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Too good to eat? Cosmetic standards and waste in agricultural supply chain

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COSMETIC STANDARDS AND WASTE IN AGRICULTURAL SUPPLY CHAIN

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Cosmetic Standards and Waste in Agricultural Supply Chain

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I hereby declare that this Master's thesis is my original work and it has been written by me in its entirety. I have duly acknowledged all the sources of information which have been used in this thesis.

This Master's thesis has also not been submitted for any degree in any university previously.

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Abstract

There is a significant amount of food wasted at the farm level due to high cosmetic standards adopted by retailers. We examine the economic incentives for retailers to adopt such high cosmetic standards and their impact on food loss. We build a sequential game between a retailer and a farmer, where the retailer signs a contract with the farmer specifying both the wholesale price and cosmetic quality standard. By adopting high cosmetic standards, retailers can motivate farmers to exert a higher effort to improve the cosmetic quality, e.g., using better seeds and applying more pesticides. As for the drivers of high cosmetic standards, we find an increase in customers' willingness-to-pay for aesthetically pleasing produces induces the retailer to adopt a higher standard or a lower standard. The retailer is more likely to adopt a higher cosmetic standard when the unit price in the processing market increases. The impact of harvesting cost variability on optimal cosmetic standard is non-monotonic. As for food loss, we find that a higher cosmetic standard does not necessarily lead to a higher food loss. When the harvesting cost variability is small, it has limited impact on food loss; when the variability is medium, it lowers food loss; when the variability is large, it increases food loss.

Contents

ACKNOWLEDGEMENT

This thesis summaries the results of my first research topic: Food Waste due to cosmetic quality standard. I really like this topic because the environmental problem is becoming severe these years and most people are not aware that food loss can be from excessive cosmetic quality standard. This research is really meaningful for me.

I am grateful for many people who help me and accompany me in my academic journey, particularly, my supervisors Prof. Pascale CRAMA and Prof. Helen ZHOU Yangfang. They give me a lot of inspiration and courage to conduct the research. One of the very excellent things that I learned from Prof. Pascale is the attitude towards research and life, to be passionate and enjoying the thing you are doing. I also think she shows me how to enjoy both research and daily life. She would deal with her working time and free space time very well. High efficiency definitely speeds up work. Besides, her charming personality attracts me. My supervisor, Prof Helen, also teaches me a lot of important things in this journey. She has very good time management concept and does things step by step according to the plan. Put tasks in order and then you are able to accomplish them much easier. I have been a teaching assistant in Helen's undergraduate class. Her passion for teaching impressed me greatly. She is really serious in preparing for her classes and she is considerate for all the students. Advice given by them is really helpful for formulating my plan and study path. I am glad to work with them. I would like to thank other committee members, Prof. Yini and Prof. Lucy, for their support and consideration during my thesis writing.

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Although I experienced some difficulties, but because of my lovely mentors, friends and parents, I overcame all of them. I sincerely give my gratitude to all of them. I would absolutely appreciate the time I spent in Singapore Management University. It not only gives me knowledge, but also provides me with a chance to study abroad and get to know a different culture.

Every journey has an end but I am positive and looking forward to next start.

1 Introduction

Although there is a global shortage of food, about one third of the food produced globally is wasted (Gustafsson, Cederberg, Sonesson, & Emanuelsson, 2013). This food waste occurs not only at the end of the supply chain (where food expires before they are consumed), but also at all steps along the supply chain, right to the very first step where the food is produced. In particular, within the fruit and vegetable sector, approximately 20% of the production is lost at farm level (Gustafsson et al., 2013). A major part of this loss is due to cosmetic blemishes or irregularity, for instance, oval apples, two-legged carrots, and straight cucumbers. Even though these food have the same taste, texture, and nutrients as regular-looking food, they are filtered out before they even reach the shelves of retailers. For example, in 2013, French beans grown for European markets saw a 15 to 20 percent waste due to cosmetic filtering, i.e., major retailers required that French beans fit into standard 9-cm bags (CNA, 2017).

Food waste due to cosmetic filtering creates significant issues. First, the irregular-looking food left unharvested in the field emits methane, a greenhouse gas more potent than carbon dioxide. Second, a significant amount of water and energy that are used in the agricultural product production process are wasted. Third, undernourishment occurs even in developed countries, where a significant proportion of the population live in food desert, with limited access to affordable fresh produce.

High cosmetic standards have been long thought to be due to government regulation, but a close look at these regulations shows that it may not be true. For instance, cosmetic standards for fresh produce in the U.S. can be traced back to regulations from the U.S. Department of Agriculture in 1917, but these regulations are voluntary and meant for the sole purpose of facilitating trade, yet they continue to be widely adopted by retailers. In the meantime, in the European Union (EU), the law regulating the standards for the appearance of 26 vegetables and fruits was rescinded in 2014, but only a handful of retailers in the E.U. have relaxed their cosmetic standards and anecdotally many retailers have even increased them (de Hooge, van Dulm, & van Trijp, 2018).

In this thesis, we aim to examine the economic incentives for the retailers to adopt high cosmetic standards and its impact on food loss. By adopting a high cosmetic standard, retailers could potentially motivate farmers to exert more efforts (which are costly) in improving the cosmetic quality of produces. For instance, using better seeds can result in better-looking tomato; applying more pesticides to oranges can reduce the probability that these oranges are affected by insect and thus more aesthetically pleasing. In particular, we examine the effect of consumers' preferences (willingness-to-pay for aesthetically pleasing produce), the presence of the processing market, and the harvesting cost uncertainty on the retailer's optimal choice of cosmetic standard.

To this end, we build a Stackelberg game between a retailer and a farmer. The retailer signs a contract with the farmer which specifies the contract price and the minimum cosmetic threshold, and then the farmer chooses the effort level in the face of yield uncertainty. A higher effort results in a higher proportion of yield that satisfies the standard; but a higher cosmetic standard reduces the proportion of produce that satisfies this standard for a given effort. After the yield is realized, the farmer decides the harvesting quantity. The retailer finally sells all qualified produce to consumers, with a selling price which increases in the cosmetic standard. Our results are summarized as follows:

1. The retailer's cosmetic standard decisions depend on the rejection rate

of produce resulting from adopting high cosmetic standard as follows: If this loss is smaller than a threshold, then the retailer adopts a high standard; otherwise, the retailer adopts a low standard.

2. We also find that a higher cosmetic standard does not necessarily lead to a higher food loss.

3a. We find that the increase in customers' willingness-to-pay for aesthetically pleasing produces induces the retailer to adopt sometimes a higher standard but sometimes a lower standard.

3b. When the unit price of the processing market increases, the retailer is more likely to adopt a higher cosmetic standard.

3c. The impact of harvesting cost variability on optimal cosmetic standard is non-monotonic. When the harvesting cost variability is small, it has limited impact on food loss; when it is medium, it lowers food loss; when it is high, it leads to higher food loss.

Contribution. Food waste and food loss have received a lot of attention in the operations management community. However, unlike the majority of the literature (Belavina, Girotra, & Kabra, 2017; Belavina, 2020; Akkas & Honhon, 2018), which studies the food waste/loss in the downstream of the supply chain, we are among the very few that study the food loss in the upstream. Richards and Hamilton (2019) also look the effect of high cosmetic standard, but they examine the interaction between a retailer and a consumer, while we examine the interaction between a retailer and a farmer, where the farmer can exert efforts to improve cosmetic standard. This thesis is also related to the random yield and random quality literature: differing from this literature where quality and yield is a result of random draw, in our model the farmer's effort can stochastically increase the produce that satisfies the minimum quality standard.

The rest of the thesis is organized as follows: We review the literature related to tackling food waste, random yield and quality, and agricultural contract in section 2. In Section 3, we develop a basic model. In section 4, we explore the conditions for the retailer to adopt high cosmetic standard and determine the corresponding food loss. In Section 5, we analyze how the two parties' optimal decisions and the food loss are affected by the consumer's willing-to-pay towards high cosmetic quality product, the existence of the processing market, and harvesting cost variation. In Section 6, we conclude with a discussion of our analysis and prescribe solutions to curb the food loss related to cosmetic filtering. All proofs are in Appendix.

2 Literature review

Our paper contributes to three streams of literature: food waste, random yield and quality, and agricultural economics.

OM research into food waste has been growing in recent years. Most of these literature focus on food waste in the downstream of the supply chain. One of the very first papers, Belavina et al. (2017), studies the impact of grocery-store density on the food waste generated at both stores and households. The analysis shows that higher density reduces food waste up to a store density threshold and it leads to higher food waste beyond this threshold. Another work that also looks into food waste from both the perspective of retailers and households is Astashkina et al. (2019). They compare food waste and transportation emissions of the retailer and households before and after the advent of online grocery retail. Through analyzing perishable grocery replenishment decisions, household's choice of the retailer, and online grocer's delivery routing, they isolate three key factors that drive the difference: whether households switch to online shopping, household's shopping patterns, and how the first two factors change where inventories are held. Numerical result shows that online retailing is beneficial for environment. Belavina (2020) explore food waste in household of online grocery retail under different patterns. They compare the financial and environmental performance of two revenue models: the pre-order model (customers pay for each delivery), and the subscription model (A customer pays a set fee and receives free delivery). They find that subscription incentivizes smaller and more frequent grocery orders, which reduces food waste.

As for retailer's food waste, Akkas and Honhon (2018) analyze food waste by examining the effect of shipment policies on product waste occurring at the retailer as well as at the manufacturer. They find that practitioners can benefit from implementing the heuristic policy they develop as well as other sophisticated shipment methods, improving profits and reducing waste. Akkas (2019) focuses on using shelf space selection to control expiration of perishable inventory. She formulates a shelf space selection problem for a single product by using an infinite horizon Markov chain model and finds that expiration will occur either for slow-moving items with a relatively short shelf life, or for items-no matter how long the shelf life of the product is-where the inventory is not rotated and the allocated shelf space is larger than the demand during the review cycle. Akkas et al. (2019) empirically examine the reasons of consumer packaged goods expiration in the grocery stores and identify methods to reduce expiration through better supply chain coordination. The coordination is in terms of the case size, time of transferring the product from the warehouse to the retailer's shelf space, manufacturer's sales incentives, replenishment workload, and minimum order rules. Akkas and Sahoo (2019) also focus on retailer-generated waste and empirically investigate that manufacturers can reduce waste for perishable items by charging the sales representatives the appropriate penalty for expiration. Compared to this literature, we examine food waste in the upstream.

Among the very few papers that examine the upstream food waste, Ata et al. (2016) examine the gleaning operations, scheduling volunteers to pick fruits and vegetables left in the field. They model the uncertainties in food and labor supplies and characterize an optimal dynamic volunteer staffing policy that depends on the number of available gleaners. Our paper, to the best of our knowledge, is the first paper that examines the implication of issues in the upstream of the food chain (i.e., farmers), examining the strategic interaction between the farmer and the retailer.

One paper close to our work is Richards and Hamilton (2019), which examines the effect of quality standard on food waste at the retail level. They model the interaction between the retailer and the consumer with price discrimination and show that the retail minimum quality standard results in surplus food at the retail level whenever the cost of imposing a minimum quality standard is sufficiently high. This is because the retailer, in order to compensate for the high cost, optimally sets a higher price than the consumer willingness-to-pay given a minimum produce quality, which results in unsold produce in the retail market. Different from their work, our work focuses on the food waste due to the interaction between a retailer and a farmer. According to the minimum quality standard adopted by the retailer, the farmer exerts effort to improve cosmetic quality.

Our paper is also related to random yield and quality literature. Random yield and quality appear in both agricultural and manufacturer literature, and have been studied extensively. Yano and Lee (1995) give a comprehensive review for the random yield in manufacturer literature. A number of study related to yield uncertainty includes Xu and Lu (2013), Yin and Ma (2015), and Li et al. (2017) , and study related to quality uncertainty includes S.Ouaret et al. (2018). We will focus on the literature more specifically concerned with agriculture. In terms of random yield, Jones et al. (2001) present a two-period hybrid seed corn production-scheduling problem. They consider the hybrid seed corn producer which can have another chance to produce in a different region. They model different distributions of random yield in two sequential growing seasons before demand occurs. As a result, the two-period production strategy has substantial economic payoff for the seed industry. Kazaz (2004) studies a two-stage olive oil production problem under yield and demand uncertainty. The producer decides the size of the olive farm to be leased under yield uncertainty in the growing season and the amount of olives to be pressed for olive oil production in the selling season under yield realization and demand uncertainty. In his model, both the unit cost of purchasing olives and the retail price of olive oil decrease in yield. The result shows that increased yield variance does not necessarily increase the optimal amount of farm space to be leased when there is a second chance to obtain supplies. Similar to Kazaz (2004), Kazaz and Webster (2011) explore the impact of yield-dependent cost. The random yield is modeled as the product of random shock and the production decision and the unit cost of purchasing fruit and the retail price of fruit also decrease in yield. They offer insights that agriculture firm would be leasing significantly less farm space under a yield-dependent cost structure compared with static costs. In our work, the yield is uniformly distributed between 0 and 1, and the farmer's effort stochastically increases the cosmetic quality.

As for random quality, Gallardo et al. (2018) find the quality of fresh produce grown on the farm is variable. Richards and Hamilton (2019) formulate farm supply as uniformly distributed quality on a unit interval with density one and they focus on the food waste at the retail level stemming from applying minimum quality standard. Noparumpa et al. (2011) examine the interrelationships among three forms of operational flexibility in mitigating agricultural yield and quality uncertainty, including downward substitution, price setting, and fruit trading. They set two grades of fruit crops (grapes) in the model. They model crop yield and quality as two stochastically proportional random variables and allow them to be correlated. They find that pricing and downward substitution flexibility play a complementary role, and fruit trading flexibility plays a substitutable role to downward substitution in the presence of pricing flexibility and also a substitutable role to pricing flexibility. However, different from the literature, the random quality and hence the qualified yield are proportionally increasing in farmers' effort in our work.

Our paper is also related to agricultural economics literature on contract when there is yield uncertainty. Contracts are widely used in the production and marketing of agricultural commodities. First, the contract can manage risk. Wang and Chen (2017) study the ordering, pricing policy and coordination in the fresh produce supply chain with portfolio option contracts. The retailer can obtain products from the supplier by wholesale price and call option portfolio contracts. Contracts can manage risks including demand uncertainty, random yield and supply price volatility. They also consider the circulation loss of fresh produce during the transportation. The result shows that the fresh produce supply chain with wholesale price and call option portfolio contracts can be coordinated and the circulation loss of fresh produce increases the management risks of the fresh produce supply chain. Besides, Hueth et al. (1999) recognize that monitoring, input control, quality measurement and locking farmer's payment to the retail price are effective methods to ensure and improve the risk-managing performance of contracts. de Zegher et al. (2019) consider company sourcing innovation by changing contract structure and channel design. Some companies switch from sourcing from commodity markets to directly sourcing from the farmer. They consider a setting with uncertain and endogenous yield and find that a linear or bonus structure contract are beneficial for the companies. Anderson and Monjardino (2019) study a double discount contract involving the fertilizer supplier, the grower and the consumer under yield uncertainty. The grower purchases fertilizer at a reduced price and sells the crop at a discount. The consumer pays a compensation to the fertilizer supplier. The endogenous yield depends on both the input level of the fertilizer and random weather-related factors. They find that benefits arise when the grower is risk-averse. The contract in our work is to motivate the farmer's effort. Our paper includes both yield uncertainty and quality uncertainty. The retailer takes advantage of contract to motivate the farmer to exert effort by adopting minimum quality standard and wholesale price, and the farmers' effort proportionally increases the cosmetic quality. Also we focus on the implication on food waste at the farm level.

3 Model

We model the interacttion between the retailer and the farmer as a Stackelberg game, with the retailer as the leader. The retailer sets a wholesale price and chooses a minimum cosmetic standard for the farmers' produce. Any produce below the retailer's minimum cosmetic quality threshold is rejected by the retailer. For instance, in the United States, oranges are graded as Fancy, No.

1, No. 2, or No. 3, based on their color and the number of blemishes. For simplicity, we assume that the retailer adopts either a high or a low standard, denoted by u_H or u_L, respectively. However, our model can be easily extended to a case with multiple discrete levels of cosmetic quality standards.

Setting minimum cosmetic quality standards can incentivize the farmer to exert higher efforts, such as using better seeds, and more fertilizer and pesticides (Heichel, 1976), to increase the cosmetic quality of the produce. For instance, damage from disease can be prevented or reduced by planting expensive but higher-quality tomato seeds destined for the fresh market. Damage due to frost in apples can be reduced by using frost fans to circulate air. We denote the effort level of the farmer by $e \in [0, 1]$ and assume that this effort only affects the quality of the produce, but it does not affect yield. The qualified quantity of the produce increases proportionally in effort e. Given a cosmetic quality standard u_i, the proportion of the yield that meets the cosmetic quality standard is:

$$(1 - \eta_i) \cdot e, i \in \{L, H\}.$$

where η_i $(0 \leq \eta_L < \eta_H < 1)$ is the rejection rate of produce failing to meet cosmetic quality standard u_i.

We assume that the cost of effort is quadratic in effort e, i.e., $\frac{1}{2} \cdot k \cdot e^2$, where $k > 0$ is a cost-related parameter. This is consistent with the intuition that as effort increases, it becomes more costly to exert a higher effort and is a common assumption in the literature (Rhee, 1996).

The farmer's effort is made in the presence of yield uncertainty, as agricultural yield depends on factors such as temperature, sunshine, and precipitation. We model the random yield, y, to be uniformly distributed, i.e.,

$y \sim \text{U}[0,1]$.

Based on the cosmetic standard level u_i, the retailer sets a selling price to customers, denoted by $r(u_i)$, as follows:

$$r(u_i) = p + \delta \cdot u_i, i \in \{L, H\},$$

where $p > 0$ is the base price and $\delta > 0$ is a measure of the consumer's sensitivity towards cosmetic quality. Thus, customers are willing to pay a premium for produce that is more aesthetically pleasing. We assume that the retailer operates under perfect competition and that all the qualified produce is sold at the retail price $r(u_i)$.

The interaction between the retailer and the farmer takes place over a five-stage game, as illustrated in Figure 1:

- At $t = 1$, the retailer and the farmer sign a contract in which the retailer sets the unit wholesale price w_f and the cosmetic threshold u_i, $i \in \{L, H\}$. The farmer accepts the contract if her expected profit is positive.
- At $t = 2$, the farmer chooses her effort level e, incurring cost $\frac{1}{2} \cdot k \cdot e^2$.
- At $t = 3$, the yield y is realized. The yield and the exerted effort level jointly determine the quantity of produce $q_{s,i}$ that meets the cosmetic standard:

$$q_{s,i} = y \cdot (1 - \eta_i) \cdot e, i \in \{L, H\}$$

- At $t = 4$, the farmer determines the optimal quantity to harvest, $q_{f,i}$, and incurs a unit harvesting cost c. By definition, we have $q_{f,i} \leq q_{s,i}$, and to avoid trivial cases, we assume that $c < w_f$, so that $q_{f,i} = q_{s,i}$. In

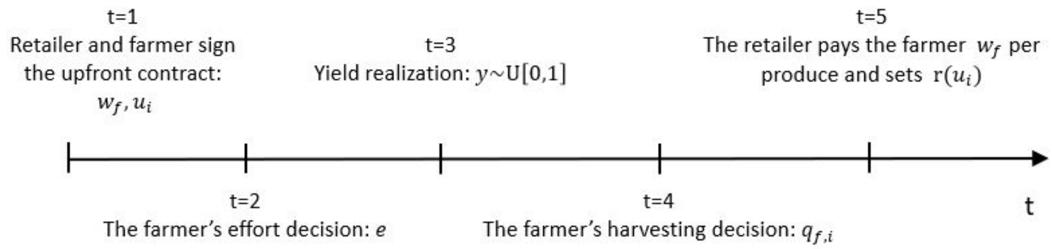


Fig 1. Timeline of events

section 5.3, we introduce harvesting cost uncertainty where $c < w_f$ no longer holds, and hence $q_{f,i}$ does not necessarily equal $q_{s,i}$.

- At $t = 5$, the retailer pays the farmer for the qualified and harvested quantity at the unit price w_f, i.e., $w_f \cdot q_{f,i}$. Then the retailer sells $q_{f,i}$ at the unit retail price $r(u_i) = p + \delta \cdot u_i$, collecting sales revenue $(p + \delta \cdot u_i) \cdot q_{f,i}$.

All the notation is summarized in Table 1. Next we will first present the solution, using backward induction. We then examine the drivers of high cosmetic standards and the food loss in the agricultural supply chain. We finally relax certain assumptions to show the robustness of our results to the model specifications.

Decision Variables		Parameters	
w_f	Wholesale price the retailer pays to the farmer	η_i	Rejection rate under u_i
u_i	Cosmetic quality standard	k	Effort cost
e	Effort; $e \in [0,1]$	c	Harvesting cost
$q_{f,i}$	Harvesting quantity under u_i; $q_{f,i} \in [0,1]$	δ	Consumer's sensitivity towards cosmetic quality
Random Variables		p	Base price
y	Stochastic yield; $y \in [0,1]$		

Table 1: Notations used in the model

4 Optimal retailer and farmer decisions and food loss

As the problem unfolds over multiple stages, we use backward induction to solve it.

4.1 Farmer's Harvesting and Effort Decision

At $t = 4$, the farmer harvests the following quantity for the fresh market

$$q_{f,i} = y \cdot (1 - \eta_i) \cdot e, i \in \{L, H\}.$$

At $t = 2$, given the contract parameters (u_i, w_f) the farmer chooses the optimal effort level to maximize her expected profit, denoted by $g(u_i, w_f, e)$, which is the expected revenue minus harvesting cost and cultivation cost as follows:

$$g(u_i, w_f, e) = \mathbb{E}_y[w_f \cdot q_{f,i} - c \cdot q_{f,i} - \frac{1}{2} \cdot k \cdot e^2]. \tag{1}$$

Here the expectation is over the random yield. The first term is the expected revenue from selling fresh produce to the retailer, the second term is the expected harvesting cost, and the third term is the cost of effort. The farmer chooses the effort level e to balance the increased cost of effort and the increase in revenue from higher qualified quantity for a given set of contract terms (u_i, w_f).

The farmer's optimal profit, denoted by $W(u_i, w_f)$, is given as follows:

$$W(u_i, w_f) = \max_{e \in [0,1]} g(u_i, w_f, e).$$

The optimal effort level given the contract terms (u_i, w_f), denoted by $e^*(u_i, w_f)$, is given as follows:

$$e^*(u_i, w_f) = \arg\max_e g(u_i, w_f, e)$$

Lemma 1. *Given the contract terms* (u_i, w_f) *where* $i \in \{L, H\}$*, the farmer's optimal effort is as follows:*

$$e^*(u_i, w_f) = \begin{cases} \frac{(1-\eta_i)\cdot(w_f-c)}{2k}, & \text{if } 0 < \frac{(1-\eta_i)\cdot(w_f-c)}{2k} < 1 \\ 1, & \text{otherwise}; \end{cases} \tag{2}$$

and the optimal profit is

$$W(u_i, w_f) = \begin{cases} \frac{(1-\eta_i)^2\cdot(w_f-c)^2}{8k}, & \text{if } 0 < \frac{(1-\eta_i)\cdot(w_f-c)}{2k} < 1 \\ \frac{(1-\eta_i)\cdot(w_f-c)-k}{2}, & \text{otherwise.} \end{cases} \tag{3}$$

Lemma 1 shows that the farmer's decision depends on the rejection rate (η_i), the difference between wholesale price and harvesting cost $(w_f - c)$, and the effort cost (k). The impact of each of these parameters is intuitive: a higher w_f increases the farmer's effort; and either a higher harvesting cost, or effort cost or rejection rate lead to a lower optimal effort. The farmer's optimal profit directly follows from the optimal effort level and is affected by the problem parameters in an identical fashion.

4.2 Retailer's contracting decision

At $t = 1$, the retailer chooses the cosmetic quality standard, u_i, and the wholesale price, w_f, to maximize the expected profit.

For a given cosmetic quality standard u_i, we can write the retailer's profit, denoted by $R(u_i)$, over the wholesale price w_f as follows:

$$R(u_i) = \max_{w_f > c} \mathbb{E}_y \left[(p + \delta \cdot u_i) \cdot (1 - \eta_i) \cdot e^*(u_i, w_f) \cdot y - w_f(1 - \eta_i) \cdot e^*(u_i, w_f) \cdot y\right] \tag{4}$$

where the first term in (4) is the expected revenue from customers, and the second term is the expected payment to the farmer. Note that the condition $w_f > c$ ensures that the farmer's participation constraint is met. The retailer then chooses the cosmetic quality standard that achieves the highest profit, i.e.,

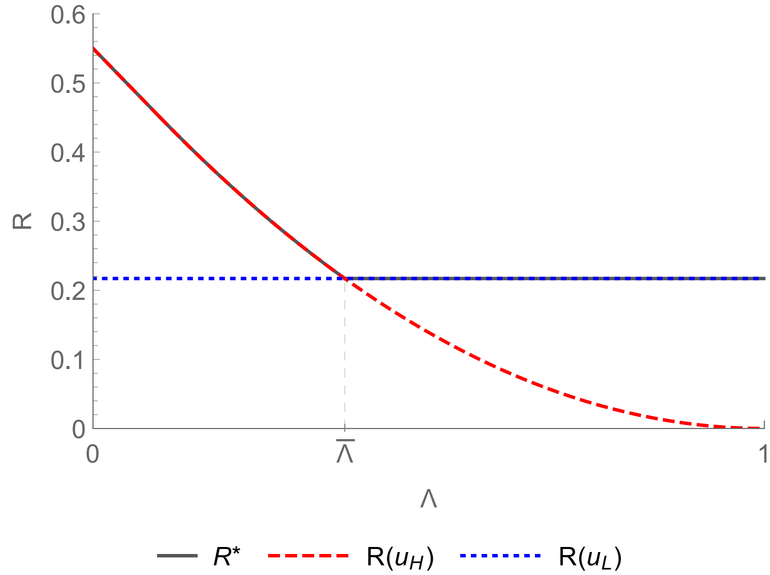
$$\begin{aligned} R^* &= \max\{R(u_L), R(u_H)\} \qquad (5) \\ \text{s.t.} \quad & W(u_i, w_f) \geq 0 \end{aligned}$$

We define

$$\Lambda = \frac{\eta_H - \eta_L}{1 - \eta_L}. \tag{6}$$

Λ is a measure of the severity of the rejection rate increase under a high cosmetic quality standard, as the rejection rate increase $(\eta_H - \eta_L)$ is divided by the worst possible rejection rate increase $(1 - \eta_L)$.

Proposition 1. *The retailer adopts a high cosmetic standard u_H when $0 < \Lambda < \bar{\Lambda}$, where $\bar{\Lambda} = \frac{\delta(u_H - u_L)}{p + \delta \cdot u_H - c}$, and a low cosmetic standard u_L otherwise.*



Note. In this example, $p = 1$, $\delta = 1$, $k = 0.45$, $c = 0$, $u_L = 0.25$, $u_H = 1$ and $\eta_L = 0$

Fig 2. Retailer's optimal profit

Given a cosmetic standard u_i, the optimal wholesale price is

$$w_f^* = \begin{cases} \frac{(p+\delta \cdot u_i + c)}{2}, & \textit{if } 0 < p + \delta \cdot u_i - c < \frac{4k}{1-\eta_i} \\ \frac{2k}{1-\eta_i} + c, & \textit{otherwise.} \end{cases} \tag{7}$$

and the retailer's optimal profit is

$$R^* = \begin{cases} \frac{(1-\eta_i)^2 \cdot (p+\delta \cdot u_i - c)^2}{16k}, & \textit{if } 0 < p + \delta \cdot u_i - c < \frac{4k}{1-\eta_i} \\ \frac{1}{2} \cdot (1-\eta_i) \cdot (p + \delta \cdot u_i - c) - k, & \textit{otherwise} \end{cases} \tag{8}$$

Proposition 1 shows that the retailer's choice of cosmetic standard is determined by the rejection rate increase Λ. If Λ is higher than the threshold $\bar{\Lambda}$, the retailer favors a low (high) cosmetic quality standard. This is because the retailer's profit depends on the quantity sold to the consumers and the margin on each unit. A higher cosmetic quality standard leads to a higher rejection rate and a higher margin even after factoring in the high wholesale price paid to the farmer to induce effort in the presence of high rejection rates. This effectively weighs the relative size of the rejection rate and the profit margin impact. Therefore, the retailer will adopt high standards only when the negative impact of the relative rejection rate increase of adopting high standards (Λ) is less than the impact of relative profit margin increase ($\bar{\Lambda}$). Figure 2 shows that the retailer's profit under low and high cosmetic quality standards for increasing Λ and illustrates the results discussed above.

Note that the retailer's optimal contract terms allow us to express the farmer's optimal effort given u_i, where $i \in L, H$ as follows:

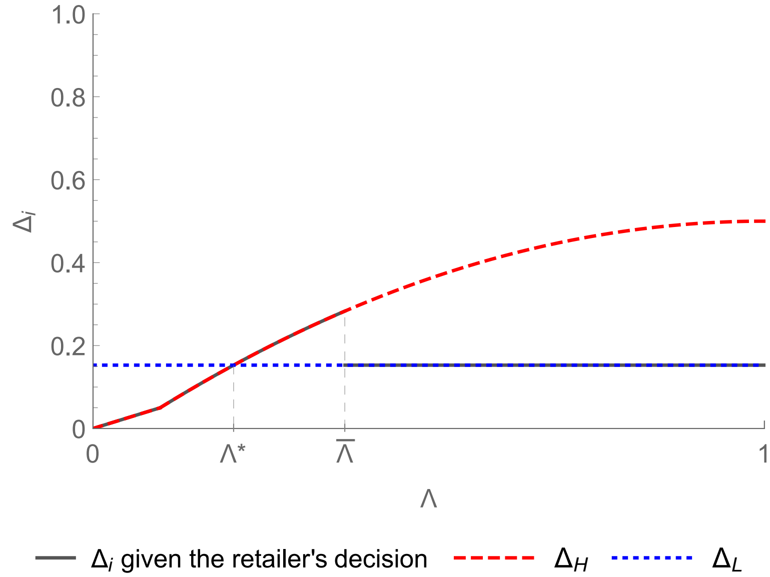
$$e^*(u_i, w_f^*) = \begin{cases} \frac{(1-\eta_i)(p+\delta \cdot u_i - c)}{4k}, & \text{if } 0 < p + \delta \cdot u_i - c < \frac{4k}{1-\eta_i} \\ 1, & \text{otherwise.} \end{cases} \tag{9}$$

4.3 Food loss from cosmetic quality standards

We know from practice that setting cosmetic quality standards can lead to food loss: the farmer only harvests the produce that meets the cosmetic standard and leaves the rest of the yield to rot in the field. We characterize the expected amount of food loss Δ_i for a given cosmetic quality standard u_i:

$$\begin{aligned} \Delta_i =& \mathbb{E}_y[[1 - (1-\eta_i) \cdot e^*(u_i, w_f)] \cdot y] \\ =& \begin{cases} \frac{1}{2} - \frac{1}{8k} \cdot (1-\eta_i)^2 \cdot (p + \delta \cdot u_i - c), & \text{if } 0 < p + \delta \cdot u_i - c < \frac{4k}{1-\eta_i} \\ \frac{1}{2} \cdot \eta_i, & \text{otherwise.} \end{cases} \end{aligned} \tag{10}$$

Intuitively, the food loss depends on the cosmetic standard in the following way. First, higher standards correspond to higher rejection rates, so that higher standards can be expected to drive up food loss. However, the retailer



Note. In this example, $p = 1$, $\delta = 1$, $k = 0.45$, $c = 0$, $u_L = 0.25$, $u_H = 1$ and $\eta_L = 0$

Fig 3. Expected food loss

pays a higher wholesale price for higher quality produce, which induces a higher farmer effort and thus drives down the total quantity rejected and reduces food loss. We know that the retailer balances these two forces when deciding on the desired cosmetic quality standard. Next we explore how the retailer's optimization indirectly affects food loss.

Proposition 2. *Food loss under u_L and u_H are compared as follows:*

(1) When $0 < p + \delta \cdot u_L - c < \frac{4k}{1-\eta_L}$, we have $\Delta_H < \Delta_L$ for $0 < \Lambda < \min\{1 - \sqrt{\frac{p+\delta\cdot u_L - c}{p+\delta\cdot u_H - c}}, 1 - \frac{(1-\eta_L)(p+\delta\cdot u_L - c)}{4k}\} < \bar{\Lambda}$ and $\Delta_L \leq \Delta_H$ otherwise.

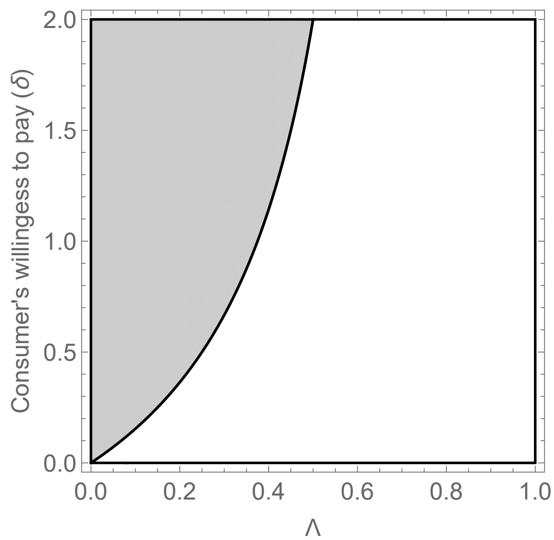
(2) When $p + \delta \cdot u_L - c \geq \frac{4k}{1-\eta_L}$, we have $\Delta_L < \Delta_H$ all the time.

The proposition is illustrated in Figure 3, which shows that adopting a high cosmetic standard u_H does not necessarily lead to higher food loss. Let $\Lambda^* = \min\{1 - \sqrt{\frac{p+\delta\cdot u_L - c}{p+\delta\cdot u_H - c}}, 1 - \frac{(1-\eta_L)(p+\delta\cdot u_L - c)}{4k}\}$. In fact, the retailer is also concerned about food loss: in a perfect competition model, the retailer can sell all he can put on the market without affecting the price; thus having a large supply of produce is always better, ceteris paribus, than having a smaller supply. That is why the retailer offers a larger wholesale price to the farmer under high quality standard, to counteract the negative impact of the higher rejection rate on the farmer's incentive to exert effort. However, the retailer's incentives are aligned with that of the farmer, where the farmer's profits are the product of quantity multiplied by profit margin, so that a higher profit margin can compensate for some additional food loss–as long as it is not too large–as observed in Figure 3 in the region $\Lambda^* < \Lambda < \bar{\Lambda}$. Note that if the problem parameters are such that even under a low cosmetic quality standard the farmer should exert full effort, then the food loss–by definition of the rejection rate $\eta_H > \eta_L$–is always lower under the low quality standard.

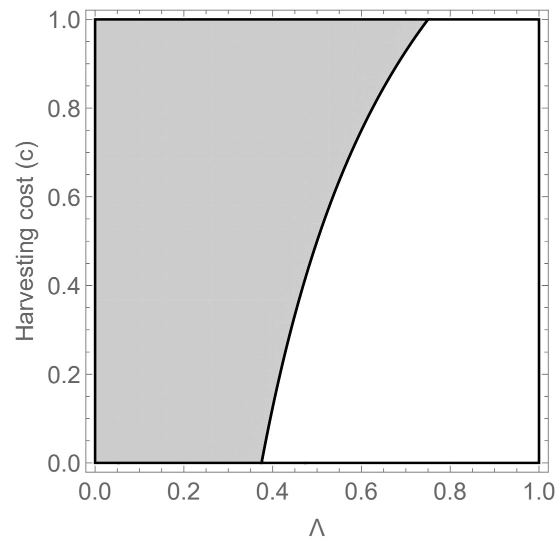
Next we will look at the drivers of the cosmetic quality standard and food loss in more detail both in terms of problem parameters, as well as some extensions to our setting that could provide alternative explanations for persistent high cosmetic quality standards.

5 Drivers of high cosmetic standard and food loss

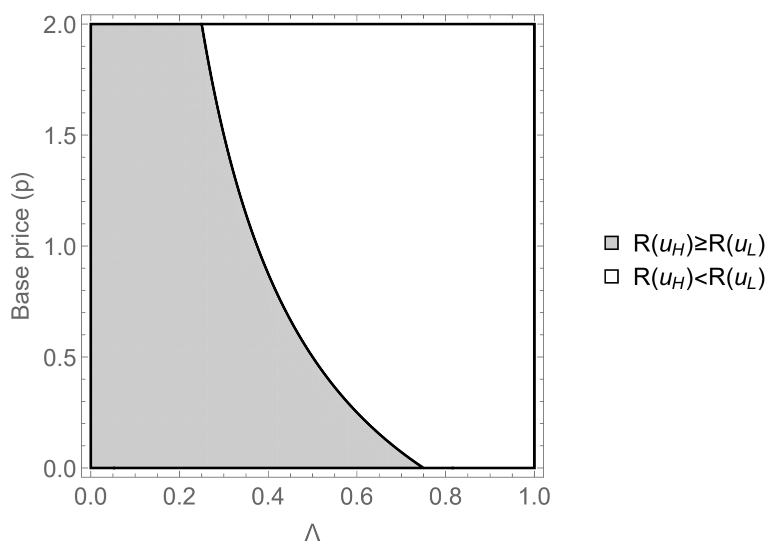
In this section, we first perform a sensitivity analysis of the results obtained in the previous section. Next we look at two extensions that may account for high cosmetic quality standards: the presence of a competing buyer of low-quality produce and variability in harvesting cost.



(a) Sensitivity analysis towards δ



(b) Sensitivity analysis towards c



(c) Sensitivity analysis towards p

Note. In this example, $p = 1$, $\delta = 1$, $k = 0.45$, $c = 0$, $u_L = 0.25$, $u_H = 1$ and $\eta_L = 0$

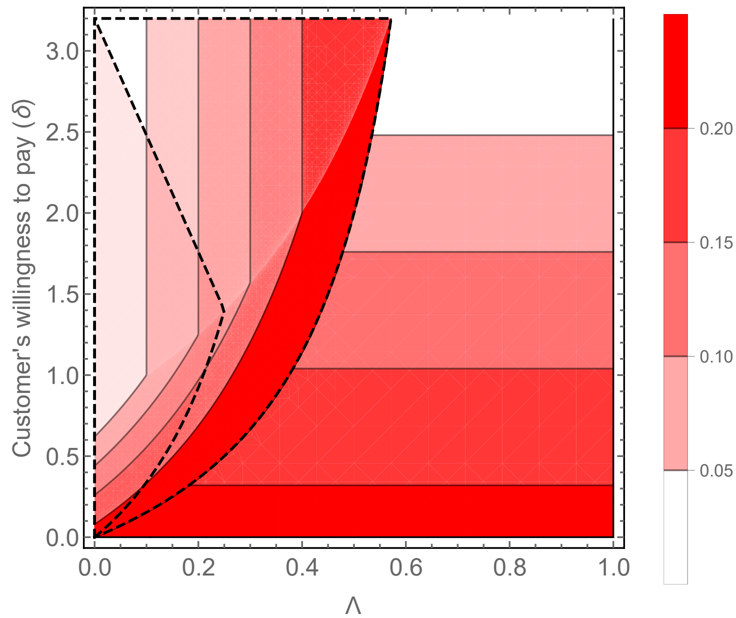
Fig 4. Sensitivity analysis of Λ's threshold towards δ, c and p

5.1 Sensitivity analysis

The retailer sets his optimal cosmetic quality standard based on the profit margin and the rejection rate. The next proposition provides a more detailed description of the possible cases.

Proposition 3. *(Drivers of high cosmetic standard) (1) If* $p - c \leq 0$ *and* $\frac{u_L}{u_H} \leq \frac{1-\eta_H}{1-\eta_L}$*,* $\bar{\Lambda}$ *is larger than all feasible* Λ*, and* u_H *is optimal.*
(2) If $p - c \geq 0$ *and* $\frac{u_L}{u_H} \geq \frac{1-\eta_H}{1-\eta_L}$*,* $\bar{\Lambda}$ *is smaller than all feasible* Λ*, and* u_L *is optimal.*
(3) In all other cases, there exist problem parameters such that either u_L *or* u_H *is optimal, depending on the threshold* $\bar{\Lambda}$*. The threshold* $\bar{\Lambda}$ *increases in* c *and decreases in* p *and* u_L*. It also increases in* δ *if* $\min\{p-c, \frac{1-\eta_H}{1-\eta_L} - \frac{u_L}{u_H}\} > 0$*, but decreases in* δ *if* $\max\{p-c, \frac{1-\eta_H}{1-\eta_L} - \frac{u_L}{u_H}\} < 0$*.*

Proposition 3 and Figure 4 show the drivers of high cosmetic standards. From proposition 1, we know that the retailer will set a high standard only when the relative rejection rate increase of setting high standards is less than the relative profit margin increase. However, the first two cases in Proposition 3 show that for certain problem parameters, the relative rejection rate increase may be either always or never higher than the threshold $\bar{\Lambda}$. In the first case, the produce is loss-making in the absence of a quality premium ($p-c \leq 0$) and the quality premium weighted by the rejection rate is higher for a high quality standard than a low quality standard (or $\delta \cdot u_H(1-\eta_H) \geq \delta \cdot u_L(1-\eta_L)$). Thus a high quality is clearly always desirable. The reverse holds for the second case. In the last case the base profit margin and the weighted quality premium do not coincide, i.e., either the base profit margin is negative but the weighted quality premium of low quality standards exceeds that of high quality standards, or the reverse holds for both comparisons. Then the threshold $\bar{\Lambda}$



Note. In this example, $p = 1$, $\delta = 1$, $k = 0.45$, $c = 0$, $u_L = 0.25$, $u_H = 1$ and $\eta_L = 0$

Fig 5. Sensitivity analysis of Δ_i towards δ

decides whether the retailer should adopt a high or a low quality standard. That threshold decreases in p (and increases in c) because as the base profit margin increases, low quality standards become relatively more attractive as having a large volume of produce become important. The threshold decreases in u_L because as u_L becomes less differentiated from u_H, the benefits (the higher profit) of the high standards are decreased while the costs, in terms of increased rejection rate, remain the same. Finally, the impact of the willingness to pay for quality, δ, depends on the sign of the base profit.

Proposition 4. *For a given u_i, when $0 < p + \delta \cdot u_i - c < \frac{4k}{1-\eta_i}$, the food loss Δ_i decreases in p and δ, but increases in c; it does not change in these parameters otherwise.*

When $0 < p + \delta \cdot u_i - c < \frac{4k}{1-\eta_i}$, the increase in base price p and customer willingness to pay δ lead to a higher wholesale price, motivating the farmer to exert a higher effort for a given cosmetic standard. The increase in effort increases qualifying yield. On the contrary, the increase in harvesting cost generates an opposite outcome. When $p + \delta \cdot u_i - c \geq \frac{4k}{1-\eta_i}$, the farmer's effort has already reached its maximum (i.e. $e^*(u_i, w_f) = 1$), thus the food loss does not change in these parameters.

5.2 The existence of the processing market

After discussing how the problem parameters in the base case explain the retailer's decision to adopt a high cosmetic quality standard, and thus impact food loss, we now look at the role of a competing source of demand. We model the processing market as a competing source of demand which does not impose a cosmetic quality standard. Fresh produce such as vegetables and fruits can also be made into processed products such as cans and packaged food, which have little to no cosmetic quality requirement on the original fresh produce. The cosmetic quality standard for the processing market is therefore regarded as 0 and all of the yield that does not satisfy the fresh market standard can be harvested and sold in the processing market. According to research by Miller and Knudson (2014), the unit wholesale price of the processed product, w_p, is typically lower than the wholesale price of the fresh produce, w_f. In this section, we will discuss the influence of the processing market on the farmer's decisions, the retailer's decisions and the resulting food loss. We assume $c < w_p < w_f$ to avoid trivial cases.

5.2.1 Farmer's harvesting and effort decision

The presence of the processing market changes the farmer's harvesting decision compared to the base case, as the farmer needs to decide on two harvesting quantities. At $t = 4$, the farmer decides the optimal quantity to harvest for the fresh market

$$q_{f,i} = q_{s,i} = y \cdot (1 - \eta_i) \cdot e, i \in \{L, H\}$$

and the optimal quantity to harvest for the processing market

$$q_{p,i} = y - y \cdot (1 - \eta_i) \cdot e, i \in \{L, H\}$$

At $t = 2$, given the contract terms (u_i, w_f) the farmer chooses the optimal effort level to maximize the expected profit, denoted by $h(u_i, w_f, e)$,

$$W(u_i, w_f) = \max_{e \in [0,1]} h(u_i, w_f, e)$$

where

$$h(u_i, w_f, e) = \mathbb{E}_y[w_f \cdot q_{f,i} + w_p \cdot q_{p,i} - c \cdot y - \frac{1}{2} \cdot k \cdot e^2] \tag{11}$$

The first term is the expected revenue from selling fresh produce to the retailer, the second term is the revenue from selling produce to the processing market, the third term is the harvesting cost, and the fourth term is the cost of effort.

Lemma 2. *In the presence of the processed market, given the contract terms* $(u_i,\ w_f)$*, where* $i \in \{L, H\}$*, the farmer's optimal effort is no more than that in the base model,*

$$e^*(u_i, w_f) = \begin{cases} \frac{(1-\eta_i)\cdot(w_f - w_p)}{2k}, & \textit{if } 0 < \frac{(1-\eta_i)\cdot\ (w_f - w_p)}{2k} < 1 \\ 1, & \textit{otherwise} \end{cases} \tag{12}$$

and the optimal profit is

$$W(u_i, w_f) = \begin{cases} \frac{(1-\eta_i)^2 \cdot (w_f - w_p)^2}{8k} + \frac{w_p - c}{2}, & \textit{if } 0 < \frac{(1-\eta_i)\cdot(w_f - w_p)}{2k} < 1 \\ \frac{(1-\eta_i)\cdot w_f}{2} + \frac{\eta_i \cdot w_p - k - c}{2}, & \textit{otherwise} \end{cases} \tag{13}$$

Compared to Lemma 1, Lemma 2 shows that besides the rejection rate (η_i) and the effort cost (k), the farmer's decision depends on the difference between the wholesale price for the fresh market and the wholesale price for the processing market ($w_f - w_p$) instead of the difference between the wholesale price and the harvesting cost ($w_f - c$): from intuition, for a given wholesale price of produce on the fresh market w_f, the farmer exerts less effort in the presence of the processing market compared to the base model. This happens because the farmer can sell the produce which is not qualified for the fresh market to the processed market. The effects of η_i and k are the same as in the base model.

5.2.2 Retailer's optimal contract decision.

At $t = 1$, the retailer decides the optimal contract terms to maximize the expected profit over u_i and w_f, similar to the base model.

Proposition 5. *The retailer adopts a high cosmetic standard u_H when $0 < \Lambda < \frac{\delta(u_H - u_L)}{p + \delta \cdot u_H - w_p}$ and a low cosmetic standard u_L otherwise.*

Given a cosmetic standard u_i, the optimal wholesale price is

$$w_f^* = \begin{cases} \frac{(p + \delta \cdot u_i + w_p)}{2}, & \textit{if } 0 < p + \delta \cdot u_i - w_p < \frac{4k}{1-\eta_i} \\ \frac{2k}{1-\eta_i} + w_p, & \textit{otherwise} \end{cases} \tag{14}$$

and the retailer's optimal profit is

$$R^* = \begin{cases} \frac{(1-\eta_i)^2 \cdot (p+\delta \cdot u_i - w_p)^2}{16k}, & \text{if } 0 < p + \delta \cdot u_i - w_p < \frac{4k}{1-\eta_i} \\ \frac{1}{2} \cdot (1-\eta_i) \cdot (p + \delta \cdot u_i - w_p) - k, & \text{otherwise} \end{cases} \tag{15}$$

It is not difficult to show that $\frac{\delta \cdot (u_H - u_L)}{p + \delta \cdot u_H - w_p} > \bar{\Lambda}$. Consequently we observe that the presence of a processing market increases the threshold below which the retailer adopts a high cosmetic quality standard u_H. Furthermore, the retailer also has to set a higher wholesale price w_f to motivate the farmer to exert effort, as the farmer can always choose to sell to the processing market instead.

From (12) and (14), we have

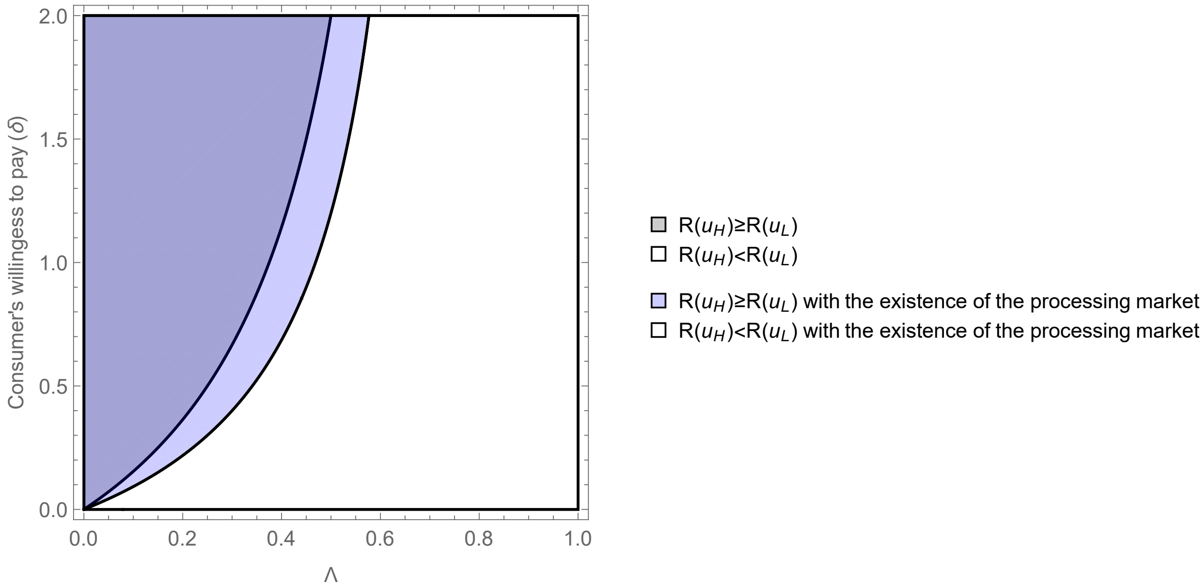
$$e^*(u_i, w_f^*) = \begin{cases} \frac{(1-\eta_i)(p+\delta \cdot u_i - w_p)}{4k}, & \text{if } 0 < p + \delta \cdot u_i - w_p < \frac{4k}{1-\eta_i} \\ 1, & \text{otherwise} \end{cases} \tag{16}$$

in the presence of the processing market.

By comparing (16) to (9), we find that given the retailer's optimal decision, the farmer's optimal effort in the presence of the processing market is no larger than the effort in the base model.

In summary, the presence of the processing market leads to a higher w_f, a lower retailer's profit, and a farmer's optimal effort not exceeding that in the base model.

However, while the broader choice of a high cosmetic quality standard and a lower farmer's effort might seem to be detrimental to food loss, this is no longer the case, as all produce that does not meet the retailer's cosmetic



Note. In this example, $p = 1$, $\delta = 1$, $k = 0.45$, $w_p = 0.4$, $c = 0$, $u_L = 0.25$, $u_H = 1$ and $\eta_L = 0$

Fig 6. Threshold of Λ changes with the existence of the processing market

quality standard can be sold to the processing market. Thus by definition, there is no food loss as long as $w_p > c$.

5.3 The variation of harvesting cost

We add harvesting cost uncertainty to the base model in Section 3 as in reality the wages of seasonal workers–often immigrants–vary due to random labor supply and demand. In case of large shock, e.g. a sudden tightening of migration policies, the harvesting cost could even exceed the wholesale price w_f set in the first stage. Hence the harvested quantity depends on the harvesting cost realized, which then affects the retailer's optimal contract terms.

In our model, the harvesting cost c_j, $j \in \{L, H\}$, is realized after the farmer exerts effort and before harvesting. The harvesting cost can be either high, at $c_H = c + \epsilon$, or low, at $c_L = c - \epsilon$, with equal probability $\frac{1}{2}$, where $0 < \epsilon < c$ is half of the range of the harvesting cost variability. Thus, the mean harvesting cost is c. We assume $p + \delta \cdot u_L > c$, as otherwise in expectation farmers will not harvest. We also assume $w_f \geq c - \epsilon$ so that the farmer always harvests under low harvesting cost.

5.3.1 Farmer's harvesting quantity

Now that the farmer faces harvesting cost uncertainty, the farmer's decision at $t = 4$ on the harvesting quantity depends on the cost realization.

At $t = 4$, given the wholesale price w_f and realized harvest cost c_j, $j \in \{L, H\}$, the farmer aims to maximize his expected profit over the harvesting quantity for the fresh market.

$$\max_q \, (w_f - c_j)\mathbb{E}_y[q] \tag{17}$$

$$\text{s.t.} \quad 0 \leq q \leq (1 - \eta_i)ey \tag{18}$$

Therefore, the farmer only harvests for the fresh market when the harvesting cost is no more than the wholesale price. That is, the farmer may choose not to harvest under high harvesting cost.

The harvesting quantity is

$$q_{fij} = \begin{cases} 0, & \text{if } w_f \leq c_j \\ (1 - \eta_i)ey, & \text{otherwise} \end{cases} \tag{19}$$

5.3.2 Farmer's optimal effort

At $t = 2$, given the contract parameter (u_i, w_f), the farmer chooses the optimal effort level to maximize the expected profit, denoted by $h(u_i, w_f, e)$,

$$W(u_i, w_f) = \max_{e \in [0,1]} h(u_i, w_f, e)$$

where

$$h(u_i, w_f, e) = \sum_{j \in L,H} \mathbb{E}_y[w_f \cdot q_{fij} - c_j \cdot q_{fij}] - \frac{1}{2} \cdot k \cdot e^2 \tag{20}$$

We determine the optimal effort level $e^*(u_i, w_f)$ in the following Lemma.

Lemma 3. *In the presence of harvesting cost variability, given the contract term $(u_i,\ w_f)$, where $i \in \{L, H\}$, the farmer's optimal effort is*

$$e^*(u_i, w_f) = \begin{cases} 0, & \text{if } 0 < w_f < c - \epsilon \\ \frac{(1-\eta_i)\cdot(w_f - c + \epsilon)}{4k}, & \text{if } c - \epsilon \leq w_f < c + \epsilon \\ \frac{(1-\eta_i)\cdot(w_f - c)}{2k}, & \text{if } c + \epsilon \leq w_f \leq \frac{2k}{1-\eta_i} + c \\ 1, & \text{otherwise} \end{cases} \tag{21}$$

We observe that there are 4 positive optimal values for the farmer's optimal effort, depending on how the wholesale price compares to the harvesting cost outcome. The first case is trivial: when the wholesale price is less than the harvesting cost, the farmer does not harvest. Thus, it is optimal for the farmer not to exert any effort. When the wholesale price is between low and the high harvesting cost outcome, the farmer only harvests under low harvesting cost $c - \epsilon$, but not under a high harvesting cost. Interestingly, in that case, a larger cost variability leads to higher effort, because the lower harvesting cost leads to a higher margin for the farmer. When the wholesale price is larger than the high harvesting cost, the farmer always harvests and harvesting cost variation does not affect farmer's effort.

5.3.3 Retailer's optimal contract decision.

At $t = 1$, the retailer chooses the cosmetic quality standard u_i and the wholesale price w_f to maximize the expected profit.

For a given cosmetic quality standard u_i, we can write the retailer's profit expression over the wholesale price as follows:

$$R(u_i) = \max_{w_f > c} \mathbb{E}_y \left[(p + \delta \cdot u_i - w_f) \cdot (1 - \eta_i) \cdot e^*(u_i, w_f) \cdot y \right] \tag{22}$$

We define

$$\begin{aligned} & R^* = \max\{R(u_L)), R(u_H)\} \\ & \text{s.t.} \quad W(u_i, w_f) \geq \underline{0} \end{aligned} \tag{23}$$

Proposition 6. *As ϵ increases, the range that the retailer adopts u_H decreases if $0 < p + \delta \cdot u_L - c \leq (7 - 4\sqrt{2})\epsilon$, stays constant if $p + \delta \cdot u_i - c \geq c + 2\epsilon$, and increases otherwise.*

Given a cosmetic standard u_i, the optimal wholesale price is

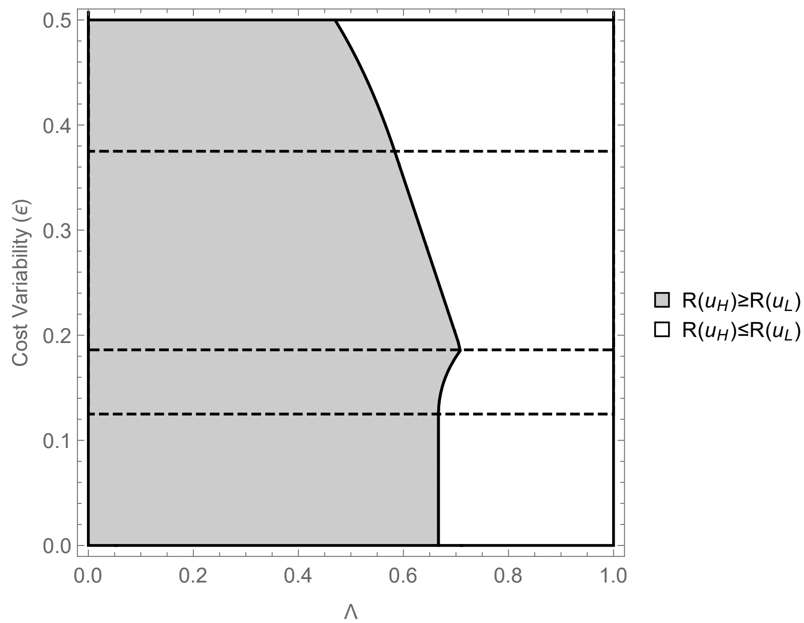
$$w_f^* = \begin{cases} \frac{(p+\delta \cdot u_i + c - \epsilon)}{2}, & \text{if } 0 < p + \delta \cdot u_i - c \leq (7 - 4\sqrt{2})\epsilon \\ c + \epsilon, & (7 - 4\sqrt{2})\epsilon < p + \delta \cdot u_i - c < 2\epsilon \\ \frac{(p+\delta \cdot u_i + c)}{2}, & 2\epsilon \leq p + \delta \cdot u_i - c \leq \frac{4k}{1-\eta_i} \\ \frac{2k}{1-\eta_i} + c, & \text{otherwise} \end{cases} \tag{24}$$

and the retailer's optimal profit is

$$R^* = \begin{cases} \frac{(1-\eta_i)^2 \cdot (p+\delta \cdot u_i - c+\epsilon)^2}{64k}, & \textit{if } 0 < p+\delta\cdot u_i - c \leq (7-4\sqrt{2})\epsilon \\ \frac{(1-\eta_i)^2 \cdot (p+\delta \cdot u_i - c-\epsilon)\epsilon}{4k}, & (7-4\sqrt{2})\epsilon < p+\delta\cdot u_i - c < 2\epsilon \\ \frac{(1-\eta_i)^2 \cdot (p+\delta \cdot u_i - c)^2}{16k}, & 2\epsilon \leq p+\delta\cdot u_i - c \leq \frac{4k}{1-\eta_i} \\ \frac{1}{2}\cdot(1-\eta_i)\cdot(p+\delta\cdot u_i - c) - k, & \textit{otherwise} \end{cases}$$

We first look at the trade-off that the retailer is facing: even though the harvesting cost is variable, when ϵ is small, it does not affect the retailer's decision because the retailer is a risk-neutral expected maximizer. As long as $w_f > c+\epsilon$, the farmer always harvests for both costs. However, ϵ begins to matter when $w_f < c+\epsilon$. The retailer has two options here. One is to increase w_f to $c+\epsilon$. In this case, the farmer will always harvest. Another option is not to change w_f. Then the farmer will harvest only half of the time (for the low cost). The retailer's preferred choice depends on the u_L and u_H setting. In proposition 6, we have the result. When $0 < p+\delta\cdot u_i - c \leq (7-4\sqrt{2})\epsilon$, the farmer only harvests under low harvesting cost $c-\epsilon$, so the increase in variability ϵ reduces harvesting cost and leads to lower w_f. When $(7-4\sqrt{2})\epsilon < p+\delta\cdot u_i - c < 2\epsilon$, the farmer harvests under both harvesting costs because the retailer sets w_f to $c+\epsilon$, and thus the increase in variability ϵ increases harvesting cost and leads to higher w_f. When $p+\delta\cdot u_i - c \geq 2\epsilon$, the farmer always harvests, thus the harvesting cost variation does not affect w_f and R^*.

Figure 7 shows that the impact of harvesting cost variability on the optimal cosmetic standard is non-monotonic. We discuss two situations below. For $\Lambda = 0.6$, as ϵ increases, the retailer changes from adopting u_H to u_L: since the retailer only harvests under low cost for u_L, the increase in variability decreases the harvesting cost and thus decreases w_f. Because the retail price



Note. In this example, $p = 1$, $\delta = 1$, $k = 0.50$, $c = 1$, $u_L = 0.25$, $u_H = 0.75$ and $\eta_L = 0$

Fig 7. Threshold of Λ changes with the harvesting cost variability

does not change, the retailer gains a higher margin under u_L. Thus, he is more willing to adopt u_L as ϵ increases. For $\Lambda = 0.68$, the retailer changes from adopting u_L to u_H then to u_L. We have explained the transformation from u_H to u_L, so now we only need to explore the shift from u_L to u_H: it happens because the retailer increases w_f to $c + \epsilon$ for u_L. As ϵ increases, w_f increases, the profit margin decreases, therefore the retailer is more willing to adopt u_H.

Given the retailer's decision, the farmer's optimal effort is as follows.

$$e^*(u_i, w_f^*) = \begin{cases} \frac{(1-\eta_i)\cdot(p+\delta\cdot u_i - c+\epsilon)}{8k}, & \text{if } 0 < p + \delta \cdot u_i - c \leq (7 - 4\sqrt{2})\epsilon \\ \frac{(1-\eta_i)\epsilon}{2k}, & (7-4\sqrt{2})\epsilon < p + \delta \cdot u_i - c < 2\epsilon \\ \frac{(1-\eta_i)(p+\delta\cdot u_i - c)}{4k}, & 2\epsilon \leq p + \delta \cdot u_i - c \leq \frac{4k}{1-\eta_i} \\ 1, & \text{otherwise} \end{cases}$$

5.3.4 Impact of harvesting cost variation on food loss

For a given cosmetic quality standard u_i, the expected amount of food loss is

$$\Delta_i = \mathbb{E}_y[[1-(1-\eta_i)\cdot e^*(u_i,w_f)]\cdot y]$$
$$= \begin{cases} \frac{1}{2}-\frac{1}{16k}\cdot(1-\eta_i)^2\cdot(p+\delta\cdot u_i-c+\epsilon), & \text{if } 0<p+\delta\cdot u_i-c\leq(7-4\sqrt{2})\epsilon \\ \frac{1}{2}-\frac{1}{4k}\cdot(1-\eta_i)^2\cdot\epsilon, & (7-4\sqrt{2})\epsilon<p+\delta\cdot u_i-c<2\epsilon \\ \frac{1}{2}-\frac{1}{8k}\cdot(1-\eta_i)^2\cdot(p+\delta\cdot u_i-c), & 2\epsilon\leq p+\delta\cdot u_i-c\leq\frac{4k}{1-\eta_i} \\ \frac{1}{2}\cdot\eta_i, & \text{otherwise} \end{cases} \tag{25}$$

When harvesting cost variability is low, it has limited impact on the food loss because the farmer harvests under both costs; when harvesting cost variability is medium, it leads to higher w_f and higher margin, thus results in higher effort and lower food loss; when harvesting cost variability is high, the farmer does not harvest under high cost, resulting in higher food loss.

6 Managerial insights and conclusion

This paper studies food waste in the upstream of agricultural supply chain. We look at how economic incentives can cause waste by developing a Stackelberg game between a retailer and a farmer, and we focus on the role of cosmetic standards. In our model, the retailer sets wholesale price and adopts either a high standard or a low standard in the contract to motivate the farmer to exert effort. Given the contract terms, the farmer decides her optimal effort, incurring a quadratic effort cost. This effort only affects produce quality but not yield. The farmer decides the harvesting quantity after yield realization, incurring a harvesting cost proportionally increasing in the harvesting quantity. We also consider the consumer's preference towards beautiful food, that is, the consumer is willing to pay a higher price for the high cosmetic quality produce. Apart from the above setting in the base model, we consider the presence of the processing market or harvesting cost variability.

To our knowledge, our paper is among the very few paper that investigates upstream food loss (i.e., the farmer). We explore the economic incentives for a retailer to adopt high cosmetic standards and show the impact of high cosmetic standards adopted by the retailer on food loss. We find that a higher wholesale price will induce the farmer to exert a higher effort, while the effort cost and the harvesting cost play an opposite role. The retailer adopts high cosmetic standards when the relative rejection rate increase is less than a threshold. An increase in harvesting cost, a decrease in the base price, and a presence of the processing market push the retailer to adopt a high standard. The effect of consumer's willingness to pay on retailer's decision depends on the net impact of rejection rate and the scale of cosmetic standards.

First, consumers' preference towards high quality sometimes induces the retailer to adopt high standards while sometimes the opposite. Next, the increase in the harvesting cost or the decrease in the base price should be compensated by higher revenue and only a high cosmetic standard can achieve it. Besides, the larger price increase from adopting high cosmetic standards. Furthermore, the presence of the processing market induces the retailer to adopt a higher wholesale price in the fresh market to stay in business because the farmer now has an alternative to sell their produce to the processing market instead of the fresh market. The increase in the wholesale price in the fresh market motivates the farmer to exert a higher effort. Relaxing the assumption that the harvesting cost is fixed, we find that the impact of harvesting cost variability on the retailer's decision is non-monotonic.

In terms of the food loss, we find that adopting a high cosmetic standard does not necessarily lead to higher food loss. This is because the retailer adopts a higher wholesale price under high cosmetic standards, which leads to a higher farmer's effort and lower food loss. When the farmer's effort does not reach maximum, the food loss decreases in the base price and the consumer's willingness to pay for high cosmetic quality, and increases in the harvesting cost. The result stems from the impact of these parameters on farmer's effort, and a higher effort increases the qualified yield and reduces food loss. Introducing the processing market significantly reduces the food loss because there is no cosmetic standard for the processing product. When harvesting cost variability is low, it has limited impact on the food loss; when harvesting cost variability is medium, it leads to higher wholesale prices and higher margin, resulting in higher effort and lower food loss; when harvesting cost variability is high, the farmer does not harvest under high cost, resulting in higher food loss. Our results provide insights for regulatory bodies to reduce food waste. For instance, the government can educate consumers that "ugly" food has the same nutrition as regular-looking food and can be safely consumed. Second, the government can provide subsidies to the farmers to incentivize them to exert a higher effort and harvest more produce.

Further research looks at links between yield and quality. One such link could be it shows that either the same or different efforts can affect both quality and yield. Another link could be correlation in quality and yield outcomes. Besides, further research can also look at the competition among retailers. In our current model, we assume a perfect competition model where the retailer has no impact on the market demand. However, if we looks into a market model where a competition is implicitly modeled that retailers' decisions can affect market demand, it might refine theses results.

7 Appendix

Proofs and Additional Results

Proof of Lemma 1. By substituting $q_{f,i} = y \cdot (1-\eta_i) \cdot e$ and $\mathbb{E}[y] = 1/2$ into (1), we obtain

$$\begin{aligned} W(u_i, w_f) &= \max_{e\in[0,1]} \mathbb{E}_y[(w_f - c) \cdot q_{f,i} - \frac{1}{2} \cdot k \cdot e^2] \\ &= \max_{e\in[0,1]} \mathbb{E}_y[(w_f - c) \cdot y \cdot (1-\eta_i) \cdot e - \frac{1}{2} \cdot k \cdot e^2] \\ &= \max_{e\in[0,1]} \left\{ (w_f - c) \cdot (1-\eta_i) \cdot e \cdot \mathbb{E}_y[y] - \frac{1}{2} \cdot k \cdot e^2 \right\} \\ &= \max_{e\in[0,1]} \left\{ (w_f - c) \cdot (1-\eta_i) \cdot e \cdot \frac{1}{2} - \frac{1}{2} \cdot k \cdot e^2 \right\} \\ &= \frac{1}{2} \max_{e\in[0,1]} \left\{ (w_f - c) \cdot (1-\eta_i) \cdot e - k \cdot e^2 \right\} \end{aligned}$$

Let $V_i(e) = (w_f - c) \cdot (1-\eta_i) \cdot e - k \cdot e^2$, by taking the first order derivative of $V_i(e)$ with respect to e, we have

$$\frac{\partial V_i(e)}{\partial e} = (1-\eta_i) \cdot (w_f - c) - 2k \cdot e$$

By taking the second order derivative of $V_i(e)$ with respect to e, we have

$$\frac{\partial^2 V_i(e)}{\partial e^2} = -2k$$

Because $\frac{\partial^2 V_i(e)}{\partial e^2} = -2k < 0$, $V_i(e)$ is concave in e, then the farmer's expected profit function $g(u_i, w_f, e)$ is concave in e. The first order condition gives the unconstrained optimal effort

$$e(u_i, w_f) = \frac{(1-\eta_i)\cdot(w_f - c)}{2k} \tag{A.1}$$

with the constraint $0 \leq e \leq 1$, we have the following farmer's optimal effort

$$e^*(u_i, w_f) = \begin{cases} \frac{(1-\eta_i)\cdot(w_f-c)}{2k}, & \text{if } 0 < \frac{(1-\eta_i)\cdot\ (w_f-c)}{2k} < 1 \\ 1, & \text{otherwise} \end{cases}$$

and her optimal profit is

$$W(u_i, w_f) = \begin{cases} \frac{(1-\eta_i)^2\cdot(w_f-c)^2}{8k}, & \text{if } 0 < \frac{(1-\eta_i)\cdot(w_f-c)}{2k} < 1 \\ \frac{(1-\eta_i)\cdot(w_f-c)-k}{2}, & \text{otherwise} \end{cases}$$ □

Proof of Proposition 1. From $0 < \eta_i < 1$, $w_f > c$ and $k > 0$, we have $W(u_i, w_f) > 0$. We formulate the retailer's profit maximization problem as

$$R^* = \max\{R(u_L)), R(u_H)\} \tag{A.2}$$

where

$$\begin{aligned} R(u_i) =& \frac{1}{2}\max_{w_f > c}\{(p+\delta\cdot u_i - w_f)\cdot(1-\eta_i)\cdot e^*(u_i)\} \\ =& \begin{cases} \frac{(1-\eta_i)^2}{4k}\max\limits_{w_f>c}\{(p+\delta\cdot u_i - w_f)\cdot(w_f - c)\}, & \text{if } 0 < \frac{(1-\eta_i)\cdot(w_f-c)}{2k} < 1 \\ \frac{1}{2}\cdot(1-\eta_i)\max\limits_{w_f>c}\{(p+\delta\cdot u_i - w_f)\}, & \text{otherwise} \end{cases} \end{aligned} \tag{A.3}$$

- If $0 < \frac{(1-\eta_i)\cdot(w_f-c)}{2k} < 1$,

$$R(u_i) = \frac{(1-\eta_i)^2}{4k} \max_{w_f>c}\{(p+\delta\cdot u_i - w_f)\cdot(w_f-c)\} \tag{A.4}$$

Let $I_i(w_f) = (p+\delta\cdot u_i - w_f)\cdot(w_f-c)$, by taking the first order derivative of $I_i(w_f)$ with respect to w_f, we have

$$\frac{\partial I_i(w_f)}{\partial w_f} = (p+\delta\cdot u_i - 2w_f + c)$$

By taking the second order derivative of $I_i(w_f)$ with respect to w_f, we have

$$\frac{\partial^2 I_i(w_f)}{\partial w_f^2} = -2$$

Because $\frac{\partial^2 I_i(w_f)}{\partial w_f^2} = -2 < 0$, $I_i(w_f)$ is concave in w_f, then $R(u_i)$ is concave in w_f. The first order condition gives the following retailer's optimal wholesale price setting,

$$w_f^* = \frac{p+\delta\cdot u_i + c}{2} \tag{A.5}$$

From $0 < \frac{(1-\eta_i)\cdot(w_f^*-c)}{2k} < 1$, we have $0 < \frac{(1-\eta_i)\cdot(\frac{p+\delta\cdot u_i+c}{2}-c)}{2k} < 1$, which is equivalent to $p+\delta\cdot u_i - c < \frac{4k}{1-\eta_i}$.

- If $\frac{(1-\eta_i)\cdot(w_f^*-c)}{2k} \geq 1$, $p+\delta\cdot u_i - c \geq \frac{4k}{1-\eta_i}$,

$$R(u_i) = \frac{1}{2}\cdot(1-\eta_i)\max_{w_f>c}\{(p+\delta\cdot u_i - w_f) \tag{A.6}$$

We take the minimum possible w_f as w_f^* because the profit function is decreasing in w_f. From $\frac{(1-\eta_i)\cdot(w_f^*-c)}{2k} \geq 1$, we have

$$w_f^* = \frac{2k}{1-\eta_i} + c \tag{A.7}$$

From (A.5) and (A.7), we have optimal wholesale price for given decision u_i

$$w_f^* = \begin{cases} \frac{(p+\delta\cdot u_i+c)}{2}, & \text{if } 0 < p+\delta\cdot u_i - c < \frac{4k}{1-\eta_i} \\ \frac{2k}{1-\eta_i} + c, & \text{otherwise} \end{cases} \tag{A.8}$$

From (A.4), (A.5),(A.6), and (A.7), we obtain the optimal profit of the retailer for given decision u_i

$$R(u_i) = \begin{cases} \frac{(1-\eta_i)^2\cdot(p+\delta\cdot u_i-c)^2}{16k}, & \text{if } 0 < p+\delta\cdot u_i - c < \frac{4k}{1-\eta_i} \\ \frac{1}{2}\cdot(1-\eta_i)\cdot(p+\delta\cdot u_i-c)-k, & \text{otherwise} \end{cases} \tag{A.9}$$

From (5), we compare the retailer's profit under u_L and u_H to decide cosmetic standard. From (A.9), we can see that for a given u_i, $i \in \{L, H\}$, there are two different expressions of the retailer's profit under different conditions. Therefore, we consider the following four cases to decide the retailer's decision on cosmetic quality standard u_i, $i \in \{L, H\}$ under different conditions:

- $0 < p+\delta\cdot u_L - c < \frac{4k}{1-\eta_L}$ and $0 < p+\delta\cdot u_H - c < \frac{4k}{1-\eta_H}$.
  If the retailer's profit $R(u_L) \geq R_(u_H)$, he adopts u_L.

$$\frac{(1-\eta_L)^2\cdot(p+\delta\cdot u_L-c)^2}{16k} \geq \frac{(1-\eta_H)^2\cdot(p+\delta\cdot u_H-c)^2}{16k}$$

Because we assume $0 < \eta_L < \eta_H < 1$ and $p + \delta \cdot u_i - c > 0$, we have

$$(1 - \eta_L) \cdot (p + \delta \cdot u_L - c) \geq (1 - \eta_H) \cdot (p + \delta \cdot u_H - c)$$

$$\frac{\delta(u_H - u_L)}{p + \delta \cdot u_H - c} \leq \frac{\eta_H - \eta_L}{1 - \eta_L} < 1.$$

By defining $\frac{\eta_H - \eta_L}{1 - \eta_L}$ as Λ, we have

$$\frac{\delta(u_H - u_L)}{p + \delta \cdot u_H - c} \leq \Lambda < 1.$$

On the contrary, if the retailer's profit $R_(u_L) < R_(u_H)$, the retailer adopts u_H.

$$\frac{(1 - \eta_L)^2 \cdot (p + \delta \cdot u_L - c)^2}{16k} < \frac{(1 - \eta_H)^2 \cdot (p + \delta \cdot u_H - c)^2}{16k}$$

through calculation we have $0 < \Lambda < \frac{\delta(u_H - u_L)}{p + \delta \cdot u_H - c}$.

- $0 < p + \delta \cdot u_L - c < \frac{4k}{1 - \eta_L}$ and $p + \delta \cdot u_H - c \geq \frac{4k}{1 - \eta_H}$.
  From $0 < p + \delta \cdot u_L - c < \frac{4k}{1 - \eta_L}$ and $p + \delta \cdot u_H - c \geq \frac{4k}{1 - \eta_H}$, we have

$$(1 - \eta_L)(p + \delta \cdot u_L - c) < (1 - \eta_H)(p + \delta \cdot u_H - c)$$

then

$$0 < \Lambda < \frac{\delta(u_H - u_L)}{p + \delta \cdot u_H - c}$$

From $0 < p + \delta \cdot u_L - c < \frac{4k}{1-\eta_L}$, we have

$$(1-\eta_L)^2 \cdot (p + \delta \cdot u_L - c)^2 < 16k^2$$

then

$$\frac{(1-\eta_L)^2 \cdot (p + \delta \cdot u_L - c)^2}{16k} < k \tag{A.10}$$

From $p + \delta \cdot u_H - c \geq \frac{4k}{1-\eta_H}$, we have

$$(1-\eta_H) \cdot (p + \delta \cdot u_H - c) \geq 4k$$

then

$$\frac{1}{2} \cdot (1-\eta_H) \cdot (p + \delta \cdot u_H - c) - k \geq k \tag{A.11}$$

From (A.10) and (A.11), we have

$$\frac{(1-\eta_L)^2 \cdot (p + \delta \cdot u_L - c)^2}{16k} < \frac{1}{2} \cdot (1-\eta_H) \cdot (p + \delta \cdot u_H - c) - k$$

then $R(u_L) < R(u_H)$. Therefore, the retailer adopts u_H when $0 < \Lambda < \frac{\delta(u_H - u_L)}{p + \delta \cdot u_H - c}$.

- $p + \delta \cdot u_L - c \geq \frac{4k}{1-\eta_L}$ and $0 < p + \delta \cdot u_H - c < \frac{4k}{1-\eta_H}$.

From $p + \delta \cdot u_L - c \geq \frac{4k}{1-\eta_L}$ and $0 < p + \delta \cdot u_H - c < \frac{4k}{1-\eta_H}$, we have

$$\frac{\delta(u_H - u_L)}{p + \delta \cdot u_H - c} \leq \Lambda < 1$$

From $p + \delta \cdot u_L - c \geq \frac{4k}{1-\eta_L}$, we have

$$(1 - \eta_L) \cdot (p + \delta \cdot u_L - c) \geq 4k$$

then

$$\frac{1}{2} \cdot (1 - \eta_L) \cdot (p + \delta \cdot u_L - c) - k \geq k \tag{A.12}$$

From $0 < p + \delta \cdot u_H - c < \frac{4k}{1-\eta_H}$, we have

$$(1 - \eta_H)^2 \cdot (p + \delta \cdot u_H - c)^2 < 16k$$

then

$$\frac{(1 - \eta_H)^2 \cdot (p + \delta \cdot u_H - c)^2}{16k} < k \tag{A.13}$$

From (A.12) and (A.13), we have

$$\frac{1}{2} \cdot (1 - \eta_L) \cdot (p + \delta \cdot u_L - c) - k > \frac{(1 - \eta_H)^2 \cdot (p + \delta \cdot u_H - c)^2}{16k}$$

then $R(u_L) > R(u_H)$. Therefore, the retailer adopts u_L when $\frac{\delta(u_H - u_L)}{p+\delta \cdot u_H - c} \leq \Lambda < 1$.

- $p + \delta \cdot u_L - c \geq \frac{4k}{1-\eta_L}$ and $p + \delta \cdot u_H - c \geq \frac{4k}{1-\eta_H}$.

  If the planner's profit $R(u_L) \geq R(u_H)$, he adopts u_L.

$$\frac{1}{2} \cdot (1 - \eta_L) \cdot (p + \delta \cdot u_L - c) - k \geq \frac{1}{2} \cdot (1 - \eta_H) \cdot (p + \delta \cdot u_H - c) - k$$

Because we assume $0 < \eta_L < \eta_H < 1$ and $p + \delta \cdot u_i - c > 0$, we have

$$(1 - \eta_L) \cdot (p + \delta \cdot u_L - c) \geq (1 - \eta_H) \cdot (p + \delta \cdot u_H - c)$$

$$\frac{\delta(u_H - u_L)}{p + \delta \cdot u_H - c} \leq \Lambda < 1.$$

On the contrary, if the retailer's profit $R(u_L) < R(u_H)$, he adopts u_H.

$$\frac{1}{2} \cdot (1 - \eta_L) \cdot (p + \delta \cdot u_L - c) - k < \frac{1}{2} \cdot (1 - \eta_H) \cdot (p + \delta \cdot u_H - c) - k$$

through calculation we have $0 < \Lambda < \frac{\delta(u_H - u_L)}{p + \delta \cdot u_H - c}$.

In summary, the retailer adopts u_L when $\frac{\delta(u_H - u_L)}{p+\delta \cdot u_H - c} \leq \Lambda < 1$ and he adopts u_H when $0 < \Lambda < \frac{\delta(u_H - u_L)}{p+\delta \cdot u_H - c}$ in the decentralized system. We have Proposition 1. □

Proof of Proposition 2. The retailer adopts u_H when $0 < \Lambda < \frac{\delta(u_H - u_L)}{p+\delta \cdot u_H - c}$ and u_L otherwise.

(1) When $0 < p + \delta \cdot u_i - c < \frac{4k}{1-\eta_i}$, $\Delta_H < \Delta_L$ is equivalent to

$$\frac{1}{2} - \frac{1}{8k} \cdot (1 - \eta_H)^2 \cdot (p + \delta \cdot u_H - c) < \frac{1}{2} - \frac{1}{8k} \cdot (1 - \eta_L)^2 \cdot (p + \delta \cdot u_L - c)$$

Then

$$(1 - \Lambda)^2 = (\frac{1 - \eta_H}{1 - \eta_L})^2 > \frac{p + \delta \cdot u_L - c}{p + \delta \cdot u_H - c}$$

$$\Lambda < 1 - \sqrt{\frac{p + \delta \cdot u_L - c}{p + \delta \cdot u_H - c}}$$

Besides,

$$1-\sqrt{\frac{p+\delta\cdot u_L-c}{p+\delta\cdot u_H-c}}<1-\frac{p+\delta\cdot u_L-c}{p+\delta\cdot u_H-c}=\frac{\delta(u_H-u_L)}{p+\delta\cdot u_H-c}$$

(2) When $0<p+\delta\cdot u_L-c<\frac{4k}{1-\eta_L}$ and $p+\delta\cdot u_H-c\geq\frac{4k}{1-\eta_H}$, $\Delta_H<\Delta_L$ is equivalent to

$$\frac{1}{2}-\frac{1}{8k}\cdot(1-\eta_L)^2\cdot(p+\delta\cdot u_L-c)>\frac{1}{2}\cdot\eta_H$$

Then

$$\frac{1-\eta_H}{(1-\eta_L)^2}>\frac{p+\delta\cdot u_L-c}{4k}$$

$$\Lambda<1-\frac{(1-\eta_L)(p+\delta\cdot u_L-c)}{4k}$$

Besides,

$$1-\frac{(1-\eta_L)(p+\delta\cdot u_L-c)}{4k}<1-\frac{p+\delta\cdot u_L-c}{p+\delta\cdot u_H-c}=\frac{\delta(u_H-u_L)}{p+\delta\cdot u_H-c}$$

(3) When $p+\delta\cdot u_L-c\geq\frac{4k}{1-\eta_L}$,

$$\Delta_L=\frac{\eta_L}{2}<\begin{cases}\frac{1}{2}-\frac{1}{8k}\cdot(1-\eta_L)^2\cdot(p+\delta\cdot u_L-c), & \text{if } 0<p+\delta\cdot u_H-c<\frac{4k}{1-\eta_H}\\ \frac{\eta_H}{2}, & \text{otherwise}\end{cases}$$

Thus, we have proposition 2.

□

Proof of Proposition 3. From proposition 1, the retailer adopts a high cosmetic standard u_H when $0<\Lambda<\frac{\delta(u_H-u_L)}{p+\delta\cdot u_H-c}$ and a low cosmetic standard u_L otherwise.

	$p-c>0$	$p-c=0$	$p-c<0$
$0 < \frac{u_L}{u_H} < \frac{1-\eta_H}{1-\eta_L}$	The retailer adopts u_H when $\delta > \frac{(\eta_H-\eta_L)(p-c)}{u_H(1-\eta_H)-u_L(1-\eta_L)}$ and adopts u_L when $0 < \delta < \frac{(\eta_H-\eta_L)(p-c)}{u_H(1-\eta_H)-u_L(1-\eta_L)}$, and he is indifferent between adopting u_L and u_H otherwise.	The retailer adopts u_H for all $\delta > 0$.	The retailer adopts u_H for all $\delta > 0$.
$\frac{u_L}{u_H} = \frac{1-\eta_H}{1-\eta_L}$	The retailer adopts u_L for all $\delta > 0$.	The retailer is indifferent between adopting u_L and u_H.	The retailer adopts u_H for all $\delta > 0$.
$\frac{u_L}{u_H} > \frac{1-\eta_H}{1-\eta_L}$	The retailer adopts u_L for all $\delta > 0$.	The retailer adopts u_L for all $\delta > 0$.	The retailer adopts u_H when $\frac{c-p}{u_H} < \delta < \frac{(\eta_H-\eta_L)(p-c)}{u_H(1-\eta_H)-u_L(1-\eta_L)}$ and adopts u_L when $\delta > \frac{(\eta_H-\eta_L)(p-c)}{u_H(1-\eta_H)-u_L(1-\eta_L)}$, and he is indifferent between adopting u_L and u_H otherwise.

Then we have

$$\delta(u_H - u_L)(1-\eta_L) > (\eta_H - \eta_L)(p-c) + \delta \cdot u_H(\eta_H - \eta_L),$$

$$[(u_H - u_L)(1-\eta_L) - (\eta_H - \eta_L)u_H]\delta > (\eta_H - \eta_L)(p-c),$$

$$[(1-\eta_H)u_H - (1-\eta_L)u_L]\delta > (\eta_H - \eta_L)(p-c).$$

Then we have the following chart. Note: From $p + \delta \cdot u_i > 0$, we have $\delta > \frac{c-p}{u_i}$. When $p-c<0$ & $\frac{u_L}{u_H} > \frac{1-\eta_H}{1-\eta_L}, \frac{c-p}{u_H} < \frac{c-p}{u_L} < \frac{(\eta_H-\eta_L)(p-c)}{u_H(1-\eta_H)-u_L(1-\eta_L)}$. Thus, only when $(p-c)[u_H(1-\eta_H)-u_L(1-\eta_L)] > 0$, or $p-c=0$ & $u_H(1-\eta_H)-u_L(1-\eta_L)=0$, both Δ_L and Δ_H exist.

When $p - c = 0$ & $u_H(1 - \eta_H) - u_L(1 - \eta_L) = 0$, the retailer is indifferent between adopting u_L and u_H, and $\Delta_L \leq \Delta_H$.

When $(p-c)[u_H(1-\eta_H) - u_L(1-\eta_L)] > 0$, the retailer sometimes adopts high standards and sometimes adopts low standards, the retailer adopts u_H when $0 < \Lambda < \frac{\delta(u_H - u_L)}{p+\delta \cdot u_H - c}$ and u_L otherwise.

By taking the first order derivative of $\frac{\delta(u_H - u_L)}{p+\delta \cdot u_H - c}$ with respect to δ, we have

$$\frac{(u_H - u_L)(p-c)}{(p+\delta \cdot u_H - c)^2},$$

Therefore, the threshold is increasing in δ when $p - c > 0$, remaining constant in δ when $p - c = 0$ and decreasing in δ when $p - c < 0$. It is easy to see that the threshold increases in c and decreases in p. The larger threshold $\frac{\delta(u_H - u_L)}{p+\delta \cdot u_H - c}$, the larger region of Λ for the retailer to choose u_H because the retailer adopts u_H when $0 < \Lambda < \frac{\delta(u_H - u_L)}{p+\delta \cdot u_H - c}$. □

Proof of Lemma 2. By substituting $q_{f,i} = y \cdot (1 - \eta_i) \cdot e$ and $\mathbb{E}[y] = 1/2$ into (11), we obtain

$$\begin{aligned}
W(u_i, w_f) &= \max_{e \in [0,1]} \mathbb{E}_y[w_f \cdot q_{f,i} + w_p \cdot q_{p,i} - c \cdot y - \frac{1}{2} \cdot k \cdot e^2] \\
&= \max_{e \in [0,1]} \mathbb{E}_y[w_f \cdot y \cdot (1 - \eta_i) \cdot e + w_p \cdot [y - y \cdot (1 - \eta_i) \cdot e] - c \cdot y - \frac{1}{2} \cdot k \cdot e^2] \\
&= \max_{e \in [0,1]} \left\{ \frac{1}{2} \cdot w_f \cdot (1 - \eta_i) \cdot e + \frac{1}{2} \cdot w_p \cdot [1 - (1 - \eta_i) \cdot e] - \frac{1}{2} \cdot c - \frac{1}{2} \cdot k \cdot e^2 \right\} \\
&= \frac{1}{2} \max_{e \in [0,1]} \left\{ (1 - \eta_i) \cdot (w_f - w_p) \cdot e - k \cdot e^2 + w_p - c \right\}
\end{aligned}$$

Let $U_i(e) = (w_f - w_p) \cdot (1 - \eta_i) \cdot e - k \cdot e^2$, by taking the first order derivative of $U_i(e)$ with respect to e, we have

$$\frac{\partial U_i(e)}{\partial e} = (1-\eta_i) \cdot (w_f - w_p) - 2k \cdot e$$

By taking the second order derivative of $U_i(e)$ with respect to e, we have

$$\frac{\partial^2 U_i(e)}{\partial e^2} = -2k$$

Because $\frac{\partial^2 U_i(e)}{\partial e^2} = -2k < 0$, $U_i(e)$ is concave in e, then the farmer's expected profit function $h(u_i, w_f, e)$ is concave in e. The first order condition gives the unconstrained optimal effort

$$e^*(u_i, w_f) = \begin{cases} \frac{(1-\eta_i)\cdot(w_f - w_p)}{2k}, & \text{if } 0 < \frac{(1-\eta_i)\cdot\ (w_f - w_p)}{2k} < 1 \\ 1, & \text{otherwise} \end{cases} \tag{A.14}$$

and the optimal profit is

$$W(u_i, w_f) = \begin{cases} \frac{(1-\eta_i)^2\cdot(w_f - w_p)^2}{8k} + \frac{w_p - c}{2}, & \text{if } 0 < \frac{(1-\eta_i)\cdot(w_f - w_p)}{2k} < 1 \\ \frac{(1-\eta_i)\cdot w_f}{2} + \frac{\eta\cdot w_p - k - c}{2}, & \text{otherwise} \end{cases}$$

Compared with the base model, the farmer exerts less effort for a given w_f with the existence of the processing market:

- For $0 < \frac{(1-\eta_i)\cdot(w_f - w_p)}{2k} < \frac{(1-\eta_i)\cdot(w_f - c)}{2k} < 1$, the optimal effort in the model with processing market is less than that in the base model.
- For $0 < \frac{(1-\eta_i)\cdot(w_f - w_p)}{2k} < 1 \leq \frac{(1-\eta_i)\cdot(w_f - c)}{2k}$, the optimal effort in the model with processing market is less than that in the base model (which is 1).
- For $1 \leq \frac{(1-\eta_i)\cdot(w_f - w_p)}{2k} < \frac{(1-\eta_i)\cdot(w_f - c)}{2k}$, the optimal efforts are the same

$(e^*(u_i, w_f) = 1)$ in two models. □

Proof of Proposition 5. (1) The proof of obtaining the threshold of Λ is similar to that of Proposition 1. From $w_p > c$, we have $\frac{\delta\cdot(u_H - u_L)}{p+\delta\cdot u_H - c} < \frac{\delta\cdot(u_H - u_L)}{p+\delta\cdot u_H - w_p}$. The larger threshold represents that a larger region of Λ that the retailer chooses u_H with the existence of the processing market.

(2) Compared with the base model, the farmer sets a larger w_f with the existence of the processing market:

- For $0 < p + \delta \cdot u_i - w_p < p + \delta \cdot u_i - c < \frac{4k}{1-\eta_i}$,
  Because $\frac{(p+\delta\cdot u_i+c)}{2} < \frac{(p+\delta\cdot u_i+w_p)}{2}$, w_f^* in the model with processing market is larger than that in the base model.

- For $0 < p + \delta \cdot u_i - w_p < \frac{4k}{1-\eta_i} \leq p + \delta \cdot u_i - c$,
  From $p+\delta\cdot u_i - c \geq \frac{4k}{1-\eta_i}$, we have $p+\delta\cdot u_i \geq \frac{4k}{1-\eta_i}+c$, then $\frac{p+\delta\cdot u_i}{2} > \frac{2k}{1-\eta_i}+\frac{c}{2}$, then $\frac{p+\delta\cdot u_i+w_p}{2} > \frac{2k}{1-\eta_i} + \frac{c}{2} + \frac{w_p}{2}$. From $w_p > c$, we have $\frac{p+\delta\cdot u_i+w_p}{2} > \frac{2k}{1-\eta_i} + \frac{c}{2} + \frac{w_p}{2} > \frac{2k}{1-\eta_i} + c$. Therefore, w_f^* in the model with processing market is larger than that in the base model.

- For $0 < \frac{4k}{1-\eta_i} \leq p + \delta \cdot u_i - w_p < p + \delta \cdot u_i - c$,
  Because $\frac{2k}{1-\eta_i} + c < \frac{2k}{1-\eta_i} + w_p$, w_f^* in the model with processing market is larger than that in the base model.

In a similar way, we have the implication for optimal effort given the retailer's optimal decision.

The retailer obtains less profit with the existence of the processing market. On the one hand, for a given w_f, the farmer's optimal effort with the processed market is no more than that in the base model, the qualified yield is thus no more than that in the base model. On the other hand, the retailer's sets a higher w_f than in the base model, which increases his cost. □

Proof of Lemma 3. We derive farmer's optimal effort for a given u_i from three cases:

1. When $w_f < c - \epsilon$, the farmer harvests nothing and her profit is

$$W(u_i, w_f) = -\frac{1}{2} \cdot k \cdot e^2$$

Thus the optimal effort is 0.

2. When $c - \epsilon \leq w_f < c + \epsilon$, the farmer only harvests under low harvesting cost $c - \epsilon$ and her profit is

$$W(u_i, w_f) = \frac{1}{2} \cdot 0 + \frac{1}{2} \cdot \frac{(1 - \eta_i) \cdot e}{2} \cdot (w_f - c + \epsilon) - \frac{1}{2} \cdot k \cdot e^2$$

From first order condition, we have

$$e^*(u_i, w_f) = \frac{(1 - \eta_i) \cdot (w_f - c + \epsilon)}{4k}$$

3. When $w_f \geq c + \epsilon$, the farmer harvests under both costs and her profit is

$$\begin{aligned} W(u_i, w_f) =& \frac{1}{2} \frac{(1 - \eta_i) \cdot e}{2} \cdot (w_f - c + \epsilon) + \frac{1}{2} \frac{(1 - \eta_i) \cdot e}{2} \cdot (w_f - c - \epsilon) - \frac{1}{2} \cdot k \cdot e^2 \\ =& \frac{(1 - \eta_i) \cdot e}{2} \cdot (w_f - c) - \frac{1}{2} \cdot k \cdot e^2 \end{aligned}$$

From first order condition, we have

$$e^*(u_i, w_f) = \begin{cases} \frac{(1-\eta_i) \cdot (w_f - c)}{2k}, & c + \epsilon \leq w_f \leq \frac{2k}{1-\eta_i} + c \\ 1, & w_f > \frac{2k}{1-\eta_i} + c \end{cases}$$

Hence we have lemma 3. □

Proof of Proposition 6. We define w_L as the wholesale price when the farmer

		Only harvest under low harvesting cost		
		$w_L^* < c - \epsilon$, then $w_L^{**} = c - \epsilon$	$c - \epsilon \leq w_L^* < c + \epsilon$, then $w_L^{**} = w_L^*$	$w_L^* \geq c + \epsilon$, then $w_L^{**} = c + \epsilon$
Harvest under both costs	$w_H^* < c + \epsilon$, then $w_H^{**} = c + \epsilon$	(1) Compare $R_L(c - \epsilon)$ with $R_H(c + \epsilon)$	(2) Distortion may happen, compare $R_L(w_L^*)$ with $R_H(c + \epsilon)$	(3) $w_f^* = c + \epsilon$
	$w_H^* \geq c + \epsilon$, then $w_H^{**} = w_H^*$	(4) Compare $R_L(c - \epsilon)$ with $R_H(w_H^*)$	(5) Compare $R_L(w_L^*)$ with $R_H(w_H^*)$	(6) $w_f^* = w_H^*$

Fig 8. Retailer's profits comparison with wholesale price distortion

only harvests under low harvesting cost and w_H as the wholesale price when the farmer harvests under both costs. Denote the unconstrained optimal w_f as ${w_f}^*$ and constrained optimal w_f as ${w_f}^{**}$. In order to get optimal wholesale price set by the retailer, we compare retailer's profits under two harvesting scenarios in Figure 8.

We also consider distortion of wholesale price. For example, when w_L^* is less than $c+\epsilon$ and thus the farmer only harvests under low harvesting cost, the retailer can increase w_L to $c+\epsilon$ to motivate the farmer to harvest under both costs. We will only consider distortion when w_L^* and w_H^* are less than $c+\epsilon$, because on the one hand, for only harvesting under low cost, if $w_L^* \geq c+\epsilon$, then we round off $w_L^{**} = c+\epsilon$. This is not distortion. On the other hand, for harvesting under both costs, if $w_H^* \geq c+\epsilon$, the retailer would prefer w_H^* rather than $c+\epsilon$. Therefore, effective distortion only happens when w_L^* and w_H^* are less than $c+\epsilon$. However, it may not always be profitable to distort w_f under the condition that w_L^* and w_H^* are below $c+\epsilon$.

Denote $R_0(u_i, w_f)$ as retailer's profit when farmer harvest nothing, $R_L(u_i, w_L)$ as retailer's profit when farmer only harvest under low cost and $R_H(u_i, w_H)$ as retailer's profit when farmer harvest under both costs.

1. When the farmer only harvests under low harvesting cost, farmer's profit

$$\begin{aligned} W(u_i, w_L) =& \frac{1}{2} \cdot \{w_L \cdot \frac{(1-\eta_i)e}{2} - (c-\epsilon)\frac{(1-\eta_i)e}{2} - \frac{1}{2} \cdot k \cdot e^2\} + \frac{1}{2} \cdot (-\frac{1}{2} \cdot k \cdot e^2) \\ =& \frac{1}{4} \cdot (1-\eta_i)(w_L - c + \epsilon) \cdot e - \frac{1}{2} \cdot k \cdot e^2 \end{aligned}$$

then optimal effort is

$$e^*(u_i, w_L) = \begin{cases} \frac{(1-\eta_i)(w_L - c + \epsilon)}{4k}, & w_L^* \leq \frac{4k}{1-\eta_i} + c - \epsilon \\ 1, & \text{otherwise} \end{cases}$$

For the retailer's profit, when $w_L^* \leq \frac{4k}{1-\eta_i} + c - \epsilon$,

$$\begin{aligned} R_L(u_i, w_L) =& (p + \delta \cdot u_i - w_L)\frac{(1-\eta_i)e}{4} \\ =& \frac{1}{16k}(1-\eta_i)^2(p + \delta \cdot u_i - w_L)(w_L - c + \epsilon) \end{aligned}$$

From the first order condition, we have

$$w_L^* = \frac{p + \delta \cdot u_i + c - \epsilon}{2} > c - \epsilon$$

- When $c - \epsilon < w_L^* < c + \epsilon$, $c < p + \delta \cdot u_i < c + 3\epsilon$, $w_L^{**} = w_L^*$,

$$R_L(u_i, w_L^*) = \frac{1}{64k}(1-\eta_i)^2(p + \delta \cdot u_i - c + \epsilon)^2$$

- When $w_L^* \geq c + \epsilon$, $p + \delta \cdot u_i \geq c + 3\epsilon$, $w_L^{**} = c + \epsilon$,

$$R_L(u_i, c + \epsilon) = \frac{\epsilon}{8k}(1-\eta_i)^2(p + \delta \cdot u_i - c - \epsilon)$$

2. When the farmer harvests under both harvesting costs, $p + \delta \cdot u_i \geq c + \epsilon$,

farmer's profit

$$\begin{aligned} W(u_i, w_H) =& \frac{1}{2}(w_H - c + \epsilon)\frac{(1-\eta_i)e}{2} + \frac{1}{2}(w_H - c - \epsilon)\frac{(1-\eta_i)e}{2} - \frac{1}{2} \cdot k \cdot e^2 \\ =& \frac{1}{2} \cdot (w_H - c)(1-\eta_i)e - \frac{1}{2} \cdot k \cdot e^2 \end{aligned}$$

then optimal effort is

$$e^*(u_i, w_H) = \begin{cases} \frac{(1-\eta_i)(w_H - c)}{2k}, & w_L^* \leq \frac{2k}{1-\eta_i} + c \\ 1, & \text{otherwise} \end{cases}$$

For the retailer's profit,

$$\begin{aligned} R_H(u_i, w_H) =& (p + \delta \cdot u_i - w_H)\frac{(1-\eta_i)e}{2} \\ =& \frac{1}{4k}(1-\eta_i)^2(p + \delta \cdot u_i - w_H)(w_H - c) \end{aligned}$$

From the first order condition, we have

$$w_H^* = \frac{p + \delta \cdot u_i + c}{2} > c$$

- When $w_H^* < c + \epsilon$, $c + \epsilon \leq p + \delta \cdot u_i < c + 2\epsilon$, $w_H^{**} = c + \epsilon$,

$$R_H(u_i, c + \epsilon) = \frac{\epsilon}{4k}(1-\eta_i)^2(p + \delta \cdot u_i - c - \epsilon)$$

- When $w_H^* \geq c + \epsilon$, $p + \delta \cdot u_i \geq c + 2\epsilon$, $w_H^{**} = w_H^*$,

$$R_H(u_i, w_H^*) = \frac{1}{16k}(1-\eta_i)^2(p + \delta \cdot u_i - c)^2$$

To obtain the results in Figure 8, we do the profit comparison as below.

For (1) and (4), since profit is 0 under u_L and is larger than 0 under u_H, the optimal wholesale price is w_H^{**}.

For (3) and (6), when $w_L \geq c+\epsilon$, profit $R_L(u_i, c+\epsilon) < R_H(u_i, c+\epsilon)$ because $R_L(u_i, c+\epsilon)$ represents retailer's profit when the farmer harvests with probability 50% and $R_H(u_i, c+\epsilon)$ represents profit when harvest all the time, with the same wholesale price, the second one should be larger. Then $w_f^* = c+\epsilon$. Besides, $R_L(u_i, c+\epsilon) < R_H(u_i, c+\epsilon) < R_H(u_i, w_H^*)$, then $w_f^* = \frac{p+\delta \cdot u_i + c}{2}$.

For (2), when $c-\epsilon \leq p+\delta \cdot u_i < c+2\epsilon$, we consider distortion of w_f here. By comparing $R_L(u_i, w_L^*)$ and $R_H(u_i, c+\epsilon)$, we have

$$R(u_i) = \begin{cases} R_L(u_i, w_L^*), & c < p+\delta \cdot u_i \leq c+(7-4\sqrt{2})\epsilon \\ R_H(u_i, c+\epsilon), & c+(7-4\sqrt{2})\epsilon < p+\delta \cdot u_i < c+2\epsilon \end{cases}$$

For (5), when $p+\delta \cdot u_i \geq c+2\epsilon$, by comparing $R_L(u_i, w_L^*)$ and $R_H(u_i, w_H^*)$, we have

$$R_L(u_i, w_L^*) < R_H(u_i, w_H^*)$$

Therefore, we have R^*.

Next, we aim to find the retailer's decision.

1. When $0 < p+\delta \cdot u_i - c \leq (7-4\sqrt{2})\epsilon$, the farmer only harvests at low cost for both u_L and u_H, the retailer adopts u_H when

$$\frac{(1-\eta_L)^2 \cdot (p+\delta \cdot u_L - c+\epsilon)^2}{64k} < \frac{(1-\eta_H)^2 \cdot (p+\delta \cdot u_H - c+\epsilon)^2}{64k}$$

$$0 < \Lambda < \frac{\delta(u_H - u_L)}{p+\delta \cdot u_H - c+\epsilon}$$

The range of adopting u_H decreases in ϵ.

2. When $0 < p+\delta \cdot u_L - c \leq (7-4\sqrt{2})\epsilon$ and $(7-4\sqrt{2})\epsilon < p+\delta \cdot u_H - c < 2\epsilon$,

the farmer only harvests at low cost for u_L and harvest at both costs under distorted wholesale price $c+\epsilon$ for u_H, the retailer adopts u_H when

$$\frac{(1-\eta_L)^2 \cdot (p+\delta \cdot u_L - c + \epsilon)^2}{64k} < \frac{(1-\eta_H)^2 \cdot (p+\delta \cdot u_H - c - \epsilon)\epsilon}{4k}$$

$$0 < \Lambda < 1 - \frac{p+\delta \cdot u_L - c + \epsilon}{4\sqrt{(p+\delta \cdot u_H - c - \epsilon)\epsilon}}$$

By taking the first order derivative of $1 - \frac{p+\delta \cdot u_L - c + \epsilon}{4\sqrt{(p+\delta \cdot u_H - c - \epsilon)\epsilon}}$ with respect to δ, we have $-\frac{\sqrt{(p+\delta \cdot u_H - c-\epsilon)\epsilon} - (p+\delta \cdot u_L - c+\epsilon)\frac{1}{2}\frac{1}{\sqrt{p+\delta \cdot u_H - c-\epsilon}}(p+\delta \cdot u_H - c - 2\epsilon)}{(p+\delta \cdot u_H - c-\epsilon)\epsilon} < 0$.

The range of adopting u_H decreases in ϵ.

3. When $0 < p+\delta \cdot u_L - c \leq (7-4\sqrt{2})\epsilon$ and $p+\delta \cdot u_H - c \geq 2\epsilon$, the farmer only harvests at low cost for u_L and harvests at both costs for u_H, the retailer adopts u_H when

$$\frac{(1-\eta_L)^2 \cdot (p+\delta \cdot u_L - c + \epsilon)^2}{64k} < \frac{(1-\eta_H)^2 \cdot (p+\delta \cdot u_H - c)^2}{16k}$$

$$0 < \Lambda < \frac{2\delta(u_H - u_L) + p - c - \epsilon}{2(p+\delta \cdot u_H - c)}$$

The range of adopting u_H decreases in ϵ.

4. When $(7-4\sqrt{2})\epsilon < p+\delta \cdot u_i - c < 2\epsilon$, the farmer harvests at both costs under distorted wholesale price $c+\epsilon$ for both u_L and u_H, the retailer adopts u_H when

$$\frac{(1-\eta_L)^2 \cdot (p+\delta \cdot u_L - c - \epsilon)\epsilon}{4k} < \frac{(1-\eta_H)^2 \cdot (p+\delta \cdot u_H - c - \epsilon)\epsilon}{4k}$$

$$0 < \Lambda < 1 - \sqrt{\frac{p+\delta \cdot u_L - c - \epsilon}{p+\delta \cdot u_H - c - \epsilon}}$$

The range of adopting u_H increases in ϵ.

5. When $(7-4\sqrt{2})\epsilon < p+\delta\cdot u_L - c < 2\epsilon$ and $p+\delta\cdot u_H - c \geq 2\epsilon$, the farmer harvests at both costs under distorted wholesale price $c+\epsilon$ for u_L and harvests at both costs for u_H, the retailer adopts u_H when

$$\frac{(1-\eta_L)^2\cdot(p+\delta\cdot u_L-c-\epsilon)\epsilon}{4k} < \frac{(1-\eta_H)^2\cdot(p+\delta\cdot u_H-c)^2}{16k}$$

$$0 < \Lambda < 1 - \frac{2\sqrt{(p+\delta\cdot u_L-c-\epsilon)\epsilon}}{p+\delta\cdot u_H-c}$$

The range of adopting u_H increases in ϵ.

6. When $p+\delta\cdot u_i - c \geq 2\epsilon$, the farmer harvests at both costs for both u_L and u_H, the retailer adopts u_H when

$$0 < \Lambda < \frac{\delta(u_H-u_L)}{p+\delta\cdot u_H-c}$$

The range of adopting u_H does not change in ϵ.

Therefore, we have proposition 6. □

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