The Optimal Environmental Tax and Urban Unemployment in a Small Open Dualistic Economy: Does Environmental Protection Aggravate Urban Unemployment with Intersectoral Capital Mobility?

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Abstract: This paper investigates how a rise in the urban pollution tax rate may affect urban unemployment and welfare in a small open Harris–Todaro (HT) model with intersectoral capital mobility. First, by formulating urban pollution as a dirty input in manufacturing, we find that an increase in the urban pollution tax rate can increase the level of urban unemployment even with intersectoral capital mobility. That is, the optimistic finding by Rapanos (2007) that environmental protection policy reduces urban unemployment in the long run does not always hold. Second, we derive the (sub)optimal pollution tax rate under urban unemployment. We find that the optimal urban pollution tax rate in an open HT economy should be *higher* than the Pigouvian tax rate (the marginal damage of pollution). This result opposes that of Beladi and Chao (2006) for a closed HT economy.

Key Words: Harris–Todaro model, industrial pollution, optimal pollution tax,

   urban unemployment

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1. Introduction

Since the beginning of this century, international cooperation between developed and developing countries for the preservation of the global environment has become more and more important. However, many developing countries have attempted to reduce domestic poverty through industrialization, and some, including China, India, Mexico, and Chile, have largely succeeded. However, they have also suffered from degradation of the domestic environment and, in some cases, increased transboundary pollution (e.g., Beghin et al. (2002)). It thus appears necessary to implement environmental preservation policies in both developed and developing economies. Therefore, it is of fundamental and practical importance to understand whether poverty reduction through industrialization is consistent with environmental preservation in a developing economy.

The recent literature on environmental preservation in developing economies has concentrated on urban unemployment as a form of poverty unique to these economies. In doing so, the focus of interest has been whether and under what conditions environmental policies will reduce urban unemployment, often employing the Harris–Todaro (HT) (1970) model (Dean and Gangopadhyay, 1997; Chao et al., 2000; Daitoh, 2003; Beladi and Chao, 2006; Rapanos, 2007; Tsakiris et al., 2008; Daitoh, 2008).

In a closed HT model with sector-specific capital, Daitoh (2003) has derived the necessary and sufficient condition for a reduction in urban unemployment and a sufficient condition for welfare improvement. Daitoh (2003) showed that welfare always improves if the urban pollution tax rate is initially set in a sufficiently low range. Beladi and Chao (2006) investigated whether developing countries have a comparative advantage in pollution-intensive goods, as claimed by the 'pollution haven' hypothesis. For this purpose, they analyzed a closed HT model with intersectoral capital mobility, showing that a developing country will have a comparative advantage in clean goods. Beladi and Chao (2006) also derived the optimal tax rate (the rate that leads to the optimal level of the preservation of raw

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materials) under urban unemployment, and found that this would be *lower* than the marginal damage of pollution (the Pigouvian tax rate) in a closed HT economy.

Given that modern developing countries are typically open economies with international trade in goods, it must be no less important to explore these issues in open HT models. Using a small open HT model with sector-specific capital, Daitoh (2008) focused on environmental protection and trade policy reform, elucidating under what conditions they are consistent with each other or work in opposite directions in improving urban unemployment and welfare. We could regard this approach as showing the short-run effects, because capital is sector specific. More importantly, Rapanos (2007) analyzed small open HT models with both (short-run) sector-specific capital and (long-run) intersectoral capital mobility. Supposing that the pollution from the urban manufacturing production has a negative externality on agricultural productivity, Rapanos (2007) investigated the effects of a change in the production tax in urban manufacturing (as the first-best policy tool for environmental regulation). It was shown that the production tax may increase or decrease urban unemployment in the short run, while it will necessarily decrease urban unemployment in the long run. At present, this rather optimistic conclusion appears to lie on the frontier of this issue. Indeed, if it does hold, development and environmental economists need not be concerned about environmental degradation in the long run when they pursue reductions in urban unemployment through industrialization.

This paper first investigates whether environmental protection policy will always reduce the level of urban unemployment in a small open HT model with intersectoral capital mobility. The results are that an increase in the urban pollution tax rate, though it always lowers the ratio of urban unemployment, can raise the level of urban unemployment if the reduction in pollution increases the marginal product of labor (MPL) in urban manufacturing. What then is the reason for the difference in the findings of this analysis and the long-run outcome in Rapanos (2007)? In response, Rapanos (2007) assumes that the amount of pollution depends on the output level of urban manufacturing, while we formulate pollution as a factor of production. As often

pointed out, especially in the trade and environment literature, formulating pollution as an input (Pethig, 1976; McGuire, 1982) and as a joint product of the good is theoretically equivalent. However, when it comes to examining the effects of environmental policy on labor employment or unemployment,[1] formulation as an input could be more appropriate because it can capture substitutability and complementarity among the factors of production in greater detail.

   As a second contribution, and unlike Rapanos (2007), this paper characterizes the optimal pollution tax rate under urban unemployment in a small open HT economy with intersectoral capital mobility. We show that the optimal pollution tax rate will be higher than the Pigouvian tax rate (marginal damage of pollution). This contrasts with the results of Beladi and Chao (2006) for a closed HT economy, where the optimal pollution tax rate is lower than the Pigouvian tax rate. The difference arises from whether the urban unemployment ratio increases (in a closed economy) or decreases (in an open economy). Intuitively, when the urban unemployment ratio falls, environmental protection policy has the additional consequence that it weakens labor market distortion. If the pollution tax rate increases up to the Pigouvian tax rate, it will improve welfare too little. Therefore, the welfare-maximizing pollution tax rate will be higher than the Pigouvian tax rate because it can afford to strengthen its effect by enhancing labor market distortion.

2. The Model

Consider a small open HT economy with intersectoral capital mobility. A rural product is the *numeraire* and the world market gives the relative price *p* of an urban manufactured good. We assume that rural production does not generate pollution, while the urban manufacturing sector emits pollution.

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[1] Interest in the relation between the environment and labor employment is also found in, e.g., Renner (1991), Mehmet (1995), and Schweinberger and Woodland (2008).

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In the urban manufacturing sector, the representative firm's production function $M(L^M, K^M, Z)$ satisfies the standard properties of a neoclassical production function and exhibits constant returns-to-scale in labor L^M, capital K^M, and a 'dirty input' Z. The substitutability and complementarity among the three factors of production play an important role in this analysis. We thus assume that the MPL will rise as capital inputs increase ($\partial M_L / \partial K^M > 0$), where the subscript represents the partial derivative. However, the MPL and the marginal product of capital (MPK) may either rise or decline with increases in the dirty input Z.

The dirty input is any factor of production that imposes a negative externality on consumer utility. For simplicity, we assume that the market for Z does not exist and that the government imposes a specific tax τ on the use of Z by firms.[2] The urban wage rate w^M is institutionally fixed and the rental rate of capital r is endogenously determined in the competitive domestic market. Given profit maximization, the value marginal product of each factor of production must equal its price:

$$pM_L(L^M, K^M, Z) = w^M, \tag{1}$$

$$pM_K(L^M, K^M, Z) = r, \tag{2}$$

$$pM_Z(L^M, K^M, Z) = \tau. \tag{3}$$

The representative rural firm's production function $A(L^A, K^A)$ satisfies standard neoclassical properties and exhibits constant returns-to-scale in labor L^A and capital K^A. The rural firm chooses K^A such that the MPK equals the rental rate of capital, and L^A to make the MPL equal the wage rate w^A:

$$A_K(L^A, K^A) = r, \tag{4}$$

$$A_L(L^A, K^A) = w^A. \tag{5}$$

The Harris–Todaro migration equilibrium condition (HT condition) then determines the labor allocation between rural and urban areas:

$$w^A = \frac{w^M L^M}{L^M + L^U} = \frac{w^M}{1 + \mu} \tag{6}$$

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[2] If production pollutes clean air, we can regard the amount of polluted air as a dirty input.

where L^U is the level of urban unemployment and $\mu = (L^U / L^M)$ is the urban unemployment ratio.[3] The labor and capital allocations are:

$$L^A + L^M + L^U = L, \tag{7}$$

$$K^A + K^M = K, \tag{8}$$

where L and K are the respective labor and capital endowments. Given p, τ, w^M, K, and L, equations (1) to (8) determine the equilibrium values of the eight unknown variables r, w^A, L^A, L^M, K^A, K^M, Z, and L^U.

The subsystem (1)–(3) is block recursive. Because the marginal product of each factor is homogeneous of degree zero, we can transform (1) to (3) into:

$$M_L(1, k^M, z) = l(k^M, z) = \frac{w^M}{p}, \tag{1'}$$

$$M_K(1, k^M, z) = \kappa(k^M, z) = \frac{r}{p}, \tag{2'}$$

$$M_Z(1, k^M, z) = \delta(k^M, z) = \frac{\tau}{p}, \tag{3'}$$

where $k^M = (K^M / L^M)$ and $z = (Z / L^M)$. Equations (1') and (3') simultaneously determine the equilibrium values k^{M*} and z^* (an asterisk denotes the equilibrium value). Substituting these into (2'), we get r^*. Since the rural MPK is homogeneous of degree zero, (4) $A_K(1, k^A) = r$ determines $k^{A*} = (K^A / L^A)^*$. Then (5) $A_L(1, k^A) = w^A$ determines w^{A*}. From (6) μ^* is determined. Given k^{M*}, k^{A*}, and μ^*, (7) $L^A + (1 + \mu^*)\ L^M = L$ and (8) $k^{A*}L^A + k^{M*}L^M = K$ simultaneously determine L^{A*} and L^{M*}. Finally, we obtain $K^{A*} = k^{A*}L^{A*}$, $K^{M*} = k^{M*}L^{M*}$, $Z^* = z^*L^{M*}$, and $L^{U*} = \mu^* L^{M*}$.

3. Pollution Tax and Urban Unemployment

Let us investigate the effects of a rise in the urban pollution tax rate, focusing on how it may affect urban unemployment. Totally differentiating (1') and (3'), we obtain the comparative static results:

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[3] Put correctly, μ is the unemployment–employment ratio in urban areas. With a slight abuse of terminology, research using HT models traditionally refers to this as the 'urban unemployment ratio'.

$$\frac{dz}{d\tau} = \frac{l_k(k^M, z)}{pD} < 0, \tag{9}$$

$$\frac{dk^M}{d\tau} = -\frac{l_z(k^M, z)}{pD}. \tag{10}$$

For the stability of equilibrium (see Appendix 1), we assume the following.

Assumption 1: $D = l_k \delta_z - l_z \delta_k < 0$ holds in equilibrium.

From (9), pollution per urban worker (z) will decrease because the urban MPL is increasing in capital input ($\partial M_L / \partial K^M = (l_k / L^M) > 0$). However, (10) implies that the capital–labor ratio k^M in urban manufacturing may either increase or decrease, depending on whether the urban MPL increases or decreases with the fall in Z: k^M increases if $l_z > 0$ holds, while k^M decreases if $l_z < 0$ holds (recall that $\partial M_L / \partial Z = (l_z / L^M)$).

Let us put forward an economic explanation for this process. We first note that the zero-profit condition $p = c(w^M, r, \tau)$ holds in urban manufacturing, where $c(w^M, r, \tau)$ is the unit cost function.[4] A rise in the urban pollution tax rate tends to increase the unit cost of urban manufacturing production. In order for the zero-profit condition to hold, the rental rate of capital in the urban area then needs to fall. Capital will thus move from urban to rural areas, leading to a downward shift in the urban MPL curve. Since this tends to decrease urban employment, the direction of change in $k^{M*} = (K^M / L^M)^*$ is ambiguous. In contrast, the rural MPL curve shifts upward and the rural wage rate will rise. During the urban-to-rural migration process, the rural wage rate declines along the rural MPL curve. We can see from (6) that when the upward shift of the rural MPL curve is smaller and/or the rural MPL curve is steeper,[5] the decline in the urban unemployment ratio μ^* will be smaller. In this situation, the level of urban unemployment $L^{U*} = \mu^* L^{M*}$ is more likely to rise.

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[4] We can confirm from (1)–(3) that the first-order conditions for cost minimization are satisfied, i.e., the relative factor price must equal the marginal rate of technical substitution.

[5] Because the rural wage rate declines more rapidly, a smaller number of people will emigrate from urban areas until the expected wage rates are equalized. The level of urban unemployment will then increase.

We can then find the changes in L^{A*} and L^{M*} by totally differentiating (7)

$L^A + (1+\mu^*)L^M = L$ and (8) $k^{A*}L^A + k^{M*}L^M = K$, regarding μ^*, k^{A*}, and k^{M*} as

exogenous parameters.

$$\frac{dL^A}{d\tau} = \frac{1}{\Delta}\left\{-k^M L^M \frac{d\mu}{d\tau} + (1+\mu)L^A \frac{dk^A}{d\tau} + (1+\mu)L^M \frac{dk^M}{d\tau}\right\} \qquad (11)$$

$$\frac{dL^M}{d\tau} = \frac{1}{\Delta}\left\{k^A L^M \frac{d\mu}{d\tau} - L^A \frac{dk^A}{d\tau} - L^M \frac{dk^M}{d\tau}\right\} \qquad (12)$$

We assume that the urban area is more capital-abundant than the rural area.[6]

$$\textit{Assumption 2:} \quad \frac{K^M}{L^M + L^U} > \frac{K^A}{L^A} \quad \text{holds in equilibrium.}$$

Under this assumption, $\Delta = k^M - (1+\mu)k^A > 0$ holds. Given $d\mu/d\tau < 0$ and $dk^A/d\tau > 0$,

the signs of (11) and (12) depend on $dk^M/d\tau$. We separate two cases of $l_z > 0$ and

$l_z < 0$. First, we consider the case where $l_z > 0$ holds, where a rise in τ increases

k^M ($dk^{M*}/d\tau > 0$). From $d\mu/d\tau < 0$ and $dk^A/d\tau > 0$, L^{A*} will increase and L^{M*} will

decrease. Thus $K^{A*} = k^{A*}L^{A*}$ will increase, while $Z^* = z^* L^{M*}$ and $L_U{}^* = \mu^* L^{M*}$ will

decrease. Therefore, a rise in the urban pollution tax rate will reduce both the level of

urban unemployment and pollution from urban manufacturing. This is qualitatively

the same result as Rapanos (2007) in that environmental protection is consistent with

a reduction in the long-run urban unemployment.

Second, consider the case where $l_z < 0$ holds, where a rise in τ decreases k^{M*}

($dk^{M*}/d\tau < 0$). Given $d\mu^*/d\tau < 0$ and $dk^{A*}/d\tau > 0$, L^{A*} may decrease and L^{M*} may

increase. If these effects are sufficiently strong, $L^{U*} = \mu^* L^{M*}$ will increase. Note that

L^{U*} may increase, even if Z^* decreases. The reason is as follows. When $Z^* = z^* L^{M*}$

decreases, L^{M*} can increase at a rate lower than the declining rate of z^*. On the

other hand, the level of urban unemployment $L^{U*} = \mu^* L^{M*}$ will rise if L^{M*} increases

at a rate higher than the declining rate of μ^*. We should note that how much μ^*

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[6] This is the stability condition for the HT equilibrium derived by Neary (1981).

declines depends on the steepness of the rural MPL curve, while the urban manufacturing production function (which is independent of the rural technology) determines the change in z^*. Therefore, a rise in the urban pollution tax rate may increase the level of urban unemployment, even if it reduces pollution from the urban manufacturing sector. This implies that the optimistic result obtained by Rapanos (2007) may not hold. That is, environmental protection policy may aggravate urban unemployment even in the long run when capital is mobile between rural and urban areas.

Proposition 1 (Pollution Tax and Urban Unemployment): *Suppose that assumptions 1 and 2 are satisfied. In a small open dualistic economy with intersectoral capital mobility, a rise in the urban pollution tax rate can either raise or lower the level of urban unemployment, even though it decreases urban pollution. That is, a rise in the urban pollution tax rate will reduce the level of urban unemployment if a reduction in pollution leads to a downward shift in the urban MPL curve. However, it may raise the level of urban unemployment if the reduction in pollution leads to an upward shift in the urban MPL curve.*

One could imagine many realistic situations where $l_z < 0$ holds. Suppose, for example, that a manufacturing firm uses machines (K^M) with energy goods (Z) causing indoor factory pollution. This pollution harms the health of workers and lowers labor efficiency. With a rise in the pollution tax rate pollution decreases, and their MPL curve will shift upward. If this effect is strong, manufacturing employment (L^M) will greatly expand. Moreover, when this effect dominates the reduction in urban unemployment ratio (μ), a rise in the urban pollution tax rate will aggravate the level of urban unemployment (L^U).

Let us comment on the implications of the negative externality of urban pollution on agricultural productivity, as in Rapanos (2007). Here the rural production function could be $A = g(Z)A(L^A, K^A)$, where the externality function $g(Z)$ is a decreasing

function. Since a rise in the urban pollution tax rate will decrease pollution, the rural wage rate $w^A = g(Z)A_L(1, k^A)$ would rise more than in the case of no production externality. The decline in μ^* would thus be larger. Therefore, the possibility of a rise in the level of urban unemployment would be smaller. However, the introduction of a production externality would not reverse the basic economic logic in our model.

4. Welfare-maximizing Pollution Tax under Urban Unemployment

We now explore the (sub)optimal pollution tax rate under urban unemployment. Let us first derive the change in GDP. Differentiating $G = A + pM$ and using $dp = 0$, we can represent the change in GDP in terms of the change in the urban unemployment ratio and pollution (see Appendix 2 for the derivation):

$$\frac{dG}{d\tau} = -\frac{w_M L_M}{1+\mu}\frac{d\mu}{d\tau} + \tau\frac{dZ}{d\tau}. \tag{13}$$

Note that the left-hand side of (13) can be positive or negative.

Next, we assume that the representative consumer's utility function $U(C^A, C^M, Z)$ is strictly quasiconcave and homothetic in rural good consumption C^A and manufactured good consumption C^M. The dirty input Z exerts a negative externality $(U_Z = \partial U/\partial Z < 0)$, and its marginal disutility is increasing or constant $(U_{ZZ} = \partial^2 U/\partial Z^2 \leq 0)$. Based on this, we can derive the expenditure function $E(p, Z, U)$, which is linear in U.

We suppose that the government transfers pollution tax revenue to consumers in a lump-sum fashion. Thus, aggregate expenditure equals GDP. Totally differentiating $E(p, Z, U) = G$ with $dp = 0$ and dividing the result by $d\tau$, we get:

$$E_Z(p, Z, U)\frac{dZ}{d\tau} + E_U(p, Z, U)\frac{dU}{d\tau} = \frac{dG}{d\tau}. \tag{14}$$

Substituting (13) yields:

$$E_U\frac{dU}{d\tau} = (\tau - E_Z)\frac{dZ}{d\tau} - \left(\frac{w^M L^M}{1+\mu}\right)\frac{d\mu}{d\tau}. \tag{15}$$

We choose the utility index such that $\partial U / \partial C^A = 1$ holds at equilibrium. We then obtain $E_U = 1$ [7] and find:

$$\frac{dU}{d\tau} = (\tau - E_Z)\frac{dZ}{d\tau} - \left(\frac{w^M L^M}{1+\mu}\right)\frac{d\mu}{d\tau}. \qquad (16)$$

The welfare-maximizing pollution tax rate τ^O must satisfy $dU/d\tau = 0$. Therefore:

$$\tau^O = E_Z + \frac{w_M L_M}{1+\mu}\left(\frac{d\mu/d\tau}{dZ/d\tau}\right). \qquad (17)$$

One could confirm this actually maximizes utility. Let us focus on the natural case where $dZ^*/d\tau < 0$ holds. Eliminating E_z in (16) using (17), we get:

$$\frac{dU}{d\tau} = (\tau - \tau^O)\frac{dZ}{d\tau}. \qquad (18)$$

Here, $dU/d\tau > 0$ holds in the range $\tau \in [0, \tau^O]$, while $dU/d\tau < 0$ holds in the range $\tau \in [\tau^O, +\infty)$. Thus, welfare is certainly maximized at τ^O.

We can conclude from (17) that the welfare-maximizing pollution tax rate is higher than the marginal damage of pollution, i.e., $\tau^O > E_Z$ holds.

Proposition 2: *In a small open dualistic economy with intersectoral capital mobility, the optimal pollution tax rate τ^O under urban unemployment will be higher than the Pigouvian tax rate represented by the marginal damage of pollution E_Z.*

This is a new result. While Beladi and Chao (2006) characterized the optimal pollution tax rate using a similar formula to (17), their model is of a closed HT economy. They showed that a rise in the urban pollution tax rate *raises* the urban unemployment ratio ($d\mu/d\tau > 0$) and that the optimal urban pollution tax rate is *lower* than the Pigouvian tax rate represented by the marginal damage of pollution E_Z. Intuitively, a rise in the urban unemployment ratio implies the enhancement of labor market distortion. Therefore, the optimal pollution tax rate should be *lower* so that this

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[7] The expenditure function is derived from the first-order condition $1 = \lambda[\partial U(C^A, C^M, Z)/\partial C^A]$ and $p = \lambda[\partial U(C^A, C^M, Z)/\partial C^M]$, where λ is the Lagrangean multiplier for the expenditure minimization problem. By the envelope theorem, $E_U(p, Z, U) = \lambda$ holds. Under $\partial U / \partial C^A = 1$, we get $\lambda = 1$ and thus $E_U = 1$.

distortive effect can weaken. In contrast, we consider, as in Rapanos (2007), a small open HT economy with intersectoral capital mobility. A rise in the urban pollution tax rate *lowers* the urban unemployment ratio ($d\mu/d\tau < 0$), implying that it *weakens* the labor market distortion. Therefore, the optimal pollution tax rate should be *higher* than the Pigouvian tax rate, because it can afford to strengthen the labor market distortion. One may wonder whether the labor market distortion really weakens, in spite of the fact that the level of urban unemployment increases. Although the HT economy has two distinct labor market distortions, i.e., institutionally fixed urban wage rate and the 'equalization of expected wage rate' hypothesis (HT migration equilibrium condition), it is well known that in HT models the welfare effect is captured by a change in a single variable, namely, the urban unemployment ratio. In this sense, we can interpret the change in μ as concisely representing labor market distortion in this economy.

Relation to Previous Studies

Finally, we discuss the relationships between this analysis and previous work concerning optimal environmental policy in HT models. Dean and Gangopadhyay (1997) and Chao et al. (2000) discussed the optimal environmental regulation in closed and small open three-good HT models with an intermediate good whose production causes environmental damage (timber is a typical example).

  Chao et al. (2000) showed that an increase in the preservation of raw materials leads to a rise in the urban unemployment ratio in a closed HT economy. However, while Chao et al. (2000, p. 45) derived the optimal level of preservation of raw materials (eq. (18)), they did not explicitly address the relation between the optimal policy and labor market distortion. They also showed that in a small open HT economy, the preservation of raw materials did not result in additional urban unemployment. This is because of the special structure of their three-good model. Because of this, they only mentioned that the optimal level of preservation is higher under free trade than no trade (Chao et al. 2000, p. 47).

Dean and Gangopadhyay (1997) discussed optimal production and export taxes on an intermediate good whose production causes environmental damage in a small open HT model. In the short run, optimal production and export taxes (interpreted as environmental taxes) are *less* than the value of marginal environmental damage that prevails under free trade. In the long run, however, these taxes are *greater* than the value of marginal environmental damage that prevails under free trade. Dean and Gangopadhyay (1997) gave detailed economic explanations for these results. Unfortunately, however, the more complicated structure of their three-good HT model made it difficult to specify (at least for the readership) the crucial factor determining the direction of the optimal environmental taxes. Because our model is simpler, we can clearly show that these opposing findings come from the difference in the direction of change in the urban unemployment ratio. In other words, among the many possible explanations put forward by Dean and Gangopadhyay (1997, pp. 334–335), what was crucial in the determination of the suboptimal environmental taxes is the statement that the production and export taxes aggravate urban unemployment in the short run while they alleviate it in the long run. This is clearly consistent with our findings.

5. Concluding Remarks

We investigated how a rise in the urban pollution tax rate may affect urban unemployment and welfare in a small open Harris–Todaro (HT) model with intersectoral capital mobility by formulating pollution as a dirty input. First, we found that a rise in the urban pollution tax rate can *raise* the level of urban unemployment, even under intersectoral capital mobility. That is, the rather optimistic result by Rapanos (2007) does not always hold, such that environmental protection policy will necessarily reduce the level of urban unemployment in the long run. Second, we derived the (sub)optimal pollution tax rate under urban unemployment. The optimal urban pollution tax rate in a small open HT economy should be *higher* than the

Pigouvian tax rate (the social marginal damage of pollution). This result opposes that of Beladi and Chao (2006) for a closed HT economy.

Before concluding, let us remark on the setting of the present model. We assume away abatement activities in the urban area that Beladi and Chao (2006) incorporated in their model. The presence of abatement activities appears desirable for their purpose, because these activities tend to increase labor employment in urban manufacturing and thus reduce the urban unemployment ratio. Beladi and Chao (2006) show that even in this setting, the urban unemployment ratio unambiguously increases, not declines. In our model, on the contrary, the urban unemployment ratio unambiguously declines with a rise in the urban pollution tax rate. The introduction of urban abatement activities would then only enhance the qualitative result.

Appendix 1: Condition for Local Stability of Equilibrium

We assume that the adjustment process toward the equilibrium is represented by:

$$\dot{z} = \phi\left(\delta(z, k^M) - \frac{\tau}{p}\right), \tag{A1.1}$$

$$\dot{k}^M = \psi\left(\frac{w^M}{p} - l(z, k^M)\right), \tag{A1.2}$$

where ϕ and ψ are positive constants. (A1.1) implies that when the marginal product of the dirty input exceeds the real rate of pollution tax, manufacturing firms will increase the dirty input. (A1.2) implies that when the marginal product of labor exceeds the real urban wage rate, manufacturing firms will increase the labor input, thereby lowering the capital intensity k^M.

By linearizing the system around the equilibrium, we obtain:

$$\begin{bmatrix} \dot{z} \\ \dot{k}^M \end{bmatrix} = \begin{bmatrix} \phi\delta_z^* & \phi\delta_k^* \\ -\psi l_z^* & -\psi l_k^* \end{bmatrix} \begin{bmatrix} z - z^* \\ k^M - k^{M*} \end{bmatrix}. \tag{A1.3}$$

We denote the coefficient matrix evaluated at the equilibrium by J^*. The equilibrium is locally stable if and only if:

$$Tr.J^* = \phi\delta_z^* - \psi l_k^* < 0, \tag{A1.4}$$

$$\det J^* = (\phi\delta_z^*)(-\psi l_k^*) - (\phi\delta_k^*)(-\psi l_z^*) > 0. \tag{A1.5}$$

Since $\delta_z < 0$ and $l_k > 0$ hold, (A1.4) always holds. Thus, the necessary and sufficient condition for the local stability of the equilibrium is (A1.5). This is satisfied if and only if $D = l_k \delta_z - l_z \delta_k < 0$ holds.

Appendix 2: Derivation of Change in GDP

The changes in the urban unemployment ratio and pollution can represent the change in GDP. Totally differentiating $G = A + pM$ yields:

$$dG = dA + pdM = \left(A_L dL^A + A_K dK^A \right) + p \left(M_L dL^M + M_K dK^M + M_Z dZ \right).$$

Substituting (1)–(5) into this, we obtain:

$$dG = w^A dL^A + r(dK^A + dK^M) + w^M dL^M + \tau dZ .$$

Using (6) and $dK^A + dK^M = 0$ by (8), we obtain:

$$dG = \frac{L^M}{L^M + L^U} w^M dL^A + w^M dL^M + \tau dZ .$$

Rearranging the terms using (7) yields:

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\begin{aligned}
dG &= \frac{L^M}{L^M + L^U} w^M (-dL^M - dL^U) + w^M dL^M + \tau dZ \\
&= \frac{w_M (L^U dL^M - L^M dL^U)}{L^M + L^U} + \tau dZ \\
&= \frac{w^M \left\{ (L^U / L^M) dL^M - dL^U \right\}}{1 + (L^U / L^M)} + \tau dZ .
\end{aligned}
$$

Substituting $dL^U = \mu dL^M + L^M d\mu$, we obtain:

$$\frac{dG}{d\tau} = -\frac{w^M L^M}{1 + \mu} \frac{d\mu}{d\tau} + \tau \frac{dZ}{d\tau} .$$

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