Increasing Returns, the Choice of Technology, and the Gains from Trade

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2007

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Abstract

This paper studies the implications of international trade in a general equilibrium model in which the returns to scale are internal and firms choose their production technologies. The production function generated from internal increasing returns and the choice of technology leads to the returns to scale similar to that based on external increasing returns. Trade always increases a country's welfare in a two-sector model in which the agricultural sector has constant returns to scale and average cost in the manufacturing sector may decrease without being bounded asymptotically by a given level of marginal cost. Why a small country may lose from trade under external increasing returns is also illustrated.

Keywords: Choice of technology, gains from trade, increasing returns, oligopolistic competition, trade policy

JEL Classification: D43, F12, F13

I thank Vinod Agarwal, Ingrid Bryan, Leo Michelis, Laura Razzolini, and David Selover for their help and suggestions. Comprehensive advice from James V. Koch has improved this paper significantly. The valuable and detailed comments from two anonymous referees are highly appreciated. I am solely responsible for all the remaining errors.

1. Introduction

Models of international trade based on increasing returns have been studied intensively in the past three decades. In the literature, the source of increasing returns may be external or internal. For models based on external returns to scale, a firm's cost decreases with total industry level of output. A firm is assumed to be too small to affect the industrial level of output significantly. An example of a model based on external increasing returns is Ethier (1982). Internal returns to scale come from spreading fixed costs of production. With a constant marginal cost, a firm's average cost decreases with its output as the fixed cost can be distributed over a larger level of output. An example of a model based on internal increasing returns is Horstmann and Markusen (1986). In both papers, labor is the only factor of production. The manufacturing sector exhibits increasing returns to scale, while the agricultural sector has constant returns to scale.

However, the two models differ in their conclusions on whether the opening of international trade is always beneficial. Under internal increasing returns, Horstmann and Markusen (1986, p. 226) show that trade always increases a country's welfare, and Venables (1985) shows this result is robust to the alternative assumption that domestic and foreign markets are segregated rather than integrated. Under external increasing returns, Ethier (1982, p. 1261) shows that if trade leads the smaller country to specialize completely in the production of agricultural goods and the larger country to specialize completely in the production of manufactures, the smaller country benefits from trade only when certain conditions are satisfied. These conditions require that either the percentage of income spent on manufactured goods be relatively low, or the degree of returns to scale be large, or that countries differ significantly in terms of their sizes. If none of these conditions is satisfied, then the smaller country loses from the opening of international trade. Thus, the opening of trade is more likely to be beneficial to the smaller country under internal increasing returns than under external increasing returns. What is the reason behind this difference of results?

We may not expect models based on different specifications of increasing returns to lead to similar results: Under internal increasing returns, with a fixed cost and a constant marginal cost, average cost is bounded asymptotically by the constant marginal cost; With external increasing returns, average cost may decrease without being bounded asymptotically by a given level of marginal cost. However, if internal increasing returns also lead to average cost unbounded asymptotically, will the implications of trade be similar under different specifications of the source of increasing returns?

In this paper, the impact of international trade is studied in a two-sector general equilibrium model in which the returns to scale are internal. The innovation of this paper is that it incorporates the choice of technology into a firm's profit maximization. One contribution of this paper is that it shows the production function generated from internal increasing returns and the choice of technology leads to a degree of the returns to scale similar to that based on external increasing returns. This allows us to analyze the case that average cost is not bounded asymptotically by a given level of marginal cost and makes the comparison of results based on different specifications of the returns to scale feasible. The incorporation of the choice of technology into our study is also justified by the observation that firms do choose their technologies optimally in reality. We show that the main result in Horstmann and Markusen's (1986) partial equilibrium model that trade always increases a country's welfare generalizes to this general equilibrium model. Trade always increases a country's welfare in a two-sector model in which the agricultural sector has constant returns to scale and average cost in the manufacturing sector may decrease without being bounded asymptotically by a given level of marginal cost. Thus, the difference of results between internal and external increasing returns does not arise from whether average cost is bounded asymptotically by a given level of marginal cost.

One natural question is why trade is always beneficial for the smaller country under internal increasing returns while it may get harmed under external returns to scale. To answer this question, we need to understand why the opening of international trade may decrease the smaller country's welfare when the returns to scale are external. This is achieved through three steps. First, we show that the specification of external increasing returns leads to the result that only the larger country produces manufactured goods. One assumption in the literature on external increasing returns is that a firm's cost is affected by domestic aggregate output, not by world aggregate output. Average cost pricing is usually assumed in models of external increasing returns. Since average cost decreases with the level of domestic aggregate output, the country with a higher labor endowment has a lower price of manufactures. With the opening of trade, if the smaller country produces any manufactures, then average cost and thus the price of manufactures in the smaller country will be higher than those in the larger country. However, without transportation costs, prices of manufactures should be the same all over the world since otherwise international arbitrage will happen. Thus, with the opening of trade, the production of manufactures will be concentrated in the country with a higher labor endowment.

Second, we establish the negative relationship between the price of manufactures and the welfare of a representative consumer living in the smaller country. The representative consumer's utility is determined by her wage income, the price of manufactures, and the price of agricultural goods. The price of agricultural goods is always normalized to one. As the agricultural sector is assumed to have constant returns to scale, without loss of generality, the wage rate can be normalized to one if the smaller country produces some agricultural goods. With the opening of trade, the price of agricultural goods and the wage rate do not change since the smaller country still produces agricultural goods. Thus, a necessary and sufficient condition for trade to lead to a decrease of the utility for the representative consumer in the smaller country is that trade leads to an increase of the price of manufactures.[1]

[1] To simplify the presentation, we assume that a consumer spends a fixed percentage of income on agricultural goods. The intuition here applies to the case with a more general utility function.

Third and finally, we illustrate why the price of manufactures with trade may be higher than that in the smaller country before trade.[2] The price of manufactures with trade may increase if trade leads to a decrease in the supply of manufactures which is caused by a decrease of the world level of workers employed in the manufacturing sector. Before trade, both countries have some workers employed in the manufacturing sector and the world level of workers employed in the manufacturing sector is the sum of workers in the two countries. With the opening of trade, only workers in the larger country may work in the manufacturing sector. Even if all workers in the larger country work in the manufacturing sector, the world output of manufactures may be lower than that before trade. If this leads to an increase of the price of manufactures, then the smaller country loses from trade. For the smaller country, though the price of manufactures is higher after trade and it imports manufactures, it could not revert to its production pattern before trade as the production of manufactures has to be concentrated in the larger country after trade.

More specifically, before trade, the number of workers in each country employed in the manufacturing sector increases with the percentage of income spent on manufactures. If the percentage of income spent on manufactures is high, the percentage of workers in each country employed in the manufacturing sector before trade is high. After the opening of trade, if labor endowments in the two countries do not differ significantly, the total number of workers in the world working in the manufacturing sector after trade (which is the labor endowment of the larger country) will be smaller than that before trade (which is the sum of manufacturing workers in both countries). If the degree of increasing returns is not high enough, with the opening of trade, the price of manufactures increases. As the price of manufactures increases (Ethier, 1982, p.1261), a typical worker in the smaller country loses from the opening of trade.

[2] If trade leads to the price of manufactures to be higher than that in the smaller country before trade, the price of manufactures with trade is higher than the prices of manufactures in both countries before trade because the larger country has a lower price of manufactures before trade.

With external increasing returns, the larger country always benefits from trade. With the opening of trade, there are two cases for the pattern of production for the larger country. In the first case, the larger country produces both types of goods.[3] The larger country benefits from trade as the wage rate and the price of agricultural goods do not change and the price of manufactures decreases. In the second case, the larger country only produces manufactures. There are two possibilities: First, if the price of manufactures decreases, the larger country benefits from trade for the same reason as in the first case; Second, if the price of manufactures increases, the larger country still gains from trade because the wage income for a worker in the larger country increases directly with the price of manufactures while only part of the wage income is spent on manufactures.

For internal increasing returns, with the opening of trade, a firm producing manufactures located at the larger country may not have a cost advantage than a firm located in the smaller country since a firm's average cost depends solely on its own level of output. Thus, with trade, manufactures may still be produced in both countries. There are two channels through which the opening of trade increases a country's welfare. First, the number of firms producing manufactures in the world after the opening of trade will not be smaller than the number of manufacturing firms in each country before trade since the size of the world market for manufactures is higher than that of each country. This may decrease a firm's monopoly power and is welfare enhancing (Brander, 1981). Second, as firms produce higher levels of output, they will choose more advanced technologies, leading to lower average costs and an increase in welfare.

Researchers feel more comfortable when results are robust to alternative specifications of the type of increasing returns. Without international trade, different specifications of increasing returns should lead to qualitatively similar results. For example, Ethier (1982) shows that the price of the product with increasing returns is lower in a country with a higher labor endowment. The

[3] In this case, the smaller country also benefits from trade.

same result holds in this model. The result that the smaller country loses from the opening of trade under external increasing returns comes from the joint assumptions of external increasing returns and a firm's cost depends on national output rather than international output. With international trade, if under external increasing returns, a firm's average cost depends on world output rather than domestic output, different specifications of increasing returns still lead to qualitatively similar results. Specifically, the opening of trade will always increase the smaller country's welfare if a firm's average cost depends on world output.

In dynamic trade models, whether production knowledge is limited domestically or spills over internationally can also be crucial in determining whether a country benefits from trade or not. In Rivera-Batiz and Romer (1991), knowledge spills over across national borders and countries always benefit from opening up. In Young (1991), learning by doing is country specific and a country may lose from opening up if the static gains from trade are dominated by the dynamic loss from trade.

The rest of the paper is organized as follows. In Section 2, we study a manufacturing firm's profit maximization. We show that the production function generated from internal increasing returns and the choice of technology leads to a degree of the returns to scale similar to that based on external increasing returns. In Section 3, we study conditions for a general equilibrium in the home country. In Section 4, we study the impact of international trade. No matter whether countries differ in their production technologies or not, it is shown that trade always increases a country's welfare in a two-sector model in which the agricultural sector has constant returns to scale and average cost in the manufacturing sector may decrease without being bounded asymptotically. In Section 5, differences between external and internal increasing returns are illustrated through examples. In Section 6, we study the impact of the imposition of a tariff. Section 7 suggests some possible extensions of the model and concludes.

2. A Manufacturing Firm's Profit Maximization

Assume two types of goods: agricultural and manufactured goods. Labor is the only factor of production. The production function of agricultural goods exhibits constant returns to scale. We assume that producing manufactures requires fixed costs of production. Thus internal increasing returns to scale exist. In this section, we study a manufacturing firm's optimal choices of technology and output to maximize profit. We are mainly interested in the implications of a manufacturing firm's choice of technology.

Manufacturing firms produce a homogenous product. The number of manufacturing firms in the home country is denoted by m. In equilibrium, the number of firms is determined by the zero-profit condition. Similar to Brander (1981), Horstmann and Markusen's (1986), Neary (2003), and Ruffin (2003), we assume that manufacturing firms engage in Cournot competition.

Following Zhou (2004), a firm may choose from a continuum of technologies.[4] Let n denote a firm's level of technology, $n \in (0, \infty)$. The fixed and marginal costs in terms of the amount of labor used associated with this technology are denoted by $f(n)$ and $\beta(n)$, respectively. Assume that the higher the value of n, the higher the fixed cost of production, but the lower the marginal cost of production. That is, $f' > 0$ and $\beta' < 0$. We also assume that $f'' > 0$ and $\beta'' > 0$. With this specification of costs, compared with a firm with a lower level of output, it is more profitable for a firm with a higher level of output to adopt a technology with a higher fixed cost and a lower marginal cost since the larger fixed cost can be distributed over a higher level of output.

Let x denote a manufacturing firm's level of output and w denote the wage rate. The price of manufactures is denoted by p_m. A manufacturing firm's profit is given by $p_m x - (f(n) + \beta(n)x)w$. A manufacturing firm takes the wage rate as given, and chooses its

[4] Zhou (2004) studies the choice of technology in a closed economy. Impact of trade on income distribution incorporating the choice of technology is studied in Zhou (2006).

output and level of technology optimally to maximize its profit. The first order condition of profit maximization with respect to output is

$$p_m + x\frac{\partial p_m}{\partial x} - \beta w = 0. \tag{1}$$

The first order condition for a firm's profit maximization with respect to technology is

$$f' + \beta' x = 0. \tag{2}$$

Equation 2 shows that a firm's optimal level of technology increases with its level of output. The second order condition requires that $-f'' - \beta'' x < 0$. It is assumed that this second order condition is satisfied. Rearrangement of Equation 2 yields

$$x = -f'/\beta'. \tag{3}$$

Plugging Equation 3 into the second order condition yields

$$f'\beta'' - f''\beta' > 0. \tag{4}$$

Without the choice of technology, average cost is bounded below asymptotically by the fixed level of marginal cost. With the incorporation of the choice of technology, average cost may decrease without a positive lower bound.[5] To demonstrate this, average cost is $\frac{f + \beta x}{x}$, which is equal to $\frac{f'\beta - f\beta'}{f'}$. Differentiation of this average cost with respect to n yields $\frac{f(f''\beta' - f'\beta'')}{(f')^2}$. Application of the second order condition 4 shows that average cost decreases with n. As n increases with a firm's level of output, average cost may decrease without being bounded asymptotically.

With the incorporation of the choice of technology, the production function generated from internal increasing returns is similar to that based on external increasing returns. This can be

[5] Obviously, average cost is bounded away from zero.

demonstrated as follows. Let l_m denote the total amount of labor a firm employs: $l_m \equiv f + \beta x$. Let ρ and τ denote positive constants. The cost functions are specified as

$$f = n^{\rho}, \tag{5}$$

$$\beta = n^{-\tau}.[6] \tag{6}$$

From Equations 3, 5, and 6, a firm's production function specifying the relationship between input and output is given by

$$x = \rho \tau^{\tau/\rho} (\tau + \rho)^{-\frac{\rho+\tau}{\rho}} (l_m)^{\frac{\rho+\tau}{\rho}}. \tag{7}$$

Since $\dfrac{\rho + \tau}{\rho}$ is always larger than 1, the above production function exhibits increasing returns to scale. The lower the value of ρ and the higher the value of τ, the higher the degree of returns to scale. In Ethier (1982), α is the degree of returns to scale in the manufacturing sector and $\alpha > 1$. By choosing ρ and τ such that

$$\frac{\rho + \tau}{\rho} = \alpha, \tag{8}$$

the degree of returns in this model will be the same as that in Ethier (1982).

We now complete the description of the manufacturing sector by imposing the free entry and exit condition. If free entry and exit exists, then this leads to zero pure profits.[7] Zero profit for a manufacturing firm requires that

$$p_m x - (f + \beta x) w = 0. \tag{9}$$

Zero profit means that the price of manufactures equals average cost, which is valid in both external and internal returns models.

[6] For cost functions 5 and 6, the second order condition 4 is always satisfied when $\rho + \tau$ is positive.

[7] In this paper, the integer constraint on the number of manufacturing firms is ignored to simplify presentation. When this constraint binds, the study here can be viewed as an approximation to a full-fledged model taking into account of the integer constraint.

3. Equilibrium in A Closed Economy

Assume two countries: home and foreign. In this section, the two countries do not engage in trade. Let's focus on the home country, since the analysis for the foreign country is similar.

We have studied a firm's profit maximization in Section 2. In this section, we establish other conditions for a general equilibrium. First, let's focus on a representative consumer's utility maximization. The number of consumers in the home country is denoted by L. A consumer's utility function is specified as $U(c_a, c_m)$, where c_a is the consumption of agricultural goods and c_m is the consumption of manufactures. Let U_a denote the partial derivative with respect to c_a and U_m denote the partial derivative with respect to c_m. With positive marginal utilities, we have $U_a > 0$ and $U_m > 0$. Let the price of agricultural goods be denoted by p_a. A representative consumer's budget constraint is

$$p_a c_a + p_m c_m = w. \tag{10}$$

The consumer takes the wage rate and the prices of goods as given and chooses quantities of consumption to maximize her utility. The consumer's utility maximization leads to

$$\frac{U_m}{U_a} = \frac{p_m}{p_a}. \tag{11}$$[8]

Second, market clearing conditions are imposed. As the agricultural sector has constant returns to scale, without loss of generality, we assume that each unit of labor is able to produce one unit of agricultural goods. Let L_a denote the amount of labor force employed in the agricultural

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[8] The following second order conditions for the representative consumer's utility maximization are assumed to be satisfied: $U_{aa} - U_{am} / p_m < 0$, and $U_{mm} - p_m U_{ma} < 0$. These second order conditions are used later on to determine the signs of comparative static studies.

sector. The total demand for agricultural goods is Lc_a and the total supply of agricultural goods is L_a. Clearance of market for agricultural goods requires that

$$Lc_a = L_a. \tag{12}$$

The total demand of manufactures is Lc_m and the total supply of manufactures is mx. Clearance of market for manufactures requires that

$$Lc_m = mx. \tag{13}$$

Labor is perfectly mobile within sectors, but immobile internationally. The demand for labor in the agricultural sector is L_a and the demand for labor in the manufacturing sector is $m(f+\beta x)$. Thus, the total demand for labor is $L_a + m(f+\beta x)$. We assume that a typical consumer has no preference for leisure. Therefore, each consumer supplies one unit of labor inelastically. The total supply of labor is L. Clearance of labor market requires that

$$L_a + m(f+\beta x) = L. \tag{14}$$

Finally, a worker's return in the agricultural sector is p_a and a worker's return in the manufacturing sector is w. As an individual may work in either sector, the return in the two sectors should be equal:

$$w = p_a. \tag{15}$$

The representative consumer's elasticity of demand of manufactures (absolute value) is defined as $\varepsilon \equiv -U_m/(U_{mm}c_m)$. Combination of a consumer's utility maximization and a firm's first order condition of profit maximization with respect to output leads to

$$p_m\left(1+\frac{x\partial p_m}{p_m\partial x}\right) = p_m\left(1-\frac{1}{m\varepsilon}\right) = \beta w. \tag{16}$$

Equation 16 is a well-established result in industrial organization. It states that a firm's price is a markup over its marginal cost of production. The size of the markup decreases with the price elasticity of demand concerning a firm's product.

Equations 2 and 9-16 form a system of nine equations defining nine variables p_a, p_m, w, n, x, c_a, c_m, m, and L_a. An equilibrium is a set of prices p_a, p_m, and w, optimal choices n and x for a firm, optimal choices c_a and c_m for a worker, a number of firms m, and a number of workers in the agricultural sector L_a, such that

(i). n and x solve Equations 2 and 16, for given w and m;

(ii). c_a and c_m solve Equations 10 and 11, for given p_a, p_m, and w;

(iii). Markets for agricultural goods, manufactures, and labor clear: Equations 12-14 are valid;

(iv). No incentive for a firm to enter or exit and no incentive for a worker to change employment: Equations 9 and 15 are valid.

For the rest of the paper, the price of agricultural goods is normalized to one: $p_a \equiv 1$. Since each worker is able to produce one unit of agricultural goods, this normalization means that the wage rate is also equal to one. Simplification of the system of Equations 2 and 9-16 leads to

$$V_1 \equiv U_m(1 - p_m c_m, c_m) / p_m - U_a(1 - p_m c_m, c_m) = 0, \tag{17}$$

$$V_2 \equiv -\beta' f / (p_m - \beta) - f' = 0, \tag{18}$$

$$V_3 \equiv (p_m - \beta)^2 \frac{\varepsilon L c_m}{p_m} - f = 0. \tag{19}$$ [9]

Equations 17-19 define three variables c_m, p_m, and n as functions of the exogenous parameter L. Interpretations of Equations 17-19 are as follows. First, for Equation 17, U_m / p_m is the marginal utility per dollar from consuming manufactures and U_a is the marginal utility per

[9] Equations 17-19 are derived as follows. First, plugging the value of c_a from Equation 10 into Equation 11 leads to Equation 17. Second, plugging the value of x from Equation 2 into Equation 9 leads to Equation 18. Finally, plugging the value of w from Equation 15, the value of m from Equation 13, and the value of x from Equation 9 into Equation 16 leads to Equation 19.

dollar from consuming agricultural goods. Thus, Equation 17 states that the marginal utility per dollar from consuming different types of goods should be equal in equilibrium. Second, for Equation 18, f' is the increase of fixed costs when a more advanced technology is chosen. As $-\beta'$ is per unit saving of marginal cost, $f/(p_m - \beta)$ is output, $-\beta' f/(p_m - \beta)$ is the total saving of marginal cost. Thus, Equation 18 states that a firm's technology is chosen optimally. Third and finally, for Equation 19, from Equations 13 and 16, a manufacturing firm's output can be expressed as $(p_m - \beta)\varepsilon L c_m / p_m$. Since $p_m - \beta$ is the profit per unit as the wage rate is equal to one, $(p_m - \beta)^2 \varepsilon L c_m / p_m$ is the product of the level of output and profit per unit, or profit excluding the fixed cost. Thus, Equation 19 is the zero profit condition for a manufacturing firm.

The following proposition studies how a firm's level of technology, the price of manufactures, and a consumer's level of consumption change with the size of a country's labor force.

PROPOSITION 1. When a country's labor endowment increases, a firm's level of technology increases, the price of manufactures decreases, and a consumer's consumption of manufactures increases.

PROOF. Total differentiation of Equations 17-19 with respect to c_m, p_m, n, and L yields

$$\begin{pmatrix} \frac{\partial V_1}{\partial c_m} & \frac{\partial V_1}{\partial p_m} & 0 \\ 0 & \frac{\partial V_2}{\partial p_m} & \frac{\partial V_2}{\partial n} \\ \frac{\partial V_3}{\partial c_m} & \frac{\partial V_3}{\partial p_m} & \frac{\partial V_3}{\partial n} \end{pmatrix} \begin{pmatrix} dc_m \\ dp_m \\ dn \end{pmatrix} = \begin{pmatrix} 0 \\ 0 \\ -\frac{\partial V_3}{\partial L} \end{pmatrix} dL. \qquad (20)$$

Let Δ denote the determinant of the coefficient matrix of the system 20. From the Appendix, stability requires that $\Delta < 0$. Partial differentiation of Equations 17-19 yields

$$\frac{\partial V_1}{\partial p_m} = -\frac{U_m}{p_m^{\ 2}} - (U_{ma} - p_m U_{aa})\frac{c_m}{p_m} < 0\,, \tag{21}$$

$$\frac{\partial V_1}{\partial c_m} = -(p_m U_{ma} - U_{mm})/\,p_m - p_m(U_{am} - p_m U_{aa}) < 0\,, \tag{22}$$

$$\frac{\partial V_2}{\partial p_m} = \frac{\beta' f}{(p_m - \beta)^2} < 0\,, \tag{23}$$

$$\frac{\partial V_2}{\partial n} = -f'' - \frac{\beta'' f}{p_m - \beta} < 0\,, \tag{24}$$

$$\frac{\partial V_3}{\partial L} = \frac{\varepsilon c_m (p_m - \beta)^2}{p_m} > 0\,. \tag{25}$$

Application of Cramer's rule on the system 20 leads to

$$\frac{dn}{dL} = -\frac{\partial V_1}{\partial c_m}\frac{\partial V_2}{\partial p_m}\frac{\partial V_3}{\partial L}/\Delta > 0\,, \tag{26}$$

$$\frac{dp_m}{dL} = \frac{\partial V_1}{\partial c_m}\frac{\partial V_2}{\partial n}\frac{\partial V_3}{\partial L}/\Delta < 0\,, \tag{27}$$

$$\frac{dc_m}{dL} = -\frac{\partial V_1}{\partial p_m}\frac{\partial V_2}{\partial n}\frac{\partial V_3}{\partial L}/\Delta > 0\,. \tag{28}$$

QED.

The intuition behind Proposition 1 is as follows. As manufactures are normal goods, other things equal, an increase of labor endowment leads to a higher level of demand for manufactures. A higher level of demand for manufactures makes the adoption of more advanced technologies more profitable since the higher fixed cost can be distributed over a larger level of output. This leads to a lower average cost. Since firms earn zero pure profits, lower cost transfers into lower prices. Lower labor cost per unit of output also leads to a higher level of per capita consumption of manufactures. Since the price of manufactures decreases with the labor endowment, a larger country has a comparative advantage in the production of manufactures.

4. Impact of the Opening of International Trade

In this section, we study the impact of international trade. We consider two cases. In the first case, the home country is sufficiently small that it cannot affect the world prices. With the opening of trade, it will specialize in the production of the product with a higher relative price in the world market. This increases the wage rate in the home country. For the home country, there are three possibilities for its pattern of consumption. First, if consumers in the home country spend on both types of goods, a consumer's welfare will be definitely higher. Second, if consumers only spend on the product with increasing returns, welfare will also be higher. Third and finally, if consumers only spend on the product with constant returns and the home country specializes in the production of this product, welfare does not change. Overall, welfare with trade in the home country cannot be lower than that without trade.

Next, we study the second case in which the home country's demand and supply affect world prices. Assume that firms in the foreign country have access to the same set of production technologies as domestic firms and consumers in the two countries have the same preferences. The only difference between our two countries is that they may differ in their endowments of labor. Without loss of generality, we assume that the home country is smaller than the foreign country. Since there is no transportation cost, international trade leads to the equalization of the prices in the two countries. For the home country, there are two possibilities for its pattern of production. One is that the home country still produces some manufactures. The second one is that the home country specializes in the production of agricultural goods.

If the home country still produces some manufactures, as trade leads to equal price of agricultural goods, this also leads to an equalization of the wage rates between the two countries. Since foreign consumers have the same wage rate and preferences and face the same prices of agricultural and manufactured goods, their level of consumption will be the same as that of domestic consumers. Plugging Equation 3 into Equation 9 yields $\Omega \equiv \beta f' - f \beta' - f' p_m = 0$. This equation leads to

$$\frac{dn}{dp_m} = -\frac{\partial \Omega}{\partial p_m} / \frac{\partial \Omega}{\partial n} > 0 . \tag{29}$$

The above inequality shows that there is a monotonic relationship between a firm's technology and the ratio of the price of manufactures to the wage rate. As the price of manufactures and the wage rates are equal in the two countries, a foreign manufacturing firm's level of technology and output will be the same as those of a domestic firm.

We denote foreign variables with asterisks. For example, we denote the amount of labor endowment in the foreign country by L^*. Equations 2, 9, and 14 are still valid in an open economy. In addition, the following conditions hold in an equilibrium with trade. First, clearance of labor market in the foreign country leads to

$$L_a^* + m^*(f + \beta x) = L^* . \tag{14*}$$

Second, since the price of agricultural goods is normalized to one and the wage rate is equal to one, a representative consumer's budget constraint is

$$c_a + p_m c_m = 1 . \tag{30}$$

Third, as the wage rate and the prices are the same in both countries and consumers have the same preferences, consumers in different countries purchase the same bundle of agricultural and manufactured goods. The world demand of manufactures is $(L + L^*)c_m$ and the world supply of manufactures is $(m + m^*)x$. Clearance of market for manufactures leads to

$$(L + L^*)c_m = (m + m^*)x . \tag{31}$$

Fourth, the world demand for agricultural goods is $(L + L^*)c_a$ and the world supply of agricultural goods is $L_a + L_a^*$. Clearance of market for agricultural goods leads to

$$(L + L^*)c_a = L_a + L_a^* . \tag{32}$$

Fifth, consumers' utility maximization leads to equalization of marginal utility per dollar from consuming different types of goods:

$$U_a = \frac{U_m}{p_m}. \tag{33}$$

Finally, a manufacturing firm's optimal choice of output leads to

$$p_m\left(1-\frac{1}{(m+m^*)\varepsilon}\right)=\beta\ . \tag{34}$$

Equation 34 is similar to Equation 16. The difference is that with an integrated world market for manufactures, the number of manufacturing firms is the sum of domestic and foreign firms, rather than the number of domestic firms.

Equations 2, 9, 14, 14*, 30, 31, 32, 33, and 34 form a system of nine equations defining nine variables p_m, m, m^*, x, c_a, c_m, L_a, $L_a{}^*$, and n. Simplification of this system of equations leads to

$$T_1 \equiv U_m / p_m - U_a = 0, \tag{35}$$

$$T_2 \equiv -\beta' f/(p_m-\beta) - f' = 0, \tag{36}$$

$$T_3 \equiv (p_m-\beta)^2\,\frac{\varepsilon(L+L^*)c_m}{p_m} - f = 0.\text{[10]} \tag{37}$$

A comparison of Equations 19 and 37 shows that with the opening of trade and an integrated world market L is replaced by $L+L^*$. Interpretations of Equations 35-37 are similar to those of Equations 17-19.

The following proposition studies the impact of the opening of international trade.

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[10] Equation 26 is derived in two steps. First, the value of x from Equation 9 is plugged into Equation 31. Second, the value of $m+m^*$ from Equation 31 is plugged into Equation 34.

PROPOSITION 2. (i) With increasing returns to scale in the manufacturing sector and constant returns to scale in the agricultural sector, international trade increases both countries' welfare. (ii) International trade leads the manufacturing sector to have a higher level of output and to adopt a more advanced technology.

PROOF. The difference between the system of Equations 35-37 and the system of Equations 17-19 is that the exogenous variable increases from L to $L + L^*$. Thus, the impact of the opening of trade is similar to that of an increase in labor endowment. Proposition 2 follows from Proposition 1. *QED.*

The intuition behind Proposition 2 is as follows. With the opening of trade, there are two effects on the manufacturing sector. First, for a given level of technology, as the size of the market is larger, each firm's output increases. This decreases the distortion from the existence of imperfect competition. This benefit is well understood in the literature (Brander, 1981). Second, this model introduces one additional effect: the adoption of more advanced technologies in the manufacturing sector. As output is larger, adoption of more advanced technologies becomes profitable. This further decreases average cost of production. As firms make zero profits, lower average cost means a lower price and a higher level of welfare.

The result that international trade leads the manufacturing sector to have a higher level of output and adopts a more advanced technology is consistent with empirical evidence. For example, Bernard and Jensen (1999) find that exporters employ more advanced technology than non-exporters.

In the second case, the home country specializes in the production of agricultural goods, and still benefits from trade. The reasoning is as follows. As the wage rate is always one and the price of agricultural goods is always one, the remaining factor affecting a representative consumer's utility is the price of manufactures. The price of manufactures in the home country will only be lower than that before trade. Otherwise, the opening of trade will not lead to a contraction of the manufacturing sector in the home country. As the price of manufactures is lower with trade, consumers in the home country benefit from trade.

Trade also increases welfare when countries may differ in their production technologies. For example, suppose the only difference between the two countries is that they have different productivities in the agricultural sector. We still assume that technologies in the agricultural sector exhibit constant returns to scale. Will the country with a higher agricultural productivity have a lower price of agricultural goods? We have normalized the output of agricultural goods produced by each worker to one. To study the impact of differences in agricultural technologies, we may use a positive constant different from one to measure the amount of agricultural goods produced by each worker. Thus, a change of agricultural productivity is captured by a change of this positive constant. By following analysis similar to that in Section 3, we are able to derive a system of equations similar to the system of Equations 17-19. It can be shown that the impact of an increase of agricultural productivity on p_m (the inverse of the relative price of agricultural goods) is ambiguous. The intuition behind this result is as follows. An increase of agricultural productivity has two effects. First, it increases the supply of agricultural goods. Second, it increases the wage rate and thus increases the demand for agricultural goods. Since it is not clear which effect dominates, the direction of trade flow is unclear. However, regardless of the direction of trade flow, trade leads to a decrease of the price of manufactures, since the size of the market for manufactures increases with trade. As a result, every country benefits from trade.

5. Discussion on Differences between External and Internal Increasing Returns

With internal increasing returns to scale, the smaller country always benefits from the opening of trade. With external increasing returns, it may lose from the opening of trade. In this section, we provide examples to illustrate the source of this difference of results.

The utility function is specified as

$$U(c_a, c_m) = \gamma \ln c_m + (1-\gamma)\ln c_a, \tag{38}$$

where γ denote a positive constant between zero and one. With this utility function, a consumer spends γ percent of income on manufactures.

Example 1: External increasing returns. From Ethier (1982, p.1261), the price of manufactures before trade in the home country is $(\gamma L)^{1-\alpha}$ and the price of manufactures after trade when the home country specializes in the production of agricultural goods and the foreign country specializes in the production of manufactures is $\dfrac{\gamma}{(1-\gamma)}\dfrac{L}{(L^*)^{\alpha}}$. For $\alpha = 1.25$, $\gamma = 90\%$, $L = 90$, and $L^* = 110$, the price of manufactures for the home country before trade will be 1/3. Before trade, the number of workers employed in the manufacturing sector in the home country is 81, while it is 99 in the foreign country. After trade, all of the 110 workers in the foreign country work in the manufacturing sector. With the opening of trade, the total number of workers in the world working in the manufacturing sector decreases from 180 to 110. The world price of manufactures after trade increases to approximately 2.27. It can be checked that a representative consumer in the home country loses from trade and a representative consumer in the foreign country gains from trade.

Example 2: Internal increasing returns. By solving the system of Equations 2 and 9-16, the price of manufactures before trade in the home country is $\dfrac{(\rho+\tau)^{1+\frac{2\tau}{\rho}}}{\rho\tau^{\frac{2\tau}{\rho}}(\gamma L)^{\frac{\tau}{\rho}}}$. After trade, the world price of manufactures is $\dfrac{(\rho+\tau)^{1+\frac{2\tau}{\rho}}}{\rho\tau^{\frac{2\tau}{\rho}}(\gamma(L+L^*))^{\frac{\tau}{\rho}}}$. The level of technology before trade is given by

$\left(\gamma L\left(\frac{\tau}{\rho+\tau}\right)^2\right)^{1/\rho}$. Let the value of ρ in Equation 5 be equal to 2 and the value of τ in Equation 6 be equal to 1/2. From Equation 8, the degree of internal returns to scale is the same as the degree of external increasing returns in Example 1. For the same set of parameter values used in Example 1, the total number of workers in the world employed in the manufacturing sector before and after trade is 180. The price of manufactures in the home country before trade is approximately 0.93. After trade, the price is approximately 0.20. As the price of manufactures decreases after trade, consumers in both countries gain from trade. Before trade, a firm's level of technology is 1.8. Each firm's technology level after trade is $6\sqrt{5}/5$.[11]

With external increasing returns, when the smaller country specializes in the production of agricultural goods, it loses from the opening of trade when the price of manufactures increases. The price of manufactures increases if the supply of manufactures decreases with the opening of trade. Suppose the degree of increasing returns to scale in the manufacturing sector is α. Before trade each country has γ per cent of its labor force employed in the manufacturing sector. If the larger country specializes completely in the manufacturing sector after trade, the larger country (the foreign country) increases its manufacturing sector output from $(\gamma L^*)^\alpha$ to $(L^*)^\alpha$. The smaller country decreases its manufacturing sector output from $(\gamma L)^\alpha$ to zero. The supply of manufactures increases if $(\gamma L)^\alpha + (\gamma L^*)^\alpha < (L^*)^\alpha$. Since α is larger than one, a sufficient but not necessary condition for this inequality to be valid is that $\gamma L + \gamma L^* < L^*$. That is, if the labor endowment of the larger country is higher than the sum of the workers in the world employed in

[11] In this example, the number of firms before trade in the home country is five. The total number of manufacturing firms in the world after trade is also five. The opening of trade leads to merger and/or exit of manufacturing firms. For these remaining manufacturing firms, their employment and output increase after the opening of trade.

the manufacturing sector before trade, then the world price of manufactures with trade will decrease. Thus, the labor endowment of the larger country is higher than the sum of workers in the world employed in the manufacturing sector before trade is a sufficient condition for the smaller country to benefit from trade.

This sufficient condition can be used to illustrate the three conditions in Ethier (1982). When a small country trades with a large country, the small country is more likely to benefit from trade if: First, countries differ significantly in terms of their sizes; Second, the percentage of income spent on manufactures is relatively small; Third, the degree of returns to scale is large. The three conditions can be understood as follows. First, when the size of the labor force in the smaller country is sufficiently smaller than that in the larger country, the world number of workers employed in the manufacturing sector with trade is less likely to be lower than that before trade since the reduction of the manufacturing sector workers in the smaller country has a limited impact on the world employment in the manufacturing sector.

Second, when the percentage of income spent on manufactures decreases, the total number of workers employed in the manufacturing sector decreases. More concretely, if the percentage of income spent on manufactures is lower than fifty per cent, then the percentage of workers employed in the manufacturing sector in each country before trade will be lower than fifty percent. Thus, the sum of the number of workers in the manufacturing sector before trade is always smaller than the labor endowment of the larger country. The sufficient condition is satisfied and the smaller country always benefits from trade.

Third, when the degree of increasing returns is high, even if world employment in the manufacturing sector decreases, the price of manufactures may not increase as the number of workers in the larger country employed in the manufacturing sector increases. If the degree of increasing returns is sufficiently high, this will make up the level of manufactured output produced by the smaller country. The reason behind this is as follows. The ratio between $(L^*)^{\alpha} - (\gamma L^*)^{\alpha}$ and $(\gamma L)^{\alpha}$ is equal to $\left(\frac{1-\gamma^{\alpha}}{\gamma^{\alpha}}\right)\left(\frac{L^*}{L}\right)^{\alpha}$. Since $\gamma < 1$ and $L^* > L$, this ratio increases with α.

Under internal increasing returns, it is impossible for the price of manufactures to increase with the opening of trade because the smaller country is still able to produce manufactures at its autarky price.

In reality, both external and internal increasing to returns are common. Without the existence of external increasing returns, it will be difficult to explain the concentration of firms producing similar products in given regions, such as the concentration of research intensive firms in Silicon Valley. The geographic concentration of industries is greatly emphasized by Porter (1990). For internal increasing returns, the existence of fixed costs is also well recognized in the literature. Which type of returns to scale is stronger may depend on the conditions within specific industries. While internal returns to scale may be stronger for dispersed industries characterized by large firms, external returns to scale may be stronger for concentrated industries with small firms.

6. The Impact of a Tariff

Does the existence of increasing returns to scale justify governmental invention? In this section, we examine the impact of a tariff imposed by the home country.[12] With the existence of a tariff, a general equilibrium model with a general utility function becomes less tractable. We proceed by using the specific utility function introduced in Section 5.[13] Assume that the two countries have access to the same production technologies specified in Section 2.

[12] Yu and Choi (1991) study the theory of tariffs under variable returns to scale and inter-industrial externalities. Brander (1995) has a survey of the literature on various policies a government may adopt to promote national welfare when strategic interaction among domestic and foreign firms is important.

[13] Yu (2005) provides an illustration of the limitations of a specific utility function.

Since the home country is smaller than the foreign country, it imports manufactures. Suppose the home country charges a per unit tariff of t on the import of manufactures. Let I denote the home country's quantity of imported manufactures. With the existence of a tariff, prices of manufactures are different in different countries. Manufacturing firms in different countries may produce different levels of output and use different technologies. When both countries produce both goods, together with Equations 2, 9, 14, and 14*, the following equations are valid in an equilibrium.

First, a foreign firm's optimal choice of technologies leads to

$$f^{*\prime}+\beta^{*\prime}x^{*}=0. \tag{2*}$$

Second, zero profit for a foreign manufacturing firm leads to

$$p_m{}^{*}x^{*}-(f^{*}+\beta^{*}x^{*})=0. \tag{9*}$$

Third, a domestic manufacturing firm's optimal choice of output yields

$$p_m\left(1-\frac{x}{mx+m^{*}x^{*}}\right)=\beta\ . \tag{39}$$

A foreign manufacturing firm's optimal choice of output yields

$$p_m{}^{*}\left(1-\frac{x^{*}}{mx+m^{*}x^{*}}\right)=\beta^{*}. \tag{39*}$$

The derivation of Equations 39 and 39* is similar to that of Equation 16. Equations 39 and 39* show that a firm's price as a markup over its marginal cost increases with this firm's market share. This is intuitive as a firm's market share is directly related to a firm's degree of monopoly power.

Fourth, as the wage rate is equal to one, the total income in the home country is $L+tI$ and the total income in the foreign country is L^{*}. Since $1-\gamma$ per cent of income is spent on agricultural goods, the world demand for agricultural goods is $(1-\gamma)(L+tI+L^{*})$. The world supply of agricultural goods is $L_a+L_a{}^{*}$. Clearance of market for agricultural goods requires that

$$(1-\gamma)(L+tI+L^{*})=L_a+L_a{}^{*}. \tag{40}$$

For the home country, the demand for manufactures is $\gamma(L+tI)$ and the value of supplied manufactures is $p_m(mx+I)$. Clearance of market for manufactures in the home country requires that

$$\gamma(L+tI)=p_m(mx+I). \tag{41}$$

Similarly, clearance of market of manufactures in the foreign country requires that

$$\gamma L^* = p_m{}^*(m^*x^* - I). \tag{41*}$$

Finally, with the tariff imposed by the home country on manufactures, the relationship between prices of manufactures in the two countries is given by

$$p_m = (1+t)p_m{}^*. \tag{42}$$

Equations 2, 2*, 9, 9*, 14, 14*, 39, 39*, 40, 41, 41*, and 42 form a system of twelve equations defining twelve variables I, p_a, p_m, $p_m{}^*$, m, m^*, x, x^* L_a, $L_a{}^*$, n, and n^*. Simplification of this system of equations yields

$$G_1 \equiv \frac{\gamma(p_m{}^* - \beta^*)^2}{(p_m{}^*)^2}\left(\frac{1}{1+t}L + L^*\right) - f^* = 0, \tag{43}$$

$$G_2 \equiv -f' - \beta' f/(p_m - \beta) = 0, \tag{44}$$

$$G_3 \equiv -\frac{\beta^{*\prime} f^*}{\frac{1}{1+t}p_m - \beta^*} - f^{*\prime} = 0. \tag{45}$$ [14]

Equations 43-45 define three variables p_m, n, and n^* as functions of the exogenous parameter t. The interpretation of Equation 43 is similar to that of Equation 37. Equation 43 is the zero

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[14] Equation 43 is derived in four steps. First, from Equation 9, x can be expressed as a function of $p_m{}^*$ and n. Similarly, x^* can be expressed as a function of $p_m{}^*$ and n^*. Second, from Equations 39 and 41, I can be expressed as a function of $p_m{}^*$ and mx. Third, by plugging this value of I into Equations 39* and 41*, mx and m^*x^* are expressed as functions of $p_m{}^*$ and n. Finally, values of mx and m^*x^* are plugged into Equations 14, 14*, and 40 to get Equation 43. Equation 44 is derived from Equations 2 and 9. Equation 45 is the counterpart of Equation 44 for the foreign country.

profit condition for a foreign manufacturing firm. With the special utility function 38, the elasticity of demand ε is equal to γ. With the existence of a tariff, for a foreign firm, the impact of an increase of $1+t$ units of labor in the home country is similar to that of an increase of one unit of labor in the foreign country. Thus, the relevant market size for a foreign firm is $\frac{1}{1+t}L+L^*$. The interpretations of Equation 44 and 45 are similar to the interpretation of Equation 36.

The following proposition studies the impact of an increase of the home country's tariff rate.

PROPOSITION 3. If the home country increases its tariff rate, then the home country's terms of trade improve and manufacturing firms in the foreign country adopt more advanced technologies.

PROOF. Total differentiation of the system of equations 43-45 with respect to p_m, n, n^*, and t leads to

$$\begin{pmatrix} \frac{\partial G_1}{\partial p_m^*} & \frac{\partial G_1}{\partial n} & 0 \\ \frac{\partial G_2}{\partial p_m^*} & \frac{\partial G_2}{\partial n} & 0 \\ \frac{\partial G_3}{\partial p_m^*} & 0 & \frac{\partial G_3}{\partial n^*} \end{pmatrix} \begin{pmatrix} dp_m^* \\ dn \\ dn^* \end{pmatrix} = \begin{pmatrix} -\partial G_1/\partial t \\ 0 \\ -\partial G_3/\partial t \end{pmatrix} dt . \tag{46}$$

Let Δ_G denote the determinant of the coefficient matrix. Stability requires that $\Delta_G < 0$. Define $\Delta_G^{p_m^*} \equiv -\frac{\partial G_1}{\partial t}\frac{\partial G_2}{\partial n}\frac{\partial G_3}{\partial n^*}$, and $\Delta_G^{n^*} \equiv \frac{\partial G_1}{\partial t}\frac{\partial G_2}{\partial n}\frac{\partial G_3}{\partial p_m^*}$. From Equations 43-45, $\Delta_G^{p_m^*} > 0$, and $\Delta_G^{n^*} < 0$. Application of Cramer's rule to the system 46 yields

$$\frac{dp_m^*}{dt} = \frac{\Delta_G^{p_m^*}}{\Delta_G} < 0, \tag{47}$$

$$\frac{dn^*}{dt} = \frac{\Delta_G^{n^*}}{\Delta_G} > 0\,. \tag{48}$$

QED.

Proposition 3 shows that the standard result that the imposition of a tariff by a country may lead to a terms of trade gain is robust to this model with endogenous choice of technologies. This terms of trade gain is also present in Horstmann and Markusen (1986). A more detailed discussion on how the imposition of a tariff may improve a country's terms of trade is available in Markusen et al. (1995, Chapter 15).

As the price of manufactures decreases, the foreign country's terms of trade deteriorate. However, a consumer in the foreign country is not harmed by the home country's imposition of a tariff. This can be demonstrated as follows. Since the wage rate and the price of agricultural goods do not change, a foreign consumer's utility increases with a decrease of the price of manufactures. A tariff also leads foreign firms to adopt more advanced technologies. This decreases a foreign firm's average cost of production and it explains why the foreign country is not harmed by the tariff.

As discussed in Eaton and Grossman (1986), an export subsidy may be difficult to implement in this type of models with integrated market for manufactures. Even if a country is able to implement an export subsidy for manufactures, there is no strong reason for this country to subsidize the export of this product. Since each firm earns no pure profit, making domestic firms more aggressive does not transfer any profit from foreign firms to domestic firms. In addition, an export subsidy may lead to a deterioration of the terms of trade of this country and an increase in government expenditure to fund the subsidy.

7. Conclusion

This paper studies the implications of international trade in a two-sector general equilibrium model based on microfoundations. We show that the production function generated from internal increasing returns and the choice of technology leads to returns to scale similar to those based on external increasing returns. The opening of international trade always increases a country's welfare in a model in which the agricultural sector has constant returns to scale and average cost in the manufacturing sector may decrease without being bounded asymptotically. Other than the well-recognized terms of trade effect, increasing returns to scale do not bring a new justification for a country to protect its manufacturing sector. Why a small country may lose from trade under external increasing returns is also illustrated.

This model may be extended in several directions. First, to understand how the opening of trade may increase the number of varieties in the manufacturing sector, the model may be generalized to the case that firms in the manufacturing sector produce differentiated rather than homogenous products. Second, to study the impact of differences in countries' factor endowments, the model may be extended to the case with two or more factors of production. Third, to address the exit of less efficient firms in the manufacturing sector, the case that firms within a country may differ in their productivities may be studied. Finally, the model may be extended to a dynamic setup with physical or human capital accumulation. During the process of capital accumulation, firms may keep on adopting more advanced technologies. The interaction between international trade and capital accumulation is an interesting topic for future research.

Appendix: The stability of the system of Equations 17-19

In this appendix, we show that the stability of the system of Equations 17-19 requires that $\Delta < 0$. First, we focus on the system of equations with Equations 18 and 19 only. Following the approach used in Samuelson (1947, Chapter 9), we assume that the level of technology increases if the marginal benefit is higher than the marginal cost. This assumption is reasonable in the sense that it resembles the standard argument that a firm increases its level of output if the marginal revenue is higher than the marginal cost. Since the marginal benefit of adopting a more advanced technology is the saving of marginal cost $-\beta' x$ and the marginal cost is the increased fixed cost f', the level of technology increases if $-\beta' x - f' > 0$, or $-f'(p_m - \beta) - \beta' f > 0$. We also assume that Equation 19 always holds. Let a dot over a variable denote its time derivative. Thus, the evolution of the system is given by

$$\dot{n} = -\beta' f / (p_m - \beta) - f', \tag{A1}$$

$$(p_m - \beta)^2 \frac{\varepsilon L c_m}{p_m} - f = 0. \tag{A2}$$

Let λ_1 denote a characteristic root for the system A1-A2. Thus, the value of λ_1 is defined by

$$\begin{vmatrix} \dfrac{\partial V_2}{\partial p_m} & \dfrac{\partial V_2}{\partial n} - \lambda_1 \\ \dfrac{\partial V_3}{\partial p_m} & \dfrac{\partial V_3}{\partial n} \end{vmatrix} = 0.$$

This leads to

$$\begin{vmatrix} \dfrac{\partial V_2}{\partial p_m} & \dfrac{\partial V_2}{\partial n} \\ \dfrac{\partial V_3}{\partial p_m} & \dfrac{\partial V_3}{\partial n} \end{vmatrix} + \lambda_1 \frac{\partial V_3}{\partial p_m} = 0. \tag{A3}$$

For the system A1-A2 to be stable, we need $\lambda_1 < 0$. From A3, since $\partial V_3 / \partial p_m > 0$, stability of the system A1-A2 requires that

$$\begin{vmatrix} \dfrac{\partial V_2}{\partial p_m} & \dfrac{\partial V_2}{\partial n} \\ \dfrac{\partial V_3}{\partial p_m} & \dfrac{\partial V_3}{\partial n} \end{vmatrix} > 0. \tag{A4}$$

Second, we study the system of three equations 17-19. We assume that the consumption of manufactured goods increases if the marginal utility per dollar from purchasing manufactured goods is higher than the marginal utility per dollar from purchasing agricultural goods. That is, c_m

increases if $U_m / p_m > U_a$, or $U_m - p_m U_a > 0$. We also assume that Equations 18 and 19 are always in equilibrium. Thus, the evolution of the system is given by

$$\dot{c}_m = U_m(1 - p_m c_m, c_m) / p_m - U_a(1 - p_m c_m, c_m), \tag{A5}$$

$$0 = -\beta' f / (p_m - \beta) - f', \tag{A6}$$

$$0 = (p_m - \beta)^2 \frac{\varepsilon L c_m}{p_m} - f. \tag{A7}$$

Let λ_2 denote a characteristic root for the system A5-A7. Thus, the value of λ_2 is defined by

$$\begin{vmatrix} \frac{\partial V_1}{\partial c_m} - \lambda_2 & \frac{\partial V_1}{\partial p_m} & 0 \\ 0 & \frac{\partial V_2}{\partial p_m} & \frac{\partial V_2}{\partial n} \\ \frac{\partial V_3}{\partial c_m} & \frac{\partial V_3}{\partial p_m} & \frac{\partial V_3}{\partial n} \end{vmatrix} = 0.$$

This leads to

$$\Delta - \lambda_2 \begin{vmatrix} \frac{\partial V_2}{\partial p_m} & \frac{\partial V_2}{\partial n} \\ \frac{\partial V_3}{\partial p_m} & \frac{\partial V_3}{\partial n} \end{vmatrix} = 0. \tag{A8}$$

Stability of the system A5-A7 requires that $\lambda_2 < 0$. From A4, A8, since $\lambda_2 < 0$, stability of the system A5-A7 requires that $\Delta < 0$.

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