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Food Distribution System in Vietnam: Nash Equilibrium and Channel Choice of Small Scale Farmers

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Abstract

Purpose: The transition from a traditional to a modern food distribution system induces several adjustments on the supply side since supermarkets must collect food on a larger scale and with higher quality standards. This situation becomes a real challenge for small scale farmers to access supply in a modern distribution channel. This gives rise to an original solution: supplying supermarkets through farmer associations or cooperatives. Based on this context of Vietnam linking to the case of distribution science, the paper proposes an industrial organization model of the food processing system in developing countries. The model presents the competitive relationship between two competing distribution systems: a traditional and a modern one. The former is composed of several retailers that sell their products on the traditional market while the latter is based on cooperatives that collect food and negotiate with supermarkets. The current study is to discuss the conditions under which the evolution of the food distribution system occurs by using the proposed model. **Research design, data, and methodology**: Based on the proposed model, the study explored the quantity flow from small producers to consumers through a Nash equilibrium and address the question of farmer repartition by a free-entry equilibrium. **Results**: The result shows that there is a unique positive equilibrium in the food market with participation of cooperative associations; Since farmers serve cooperative associations, they not only receive quantity incentive prices but also share profits within their organization. **Conclusions**: This study shows a unique distribution equilibrium where the profits of farmers working for middlemen and cooperatives are maximized. Further insights were discussed.

Keywords: Distribution Science, Supply Channel Choice, Imperfect Competition, Cooperatives, Supermarket, Industrial Organization

JEL Classification Code : C61, D43, Q13, Q18

1. Introduction

In recent years, fruit and vegetable production has rapidly increased in Vietnam to deliver enough fresh food to growing cities. We can therefore expect that this also induces changes in the production and distribution of fresh food in the country. However, the production system does not really change: most of the food is still produced by farmers who only own small exploitations, almost smaller than 1 hectare (see for instance Van Hung, MacAulay, & Marsh, 2007, or the General Statistics Office of Viet Nam (GSO), 2017). It is in fact the distribution system that is really in transition. As in several developing countries, the growth of cities and the improvement of standards of living (for at least a part of the population) have led to a transition in the food distribution system, which moves from a traditional structure based on "street markets" or "organized bazaars" to more modern supply channels mainly based on supermarkets and trading centers. Although the market

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share of this distribution system remains limited in Vietnam, it grows quickly. In Ho Chi Minh City, the first supermarket opened in 1993; in 2006, they distributed only 2% of the vegetables, but in 2012, their market share grew more than 10% (see Cadilhon, Moustier, Poole, Tam, & Fearne, 2006; Maruyama & Trung, 2007, 2012; Maruyama, 2010). According to the GSO, as of December 31, 2018, there were 8,475 markets nationwide, 1,009 supermarkets, and 210 commercial centers (GSO, 2019).

This change, as in several other developing countries, largely contributes to the emergence of a dual food distribution system and illustrates an interesting case of the distribution science. We find, on the one side, a traditional system in which several collectors called middlemen to buy fruits and vegetables from farmers and sell these directly to consumers on “street markets” or to urban-based wholesalers in “organized bazaars.” Most of these vegetables are transported to the market using two-wheeled vehicles at low cost but with no concern for the quality of the product. On the other side, we find supermarkets that often sell products of higher standards based on a more efficient and safer food collection system (see for instance Moustier, 2007, or Cadilhon et al., 2006). However, as noted by Maruyama and Trung (2012), they sell their products at higher prices to wealthier customers. Hence, the emergence of this dual distribution system has much to do with vertical differentiation: consumers with higher concern for quality (freshness and safety) are more likely to shop at formal markets while others buy their vegetables from street markets.

This transition from a traditional to a modern food distribution system also induces some adjustments on the supply side since supermarkets must collect food on a larger scale and with higher quality standards. This becomes a real challenge if one considers that there are, since the decollectivization of 1988, only small landholders with less than 1 hectare on average (Van Hung et al., 2007). This gives rise to an original solution: supplying supermarkets through farmer associations or cooperatives (see Dung, 2010, or the webpage of the Viet Nam Cooperative Alliance (VCA, 2020)). Even though it is not clear whether these associations primarily supply supermarkets or support public and international food quality improvements (Moustier, Tam, Anh, Binh, & Loc, 2010), these cooperatives largely contribute to the emergence of supermarkets. They freely contract with farmers to collect products, organize distribution on a large scale with higher quality standards, and negotiate with supermarkets. These organizations also open new opportunities to farmers or at least the option to choose distribution channels for which they want to work.

To summarize, we can say that the Vietnamese food distribution system has several peculiar features: (i) a dual system based on vertical differentiation, (ii) a traditional low-quality distribution channel in which several middlemen with up- and downstream market powers compete, (iii) a modern distribution channel based on the cooperation between farmer associations and supermarkets, and (iv) the ability of farmers to choose the channel to work for. Based on such observation, we construct an industrial organization model for the food system in Vietnam that integrates the four basic features above.

Our main objective is to use such a model to discuss the conditions under which this evolution of the food distribution system occurs. The basic structure of our model can be summarized by two potential distribution channels. The first one provides low-quality food and is based on standard intermediaries called middlemen. They exercise an upstream market power on small landholders and implicitly control the price of low-quality food (Cournot competition). The second channel is controlled by farmer associations and supermarkets. The first delivers fresh food produced by farmers who decide to join cooperatives and negotiate (Nash bargaining) with supermarkets, which wield a monopoly power on the demand for high-quality food. Farmers are nevertheless free to work either for cooperatives or middlemen and compare their expected profit. The equilibrium distribution of the farmers is obtained through the free-entry/exit equilibrium.

The paper is organized as follows. In section 2, we refer to the description of the dual food distribution system and the role of cooperative associations in supporting small-scale farmers through a brief literature review. Section 3 explains the study methodology. Section 4 presents the main research results by proposing a theoretical model and discussion. Section 5 concludes the study. The secondary results are relegated to the appendix.

2. Literature Review

Retail market and supply channels: For the retailing market, Amchang and Song (2018) has studied a distribution network of online retailing for a case study in Bangkok, Thailand, while Hung (2020) has analyzed factors influences the market share of retailers in retailing market competition for the case of Vietnam; or researches of Jeong (2017) for large-scale retailing types in South Korea; and Jang and Choung (2020) for the effects of attitude, subjective norm, and behavioral intention on perceived values in traditional marketplaces. For supply channels: Muneer (2020) proposes a model to provide an understanding of the supply chain integration and supply chain information practices' impact on the manufacturing industries. Coo (2018) has indicated customer satisfaction factors of Supply Chain Management Support Center

(SCSC); for the effect of win-win growth policies on sustainable supply chain and logistics management, Kim and Song (2019) has studied for the case of South Korea. In the particularly issue of the food retail market, readers can be consulted by several researchers. For instance, Truong and Nguyen (2020) has addressed the question of organic food purchasing decisions of kindergartens in Ho Chi Minh City, Vietnam, while Xue and Jun (2020) has examed the factors influencing Chinese online shopping distributions of fresh agricultural products. Other studies of Baek and Kim (2020) for the Korean Onion Market, or Cha, and Lyu (2019) for the influence of SNS characteristics on the brand image of infant food products; and Hidayat, Pabuayon, and Muawanah (2020) for marketing practices and value-added fish product in East Indonesia. Readers also can refer for more researches in this subjects at Su and Youn (2011); Ishaq, Hussain, Khaliq, and Waqas (2012); and Ryu (2019).

The food distribution system in developing countries and particularly in Vietnam: Maruyama and Trung (2007, 2010, 2012) had a series of works analyzing the duality of food processing in Vietnam with peculiar features. Most of the foods are distributed through two distribution channels: traditional and modern. Traditional food distribution entails selling foods without explicit consideration for the quality of the products while the modern supply channel often sells products of higher standards based on a more efficient food collection system at higher prices. These two systems compete with each other, as consumers freely move between them by product differentiation. For other econometric studies on the demand for fresh food in Vietnam, the reader is referred to Mergenthaler, Weinberger, and Qaim (2009). The same food system transformation toward modern food distribution channels occurs in several developing countries (see Readon, Timmer, Barrett, & Berdegue, 2003, for an overview) in Latin America (Balsevich, Berdegué, Flores, Mainville, & Reardon, 2003; Hernández, Reardon, & Berdegué, 2007), Indonesia (Suryadarma, Poesoro, Budiyati, Rosfadhila, & Suryahadi, 2010; Soetriono, Soejono, Hani, Suwandari, & Narmaditya, 2020) , or Thailand (Gorton, Sauer, & Supatpongkul, 2011).

The role of cooperatives and the channel choice of farmers: In Vietnam (Moustier, Tam, Anh, Binh, & Loc, 2010) has shown that cooperatives largely contribute to the emergence of supermarkets. They freely contract with farmers to collect products, organize distribution on a large scale with higher quality standards, and negotiate with supermarkets. These organizations also open new opportunities for farmers or at least provide them the possibility to choose distribution channels for which they would work. For papers related to cooperatives and imperfect competition after the seminal contribution of Nourse (1922), readers can consult, for instance, Levay (1983), Sexton (1986, 1990), and Staatz (1983). For farmers' strategy to adapt the transformation of distribution channel, the reader is also referred to Hernández et al. (2007), which studies supermarkets versus traditional distribution channels in the Guatemala tomato market, or Woldie (2010) and Woldie and Nuppenau (2011), which explicitly discuss cooperatives. Sedyati, Djatmika, Wahyono, and Utomo (2019) analyzes the adaptation strategies of tobacco farmers to deal with an unfavorable trading system based on farmer group organizations, partnerships, self-capacity building; Nguyen (2020) studies the factors affecting the Vietnamese farmers' intention to accept organic farming, which indicates that attitudes, subjective norms, and perceived behavioral control have a positive influence on farmers' intention to accept organic farming in Vietnam.

3. Research Methods

The food distribution system has been addressed by different methodologies and approaches in the distribution science. For instance, Maruyama and Trung (2007, 2010, 2012) used a statistical approach to show the problems faced by the modern retail sector in Vietnam in developing their position in the retail market competition. The role of farmer organizations in delivering food for farmers through modern distribution channels is discussed in the empirical work of Moustier et al. (2010). Concerning food distribution in the context of consumers, Jia, Park, and Kim (2018) analyzed distribution preference between official and unofficial channels by collecting a sample of 800 customers. Cho and Mukoyama (2018) established a process model of retail format creation based on secondary data. Jang, Baek, and Kim (2018) studied the food market of Vietnam based on the brand equity model and used structural equation model analysis. The sustainable supply chain in the case of Korea has been analyzed by Kim and Song (2019). Ngo Chi, Le Hoang Ba, Hoang Thanh, Le Quang, and Le Van (2019) addressed the question of linkages in modern distribution channels formation for agricultural products consumption in Vietnam.

In this paper, we use the framework of imperfect competition by McCorriston (2002), Sexton and Lavoie (2001), and Myers, Sexton, and Tomek (2010) to construct the model. Our modeling strategy also borrows several arguments from industrial organizations. To consider the existence of a dual system based on quality differentiation, we use a standard vertical differentiation choice model adapted from Mussa-Rosen (1978): consumers with a heterogeneous valuation for quality go to either "street markets" or supermarkets. The low-quality distribution channel is modeled in a standard way. The intermediaries, referred to as middlemen, directly buy food from the farmers. They exercise an oligopsony market power because of land fragmentation (for a general discussion on oligopsony power, see Rogers & Sexton, 1994) and engage in a Cournot competition on the downstream low-quality food market. The high-quality food channel is less usual. Since supermarkets are less developed, we introduce monopoly power on the downstream market, but to obtain high-quality food, the supermarket has to negotiate with a cooperative. This process is captured by a Nash bargaining model with an asymmetric negotiation power (see for instance Binmore & Dasgupta, 1987). The cooperative retribute the farmers per unit and shares the profits. Finally, the farmers have the ability either to sell their products to the middlemen or to join a cooperative. The equilibrium distribution is obtained by a free-entry and- exit condition in the sense that no farmer wants to change the distribution channel for which they work.

By transformation, we mean two things: (i) the conditions that ensure that, at a free-entry equilibrium, both distribution channels are active and (ii) the change that contributes to the development of an existing modern food distribution channel. However, this requires, as a first step, a study of the conditions that characterize the equilibrium of our model. Since the farmers decide to which channel they would sell their products, we first analyze the food flow in both channels for any distribution of farmers between the two sectors. These quantities are obtained by a global Nash equilibrium, which considers the interactions between both demands. We then deduce the farmer-expected profits from each channel and study the free-entry equilibrium distribution.

4. Results and Discussion

4.1. Overview and assumption

Since landholders are few, we decide to introduce a continuum [0, 1] of identical farmers a proportion of ρ which works for the cooperatives. Each farmer is characterized by the production function $q = f(\lambda) = \sqrt{\lambda}$, which transforms labor into vegetables. We normalize the wage ω to 1 and note by p_m and p_c the price paid by the middlemen and the cooperative, respectively, for one unit of production. Since each farmer decides how many times they spend on their activity, a standard profit maximization condition tells us that the individual vegetable supply is given by $q = \frac{p}{2}$, where p stands for the price paid either by the middlemen or the cooperative. We can therefore say that, for a given reparation $\rho \in [0,1]$ of the farmers between the two sectors, the aggregated supply to each channel is given by

$$Q_\ell = (1-\rho)\frac{p_m}{2} \text{ and } Q_h = \rho\frac{p_c}{2}$$

Where Q_ℓ and Q_h stand for the quantities delivered to the middlemen and the cooperative, respectively. Since we work with Cournot competition, we observe that the inverse supply functions are given by

$$P_c(Q_h, \rho) = \frac{2Q_h}{\rho} \text{ and } P_m(Q_\ell, \rho) = \frac{2Q_\ell}{1-\rho} \tag{1}$$

4.1.1. Consumer behavior and the inverse demand for both qualities

We introduce vertical differentiation in line with Mussa-Rosen (1978). Let us denote by h and ℓ the quality index associated with a high- and low-quality product with, of course, $h > l$. Each consumer that belongs to a continuum $[0, K]$ is characterized by a specific willingness to pay for each kind of food. These reservation prices are given by $\theta.h$ and $\theta.\ell$, where θ is uniformly distributed across the population. If p_ℓ and p_h denote the prices for low- and high-quality food, respectively, it is a routine exercise to find the index of the first consumer $\underline{\theta} = \frac{P_\ell}{\ell}$, who is willing to buy low-quality food, and the index $\bar{\theta} = \frac{P_h - P_\ell}{h-\ell}$ of one who is indifferent to low- and high-quality food. Since θ is uniformly distributed $[0, K]$, we can say that the demand functions for both qualities are given by

$$\begin{pmatrix} D_\ell(P_\ell, P_h) \\ D_h(P_\ell, P_h) \end{pmatrix} = \begin{pmatrix} \bar{\theta} - \underline{\theta} \\ K - \bar{\theta} \end{pmatrix} = \begin{pmatrix} \frac{P_h - P_\ell}{h-\ell} - \frac{P_\ell}{\ell} \\ K - \frac{P_h - P_\ell}{h-\ell} \end{pmatrix}$$

We can therefore say that the inverse demand function is given by

$$\begin{pmatrix} P_\ell(Q_\ell, Q_h) \\ P_h(Q_\ell, Q_h) \end{pmatrix} = \begin{pmatrix} \ell(K - Q_\ell - Q_h) \\ h(K - Q_h) - \ell(Q_\ell) \end{pmatrix} \tag{2}$$

4.1.2. The traditional food distribution system

This distribution system is quite standard. There are m symmetric retailers called middlemen that collect food at price p_m from the farmers and sell these products on street markets at price p_ℓ. For simplicity, we assume only one level of intermediation. They wield oligopsony and oligopoly power on their upstream and downstream market, respectively. This means, in a Cournot tradition, they choose the amount q_ℓ of food that they carry from the farmers to the consumers by considering the effect of their choice on the $P_m(Q_\ell, \rho)$ upstream and $P_m(Q_\ell, Q_h)$ downstream equilibrium prices. We also assume that each middleman supports a constant marginal cost c_m per unit of food delivered to street markets. This unit cost must of course be lower than ℓK, the highest willingness to pay for low-quality food. We even introduce the quantity $K_m :=$

$\ell K - C_m$, which measures the highest per-unit margin that can be obtained by a middleman. This profitability measure will be important later.

4.1.3. The high-quality distribution channel

At least in the Vietnamese case, this channel is mainly composed of farmer associations and supermarkets. We simplify the presentation by introducing only one supermarket and one cooperative. But in opposition to the previous channel, we assume that these two intermediaries enter into a negotiation process: the cooperative can control food quality and secure the stock of the supermarket, which then benefits from vertical product differentiation. The outcome of this process refers to a Nash bargaining solution. This means that they choose together the quantity Q_h of high-quality food delivered to the market and set an internal price p_c, which ensures that the farmers produce the required amount of food. These choices maximize their joint profit net of global cost c_s per unit of food. The net profit is shared between the two according to their bargaining power. We denote by $\alpha \in [0,1]$ the proportion obtained by the cooperative and introduce, as for the middlemen, the quantity $K_s = K_h - c_s$ to measure the profitability of this channel. Moreover, we assume that $c_s > c_m$ since the supermarket delivers higher-quality goods than middlemen.

This channel's main difference from the preceding channel is that food is provided by a cooperative. It not only offers a per-unit price p_c to their members but also equally shares a part $s(\rho) \in [0,1]$ of its profit between the farmers. The part $(1 - s(\rho))$ covers organizational costs: it can be viewed as a participation fee that finances the life of the cooperative or even a reserve for future investments and development. Since these costs often strongly increase with the size of the cooperative, we assume that the shares left to the farmers decrease more than proportionally to the size ρ, i.e., that $\frac{s\prime(\rho)\rho}{s(\rho)} < -1$. Moreover, we say that $s(0) = 1$ and $s(1) = 0$, i.e., there is no cost if the supermarket is inactive while these costs hold all the profits when all farmers work for the cooperative.

4.2. The Nash equilibrium of the food distribution system

Since we solve this model backward, we take the distribution $\rho \in [0,1]$ of the farmers between these two channels as a given and construct the total food amount carried by each channel. These quantities, through a Nash equilibrium, consider the competition between the middlemen and the interaction between both markets.

In the traditional sector, the middlemen exercise an oligopsony power on the farmers who work for them and an oligopoly power on the low-quality food market. This means that in a Cournot tradition, each of them has an incentive to trade a quantity qi, which maximizes their profit by anticipating the effect of their choice on up- and downstream prices. Since the inverse supply of farmers and the inverse demand for low-quality goods are given by equations (1) and (2), this quantity q^* solves (at (3)).

However, to compute these quantities, we also need to define the optimal behavior of the supermarket. Since distributors cooperate with farmer associations, they choose Q_h, which maximizes their joint profit (the profit distribution aspect will be addressed in the next section).

$$\forall i, q_i^* \in \max_{q_i} \left(p_\ell \left(Q_h^*, \sum_{\substack{j=1 \\ j\neq i}}^{m} q_j^* + q_i \right) - p_m \left(\sum_{\substack{j=1 \\ j\neq i}}^{m} q_j^* + q_i, \rho \right) - c_m \right) q_i \tag{3}$$

This joint profit considers (i) the income that the supermarket obtains by exercising its monopoly power, (ii) the price that cooperatives must pay the farmers to obtain the required amount of vegetables, and (iii) the unit operating cost of both players c_s. From equations (1) and (2), we can therefore say that

$$Q_h^* \in \max_{Q_h} \left(P_h \left(Q_h, \sum_{i=1}^{m} q_i^* \right) - P_c(Q_h, \rho) - C_s \right) Q_h \tag{4}$$

Since these different optimization problems are strictly concave, we know that a Nash equilibrium satisfies the following set of first-order condition (with $Q_\ell^* - \sum_{i=1}^{m} q_i^*$):

$$\forall_i, \left(\frac{\partial P_\ell(Q_h^*, Q_\ell^*)}{\partial Q_\ell} - \frac{\partial P_m(Q_\ell^*, \rho)}{\partial Q_\ell} \right) q_i^* + (P_\ell(Q_h^*, Q_\ell^*) - P_m(Q_\ell^*, \rho) - c_m) = 0 \tag{5}$$

and

$$\left(\frac{\partial P_h(Q_h^*, Q_\ell^*)}{\partial Q_h} - \frac{\partial P_c(Q_h^*, \rho)}{\partial Q_h} \right) Q_h + (P_h(Q_h^*, Q_\ell^*) - P_c(Q_h^*, \rho) - c_s) = 0 \tag{6}$$

Since the middlemen are symmetric, we can, as usual under Cournot competition, sum all i the equation set (5) and say that the quantities (Q_h^*, Q_ℓ^*), which are traded in each channel, are given by

$$\begin{cases} \left(\frac{\partial P_\ell(Q_h^*,Q_\ell^*)}{\partial Q_\ell} - \frac{\partial P_m(Q_\ell^*,\rho)}{\partial Q_\ell}\right) Q_\ell^* \\ +m(P_\ell(Q_h^*,Q_\ell^*) - P_m(Q_\ell^*,\rho) - c_m) = 0 \\ \left(\frac{\partial P_h(Q_h^*,Q_\ell^*)}{\partial Q_h} - \frac{\partial P_c(Q_h^*,\rho)}{\partial Q_h}\right) Q_h^* \\ +(P_h(Q_h^*,Q_\ell^*) - P_c(Q_h^*,\rho) - c_s) = 0 \end{cases}$$

Finally, if we introduce the farmer inverse supplies (equation (1)) and the inverse demands (equation (2)), we can say that (Q_h^*, Q_ℓ^*) solves

$$\begin{cases} \left(\mu\left(\ell + \frac{2}{1-\rho}\right) Q_\ell^* + \ell Q_h^*\right) = K_m \\ \ell Q_\ell^* + \left(2h + \frac{4}{\rho}\right) Q_h^* = K_s \end{cases} \quad \text{with} \quad \mu := \left(1 + \frac{1}{m}\right) \quad (7)$$

However, this does not mean that this system always adopts positive solutions. In fact, in our presentation of the Nash equilibrium conditions, we implicitly assumed that both distribution channels are active. However, since they compete for the same consumers, if one sector initially has too strong of an advantage, the other cannot survive. If we now remember that K_m and K_s, i.e., the difference between the highest reservation price and the unit cost in each channel, can be viewed as profitability indexes, it is not surprising that this ratio $\frac{K_m}{K_s}$ must be bounded from above and from below to ensure that none of the two sectors has an excessively strong competitive advantage.

Proposition 1: *This game admits, for all* $\rho \in]0,1[$, *a unique positive equilibrium* $(Q_\ell^*(\rho), Q_h^*(\rho)) \gg 0$ *if and only if* $\frac{\ell}{2(h+2)} < \frac{K_m}{K_s} < \mu\left(1 + \frac{2}{\ell}\right)$.

We can also verify the trade quantity at equilibrium for each sector; by solving system (7), the trade of the middlemen is given as

Besides this result, we can also characterize the effect of a change in the degree of competition in the traditional channel, in the repartition of the farmers, or the cost structure on the equilibrium prices and quantities. This provides us the opportunity to show that our model, even if it looks like a Cournot equilibrium, integrates several general equilibrium effects that produce unusual results.

$$Q_\ell = \frac{\left(2h + \frac{4}{\rho}\right) K_m - \ell K_s}{\mu\left(\ell + \frac{2}{1-\rho}\right)\left(2h + \frac{4}{\rho}\right) - \ell^2} \quad (8)$$

while the sale of the modern distribution system is

$$Q_h = \frac{\mu K_s\left(\ell + \frac{2}{1-\rho}\right) - \ell K_m}{\mu\left(\ell + \frac{2}{1-\rho}\right)\left(2h + \frac{4}{\rho}\right) - \ell^2} \quad (9)$$

To illustrate this idea, let us first increase the degree of competition in the traditional distribution channel. If the number of middlemen increases, one usually expects, under Cournot competition, that more low-quality goods are traded at a lower price. However, this last effect also induces a substitution process: lower prices of vegetables sold on street markets reduce the attractiveness of supermarkets, which then reacts by decreasing their own prices to limit the negative effect on its market share. In other words, more competition in the traditional channel reduces supermarkets' downstream market power.

Market interaction also muddles the effect of the increase in the proportion of farmers working for cooperatives. As expected, the equilibrium quantity traded by supermarkets increases while the one traded by middlemen decreases. However, we cannot really conclude the effect of these quantity changes on the final prices in both sectors because of the interactions of both final demands.

Alterations in the cost structure induce more usual conclusions. In the distribution channel where the cost of intermediaries increases, the equilibrium prices at which these goods are sold increase while the quantities traded decrease. However, this distribution channel also becomes less competitive to the other. This last one can increase both prices and quantities.

The following summarizes this discussion:

Proposition 2: *We can show the following:*

(i) More competition between middlemen (i.e., a large m) increases the quantity they trade and reduces the prices (i.e., $\frac{\partial Q_\ell^*}{\partial m} > 0$ *and* $\frac{\partial P_\ell^*}{\partial m} < 0$*), but because of a substitution effect, the supermarket sells less at a lower price (i.e.,* $\frac{\partial Q_h^*}{\partial m} < 0$ *and* $\frac{\partial P_h^*}{\partial m} < 0$*).*

(ii) If more farmers work for cooperatives (i.e., a large ρ*), supermarkets increase their market share (i.e.,* $\frac{\partial Q_h^*}{\partial \rho} > 0$ *and* $\frac{\partial Q_\ell^*}{\partial \rho} < 0$*), but because of market interactions, the prices can either increase or decrease in both sectors.*

(ii) If the cost increases in one distribution channel, quantities decrease (i.e., $\frac{\partial Q_\ell^*}{\partial c_m} < 0$ *or* $\frac{\partial Q_h^*}{c_s} < 0$*) while prices*

increase (i.e., $\frac{\partial P_\ell^*}{c_m} > 0$ *or* $\frac{\partial P_h^*}{c_s} > 0$*). The other sector always benefits from this disadvantage since price and quantities rise (i.e.,* $\frac{\partial Q_h^*}{\partial c_m} > 0$ *and* $\frac{P_h^*}{c_m} > 0$*, or* $\frac{\partial Q_\ell^*}{c_s} > 0$ *and* $\frac{\partial P_\ell^*}{\partial c_s} > 0$*).*

4.3. Optimal distribution of farmers between channels

4.3.1. The wealth of each kind of farmer

Let us begin with the farmer providing food to the middleman. They are in proportion (1) and behave competitively. Their indirect profit is given by $\pi_f^m(p) = \frac{1}{4}p_m^2$. If we now know that the inverse supply of vegetables is given by $p_m = \left(2\frac{Q_\ell}{(1-\rho)}\right)$ and the trade quantities are obtained in (8) and (9), their profit is given by

$$\pi_f^m(m,\rho,c_s,c_m) = \left(\frac{Q_\ell^*(m,\rho,c_s,c_m)}{(1-\rho)}\right)^2 \quad (10)$$

The computation for the profit of **farmers working with cooperatives** is less obvious. It consists of two parts: one related to their activity as producers and the other linked to their membership in the cooperative.

The first part is easy to compute since the cooperative pays a unit price for vegetables to obtain the desired amount of food. This part can therefore be computed the same way as in equation (10) as long as $Q_\ell^*(m,\rho,c_s,c_m)$ is replaced by $Q_h^*(m,\rho,c_s,c_m)$ and $(1-\rho)$ by ρ.

To compute the second part, we first have to look at the total rent generated by the high-quality-food channel. At the Nash equilibrium, this quantity is given by

$$\text{Total rent} = \left(P_h\left(Q_h, Q_\ell^*(m,\rho,c_s,c_m)\right) - P_c(Q_h,\rho) - c_s\right)Q_h\Big|_{Q_h=Q_h^*(m,\rho,c_s,c_m)}$$

Using first-order profit maximization condition (6), it becomes

$$\left(\frac{\partial P_h(Q_h^*,Q_\ell^*)}{\partial Q_h} - \frac{\partial P_c(Q_h^*,\rho)}{\partial Q_h}\right)Q_h^* + \left(P_h(Q_h^*,Q_\ell^*) - P_c(Q_h^*,\rho) - c_s\right) = 0$$

Also, under our specification, we can say that

$$\textit{Total rent} = \left(\frac{\partial P_h(Q_h^*,Q_\ell^*)}{\partial Q_h} + \frac{\partial P_c(Q_h^*,\rho)}{\partial Q_h}\right) + (Q_h^*)^2 = \left(h+\frac{2}{\rho}\right)\left(Q_h^*(m,\rho,c_s,c_m)\right)^2$$

This total rent is first shared by the cooperative and the supermarket: a proportion $\alpha \in [0,1]$ is left to the cooperative, which keeps a proportion $(1-s(\rho))$ to maintain and develop their activities while equally redistributing the remaining proportion $s(\rho)$ to their members, i.e., in the proportion given by $\frac{1}{\rho}$.

By adding these two parts, we can say that the profit of a farmer working for a cooperative is given by

$$\mu_f^c(m,\rho,c_s,c_m) = \left(\frac{Q_h^*(m,\rho,c_s,c_m)}{\rho}\right)^2 + \frac{s(\rho)}{\rho}(\alpha Totalrent) \quad (11)$$

$$= \left(\frac{Q_h^*(m,\rho,c_s,c_m)}{\rho}\right)^2 [1+\alpha s(\rho)(\rho h+2)] \quad (12)$$

4.3.2. Equilibrium distribution

We can now study the equilibrium distribution of the farmers between both sectors. To define this distribution, we introduce a free-entry equilibrium concept. That is, since farmers can usually move freely from one sector to another until their profits are the same in both sectors and there are no incentives to leave the sector they are operating in, this last condition, captured in our continuous setting of the profit slope, functions at equilibrium. However, to explain our definition, we also have to consider corner equilibrium, hence the following:

Definition 1: *A distribution* $\rho^* \in [0,1]$ *is a free-entry equilibrium if and only if the following apply:*

If $\rho^* \in [0,1]$ *, we must have* $\mu_f^c(m,\rho^*,c_s,c_m) = \mu_f^m(m,\rho^*,c_s,c_m)$, $\frac{\partial \mu_f^c(m,\rho^*,c_s,c_m)}{\partial \rho} < 0$, *and* $\frac{\mu_f^m(m,\rho^*,c_s,c_m)}{\partial \rho} > 0$*; we can say that both distribution channels are active.*

If $\rho^* = 0$*, either* $\pi_f^c(m,0,c_s,c_m) < \mu_f^m(m,0,c_s,c_m)$ *or* $\pi_f^c(m,0,c_s,c_m) = \mu_f^m(m,0,c_s,c_m)$ *and* $\lim_{\rho\to 0^+}\frac{\partial \mu_f^c(m,\rho,c_s,c_m)}{\partial \rho} < 0$*; in this case, the supermarket is not active.*

If $\rho^* = 1$*, either* $\pi_f^c(m,1,c_s,c_m) > \mu_f^m(m,1,c_s,c_m)$ *or* $\pi_f^c(m,1,c_s,c_m) = \mu_f^m(m,1,c_s,c_m)$ *and* $\lim_{\rho\to 1^-}\frac{\partial \mu_f^c(m,\rho,c_s,c_m)}{\partial \rho} > 0$*; in this case, the middlemen are not active.*

In our general setting, several situations may occur depending on the choice of parameters. This is why we will conduct our discussion stepwise. If we consider the Vietnamese case in which street markets are organized, it is important to first introduce the conditions of the parameters that ensure that supermarkets are viable. Second, we discuss the condition that ensures the coexistence of both channels. Finally, we provide conditions that ensure the existence and uniqueness of equilibrium.

To make sure that the supermarket emerges, we have to make sure, for instance, that $\pi_f^c(m,0,c_s,c_m) > \mu_f^m(m,0,c_s,c_m)$. This means that when only a few farmers work for a cooperative, each farmer would expect higher returns when joining it. Since this expectation must be rational, it is directly linked to the relative profitability of the middlemen with respect to the supermarket. If we define this quantity by the ratio of the difference of the highest reservation price and the cost in both sectors, a natural assumption is to introduce an upper bound on this quantity to limit the relative profitability of street markets. More precisely, we can claim the following:

Proposition 3: *The supermarket is active (i.e., $\rho^* > 0$) if and only if* $\frac{K_m}{K_s} < \frac{\mu(\ell+2\sqrt{1+2\alpha})}{4+\ell\sqrt{1+2\alpha}}$.

However, this necessary and sufficient condition only makes sure the supermarket is active but does not exclude a situation in which it is the only activated distribution channel. We therefore also find a condition that excludes = 1. Here, we try to make sure that $\pi_f^c(m,1,c_s,c_m) < \mu_f^m(m,1,c_s,c_m)$. Using the previous symmetric interpretation, this now required a lower bound on the ratio $\frac{K_m}{K_s}$ to limit the market power of the supermarket.

Proposition 4: *Street markets are active (i.e., $\rho^* < 1$) if and only if* $\frac{K_m}{K_s} > \frac{\mu\ell+2}{2h+4}$.

The combination of the conditions in both previous propositions does not imply that an inner equilibrium exists; it simply ensures that both distribution channels are open. In fact, these two previous conditions simply imply that $\rho^* \in]0,1[$ exists with the property $\mu_f^c(m,\rho^*,c_s,c_m) = \mu_f^m(m,\rho^*,c_s,c_m)$. To make sure this farmer distribution between both sectors is an equilibrium, we also have to check that at this ρ^*, no farmer has an incentive to move to the other sector, in other words, that $\frac{\partial\mu_f^c(m,\rho^*,c_s,c_m)}{\partial\rho} < 0$ and $\frac{\mu_f^m(m,\rho^*,c_s,c_m)}{\partial\rho} > 0$. However, these last conditions are difficult to check because they are properties of the profit function slope evaluated at distributions ρ^* at which the profits are the same. This is why we introduce stronger conditions that make sure that the profits of farmers working for a cooperative decrease while those obtained from working with middlemen increase. Such a restriction provides not only existence but also uniqueness.

Proposition 5: *If* $\mu max\left\{\frac{\ell+\frac{2}{\mu}}{2h+4}, \frac{\ell+2}{4\mu+\ell}\right\} < \frac{K_m}{K_s} < \mu min\left\{\frac{(\ell+2)\sqrt{1+2\alpha}}{4+\ell\sqrt{1+2\alpha}}, \frac{(\ell-h)+2}{\ell+2}\right\}$, *then there exists a unique distribution $\rho^* \in]0,1[$ of farmers between two sectors.*

5. Conclusions

Farmer associations or cooperatives associations play an important role in supporting small scale farmers accessing the modern food distribution channel to supply agricultural products. The paper contributes to the field of distribution science. We show a unique positive equilibrium in the food retail market with the participation of cooperative associations in the food system. Several effects of the costs, the competition between middlemen and the proportion of farmers serving cooperatives on traded quantities, and the prices of both sectors are analyzed at this market equilibrium. We indicate that, at distribution equilibrium, since farmers serve cooperatives, they not only receive quantity incentive prices but also share profits within their organization. Since we can verify the profits of farmers working for each sector, we can therefore study the emerging conditions of each distribution system that allow middlemen and supermarkets to be active in the market at equilibrium. We finally show a unique distribution equilibrium where the profits of farmers working for middlemen and cooperatives are maximized.

The model shows that at market equilibrium, to develop their position, supermarkets must decrease costs and at the same time reduce the market power of the middlemen. The model also explains the specific role of cooperatives in supporting farmers' access to supermarkets by offering incentive quantity prices and profit-sharing. The results of our model are consistent with those of several empirical studies, particularly in the context of Vietnam, which claim that the food market sharing of supermarkets is still limited and that supermarkets should expand their fresh food category, enhance their location convenience, and lower their costs to deliver more foods. This is also linked with studies that have found that cooperatives are the contributing factor to farmers' ability to sell products at supermarkets.

This paper opens a perspective of building public policy related to distribution science for the food distribution system. This refers not only to a policy that incentivizes farmers to serve cooperatives to develop modern distribution channels but also one that promotes food market competition and the wealth of farmers and consumers.

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Appendixes

Appendix 1: Proof of proposition 1

We have to show that the following system has a positive solution:

$$\underbrace{\begin{bmatrix}\left(1+\frac{1}{m}\right)\left(\ell+\frac{2}{1-\rho}\right) & \ell \\ \ell & \left(2h+\frac{4}{\rho}\right)\end{bmatrix}}_{:=A}\begin{bmatrix}Q_\ell^* \\ Q_h^*\end{bmatrix}=\begin{bmatrix}\ell K-c_m \\ hK-c_s\end{bmatrix} \quad (13)$$

This means that the last vector of the previous equation must be in the positive cone generated by the two-column of the matric which gives us our linear system of equation. So, if we normalize the second component of these vectors to 1, and we can verify that:

$$\frac{1}{\ell}\left(1+\frac{1}{m}\right)\left(\ell+\frac{2}{1-\rho}\right)>\frac{\ell K-c_m}{hK-c_s}>\frac{\ell}{\left(2h+\frac{4}{\rho}\right)}$$

We can assert that a unique positive solution exists. Since we have assumed that$0<\ell K-c_m<hK-c_s$, the first inequality is obvious: the first term is bigger than 1 while the second is smaller than 1. Concerning the second inequality, let us recall that we have also assumed that $2(\ell K-c_m)>(hK-c_s)$ or in other words $\frac{\ell K-c_m}{hK-c_s}>\frac{1}{2}$. Now let us observe that:

$$\frac{\ell}{\left(2h+\frac{4}{\rho}\right)}=\frac{1}{2}\frac{\ell}{h}\underbrace{\left(\frac{1}{1+\frac{2}{\rho}}\right)}_{<1}<\frac{1}{2} \text{ since } \ell<h \text{ by assumption.}$$

Appendix 2: Proof proposition 2

Let us first note:

$$a(m,\rho):=\left(1+\frac{1}{m}\right)\left(\ell+\frac{2}{1-\rho}\right)>0 \quad \text{and} \quad b(\rho)=2\left(h+\frac{2}{\rho}\right)>0 \quad (14)$$

And observe that,

$$\frac{\partial a}{\partial m}=-\frac{1}{m^2}\left(\ell+\frac{2}{1-\rho}\right)<0 \quad , \quad \frac{\partial a}{\partial \rho}=\frac{2\mu}{(1-\rho)^2}>0 \quad \text{and} \quad \frac{\partial b}{\partial \rho}=-\frac{4}{\rho^2}<0 \quad (15)$$

If we now differentiate equation (13), we obtain:

$$\begin{bmatrix}\frac{\partial a}{\partial m}Q_\ell & \frac{\partial a}{\partial \rho}Q_\ell \\ 0 & \frac{\partial b}{\partial \rho}\end{bmatrix}.\begin{bmatrix}\partial m \\ \partial \rho\end{bmatrix}+A.\begin{bmatrix}\partial Q_\ell \\ \partial Q_h\end{bmatrix}=-\begin{bmatrix}1 & 0 \\ 0 & 1\end{bmatrix}.\begin{bmatrix}\partial c_m \\ \partial c_s\end{bmatrix}$$

In other words:

$$\begin{bmatrix}\frac{\partial Q_\ell}{\partial m} & \frac{\partial Q_\ell}{\partial \rho} & \frac{\partial Q_\ell}{\partial c_m} & \frac{\partial Q_\ell}{\partial c_s} \\ \frac{\partial Q_h}{\partial m} & \frac{\partial Q_h}{\partial \rho} & \frac{\partial Q_h}{\partial c_m} & \frac{\partial Q_h}{\partial c_s}\end{bmatrix}$$

$$=-\begin{bmatrix}a(m,\rho) & \ell \\ \ell & b(\rho)\end{bmatrix}^{-1}\begin{bmatrix}\frac{\partial a}{\partial m}Q_\ell & \frac{\partial a}{\partial \rho}Q_\ell & 1 & 0 \\ 0 & \frac{\partial b}{\partial \rho}Q_h & 0 & 1\end{bmatrix}$$

$$=\frac{1}{\det(A)}\begin{bmatrix}-\rho(b)\frac{\partial a}{\partial m}Q_\ell & -\rho(b)\frac{\partial a}{\partial \rho}Q_\ell+\ell\frac{\partial b}{\partial \rho}Q_h & -b(\rho) & \ell \\ \ell\frac{\partial a}{\partial m}Q_\ell & \ell\frac{\partial a}{\partial \rho}Q_\ell-a(m,\rho)\frac{\partial b}{\partial \rho} & \ell & -a(m,\rho)\end{bmatrix}$$

If we now use equation (14), (15) and the fact that $Q_\ell, Q_h \gg 0$ at equilibrium, we can say that:

$$sign\left(\begin{bmatrix}\frac{\partial Q_\ell}{\partial m} & \frac{\partial Q_\ell}{\partial \rho} & \frac{\partial Q_\ell}{\partial c_m} & \frac{\partial Q_\ell}{\partial c_s} \\ \frac{\partial Q_h}{\partial m} & \frac{\partial Q_h}{\partial \rho} & \frac{\partial Q_h}{\partial c_m} & \frac{\partial Q_h}{\partial c_s}\end{bmatrix}\right)=\begin{bmatrix}+ & - & - & + \\ - & + & + & -\end{bmatrix} \quad (16)$$

If we now interested in the effect of the parameters on the prices, let us now observe that,

$$\begin{bmatrix}\frac{\partial P_\ell}{\partial m} & \frac{\partial P_\ell}{\partial \rho} & \frac{\partial P_\ell}{\partial c_m} & \frac{\partial P_\ell}{\partial c_s} \\ \frac{\partial P_h}{\partial m} & \frac{\partial P_h}{\partial \rho} & \frac{\partial P_h}{\partial c_m} & \frac{\partial P_h}{\partial c_s}\end{bmatrix}=\begin{bmatrix}\frac{\partial P_\ell}{\partial Q_\ell} & \frac{\partial P_\ell}{\partial Q_h} \\ \frac{\partial P_h}{\partial Q_\ell} & \frac{\partial P_h}{\partial Q_h}\end{bmatrix}.\Delta_Q$$

$$=\frac{1}{\det(A)}\begin{bmatrix}-\ell & -\ell \\ -\ell & h\end{bmatrix}$$

$$.\begin{bmatrix}-b(\rho)\frac{\partial a}{\partial m}Q_\ell & -b(\rho)\frac{\partial a}{\partial \rho}Q_\ell+\ell\frac{\partial b}{\partial \rho}Q_h & -b(\rho) & \ell \\ \ell\frac{\partial a}{\partial m}Q_\ell & \ell\frac{\partial a}{\partial \rho}Q_\ell-a(m,\rho)\frac{\partial b}{\partial \rho} & \ell & -a(m,\rho)\end{bmatrix}$$

with

$$\det(A)=\mu\left(\ell+\frac{2}{1-\rho}\right)\left(2h+\frac{4}{\rho}\right)-\ell^2$$

$$=\frac{\ell^2}{(1-\rho)\rho}\left[2\mu\underbrace{\left((1-\rho)+\frac{2}{\ell}\right)\left(\frac{h}{\ell}\rho+\frac{4}{\ell}\right)}_{>1 \text{since} h>l \text{and} \mu>1}-(1-\rho)\rho\right]>0$$

Let us now observe that,

$$\begin{cases} b(\rho)-\ell = 2\left(h+\frac{2}{\rho}\right)-\ell > 0 \text{ since } (h>l) \\ b(\rho)-h = h+\frac{4}{\rho} > 0 \\ a(m,\rho)-\ell = \frac{\ell}{m}+\left(1+\frac{1}{m}\right)\left(\frac{2}{1-\rho}\right) > 0 \\ \frac{h}{\ell}a(m,\rho)-\ell = h\left(1+\frac{1}{m}\right)\left(1+\frac{2}{(1-\rho)\ell}\right)-\ell > 0 \\ \text{since}(h>l) \end{cases}$$

We can therefore conclude that,

$$Sign\left(\begin{bmatrix} \frac{\partial P_\ell}{\partial m}\frac{\partial P_\ell}{\partial c_m}\frac{\partial P_\ell}{\partial c_s} \\ \frac{\partial P_h}{\partial m}\frac{\partial P_h}{\partial c_m}\frac{\partial P_h}{\partial c_s} \end{bmatrix}\right) = \begin{bmatrix} -++ \\ -++ \end{bmatrix}$$

Appendix 3: Proof proposition 3

To verify that the supermarket is active at equilibrium, we have to make sure that the profit that a farmer owns from the cooperative is higher than the profit obtained by working with the middlemen when is small. In other words, we have to verify that:

$$\lim_{\rho\to 0}\Delta(m,\rho,c_s,c_m) := \lim_{\rho\to 0}\left(\pi_f^c(m,\rho,c_s,c_m)-\pi_f^m(m,\rho,c_s,c_m)\right) > 0$$

If we now use equation (10) and (12), we can note that we have the difference of two square functions. Since the quantities which are produced are strictly positive, it is equivalent to check:

$$\lim_{\rho\to 0}\left[\left(\frac{Q_h^*(m,\rho,c_s,c_m)}{\rho}\right)\sqrt{1+\alpha s(\rho)(\rho h+2)} - \left(\frac{Q_\ell^*(m,\rho,c_s,c_m)}{\rho}\right)\right] > 0$$

We moreover know that $Q_\ell^*(m,\rho,c_s,c_m)$and $Q_h^*(m,\rho,c_s,c_m)$ at (8) and (9), it follows by a computation that:

$$\lim_{\rho\to 0}\left(\frac{Q_h^*(m,\rho,c_s,c_m)}{\rho}\right) = \lim_{\rho\to 0}\left(\frac{\mu K_s(\ell(1-\rho)+2)-(1-\rho)\ell K_m}{\mu(\ell(1-\rho)+2)(2h\rho+4)-\ell^2\rho(1-\rho)}\right) = \left(\frac{\mu K_s(\ell+2)-\ell K_m}{4\mu(\ell+2)}\right) \quad (17)$$

And

$$\lim_{\rho\to 0}\left(\frac{Q_\ell^*(m,\rho,c_s,c_m)}{1-\rho}\right) = \lim_{\rho\to 0}\left(\frac{\left((2h\rho+4)K_m-\rho\ell K_s\right)}{\mu(\ell(1-\rho)+2)(2h\rho+4)-\ell^2\rho(1-\rho)}\right) = \left(\frac{K_m}{\mu(\ell+2)}\right)$$

Since we have assumed that$\lim_{\rho\to 0}s(\rho)=1,$ we can say that:

$$\lim_{\rho\to 0}\Delta(m,\rho,c_s,c_m) > 0$$

$$\Leftrightarrow \frac{1}{4\mu(\ell+2)}\left(\mu K_s(\ell+2)\sqrt{1+2\alpha}-\ell K_m-4K_m\right) > 0$$

$$\Leftrightarrow \frac{K_m}{K_s} < \frac{\mu(\ell+2)\sqrt{1+2\alpha}}{4+\ell\sqrt{1+2\alpha}}$$

Appendix 4: Proof proposition 4

By asymmetric argument, the street markets are active if $\lim_{\rho\to 1}\Delta(m,\rho,c_s,c_m) < 0$. The simplification of Δ can be done in the same way, and since

$$\begin{cases} \lim_{\rho\to 1}\left(\frac{Q_h^*(m,\rho,c_s,c_m)}{\rho}\right) = \frac{K_s}{2h+4} \\ \lim_{\rho\to 1}\left(\frac{Q_\ell^*(m,\rho,c_s,c_m)}{1-\rho}\right) = \frac{(2h+4)K_m-\ell K_s}{2\mu(2h+4)} \end{cases}$$

And$\lim_{\rho\to 1}s(\rho)=0$, we can say that:

$$\lim_{\rho\to 0}\Delta(m,\rho,c_s,c_m) > 0$$

$$\Leftrightarrow \frac{1}{2\mu(2h+4)}\left(2\mu K_s-\left((2h+4)K_m-\ell K_s\right)\right) < 0$$

$$\Leftrightarrow \frac{K_m}{K_s} > \frac{\mu\ell+2}{2h+4}$$

Appendix 5: Proof proposition 5

Before moving to our main result, let us first check two main intermediaries' properties:

(i) $\frac{K_m}{K_s} < \mu\frac{(\ell-h)+2}{\ell+2}$ then $\frac{\partial q_h}{\partial \rho} := \partial\left(\frac{Q_h^*}{\rho}\right)/\partial\rho < 0$

Let us first recall that (see for instance equation (17)), q_h^*can be written as:

$$q_h^* = \frac{\ell(K_m-\mu K_s)\rho+(\mu K_s(\ell+2)-\ell K)}{(\ell^2-2\mu\ell h)^2+(2\mu\ell h+4\mu-4\mu\ell^2)\rho+(4\mu\ell+8\mu)} = \frac{N}{D}$$

From that point of view, we can observe that the numerator N is linear in ρwhile the denominator D is quadratic in this variable. It follows that $\frac{\partial q_h^*}{\partial\rho} = \frac{1}{D^2}f(\rho)$ where $f(\rho) = A\rho^2+B\rho+C$ is a quadratic function. These parameters can be obtained by a simple exercise of computation. Since we have assumed that $\mu\in[1,2]$, $\frac{K_m}{K_s} < 1$ and $h > l$ we can say that:

$$A = -\ell^2(\mu K_s-K_m)(2\mu h-\ell) = -\ell S(2\mu h-\ell) < 0$$
$$B = 2(\ell(\mu K_s-K_m)+2\mu K_s)(2\mu h-\ell)\ell = 2(\ell S+2\mu K_s)(2\mu h-\ell)\ell > 0$$

$$C = -\ell S(\ell+2)4\mu-(\ell S+2\mu K_s)\left(\ell(2\mu h-\ell)+4(h-\ell)\right) < 0$$

In which, to simplify, we set: $(\mu K_s-K_m) = S > 0$.

Moreover, $\forall\rho\in[0,1]$, $f'(\rho) = 2A\rho+B > 2A+B = 4\ell(2\mu h-\ell)\mu K_s > 0$. The function $f'(\rho)$ is therefore increasing on [0,1]. So if $f'(1) < 0$, we conclude that$\frac{\partial q_h^*}{\partial\rho} < 0$. Let us check this last point.

By a simple exercise of computation, we obtain that: $f'(1) = A + B + C < 0$ if:

$$S(2\ell + 4 + \ell h) + h(\ell S + 2\mu K_s) < 0$$
$$\Leftrightarrow (2\ell + 4)K_m - (2\ell\mu + 4 - 2\mu h)K_s < 0$$
$$\Leftrightarrow \frac{K_m}{K_s} < \frac{\mu(\ell - h) + 2\mu}{\ell + 2}$$

(ii) if $\frac{\mu(\ell+2)}{(4\mu+\ell)} < \frac{K_m}{K_s}$ then $\frac{\partial q_\ell^*}{\partial\rho} := \partial\left(\frac{Q_\ell^*}{1-\rho}\right)/\partial\rho > 0$

By using the same argument and computation as the previous property, we obtain that: $\frac{\partial q_\ell^*}{\partial\rho} = \frac{1}{D^2} f'(\rho)$where $f'(\rho) = A\rho^2 + B\rho + C$. Since$\frac{1}{2} < \frac{K_m}{K_s} < 1,\ h > land\mu = \left(1 + \frac{1}{m}\right) > 1$, we obtain that:

$$A = -(2hK_m - \ell K_s)(\ell^2 - 2\mu\ell h) > 0$$
$$B = -2(\ell^2 - 2\mu\ell h)4K_m > 0$$
$$C = (2hK_m - \ell K_s)(4\mu\ell + 8\mu)$$
$$-(2\mu\ell h + 4\mu h - 4\mu\ell - \ell^2)4K_m$$

We observe that,
$\frac{d(f(\rho))}{d\rho} = -(2hK_m - \ell K_s)(\ell^2 - 2\mu\ell h)\rho - 2(\ell^2 - 4\mu\ell h)4K_m > 0$ at $\rho = 0$, which implies that $f'(\rho)$is increasing function at $\rho = 0$. Since we have in hand $A = -(2hK_m - \ell K_s)(\ell^2 - 2\mu\ell h) > 0$ and $\frac{d(f(\rho))}{d\rho} > 0$ at $\rho = 0$, to have $\frac{\partial q_\ell^*}{\partial\rho} := \partial\left(\frac{Q_\ell^*}{1-\rho}\right)/\partial\rho > 0$, what remain now is to verify $f'(1) > 0$. Since we have $A > 0$ and$B > 0$, we, therefore, have to check the sign of C. In fact:

$$C = (2hK_m - \ell K_s)(4\mu\ell + 8\mu) - (2\mu\ell h + 4\mu h - 4\mu\ell - \ell^2)4K_m$$
$$= (16\mu\ell + 4\ell^2)K_m - (4\mu\ell^2 + 8\mu\ell)K_s > 0 \text{ if}$$

$$\frac{K_m}{K_s} > \frac{4\mu\ell^2 + 8\ell}{16\mu\ell + 4\ell^2} = \frac{\mu(\ell+2)}{(4\mu+\ell)}.$$

To have the main result, we have to now make that: $\frac{\partial\pi_f^c(m,\rho^*,c_m,c_s)}{\partial\rho} < 0$ and $\frac{\partial\pi_f^m(m,\rho^*,c_m,c_s)}{\partial\rho} > 0$. Let us now recall the result of $\pi_f^c(m,\rho^*,c_m,c_s)$and $\pi_f^m(m,\rho^*,c_m,c_s)$ given at (10) and (12), which are:

$$\pi_f^m(m,\rho,c_s,c_m) = \left(\frac{Q_\ell^*(m,\rho,c_s,c_m)}{(1-\rho)}\right)^2$$

And

$$\mu_f^c(m,\rho,c_s,c_m) = \left(\frac{Q_h^*(m,\rho,c_s,c_m)}{\rho}\right)^2 [1 + \alpha s(\rho)(\rho h + 2)]$$

From this result, since we have in hand that $\frac{\partial q_\ell^*}{\partial\rho} := \partial\left(\frac{Q_\ell^*}{1-\rho}\right)/\partial\rho > 0$, we obtain that $\frac{\partial\pi_f^m(m,\rho^*,c_m,c_s)}{\partial\rho} > 0$, we have to now prove that$\frac{\partial\pi_f^c(m,\rho^*,c_m,c_s)}{\partial\rho} < 0$. Since we have the property that $\frac{\partial q_h}{\partial\rho} := \partial\left(\frac{Q_h^*}{\rho}\right)/\partial\rho < 0$, let us now proof that $\frac{\partial\pi_f^c(m,\rho^*,c_m,c_s)}{\partial\rho} < 0$. Since we have assumed that$\frac{ds(\rho)}{d\rho}\frac{\rho}{s(\rho)} < 0$, we obtain that:

$$\pi'_{c/f}(\rho) = 2\left(\frac{q_h(\rho)}{\rho}\right)\frac{\frac{d(q_h(n))}{\rho}}{d\rho}[1 + \alpha s(\rho)(\rho h + 2)] + \left(\frac{q_h(\rho)}{\rho}\right)^2 \left(\alpha s'(\rho)(\rho h + 2) + \alpha h s(\rho)\right)$$

$$= 2\left(\frac{q_h(\rho)}{\rho}\right)\frac{\frac{d(q_h(n))}{\rho}}{d\rho}[1 + \alpha s(\rho)(\rho h + 2)] + \left(\frac{q_h(\rho)}{\rho}\right)^2 \alpha\left(2s'(\rho) + h\left(s'(\rho) + s(\rho)\right)\right)$$

$$= 2\left(\frac{q_h(\rho)}{\rho}\right)\underbrace{\frac{\frac{d(q_h(n))}{\rho}}{d\rho}}_{<0}[1 + \alpha s(\rho)(\rho h + 2)] + \left(\frac{q_h(\rho)}{\rho}\right)^2 \alpha\left(2\underbrace{s'(\rho)}_{<0} + hs(\rho)\left(\underbrace{\frac{s'(\rho)\rho}{\partial\rho}}_{<-1} + 1\right)\right) < 0$$