δ_{00j}, and the student-specific deviation from a class' outcome, e_{0ij}, while u_{dij} is the common error term.

To account for heterogeneity over the treatment time, we estimate the second model with an interaction variable included. This variable is a product of the treatment dummy and the day indicator. The interaction term between the day and treatment captures the effect of being in the treatment classroom as compared to the control classroom. Similar to the first model, this specification contains day and classroom fixed effects along with the random portion:

$$y_{dij} = \beta_{000} + B_{110}\left(Treat_{dij} * Day_{dij}\right) + B_{020}X_{dij} + B_{100}Day_{dij} + \delta_{00j} + e_{0ij} + u_{id} \quad (2)$$

We control for several demographic and socio-economic effects derived from the results of a questionnaire that was distributed among parents of participating students prior to the beginning of the study. Given parents' responses, several independent variables were constructed: age shows children's age in months; *sex* is a binary variable accounting for students' gender;

income is an ordinal multilevel variable that defines the annual average family income on the interval from $0 to more than $100 000 (e.g., level 1 is the lowest level of income, which falls in the range below $24999, while the highest level 5 is designated for those incomes exceeding $100 000); *marital status* is a categorical variable that contains five categories depending upon whether the parent is married, in relation, in divorce, single or widowed; *race* is another categorical variable that points to children's race (Indian, Asian Pacific, African American, Hispanic, White Caucasian or more than two); education is a categorical variable for a parent's education level. For estimation purposes, the last three controls were simplified by combining several categories into larger clusters. For example, parents are indexed 1 if they are married or in relation and 0 if everything else. Similarly, white parents and those with the Bachelor degree and higher are indexed 1.

4.6 Results

As a result of 45 visits to Indiana schools in the fall 2016, more than 4000 digital photographs of lunch were collected. After removing duplicates, 3785 photographs were categorized as either tray lunch (2065) or home lunch (1720). Tray lunch photographs were further used to extract food waste data and construct outcome variables, while photographs of home lunch were discarded. 25 photographs were only taken during one point in time and therefore could not be paired.

4.6.1 Reliability check

To assess the reliability of food waste estimates made by three observers, intra-class correlation was applied as discussed in McGraw and Wong (1996). Table 4.3 contains the results of estimation of inter-rater reliability for both types of waste across different schools. The reported coefficients show the degree of absolute agreement between observers (raters) based on the numerical estimates of waste. In all cases, the value of the coefficients exceeds 0.9 implying a substantial level of reliability of extracted estimates of food waste (Shrout 1998). This finding also confirms that the quarter-based method can be used to convert the photographic image of food into numerical data with accuracy.

Table 4.3. Inter-rater reliability across schools

	School 1		**School 2**		**School 3**	
Period	total waste	FV waste	total waste	FV waste	total waste	FV waste
total	0.943	0.959	0.951	0.92	0.954	0.961
intervention	0.948	0.956	0.955	0.966	0.958	0.957

Measurements are based on the ICC(A,1) as in McGraw and Wong (1996). All coefficients are found to be statistically different from zero.

4.6.2 Randomization tests

Tables 4.4 and 4.5 summarize the results of randomization of the study objects. Out estimates are based on the total student contingent of 94 people (with 61 in the treatment group). In total, 41 students were excluded from analysis due to missing data. Table 4.4 shows the distribution of students across treatment and control groups in terms of different demographic and socio-economic characteristics prior to the beginning of the study. It appears that students with diverse backgrounds were fairly equally assigned to either group. There is no statistical difference in the pre-treatment baseline variables for the two groups, except for race, with low significance level ($p<0.1$).

Table 4.4. Mean/frequency comparison of the pre-treatment base variables

Variable Name	Treatment Group	Control Group	All
Age (months)	95.344	93.757	94.787
	(11.124)	(3.791)	(9.239)
Female	0.442	0.393	0.425
	(0.500)	(0.496)	(0.497)
Parent Marital Status = Married / In Relation	0.770	0.696	0.744
	(0.424)	(0.466)	(0.438)
Parent Education Level = Bachelor's Degree and higher	0.442	0.515	0.468
	(0.500)	(0.507)	(0.501)
Race = White	0.950	0.848	0.914
	(0.218)	(0.364)	(0.280)
N	61	33	94

Standard deviations are in parentheses

Table 4.5 contains the results of a linear regression of key population factors on a treatment variable and an intercept (a balance test). This model was run to determine if placement of students to the treatment group is biased towards certain demographic classes. Our findings show that students assigned to the treatment group are not statistically different from others in terms of their age, gender or race. The parent's relationship status as well as education level are also found to bear no connection to how students were selected into the study groups.

Table 4.5. Differences between the base characteristics of students in the treatment and control groups (N = 94)

Variable Name	Difference between Treatment and Control Group
Age (months)	0.932
	(1.128)
Female	0.035
	(0.117)
Parent Marital Status = Married / In Relation	0.046
	(0.111)
Parent Education Level = Bachelor's Degree and higher	-0.036
	(0.119)
Race = White	0.107
	(0.073)

Standard errors in parentheses are corrected for heteroscedasticity and clustered at individual level. * p < 0:10, ** p < 0:05, *** p < 0:01.

4.6.3 School intervention effects

The results of the school education intervention program are presented in Appendices B and C respectively[2]. This estimation is based on data from 28 school visits over the intervention phase in October and November 2016. During that period, 2127 photographs of school lunch were collected, out of which 1155 are the photographs of cafeteria trays that were used to estimate consumption outcomes.

The reported results in Appendix B indicate that the classroom intervention education program has no statistically significant effect on students in the lunchroom when controlling for various demographic and socio-economic characteristics of students as well as school environment

[2] The reported results are for two outcome variables: FV order and FV waste. While we also estimated the amount of total waste, it is irrelevant from analytical perspective.

and daily shocks. Thus, we reject the research hypotheses formulated in the introductory part. Students in the treatment group didn't increase either selection or consumption of fruits and vegetables compared to the control group.

The results in Appendix C contain the additional interaction term between the treatment dummy and the days of intervention. It is shown that the students from the treatment group ordered less fruits and vegetables during the intervention phase compared to the control group students. However, this finding is not statistically significant. Similarly, it was found that the treatment group students wasted less food than the control group students. But this results is neither statistically significant.

4.7 Conclusions

We didn't find a statistically significant evidence for the impact of the nutrition education intervention program on the selected students from Indiana elementary schools. In particular, students from the treatment group did not increase either selection or consumption of fruits and vegetables following the in-class modules promoting the benefits of such a diet.

There may be several explanations of this outcome. One is that our study was based on a single component intervention design that makes it rather distinct from the majority of similar studies, whose designs are predominantly multi-component. The example of studies combining education with gardening shows that the experience beyond the classroom might be crucial to enhance the intervention's learning effect (McAleese and Rankin, 2007; Parmer et al., 2009). Furthermore, our intervention did not include additional rewards to incentivize students to increase their fruit and vegetable intake and reduce waste. These incentives, mostly in the form of small financial rewards, can be a significant factor affecting students' cafeteria consumption (Just and Price, 2013). Besides, the intervention program was limited to just several weeks, which is comparatively short, given that larger education intervention studies usually last months or even years.

Taking into account these considerations, one possible suggestion for future research would be to extend the outreach of an intervention program to the family members or significant others who might be helpful in development of useful consumption habits at home. Arranging informal activities beyond the classroom that focus on a good nutrition message should be also prioritized.

4.8 References

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APPENDIX A. DERIVATION OF THE SOCIAL-OPTIMAL HOUSEHOLD TAX AND SUBSIDY

The first-order conditions (4a)-(4c) in the main text yield additional economic insights summarized in proposition 1 below.

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

$$\varepsilon_{W,X} \propto \frac{-r}{p_f+\tau}. \tag{A1}$$

The above result can be derived by multiplying both sides of the equation (6) in the main text with X/W. 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 divided by the effective food price plus disposal tax. As can be noted, the elasticity of food waste to preserving capital, $\varepsilon_{W,X}$, becomes more inelastic in response to an increase in the denominator on the right-hand side of (A1). Thus, households tend to reduce less waste even as preservation capital increases. They buy less food and therefore generate less waste in response to a positive change in the denominator. As a result, food preservation becomes less important. Proposition 1 also reveals that taxes and government incentives can be considered substitutes (more on this in Corollary 2 in the main text). A positive change in the numerator (the price of food preservation) has an opposite effect on households' behavior. An increase in *r* translates into a higher elasticity of food waste to food preservation. To buy food preservation at a higher price, the absolute value response of food waste to preservation capital must be larger.

Total differentiation of the indirect utility function in (7) with respect to the waste-disposal tax and the price of food preserving capital gives:

$$\frac{dV}{d\tau} = -\lambda W - \delta' \frac{dP}{d\tau} - \gamma' \frac{dS}{d\tau} + \rho' \frac{dG}{d\tau} \tag{A2}$$

$$\frac{dV}{dr} = -\lambda X - \delta' \frac{dP}{dr} - \gamma' \frac{dS}{dr} + \rho' \frac{dG}{dr} \tag{A3}$$

From the first-order conditions above, the derived level of waste is a function of tax, price of food preservation, as well as the levels of food and preservation capital:

$$W = [\tau , r, F(\tau , r,), X(\tau , r,)] \tag{A4}$$

A reaction of food waste to a change in both the level of tax and the price of food preserving capital can be found by totally differentiating the above equation:

$$\frac{dW}{d\tau} = \frac{\partial W}{\partial \tau} + \frac{\partial W}{\partial F}\frac{\partial F}{\partial \tau} + \frac{\partial W}{\partial X}\frac{\partial X}{\partial \tau} < 0 \tag{A5}$$

$$\frac{dW}{dr} = \frac{\partial W}{\partial r} + \frac{\partial W}{\partial F}\frac{\partial F}{\partial r} + \frac{\partial W}{\partial X}\frac{\partial X}{\partial r} > 0 \tag{A6}$$

To substantiate interpretation of and the choice of signs in the above equations, we carry out an additional analysis of the equations (4a)-(4c) in the main text. The results of this analysis are summarized in the following propositions and corollary below. The corresponding proofs are placed in the end of the given appendix.

Proposition 2. In the absence of any backfire effect, the elasticity of food preservation capital to a disposal tax is negatively proportional to the elasticity of food waste to preservation

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

Because an increase in food preservation should effectively result in less waste, the elasticity of food waste with respect to preservation is negative, $\varepsilon_{W,X} < 0$, thus resulting in the positive elasticity of food preservation capital to a disposal tax, $\varepsilon_{X,\tau} > 0$.

Based on the Proposition 2, the response of food preservation to a disposal tax and the response of food waste to preservation are inversely related. As $\varepsilon_{W,X} < 0$ and $\varepsilon_{X,\tau} > 0$, it follows that a higher disposal tax induces households to apply more preservation that in turn results in less waste. Furthermore, households who are responsive to reducing food waste through preservation (more elastic $\varepsilon_{W,X}$) are also more responsive to a disposal tax (more elastic $\varepsilon_{X,\tau}$). However, as shown in the proof section below, there is a negative rebound effect. While an increase in the disposal tax stimulates preservation, the negative rebound effect makes the increase in preservation less pronounced. Only if the second-order partials equal zero, $\frac{\partial^2 u}{\partial F \partial X} = \frac{\partial^2 W}{\partial F^2} = \frac{\partial^2 u}{\partial F^2} = \frac{\partial^2 W}{\partial F \partial X} = 0$, 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, $\varepsilon_{F,\tau} < 0$. It turns out that a higher disposal tax should have a negative effect on food purchases. This effect is a realization of the Law of Demand as a disposal tax increases the effective food prices (equation 5 in the main text).

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 $\varepsilon_{X,r} < 0$. However, $\varepsilon_{F,r} \lessgtr 0$. It follows that the elasticity of food preservation to the price of a food preservation technology is negative. This result is a manifestation of the Law of Demand for preservation capital. On the other hand, it is hard to determine the sign of the elasticity of food to the price of food preservation. This should be an indication that food can be either a complement or substitute commodity for food preservation capital.

Corollary 1. As a consequence of Proposition 4, the elasticity of food waste to the preservation price is positive if food preservation reduces waste: $\varepsilon_{W,r} > 0$, if $\varepsilon_{W,X} < 0$. This observation is rather trivial. As long as food preservation results in less waste, then a more expensive preservation technology will make households generate more waste.

The results in Propositions 1-4 and Corollary 1 contain all important information necessary to finish derivation of the expressions for optimal food waste tax and government incentive. Similar to (A5) and (A6), we can derive the first-order effects of a disposal tax and the price of food preservation on the environmental degradation, food insecurity and the net effect of government intervention by totally differentiating (10), (9) and (8) respectively:

$$\frac{dP}{d\tau} = \left(\frac{dZ}{dW} + \frac{dD}{dW}\right)\frac{dW}{d\tau} < 0 \tag{A7}$$

$$\frac{dP}{dr} = \left(\frac{dZ}{dW} + \frac{dD}{dW}\right)\frac{dW}{dr} > 0 \tag{A8}$$

$$\frac{dS}{d\tau} = \frac{dS}{dW}\frac{dW}{d\tau} < 0 \tag{A9}$$

$$\frac{dS}{dr} = \frac{dS}{dW}\frac{dW}{dr} > 0 \tag{A10}$$

$$\frac{dG}{d\tau} = W + \tau\frac{dW}{d\tau} - s\frac{\partial X}{\partial \tau} \gtrless 0 \tag{A11}$$

$$\frac{dG}{ds} = -X + \tau\frac{dW}{ds} - s\frac{\partial X}{\partial s} \gtrless 0 \tag{A12}$$

The price of food preservation above is a price after subtracting the amount of subsidy from the original market price ($r = r^o - s$). The results in A7-A12 can be further substituted into A5-A6. The resulting two expressions, when divided by the Lagrange multiplier (λ), represent the marginal monetary welfare effects of the disposal tax and preservation mechanism respectively:

$$\frac{1}{\lambda}\frac{dV}{d\tau} = -W - (E^{PW} + E^{SW})\frac{dW}{d\tau} + \frac{\rho'}{\lambda}\left(W + \tau\frac{dW}{d\tau} - s\frac{\partial X}{\partial \tau}\right)$$

$$\frac{1}{\lambda}\frac{dV}{ds} = X - (E^{PW} + E^{SW})\frac{dW}{ds} + \frac{\rho'}{\lambda}\left(-X + \tau\frac{dW}{ds} - s\frac{\partial X}{\partial s}\right)$$

To find a closed-form solution to the social-optimal disposal tax in (11), we set the first equation above to zero and multiply it by $\frac{\tau}{W}$:

$$-\tau - MEC\varepsilon_{W,\tau} + \frac{\rho'}{\lambda}\left(\tau + \tau\varepsilon_{W,\tau} - \frac{sX}{W}\varepsilon_{X,\tau}\right) = 0$$

Solving for τ yields the desired outcome. Similarly, we set the second equation to zero and multiply it by $\frac{s}{X}$:

$$s - MEC\varepsilon_{W,s}\frac{W}{X} + \frac{\rho'}{\lambda}\left(-s + \tau\varepsilon_{W,s}\frac{W}{X} - s\varepsilon_{X,s}\right) = 0$$

Solving for s yields a closed-form solution to the social-optimal incentive in (12).

Mathematical proofs. For propositions 2, 3, and 4, we derive the indirect utility function by substituting the demands for food and food preservation and the shadow price (as solutions to the first-order conditions (4a)-(4c) in the main text) back into (4). Differentiating the resulting function with respect to τ yields

$$\frac{\partial^2 u}{\partial F^2}\frac{\partial F}{\partial \tau} + \frac{\partial^2 u}{\partial F \partial X}\frac{\partial X}{\partial \tau} - p\frac{\partial \lambda}{\partial \tau} - \tau\frac{\partial W}{\partial F}\frac{\partial \lambda}{\partial \tau} - \lambda\tau\frac{\partial^2 W}{\partial F \partial X}\frac{\partial X}{\partial \tau} - \lambda\tau\frac{\partial^2 W}{\partial F^2}\frac{\partial F}{\partial \tau} - \lambda\frac{\partial W}{\partial F} = 0, \tag{A13a}$$

$$\frac{\partial^2 u}{\partial F \partial X}\frac{\partial F}{\partial \tau} + \frac{\partial^2 u}{\partial X^2}\frac{\partial X}{\partial \tau} - r\frac{\partial \lambda}{\partial \tau} - \tau\frac{\partial W}{\partial X}\frac{\partial \lambda}{\partial \tau} - \lambda\tau\frac{\partial^2 W}{\partial F \partial X}\frac{\partial F}{\partial \tau} - \lambda\tau\frac{\partial^2 W}{\partial X^2}\frac{\partial X}{\partial \tau} - \lambda\frac{\partial W}{\partial X} = 0, \tag{A13b}$$

$$-p\frac{\partial F}{\partial \tau} - \tau\frac{\partial W}{\partial F}\frac{\partial F}{\partial \tau} - W - \tau\frac{\partial W}{\partial X}\frac{\partial X}{\partial \tau} - r\frac{\partial X}{\partial \tau} = 0, \tag{A13c}$$

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 (A13) with Cramer's Rule by denoting

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

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

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

where $\frac{\partial^2 u}{\partial F^2}$ and $\frac{\partial^2 u}{\partial X^2} < 0$, by the Law of Diminishing marginal utility.

Proposition 2 Proof

$$\frac{\partial X}{\partial \tau} = \left[\lambda\frac{\partial W}{\partial F}a_{23}a_{31} + a_{13}a_{21}W - \lambda\frac{\partial W}{\partial X}(a_{13})^2 - a_{11}a_{23}W\right]\Big/|H|, \tag{A14}$$

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) in the text with respect to r yields

$$\frac{\partial^2 u}{\partial F^2}\frac{\partial F}{\partial r} + \frac{\partial^2 u}{\partial F \partial X}\frac{\partial X}{\partial r} - p\frac{\partial \lambda}{\partial r} - \tau\frac{\partial W}{\partial F}\frac{\partial \lambda}{\partial r} - \lambda\tau\frac{\partial^2 W}{\partial F \partial X}\frac{\partial X}{\partial r} - \lambda\tau\frac{\partial^2 W}{\partial F^2}\frac{\partial F}{\partial r} = 0, \tag{A15}$$

$$\frac{\partial^2 u}{\partial F \partial X}\frac{\partial F}{\partial r} + \frac{\partial^2 u}{\partial X^2}\frac{\partial X}{\partial r} - r\frac{\partial \lambda}{\partial r} - \tau\frac{\partial W}{\partial X}\frac{\partial \lambda}{\partial r} - \lambda\tau\frac{\partial^2 W}{\partial F \partial X}\frac{\partial F}{\partial r} - \lambda\tau\frac{\partial^2 W}{\partial X^2}\frac{\partial X}{\partial r} - \lambda = 0, \tag{A16}$$

$$-p\frac{\partial \lambda}{\partial r} - \tau\frac{\partial W}{\partial F}\frac{\partial F}{\partial r} - X - \tau\frac{\partial W}{\partial F}\frac{\partial X}{\partial r} - r\frac{\partial X}{\partial r} = 0. \tag{A17}$$

Proposition 4 Proof

Solving (A15)-(A17) 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 $\frac{\partial F}{\partial r} \lesseqgtr 0$.

Converting to elasticities yields Proposition 4.

APPENDIX B. IMPACT OF TREATMENT ON THE AMOUNT OF FRUITS AND VEGETABLES ORDERED AND WASTED

Variable Name	Fruits and Vegetables Ordered (gm)	Fruits and Vegetables Wasted (gm)
Treatment	3.221	2.839
	(3.355)	(2.536)
Age (months)	-0.021	-0.431
	(0.310)	(0.380)
Female	-2.217	-11.453*
	(8.835)	(7.811)
Parent Marital Status = Married/ In Relation	-10.376	-6.813
	(9.637)	(9.071)
Parent's Education Level = Bachelor's Degree and higher	2.864	-5.760
	(4.083)	(4.622)
Race = White	4.118	2.600
	(5.618)	(6.308)
Classroom 1	-95.611***	-100.614***
	(2.307)	(2.934)
Classroom 2	-94.156***	-97.128***
	(4.802)	(4.081)
Classroom 3	-50.779***	-77.437***
	(4.325)	(5.196)
Classroom 4	-63.601***	-81.685***
	(8.002)	(7.065)
Classroom 5	9.681	15.510
	(6.442)	(6.136)
Classroom 6	5.579**	3.794
	(2.325)	(2.749)
Classroom 7	10.996***	35.734***
	(3.288)	(2.896)

Continued

Appendix B. continued

Variable Name	Fruits and Vegetables Ordered (gm)	Fruits and Vegetables Wasted (gm)
Classroom 8	8.665	-30.290***
	(5.592)	(6.077)
Day 2	14.730	22.056
	(35.433)	(27.773)
Day 3	-13.240	-13.577
	(19.156)	(15.236)
Day 4	-11.234	10.291
	(24.045)	(12.460)
Day 5	-33.408*	-17.386
	(18.674)	(14.246)
Day 6	-25.805*	0.272
	(16.308)	(8.971)
Day 7	-22.271	-25.897
	(43.730)	(28.588)
Day 8	23.439**	22.235**
	(9.748)	(10.758)
Day 9	-6.698	-12.994
	(12.392)	(12.983)
Day 10	-36.994**	1.138
	(39.525)	(28.242)
Constant	228.252***	232.062***
	(32.789)	(27.504)
Random effects		
Var (Class)	0.000	0.000
	(-)	(7.67e-07)
Var (Student)	79.802	143.548
	(245.611)	(141.0709)
Var (Residual)	3377.919	3824.306
	(687.165)	(507.856)
Observations	499	499

Standard errors in parentheses are corrected for heteroscedasticity and clustered at classroom level. * p < 0:10, ** p < 0:05, *** p < 0:01. Day 1, Classroom 9, and Classroom 10 are omitted due to collinearity.

APPENDIX C. HETEROGENEITY IN THE IMPACT OF NUTRITION EDUCATION ON THE AMOUNT OF FRUITS AND VEGETABLES ORDERED AND WASTED THROUGH THE INTERVENTION DAYS

Variable Name	Fruits and Vegetables Ordered (gm)	Fruits and Vegetables Wasted (gm)
Days (continuous time variable)	0.693	-0.669
	(1.926)	(1.058)
Treatment*Days	-4.40	-0.919
	(2.855)	(1.849)
Age (months)	-0.046	-0.550
	(0.289)	(0.362)
Female	-2.688	-12.005
	(8.383)	(8.014)
Parent Marital Status = Married/ In Relation	-10.237	-5.346
	(10.384)	(9.559)
Parent's Education Level = Bachelor's Degree and higher	4.463	-5.401
	(5.329)	(5.321)
Race = White	1.440	-2.070
	(5.904)	(7.472)
Constant	214.719***	242.727***
	(34.985)	(32.526)

Continued

Appendix C. continued

Variable Name	Fruits and Vegetables Ordered (gm)	Fruits and Vegetables Wasted (gm)
Classroom 1	-91.466***	-90.620***
	(2.131)	(2.741)
Classroom 2	-49.552*	-76.596***
	(25.825)	(16.642)
Classroom 3	-0.295	-56.549***
	(26.694)	(16.635)
Classroom 4	-58.996***	-74.736***
	(5.715)	(4.245)
Classroom 5	9.393*	22.976***
	(5.623)	(4.115)
Classroom 6	49.591*	24.131
	(25.450)	(15.632)
Classroom 7	52.748**	53.170**
	(25.082)	(17.266)
Classroom 8	9.174	-23.394***
	(6.372)	(6.110)
Classroom 9	45.069*	17.923
	(23.990)	(14.954)

Continued

Appendix C. continued

Variable Name	Fruits and Vegetables Ordered (gm)	Fruits and Vegetables Wasted (gm)
Random effects		
Var (Class)	0.000	0.000
	(0.000)	(0.000)
Var (Student)	57.839	138.948
	(50001.62)	(142.769)
Var (Residual)	3646.899	4058.369
	(45631.85)	(501.524)
Observations	499	499

Standard errors in parentheses are corrected for heteroscedasticity and clustered at classroom level. * p < 0:10, ** p < 0:05, *** p < 0:01. Classroom 10 is omitted due to collinearity.