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Population, technological conversion, and optimal environmental policy

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Abstract We consider an economy comprising two production sectors. A manufactured goods sector emits environmental pollutants during production. The other sector is an agricultural goods sector producing with constant returns to scale. It is used as numeraire. In our model, moreover, it is possible for the firms in the manufactured goods sector to select the production technology of intermediate goods out of two technologies: a "classical technology" with constant returns to scale or "modern technology" with increasing returns to scale. We explain the environmental Kuznets curve, which is described in many empirical studies of environmental economics, by using our theoretical model and show some relations between the technological conversion and the generating factor of the environmental Kuznets curve. Moreover, we consider a case in which a population can move freely between regions and in which this technological conversion affects the population distribution in the long run.

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1 Introduction

Many kinds of industries or population agglomerate in particular cities or regions as a result of various economic influences. Although many studies of international

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economics analyze the movement of goods between regions or countries, most have ignored the spatial factor to avoid analyzing the models in spite of its importance.

Many studies of international economics and urban economics have introduced increasing returns to scale into their own models since Dixit and Stiglitz (1977) constructed the monopolistic competition model. The monopolistic competition model allows us to deal with increasing returns to scale in the economics model. It contributes to an explanation of agglomeration of firms or households in particular cities or regions. One pioneering study among them is one by Krugman (1991), which shows the importance of the relation between the transportation cost of goods and a variety of differentiated goods for their agglomeration. Abdel-Rahman and Fujita (1990) described the effect of Marshallian externalities on population distribution among regions. Moreover, Krugman and Elizondo (1996) extended Krugman (1991) to a three-country model and inferred the possibility of agglomeration into one region when a government, which has two regions in the same country, relaxes a tariff to a third country. Fujita et al. (1995) analyzed these core-periphery models and its applied model in detail. They explain the endogenous agglomeration mechanism because of the increase of variety of differentiated goods and transportation cost. They show that agglomeration of population engenders technological progress or the division of the production process and contributes to the increase of real wages and the standard of living. Moreover, such a system attracts more population in one region.

In contrast, many investigators have presented studies that have examined industrialization. One exemplary paper among them was presented by Murphy et al. (1989). They showed that some big push is required to achieve industrialization as some production level induces firms to convert from technology with constant returns to scale to that with the increasing returns to scale. Bjorvatn (2000) introduces the infrastructure to bring increasing returns to scale into his model and discusses the effect of such infrastructure on urban industrialization.

Yamamoto (2005) introduces the concept of industrialization into the core-periphery model. Yamamoto (2005) assumes that manufactured goods firms have the possibility of choosing classical technology with constant returns to scale or modern technology with increasing returns to scale. Under this situation, if the number of households in one region is relatively small, the manufactured goods firms choose not the modern technology, but the classical technology because the marginal production cost of manufactured goods using the modern technology is higher than the marginal cost of using the classical technology. On the other hand, if numerous households agglomerate there, the marginal production cost of manufactured goods with modern technology is lower than that using the classical technology. Moreover, he considers that the pattern of agglomeration between regions or the technology determined by firms endogenously.[1]

We extend Yamamoto (2005) by introducing environmental factors into the manufacturing sector. This extension is not discussed in Yamamoto (2005), which allows the introduction of an original feature presented in this paper. Regarding the determination

[1] His model follows the core-periphery model, which is presented by Krugman (1991), Fujita et al. (1995) and so on, fundamentally. Moreover designates technology with constant returns to scale as "cottage technology".

of technology used by manufactured goods firms, we use the framework constructed by Yamamoto (2005) that technology chosen by manufactured goods firms depends on the distribution of population which is determined in migration equilibrium. However, we discuss the government's environmental policy with regard to pollution because our model includes the problem of environmental pollution created by the production sector.

We show that technological conversion caused by agglomeration affects the government's environmental policy. The manufacturing sector produces its goods with classical technology, which has constant returns to scale when the population in one region is relatively small. The production per capita engenders decreasing returns to scale for labor. Therefore, presuming that other conditions are constant, the production per capita tends to decrease concomitant with the increase of population. The government adopts a policy that relaxes restrictions on environment and induces the manufactured goods sector to increase its production, to make up for the shortfall in production per capita because of the population increase. On the other hand, the manufactured goods sector chooses more effective modern technology that has increasing returns to scale when the population is relatively large. Because the manufacturing sector chooses the modern technology with increasing returns to scale, the production per capita increases as the population increases under the situation that other conditions are constant. The government must reinforce the optimal constrain for environment because this situation affords regulation of environmental pollution. This analysis demonstrates that the optimal environmental policy required in such a region is changed because of the conversion of production technology caused by agglomeration. We infer that the relation between population and pollution is similar to the Environmental Kuznets Curve under appropriate parameters.

The Environmental Kuznets Curve represents the relation between income and the pollution that many environmental economists have noted since a study by the World Bank (1992) presented it. The shape of the Environmental Kuznets Curve is an inverted U-shape. Presuming that this relation is satisfied, environmental regulation works and allows sustainable economic growth. John and Pacchenino (1994), Seldon and Song (1995), and Stokey (1998) are some theoretical studies that have addressed the Environmental Kuznets Curve. On the other hand, Grossman and Krueger (1995) and Ikazaki (2002) consider an empirical analysis. Ikazaki (2002) presented the relation between GDP per capita and NOx emission (see Fig. 1). His analytical results are similar to the Environmental Kuznets Curve. Agglomeration engenders more efficient technology, which consequently allows the government to create stricter regulations. Thereby, it is possible to decrease pollution emissions under an optimal policy for the environment. Many studies have analyzed this Environmental Kuznets Curve using empirical methods, but few papers have analyzed it using theoretical models and thereby clarified the relation between the population and the pollution. This point is an original task presented in this paper.

This paper is organized along the following lines. First, we present a basic model of a two sector-one region economy and describe the respective behaviors of the sectors. Section 3 analyzes the conversion of technology in the manufactured goods sector and discusses the optimal environmental policy. Moreover, we describe the relation between the population and the pollution level in this section. Finally, we conclude

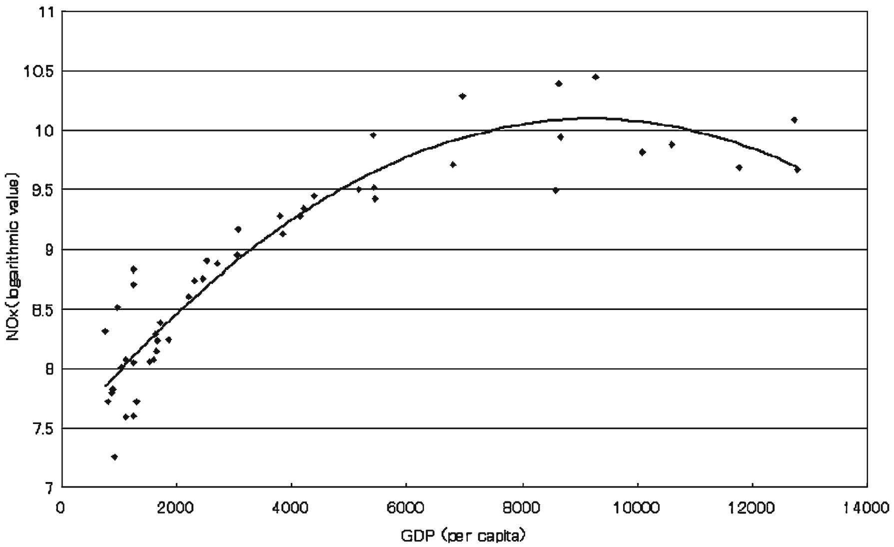

Fig. 1 NOx and GDP: Ikazaki (2002)

this paper and present some points that we do not discuss in the text and suggest some that remain as future subjects for examination.

2 The model

2.1 Production sector

2.1.1 Final goods sector

We consider two final goods. One of them is the manufactured good labeled good 1. The other is an agricultural good labeled good 2. The markets for both goods are perfectly competitive. Pollution is produced with jointly with good 1. Following Copeland and Taylor (1994), (1999), and Stokey (1998), we assume that the output of good 1 can be written as a function of pollution and effective input (in our model, labor). We establish the production function of good 1 as

$$Y_1 = AM^{\alpha}D^{1-\alpha}, \tag{1}$$

where Y_1, M, D, and A, respectively, indicate the output of manufactured goods, the input as intermediate goods, the pollution level, the parameter of productivity in good 1. The parameter α is assumed as $0 < \alpha < 1$. Note that the production function of good 1 is analytically equivalent to treating pollution as an input that can be substituted for M in the production of good 1.

Manufactured goods production requires intermediate goods as input factors. Although labor is the only input factor to produce intermediate goods, it is possible for the manufactured goods sector to choose the classical technology or modern technology to produce them. Presuming that the manufactured goods sector selects the classical technology, the intermediate goods M is produced with the constant returns to scale respect to labor. The other technology (modern technology) requires the differentiated intermediate goods as input factor. We follow Yamamoto (2005) to establish this technology. Modern technology, with its increasing returns to scale, is described by the Dixit and Stiglitz type monopolistic competition model.

Agricultural goods are produced with constant returns to scale and require only labor as an input. We assume that one unit of labor is transformed into one agricultural goods. Furthermore, we assume that mobility between labor sectors is free. Therefore, the wages of unit labor are equal among all sectors.

2.1.2 Intermediate goods sector

Manufactured goods require M as input. Two technologies can produce intermediate goods. To begin with, we consider the case in which the manufactured goods sector produces intermediate goods M by the classical technology with constant returns to scale. We assume that production of a unit of M requires a_c units of labor. We assume that the market for M is perfectly competitive. Let p_c represent the price of intermediate goods produce using classical technology.[2] Presuming that intermediate goods M are produced with this technology, the intermediate goods price is

$$p_c = a_c w, \tag{2}$$

where w indicates the wage rate per unit of labor.

Next we consider the case that M is produced using modern technology with increasing returns to scale. Presuming that the manufactured goods sector chooses the modern technology, M is produced from inputs of the differentiated goods. In this case, the intermediate goods market is a monopolistic competition model as conceptualized by Dixit and Stiglitz (1977). Thus, the production function of M with the modern technology is as follows:

$$M = \left(\int_0^n z_i^{\frac{\sigma-1}{\sigma}} \mathrm{d}i \right)^{\frac{\sigma}{\sigma-1}}, \tag{3}$$

where n denotes the measure (number)[3] of the available intermediate goods, and z_i $(i \in [0, n])$ is the quantities of ith intermediate goods used at production activities. The parameter σ is assumed as $\sigma > 1$. We consider the following cost minimization

[2] Subscript c denotes the level of classical technology throughout this paper.

[3] We assume the product space of the intermediate goods to be continuous rather than discrete and ignore integer constraints on the number of goods.

problem to derive the factor demand function of the manufactured goods sector:

$$\min_{z_i} \int_0^n p_i z_i \mathrm{d}i \quad \text{s.t.} \quad M = \left(\int_0^n z_i^{\frac{\sigma-1}{\sigma}} \mathrm{d}i \right)^{\frac{\sigma}{\sigma-1}} \tag{4}$$

where p_i $(i \in [0, n])$ is the price of ith intermediate good. Solving this minimization problem, the factor demand z_i is the following equation when M is given:

$$z_i = M \left(\frac{p_i}{G} \right)^{-\sigma}, \tag{5}$$

where $G \equiv \left(\int_0^n p_i^{1-\sigma} \mathrm{d}i \right)^{\frac{1}{1-\sigma}}$. G is the minimum cost to produce one unit of intermediate goods M; it is the marginal cost with respect to M for the manufactured goods sector. Note that G is regarded as the price of M when M is produced by the modern technology.

Next, we consider the supply side of the intermediate goods. We assume that the only input factor of z_i is labor. The input factor includes both the marginal labor input (a_m), which depends on output, and fixed labor input (f), which is independent in output. Under this setting, the profit of each differentiated good is given by

$$\pi_i = p_i z_i - w(a_m z_i + f). \tag{6}$$

Because the number of firms is large under the monopolistic competition market, neither firm's behavior affects the price index of the intermediate goods market. Therefore, we can derive the price of each intermediate goods which comprise marginal cost because the elasticity of derived demand of intermediate goods is approximated by the elasticity of substitution between varieties. That is,

$$p_i = \left(\frac{\sigma}{\sigma - 1} \right) a_m w. \tag{7}$$

We can simplify this price without a loss of generality by setting $a_m = (\sigma - 1)/\sigma$ and rewrite p_i as $p_i = w$. Moreover, the zero-profit condition implies that the equilibrium output of each firm is

$$z^* = f\sigma. \tag{8}$$

Finally we determine the number of intermediate goods firms using modern technology. Let L_m represent the labor working in the manufactured goods sector. In that case, the number of intermediate goods firms is determined as follows:

$$n^* = \frac{L_m}{f\sigma}. \tag{9}$$

Therefore, when intermediate goods are produced using modern technology, the cost per unit of M is given as

$$(n^*)^{\frac{1}{1-\sigma}} w = \left(\frac{L_m}{f\sigma}\right)^{\frac{1}{1-\sigma}} w. \tag{10}$$

2.2 Pollution emission

Production function (1) means that pollution is emitted in spite of the production technology chosen by this sector. Because the manufactured goods sector always emits pollution in production, they must pay an emission tax to the government.[4] We denote the tax rate as τ. So, the total cost of pollution is given as τD. The production function of manufactured goods indicates that the more pollution increases under the situation where other conditions are constant, the more production increases. Consequently, if no taxation exists for the environment, the manufactured goods sector increases output and the pollution emission without bound.

2.3 Cost of manufactured goods

Recall our assumption that the manufactured goods sector is perfectly competitive. Thereby, the manufactured goods price is equal to the marginal cost. The intermediate goods price is given as $p_c = a_c w$ when the classical technology is chosen. Considering the shape of the production function, the marginal cost of manufactured goods under the classical technology C'_c is given as

$$C'_c(Y_1) = A^{-1}\left(\frac{p_c}{\alpha}\right)^{\alpha}\left(\frac{\tau}{1-\alpha}\right)^{1-\alpha}. \tag{11}$$

We can rewrite (11) as

$$C'_c(Y_1) = A^{-1}\left(\frac{1}{\alpha^{\alpha}(1-\alpha)^{1-\alpha}}\right)\tau^{1-\alpha}(a_c w)^{\alpha}. \tag{12}$$

On the other hand, the marginal cost of manufactured goods produced by modern technology is derived from the shape of the production function as follows:

$$C'_m(Y_1) = A^{-1}\left(\frac{G}{\alpha}\right)^{\alpha}\left(\frac{\tau}{1-\alpha}\right)^{1-\alpha}. \tag{13}$$

[4] We can strictly interpret this tax rate as the emission rights fee.

Substituting (10) for (13), we can rewrite C'_m as follows:

$$C'_m(Y_1) = A^{-1}\left(\frac{1}{\alpha^\alpha(1-\alpha)^{1-\alpha}}\right)\tau^{1-\alpha}\left(\frac{L_m}{f\sigma}\right)^{\frac{\alpha}{1-\sigma}} w^\alpha. \tag{14}$$

2.4 Technology choice

We take the price of agricultural goods numeraire. That is, the price of good 2 is normalized to unity. It means that the wage rate also becomes one because one unit of labor is transformed to one agricultural goods. The cost functions of manufactured goods are as follows.

$$C'_c(Y_1) = A^{-1}\left(\frac{1}{\alpha^\alpha(1-\alpha)^{1-\alpha}}\right)\tau^{1-\alpha}(a_c)^\alpha \tag{15}$$

$$C'_m(Y_1) = A^{-1}\left(\frac{1}{\alpha^\alpha(1-\alpha)^{1-\alpha}}\right)\tau^{1-\alpha}\left(\frac{L_m}{f\sigma}\right)^{\frac{\alpha}{1-\sigma}} \tag{16}$$

The manufactured goods sector adopts less technology than the other. For that reason, the following condition must be satisfied to produce goods with the modern technology:

$$\left(\frac{L_m}{f\sigma}\right)^{\frac{1}{1-\sigma}} \leq a_c. \tag{17}$$

Let L_m^* represent the critical point of indifference to both technologies:

$$L_m^* = f\sigma a_c^{1-\sigma}. \tag{18}$$

It is assumed that entries into the intermediate goods sector can be coordinated in the choice of technology, classical or modern. Simultaneous entries of firms into the intermediate goods sector are necessary for the start of the operation of modern technology.[5]

As depicted in Fig. 2, if the labor input into the manufactured goods sector is larger than L_m^*, the input factor M of manufactured goods is produced using modern technology with increasing returns to scale. Therefore we can derive the following lemma regarding this critical point L_m^*.

Critical point L_m^* causes technological conversion in the manufactured goods sector

- L_m^* is the decreasing function with respect to a_c.
- L_m^* is the increasing function with respect to the fixed cost of the modern technology.

[5] Saxenian (1994) reported that Stanford university played a role in the coordination of the developing process of Silicon valley.

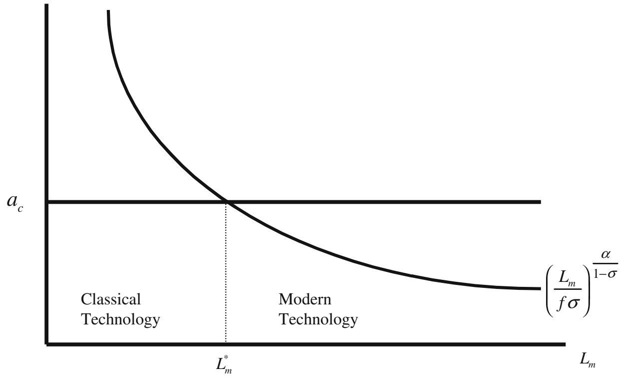

Fig. 2 Manufactured goods sectors' choice and technology

We have discussed the production side of manufactured goods and agricultural goods. Recall that intermediate goods prices with the classical technology and modern technology are denoted respectively by p_c and G. Since the manufactured goods market is competitive, the manufactured goods price is equal to the marginal cost. Then, we can obtain

$$p = \begin{cases} A^{-1}\gamma\tau^{1-\alpha}(a_c)^{\alpha} & \text{(Classical technology)} \\ A^{-1}\gamma\tau^{1-\alpha}\left(\frac{L_m}{f\sigma}\right)^{\frac{\alpha}{1-\sigma}} & \text{(Modern technology)} \end{cases} \tag{19}$$

where p is the price of good 1 and γ is defined as $\gamma \equiv \left(\frac{1}{\alpha^{\alpha}(1-\alpha)^{1-\alpha}}\right)$. Note that p also denotes the relative price because the price of good 2 is unity.

2.5 Household

We assume that all households in the region are homogeneous: all households have the same utility function. Each household has one unit of labor. That labor is supplied to the production sector to earn a wage income. Tax revenue from environmental tax is redistributed to households in the region. Next we specify each household's utility function as

$$U = \frac{(c_1^{\phi}c_2^{1-\phi})^{1-\theta} - 1}{1-\theta} - BD, \tag{20}$$

where c_1, c_2, and B, respectively, signify the manufactured goods consumption, agricultural goods consumption, and the damage parameter for pollution.[6] The parameters ϕ and θ are assumed as $0 < \phi < 1$ and $\theta > 0$. Let C_1 and C_2 represent the respective

[6] We consider the damage by social pollution, which is caused by manufactured goods sector, as a kind of public goods ('bads') with negative externality for residents in that region. Thus, the damage parameter B is common variable for all residents in the region.

aggregated demands of manufactured goods and agricultural goods. The aggregated demands of both goods are

$$C_1 = \frac{\phi I}{p}, \tag{21}$$

and

$$C_2 = (1 - \phi) I, \tag{22}$$

where I is defined by the following equation:

$$I \equiv wL + \tau D = L + \tau D$$

Here, L denotes the total population in this economy.

3 Technological conversion and environmental Policy

Initially, we consider autarky. Note that $C_1 = Y_1, \quad C_2 = Y_2$ is satisfied in autarky. The following equation is satisfied because of the consumption behavior of households:

$$(1 - \phi) p Y_1 = \phi Y_2.$$

Moreover, taking account of $\alpha p Y_1 = p_M M = vL, \quad Y_2 = (1 - v)L$, we obtain

$$\frac{pY_1}{Y_2} = \frac{vL}{\alpha(1 - v)L},$$

where $v \equiv L_m/L$. Note that v denotes the share of labor in manufactured goods sector to total population.[7] Consequently, we can obtain

$$v^a = \frac{\alpha\phi}{\alpha\phi + 1 - \phi} \tag{23}$$

where v^a denotes the level equilibrium values of v. Since the parameters $0 < \alpha < 1$ and $0 < \phi < 1$, then $v^a \in (0, \ 1)$. We understand that this v^a is less than unity. Therefore, we have derived the share of production sector endogenously.

3.1 The case in which classical technology is chosen

We next consider equilibrium under the situation in which the manufactured goods sector selects either the classical technology or the modern technology.

[7] The manufactured good sector includes the intermediate goods sector as an input factor of manufactured goods.

We consider here that the manufactured goods sector chooses the classical technology to produce the intermediate goods. We define the income and consumption of goods i $(i = 1,\ 2)$ per capita as follows:

$$y_i \equiv \frac{Y_i}{L},$$
$$c_i \equiv \frac{C_i}{L}.$$

Because $c_i = y_i \equiv \frac{Y_i}{L}$ is satisfied, the consumption of both goods is

$$\frac{C_1}{L} \equiv c_1 = A\left(\frac{v^a}{a_c}\right)^{\alpha} L^{\alpha-1} D^{1-\alpha} \tag{24}$$
$$\frac{C_2}{L} \equiv c_2 = 1 - v^a. \tag{25}$$

Substituting c_1, c_2 into the utility function, the utility level is given as

$$U = \frac{[A^{\phi}(\frac{v^a}{a_c})^{\alpha\phi} L^{(\alpha-1)\phi}(1 - v^a)^{1-\phi} D^{(1-\alpha)\phi}]^{1-\theta} - 1}{1-\theta} - BD. \tag{26}$$

As shown in Eq. (26), the households' utility level depends on the pollution level D. The government can control this pollution level by imposing an emission tax for pollution τ on the manufactured goods sector. Presuming that the government's purpose is to maximize the household's utility level, the government determines the optimal pollution level to maximize the household's utility level shown in Eq. (26). The pollution demand of the manufactured goods sector is determined by the cost minimization behavior of the manufactured goods sector and depends on the emission tax τ. On the other hand, the pollution supply (regulation level of pollution) is determined by the government's environmental policy. Therefore, the government establishes the emission tax τ where the pollution demand is equal to the desired regulation level of pollution. As a result, it maximizes the utility level of households (28) with respect to the pollution level D. We can therefore determine the optimal pollution level under the case in which the classical technology is chosen as follows.

$$D_c = \left[\frac{(1-\alpha)\phi}{B}\left(A^{\phi}\left(\frac{v^a}{a_c}\right)^{\alpha\phi} L^{(\alpha-1)\phi}(1 - v^a)^{1-\phi}\right)^{1-\theta}\right]^{\frac{1}{1+(\theta-1)(1-\alpha)\phi}}. \tag{27}$$

Finally we refer to the relation between the population and the price of manufactured goods, which is the relative price of the manufactured goods to the agricultural goods. Taking account the following relation, we know that $\tau = \frac{(1-\alpha)v^a L}{\alpha D}$:

$$\frac{p_c M}{\tau D} = \frac{w v^a L}{\tau D} = \frac{\alpha}{1-\alpha}.$$

Substituting the above equation and $w = 1$ into (12), we can derive the following equation:

$$p = \frac{a_c^{\alpha}}{A\alpha}\left(\frac{v^a L}{D}\right)^{1-\alpha}.$$

We can understand some facts from the above relation. First, p is the increasing function of L. Consequently, the population increases the demand of manufactured goods and increases their price. On the other hand, p is the decreasing function of the pollution D. This means that the more the manufactured goods sector can emit the pollution in the process of production, the more it can produce manufactured goods.

3.2 The case in which modern technology is chosen

We next consider the case in which the manufactured goods sector chooses the modern technology to produce the intermediate goods. As depicted in Fig. 2, the population must be relatively large to induce the manufactured goods sector to choose modern technology. We can derive the consumption per capita of both goods as the following because of the shape of utility function.[8]

$$\frac{C_1}{L} \equiv c_1 = A(v^a L)^{\frac{\alpha\sigma}{\sigma-1}}(f\sigma)^{\frac{-\alpha}{\sigma-1}} D^{1-\alpha} L^{-1}, \tag{28}$$

$$\frac{C_2}{L} \equiv c_2 = 1 - v^a. \tag{29}$$

Substituting Eqs. (28) and (29) into (20), the indirect utility function of households for the case in which modern technology is chosen is given as

$$U = \frac{\left[A^{\phi}(v^a)^{\frac{\alpha\sigma\phi}{\sigma-1}}(f\sigma)^{\frac{-\alpha\phi}{\sigma-1}} L^{\phi(\frac{\alpha\sigma}{\sigma-1}-1)}(1-v^a)^{1-\phi} D^{(1-\alpha)\phi}\right]^{1-\theta} - 1}{1-\theta} - BD.$$

The utility level is known to depend on the emission of pollution D as well. Because the government's purpose is to maximize the utility level of households, the optimal level of pollution, which the government determines, is

$$D_m = \left[\frac{(1-\alpha)\phi}{B}\left(A^{\phi}(v^a)^{\frac{\alpha\sigma\phi}{\sigma-1}}(f\sigma)^{\frac{-\alpha\phi}{\sigma-1}}(1-v^a)^{1-\phi}\right)^{1-\theta} L^{\phi(1-\theta)(\frac{\alpha\sigma}{\sigma-1}-1)}\right]^{\frac{1}{1+(\theta-1)(1-\alpha)\phi}}. \tag{30}$$

[8] Here, the only important point is that the production function with modern technology exhibits increasing returns with respect to labor input. Even if we assume $Y = L^{\beta} D^{1-\alpha}$ where $\beta > \alpha$, the resemble results can be obtained.

We again refer to the relation between population and the manufactured goods price. Taking $\tau = \frac{(1-\alpha)v^a L}{\alpha D}$ into account, the relative price is given as

$$p = \frac{(f\sigma)^{\frac{\alpha}{\sigma-1}}}{A\alpha}(v^a L)^{\frac{\sigma(1-\alpha)-1}{\sigma-1}} D^{\alpha-1}.$$

Note that p is the decreasing function of D. We can also show that p is the decreasing function of L if $\frac{\alpha\sigma}{\sigma-1} > 1$. We will discuss these parameter restrictions in Sect. 3 in detail.

In our model, the notation 'D' denotes the total pollution (see Eq. (1) and the definition of D). So, the total pollution is negatively correlated with population when population level is high. When population is large, the effect of increasing returns enables government to adopt strict environmental policy. If we consider per capita pollution, it decreases with population for all L. Note that the optimal value of total pollution is a concave function with respect to L when L is small (when cottage technology is adopted) and it decreases with L when L is large (when modern technology is adopted). Note also that when the population is large, per capita pollution decreases more drastically as population increases. When population level is relatively high (low), the improvement curve is steeper (gentler) than the population-growth curve.

3.3 Population and pollution

This section describes the relation between the population and pollution level. Here we define the total number of households with one unit of labor in one region as "population". The critical point to convert technology from classical technology to modern technology is denoted as (18). The classical technology is chosen when the population in the region is relatively small. Stated more strictly, the classical technology is chosen when the following condition is satisfied.

$$L^* < (v^a)^{-1} f\sigma a_c^{1-\sigma} \tag{31}$$

The optimal pollution D under the classical technology is an increasing function of population L. However, the technology to produce intermediate goods is converted from the classical technology to the modern technology when the population is larger than this critical point L^*. The optimal pollution D under the modern technology is a decreasing function of population L if $\theta > 1$ and $\frac{\alpha\sigma}{\sigma-1} > 1$. Thus, the optimal pollution level D may be an inverted-U shaped with respect to population L.

This relation is similar to the Environmental Kuznets Curve; it an inverted-U shape with respect to GDP. We are now able to provide the following intuitive connotation to such a conclusion. The manufactured goods sector chooses the classical technology to produce products when the population is relatively small. In this situation, the output of manufactured goods shows decreasing returns to scale with respect to labor input. Therefore, the output of this good per capita decreases as the labor input (population) increases under the condition that other inputs are constant. Government must relax the regulation regarding the environment with the increase in a population level to restrain such a reduction. However, the manufactured goods sector can choose the modern technology to produce goods when the population in the region is larger than the critical point L^*. Presuming that some parameters satisfy $\theta > 1$ and $\alpha\sigma/(\sigma - 1) > 1$, the manufactured goods sector has increasing returns to scale with respect to labor input. Consequently, the increase of population L increases the consumption level because of increasing returns to scale. Although the marginal utility of manufactured goods shrinks according to the increasing population or consumption level, the marginal disutility for pollution grows. For that reason, the government has an incentive to introduce a severe regulatory policy for pollution. The following proposition is suggested by the above analysis.

Proposition 1 *Presuming that* $\theta > 1$, $\frac{\alpha\sigma}{\sigma-1} > 1$ *is satisfied, the optimal pollution level increases with respect to the population, when* $L < L^*$. *On the other hand, the optimal pollution level decreases with respect to the population, when* $L > L^*$. *Therefore, the optimal pollution level* D *shows an inverted-U-shaped trace with respect to population* L.

Moreover, we can describe the relation between the optimal pollution and population due to Proposition 1.

We discuss the adequacy of these parameter restrictions. The restriction $\theta > 1$ seems to be reasonable if we review some growth models. For example, in typical growth models, the value of σ is assumed to be 1.5–2 (e.g., Lucas 1998; Barro and Sala-i-Martin 1995). This parameter restriction is also necessary to yield sustainable growth in the model of Stokey (1998) and Aghion and Howitt (1998, Chap. 5). Therefore, this parameter restriction seems to be reasonable.

The interpretation behind this conclusion is as follows. The large values of θ imply that marginal utility declines rapidly as c increases because θ is the elasticity of marginal utility. In other words, the marginal benefit of pollution declines rapidly as L increases (L is positively correlated with c when $L > (v^a)^{-1} L_m^*$). For that reason, it is valuable to regulate pollution strictly as L increases.

$\frac{\alpha\sigma}{\sigma-1} > 1$ is equivalent to $\alpha > \frac{\sigma-1}{\sigma}$. Here, α is the share of the effective input and $1 - \alpha$ is that of pollution. The definition of the share of the pollution is not easy. One conception is that it is regarded as expenditures on pollution abatement costs per GDP. As noted by Brock and Taylor (2005), these costs are small. They assert that many OECD countries devote 1.2–2.6% of GDP to pollution-abatement activities. Consequently, α is about 0.98 if we use this interpretation. If $\alpha = 0.98$, then $\frac{\alpha\sigma}{\sigma-1} > 1$ is equivalent to $\sigma < 50$. This restriction related to σ is reasonable in light of the literature related to urban economics, e.g. Fujita et al. (1995), which assumes $\sigma = 4$.

This relation is similar to the Environmental Kuznets Curve if we consider the population as directly reflecting the level of agglomeration or development in the region. Regarding the Environmental Kuznets Curve, many studies have attempted to elucidate it using empirical analysis. The difference between those numerous studies and the present examination regarding the Environmental Kuznets Curve is that technological conversion produces the Environmental Kuznets Curve in this study.

It is interesting to compare our model with that of Stokey (1998). Both models show an inverted-U-shaped relationship between effective inputs and pollution. However, the reasons underlying the conclusions are different. The Stokey model (1998) includes a limit to substitution possibilities based on the assumption that output is bounded above for a given effective input (e.g. physical capital). The marginal benefit of pollution is so large that pollution should not be regulated if physical capital is scarce. The optimal level of pollution corresponds to a corner solution. However, a critical point exists; if physical capital exceeds that point, then an environmental policy should be enforced because the marginal damage of pollution becomes serious. For large values of physical capital, pollution might decrease as physical capital increases if $\sigma > 1$. Consequently, the reason to yield the inverted-U-shaped relationship is the change to interior solution from a corner solution of optimal pollution levels.

In our model, we assume that the technological conversion which is induced by the population increment affects the optimal environmental policy. Production technology exhibits positive and diminishing marginal products with respect to labor if the population level is low. Per capita income decreases as population increases for a given value of D. For that reason, to compensate for this negative effect, the government must relax the environmental restrictions as population increases. On the other hand, if the population level is high, production technology exhibits increasing marginal products with respect to labor. In this case, the government can afford to regulate pollution because the marginal benefit of pollution is already high.

Finally, we assert that this inverted-U-shaped relationship between population and pollution is optimal. Whether this relationship is supported empirically or not remains an issue for further study.

4 Migration

4.1 Utility level and population level

We discussed technology conversion and the optimal environmental policy in the previous section. We also considered the manufactured goods sector with the emission of pollution in the process of production, the technological conversion of manufactured goods sector, and the optimal environmental policy enforced by the government. Results of that analysis showed that a derived relation between the pollution and the population forms an inverted-U shape with respect to population L. That relation resembles the Environmental Kuznets Curve, which many environmental economists have examined. We specifically examined the relation between the pollution level and the population in the preceding section. However, herein, we mainly describe the utility level and the population. The optimal pollution levels achieved using classical technology and modern technology are given respectively as D_c and D_m. Substituting D_c or D_m into the utility function, we derive the relation between the population and utility. Presuming that σ exists from 1 to $\frac{1}{1-\alpha}$ and $\theta > 1$, we know that the relation between the population level L and the utility level U is a U shape with respect to population L. Moreover, the top of the U curve is known to be consistent with the previously described crucial point, which illustrates the point of technological conversion chosen for the production of manufactured goods. We are therefore able to provide the following intuitive connotation to such a conclusion. The output per capita is a decreasing function with respect to the population. Furthermore, the pollution level

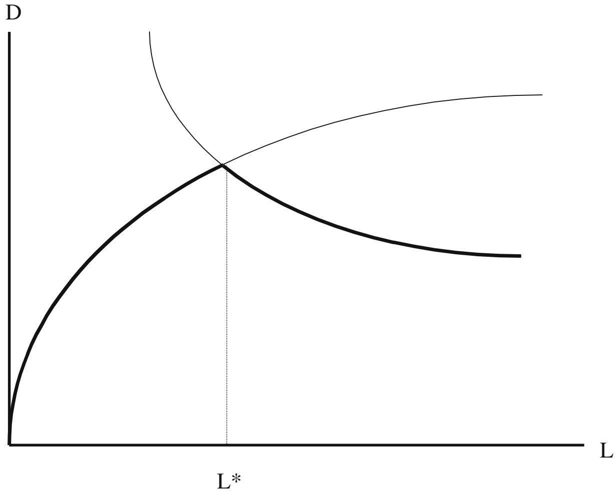

Fig. 3 The relation between the optimal pollution and population

is an increasing function with respect to the population in the region where the population is small and the classical technology is chosen. Consequently, the population and the utility level are negatively related if the population level is of this range. On the other hand, the output per capita has a positive relation to the population level because of the increasing returns to scale in the intermediate goods sector in this range. Moreover, the optimal pollution has a negative correlation to the population because it is possible for the government to adopt a stricter environmental policy with respect to pollution. Therefore, the relation between the population and pollution exhibits a U-shaped curve.

4.2 Migration between regions

We consider the migration between regions without the trade of goods, presuming that the relation between the population and the pollution follows the U-shaped curve.

4.2.1 The case in which other regions provide equal utility

Next the common utility level of households is established for other regions. Let U' represent that common utility level. This view is similar to the open city model. Households in a region consider this utility level U' as given (see Fig. 3). Presuming that the population given in initial stages is larger than L_1, the households in other regions have an incentive to migrate to this region because the utility level established in this region is higher than the U' of other regions. Moreover, the households there continue flowing into this region until the utility level established in this region is equal to the common utility level U'. Thereby, presuming that the initial population is given as between L_2 and $L_1 (L_2 < L < L_1)$, the households here have an incentive to migrate to other regions because the utility level established in this region is smaller

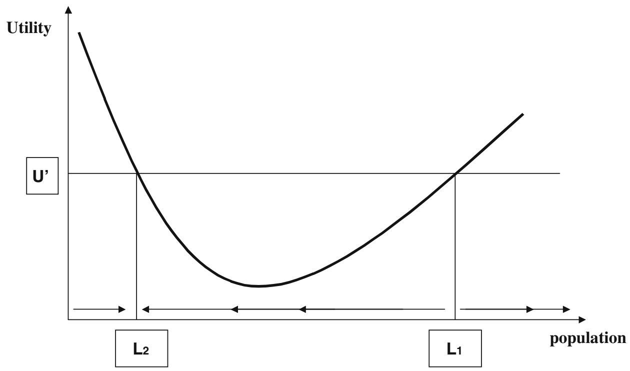

Fig. 4 The case in which the utility in other regions is U'

than the U' provided in other regions. In this manner, the outflow of households from this region continues until the population in this region is equal to L_2. Moreover, if the initial population is sufficiently close to L_1, it is possible to convert from the modern technology to the classical technology in the process of this outflow. Finally, presuming that the initial population is smaller than $L_2 (L < L_2)$, the utility level established in this region is higher than U' done in other regions. The households in other regions have an incentive to migrate to this region and the inflow of population continues until L_2 is achieved (Fig. 4).

4.2.2 The case with two symmetric regions

We have discussed the case in which the utility level in the other region does not change itself regardless of the population in one region. Hereafter, we consider a case with a two-region economy. Let $\overline{L}$ represent the total population in the economy composed by two regions. The change of population in one region alters the population in the other region. For that reason, the utility level in one region depends on that of the other. Moreover, we must note that two situations may occur as a result of a change in the total population. One situation can result from a total population that is relatively large. Strictly speaking, the critical point to convert the technology type is smaller than $\overline{L}/2 = L_1$. We can describe this situation as that in Fig. 5. Three equilibria exist in this case. One symmetric equilibrium posits that both regions have equal population. As shown in Fig. 5, this symmetric equilibrium is unstable. On the other hand, we know that others are stable from the same figure. Consequently, it is easy to reach an equilibrium that is not uniform.

Next we consider the case in which the total population is relatively small. Strictly speaking, this is the case in which the crucial point of technological conversion is larger than $\overline{L}/2 = L_1$. It has already been established in this study that a symmetric equilibrium is unique stable equilibrium. The symmetric equilibrium is unstable in the case in which total population is relatively large (see Fig. 6).

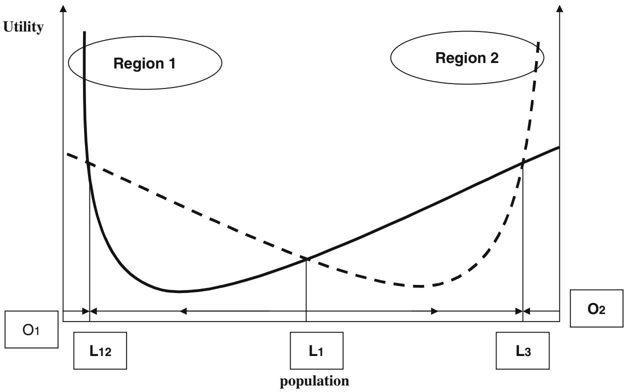

Fig. 5 The case in which the total population is relatively large

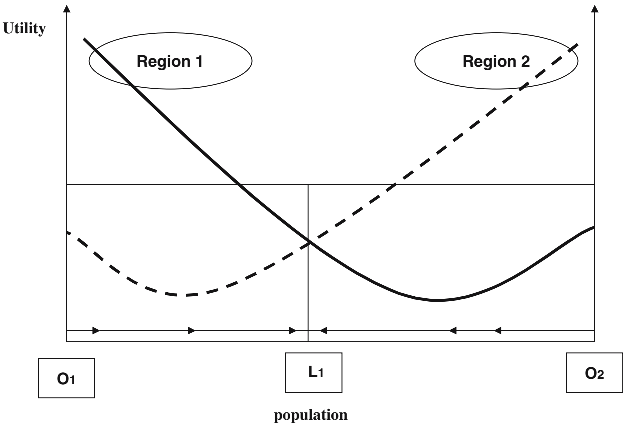

Fig. 6 The case in which total population is relatively small

5 Concluding remarks

This paper examined a simple general equilibrium model with a manufactured goods sector and an agricultural goods sector. It was extended on some points of view. One is that the manufactured goods sector emits some amount of pollution during production. That pollution damages the environment, thereby affecting the households' utility. Another salient point that it is possible for the manufactured goods sector to choose technology that is used to produce intermediate goods in this framework. No model includes pollution emissions caused by the manufactured goods sector in the studies of Krugman (1991) and others. We adopt the framework that Murphy et al. (1989) or Yamamoto (2005) constructed for examination of technological conversion. However, in the framework of the present study, the government can determine an optimal environmental policy that affects the equilibrium presented in studies that explore the influence of a "Big push" like that of Murphy et al. (1989), Yamamoto (2005) and others. Those studies strongly rely on the initial values.

As the result of analysis using our model, we can achieve the following results. First, the manufactured goods sector converts from classical technology with constant returns to scale to the modern technology with increasing returns to scale as the regional population increases. Adopting the optimal environmental policy for each technology, that is, controlling the emission tax for pollution, the optimal emission of pollution under this situation is an increasing function with respect to the population when classical technology is chosen. However, it is a decreasing function with respect to population in the case where the modern technology is used after the population exceeds a threshold level to convert the technology. Consequently, the Environmental Kuznets Curve, shown by many empirical studies to have an inverted U-shape with respect to economic growth, results from technological conversion. Presuming that we consider L as the level of either agglomeration or economic growth, the relation between the population and the pollution derived in this paper is similar to that of the Environmental Kuznets Curve. A salient difference separating those numerous studies and our analyses regarding the Environmental Kuznets Curve is the point that technological conversion produces the Environmental Kuznets Curve that is explored herein. This point is an original feature of the model derived in this paper.

We simplify our model to avoid various complications and consider the small country model following Ikazaki (2003). However, we should ideally account for trade between regions as Krugman (1991) and Yamamoto (2005) have. It is possible that the transportation cost of goods is an important factor when we expand this point. Moreover, it is important to account for transboundary pollution, as that analyzed in Hosoe et al. (2001). These points will be addressed in analyses to be undertaken in future studies.

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