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1. Introduction

In an attempt to examine the backward incidence of environmental pollution control, Yohe(1979) employed a general two-sector, three-factor model developed by Batra and Casas (1976). Specifically, he analyzed the backward incidence of pollution control on the factors of production in a two-sector model with a variable coefficient technology. Yu and Ingene(1982) later extended Yohe's works to the case of region specific production factor. Forster(1984) simplified their results using the techniques of the duality theory.

Kitabatake and Nishioka(1986) analyzed the dynamic aspects of environmental damage in a two-sector model with a fixed coefficient technology. Assuming that objective of a regional economy is to maximize the discounted sum of net regional revenue, they showed that the optimal trajectory to the stationary state has the following property: As the endowment of a production factor decreases due to an increase in emitted pollutants, the industry which uses that factor relatively intensively will expand at the sacrifice of the other sector. This result is similar to the wellknown Rybczynski lemma in the field of international trade. It was also shown that the sufficiency condition for the optimality requires the convexity of the damage function.

Kitabatake and Nishioka(1986) is mainly concerned with the optimal solution of dynamic analysis. In this paper, we extend their analysis to a competitive economy model of the Batra-Casas-Yohe type. In section 2, we extend the Yohe model to include environmental damage on the endowment of one production factor. That is, we assume that one of the factor endowments depreciates due to an increase in pollution. An example may be the case of environmental resource stock such as ground-water resource, the size and/or quality of which may decrease with the increase of pollution. In this section, we analyze the backward incidence of pollution control policy. We assume that the regional government imposes pollution control measure to maximize national income. Here, we see that the convexity of the damage function ensures the stability of competitive solution.

In section 3, we introduce a linear damage function into the Batra-Casas Model to analyze another type of environmental policy, compensation policy. In the case of pollution control policy in section 2, we implicitly assumed that the regional government had no concern over the remaining pollution damage despite the pollution control. In this section, we consider the backward incidence of damage compensation policy, where the regional government requires the polluters to pay compensation to pollution victims. The final section summarizes the main results obtained in the study.

2. Backward incidence of pollution control policy

First, we briefly summarize the basic structure of the Yohe model. In his model, a perfectly competitive economy is composed of a polluting sector (X_1) and a nonpolluting sector (X_2) with strictly quasiconcave, linearly homogeneous production functions,

$$X_1 = F_1(K_1, L_1, Z)$$

$$X_2 = F_2(K_2, L_2)$$

where K_j, L_j, and Z denote capital, labour, and pollution employed in the j-th sector, respectively. Due to the linear homogeneity assumption, these two equations are rewritten, in terms of the input-output coefficients a_{Kj}, a_{Lj}, a_Z for j=1 and 2, as follows,

$$1 = f_1(a_{K1}, a_{L1}, a_Z) \qquad (1)$$

$$1 = f_2(a_{K2}, a_{L2}) \tag{2}$$

If we assume perfect intersectoral mobility of all nonspecific factors, perfect factor price flexibility and the seriousness of the pollution problem in the economy, full employment of all three factors is guaranteed as follows:

$$a_{L1}X_1 + a_{L2}X_2 = L \tag{3a}$$

$$a_{K1}X_1 + a_{K2}X_2 = K \tag{3b}$$

$$a_{Z1}X_1 = Z \tag{3c}$$

where L and K represent the available supply of labour and capital, respectively, and Z the total amount of allowable pollution. Under perfect competition and assuming nonspecialization in production, unit cost of each commodity equals its market price. Let w be the wage rate, r the rental on capital, t the shadow price of the pollution constraint, and P_j the price of the jth good. Then the final equation set of the Yohe model is written as,

$$a_{L1}w + a_{K1}r + a_{Z1}t = P_1 \tag{4a}$$

$$a_{L2}w + a_{K2}r = P_2 \tag{4b}$$

where, with quasi-concave and linearly homogeneous production function, each input-output coefficient is homogeneous of degree zero in the factor prices:

$$a_{i1} = a_{i1}(w,r,t) \qquad \text{for} \quad i=K,L,Z \tag{5a}$$

$$a_{i2} = a_{i2}(w,r) \qquad \text{for} \quad i=K,L \tag{5b}$$

This completes the description of the main structure of Yohe model. The main results obtained by Yohe, especially his Propositions 1 and 3, are summarized by the simple geometry used by Forster(1984). Figure 1, which modifies Forster's Figure 2 in reference to Woodland(1982,p73), depicts the iso-cost curves for the two sectors in the factor price space, where sector

1 is assumed to be capital intensive. The iso-cost curves are derived from (4a) through (5b) as follows:

$$c_1(w,r,t) = P_1$$

$$c_2(w,r) = P_2$$

As more stringent environmental regulation leads to higher shadow price t^*, Figure 1 shows that the iso-cost curve for sector 1 shifts inward towards the origin and, consequently, the equilibrium wage rate must rise from w^0 to w^1 and the rental rate must fall from r^0 to r^1.

Figure 1 also depicts the optimal input vectors which are drawn perpendicular to the iso-cost curves at E^0 and E^*, the diversification cones, and the endowment vector, $V^0 = (K^0, L^0)$. The figure illustrates Yohe's Proposition 3 that, as pollution control becomes more restrictive, the polluting sector of sector 1 will contract and the nonpolluting sector of sector 2 will expand.

In this section we deal with the case where the total supply of one production factor is negatively affected by pollution. The examples may be the case of ground-water resource, the size and quality of which are affected by the discharged pollutants from the manufacturing sector. Here, we assume pollution adversely affects environmental resource endowment and reinterpret "w" as the resource rent. Although we may alternatively assume that pollution adversely affects labour endowment such that the attractiveness of the living environment is diminished and consequently people leave the region in question, this kind of assumption seems to contradict the small country assumption. Thus equation (3a) is rewritten as,

$$a_{L1}X_1 + a_{L2}X_2 = L(Z) \tag{3a'}$$

where $L(0)=L_0$ and $\partial L(Z)/\partial Z = L_Z < 0$.

We now begin to study how this modification affects Yohe's results, his Proposition 1 through 3. For later use, we duplicate, with relevant modifications, some of the equation sets derived by Yohe. First of all, totally differentiating (3a'), (3b) and (3c), we obtain,

$$\lambda_{L1}X_1^* + \lambda_{L2}X_2^* = L(Z)^* - (\lambda_{L1}a_{L1}^* + \lambda_{L2}a_{L2}^*) \qquad (6a)$$

$$\lambda_{K1}X_1^* + \lambda_{K2}X_2^* = K^* - (\lambda_{K1}a_{K1}^* + \lambda_{K2}a_{K2}^*) \qquad (6b)$$

$$\lambda_{Z1}X_1^* = Z^* - \lambda_{Z1}a_{Z1}^* \qquad (6c)$$

, where the following notations are used:

$X_i^* = dX_i/X_i$: the percentage change in X_i

$\lambda_{ij} = a_{ij}X_j/i$ $(i=K,L(Z),Z)$: the proportion of the total supply of the i-th factor employed in the j-th sector

A similar manipulation of (4) leads to,

$$P_1^* = \theta_{L1}w^* + \theta_{K1}r^* + \theta_{Z1}t^* \qquad (7a)$$

$$P_2^* = \theta_{L2}w^* + \theta_{K2}r^* \qquad (7b)$$

where we utilized the cost minimizing constraint on a linearly homogeneous production function, $wda_{Lj}+rda_{Kj}+tda_{Zj}= 0$, and

$\theta_{ij} = a_{ij}x(\text{factor price})/P_j$: the cost share allocated to the i-th factor in the j-th sector

The final set of equations is obtained by totally differentiating (5) as follows,

$$a_{L1}^* = -\theta_{K1}\sigma_{KL}^1(w^* - r^*) \qquad (8a)$$

$$a_{K1}^* = \theta_{L1}\sigma_{KL}^1(w^* - r^*) - \theta_{Z1}\sigma_{KZ}^1(w^* - t^*) \qquad (8b)$$

$$a_{Z1}^* = -\theta_{K1}\sigma_{KZ}^1(w^* - t^*) \qquad (8c)$$

$$a_{L2}^* = -\theta_{K2}\sigma_{KL}^2(w^* - r^*) \qquad (8d)$$

$$a_{k2}^* = \theta_{L2}\sigma_{KL}^2(w^* - r^*) \qquad (8e)$$

where σ_{ik}^j are the Allen's partial elasticity of substitution.

If we eliminate X_1^* and X_2^* from the first equation set (6), we obtain

$$E_w w^* + E_r r^* + E_t t^* = B_{ZL}K^* + (B_{KZ}L(Z)^* + B_{KL}Z^*) \quad (9)$$

where the exact expression for $E_w, E_r, E_t, B_{ZL}, B_{KZ}$, and B_{KL} are referred to Yohe(p190-191). Now we may rewrite eqs. (7) and (9) as follows:

$$\begin{pmatrix} \theta_{L1} & \theta_{K1} & \theta_{Z1} \\ \theta_{L2} & \theta_{K2} & 0 \\ E_w & E_r & E_t \end{pmatrix} \begin{pmatrix} w^* \\ r^* \\ t^* \end{pmatrix} = \begin{pmatrix} P_1^* \\ P_2^* \\ B_{ZL}K^* + (B_{KZ}L(Z)^* + B_{KL}Z^*) \end{pmatrix} \quad (10)$$

Employing Cramer's rule, we see that

$$\left.\begin{aligned} w^* &= -\theta_{Z1}\theta_{K2}(B_{KL}+B_{KZ}L_Z Z/L)Z^*/D \\ r^* &= \theta_{Z1}\theta_{L2}(B_{KL}+B_{KZ}L_Z Z/L)Z^*/D \\ t^* &= (\theta_{L1}\theta_{K2}-\theta_{L2}\theta_{K1})(B_{KL}+B_{KZ}L_Z Z/L)Z^*/D \end{aligned}\right\} \quad (10a)$$

where $D < 0$ is the matrix determinant of equation (10) and $(\theta_{L1}\theta_{K2} - \theta_{L2}\theta_{K1}) < 0$ follows from the assumption that sector 2 is environmental resource intensive. Based on (10a), we know that the signs of w^*Z^*, r^*Z^*, t^*Z^* depend on the sign of the term $G \overset{\Delta}{=} (B_{KL}+B_{KZ}L_Z Z/L)$ or that of the term $((a_{K2}a_{L1}-a_{L2}a_{K1})-a_{K2}a_{Z1}L_Z)$, where the signs of $(a_{K2}a_{L1}-a_{L2}a_{K1})$ and L_Z is assumed to be negative. For the case of convex(concave) damage function, the sign of G is likely to be negative(positive) for small values of Z and to be positive(negative) for large values of Z. We may now present the modified version of the Yohe's Proposition 1. If $K^*=P_1^*=P_2^*=0$, then the stricter pollution control generates the situation, where the real returns of capital and environmental resource move in opposite directions and those of environmental resource and pollution in the same directions. Especially we obtain the situation as shown in Figure 1 for the case of convex damage function with small values of Z or that of concave damage function with large value of Z.

Yohe's Proposition 3, which imitates Batra and Casas's theorem 6(1976,p34), says that as pollution control becomes more restrictive

($Z^*<0$), at constant commodity price and factor endowment, the polluting sector will contract ($X_1^*<0$), and the nonpolluting sector will expand ($X_2^* > 0$). In our model this holds in the special situation depicted in Figure 1. That is, from (6b), (6c) and (8) we obtain

$$\lambda_{Z1}X_1^* = Z^* + \lambda_{Z1}\theta_{K1}\sigma_{KZ}^1(w^*-t^*)$$

$$\lambda_{K2}X_2^* = -\lambda_{K1}X_1^* - (\lambda_{K1}\theta_{L1}\sigma_{KL}^1+\lambda_{K2}\theta_{L2}\sigma_{KL}^2)(w^*-r^*) + \lambda_{K1}\theta_{Z1}\sigma_{KZ}^1(w^*-t^*)$$

Then the above discussion coupled with equation (10a) reveals that the original Proposition 3 unambiguously holds for the case of $G < 0$.

The major difference between Yohe's model and the extended version lies in Yohe's Proposition 2 saying that national income falls with the stricter pollution control. Totally differentiating the identity,

$$Y = wL(Z) + rK + tZ$$

reveals that,

$$\begin{aligned} Y^* &= (\theta_L w^*+\theta_K r^*+\theta_Z t^*) + (\theta_L L_Z Z/L + \theta_Z)Z^* \\ &= Z^*(t+wL_Z)Z/Y \end{aligned} \qquad (11)$$

where we used the relation $\theta_L w^*+\theta_K r^*+\theta_Z t^*= 0$ (see Batra and Casas (p31) for proof). Here θ_i is the total i-th factor cost divided by national income. In our model, if the marginal cost of pollution control (t) is less than the marginal benefit of pollution control (wL_Z), then national income increases with the stricter pollution control, while in the original Yohe model the marginal benefit of pollution control is zero, and consequently, national income cannot increase.

Figure 2 describes graphically the modified version of Yohe's Proposition 2, where Figure 2(a) and 2(b) correspond to the case of concave damage function and that of convex damage function, respectively. If we assume that the regional government is empowered to impose pollution control measures so as to maximize national income, the case of convex damage function (i.e., the environmental resource supply function is a concave function of pollution variable) leads to a unique stable pollution control constraint, while that of concave damage function to an unstable pollution control constraint. That is, in case of convex damage function, the pollution constraint specified by environmental policy converges, under the regional objective of national income maximization, to an equilibrium for a dynamic two sector model in Kitabatake and Nishioka (1986) also requires the convex damage function.

In the case of concave damage function, we obtain two polar cases of environmental policy, which are no pollution control and the strictest pollution control of zero pollution, depending on the initial pollution constraint and the imputed value of pollution constraint. However, when we consider the effects of changing Z on the factor prices, it is rather ambiguous, at this moment, as to what kind of figure we obtain, instead of Figure 2.

3. Backward incidence of damage compensation policy

In the previous section, we interpreted "t" to be the shadow price of pollution control. However, the history of environmental policy in Japan shows that the damage compensation policy usually precedes the pollution control policy (see Gresser et al.(1981, ch.1)). Thus, it may be better to interpret "t" to be the damage compensation rate. To facilitate this line of reasoning, we introduce a linear damage function into the Batra-Casas model (1976) as follows:

$$L(Z) = L_0 - eZ \qquad (12)$$

where "L_0" and "e" are an initial amount of labour(or some environmental resource stock) and a positive constant in units of labour loss per unit of pollution, respectively. Furthermore, we assume that both sectors are polluting. Thus equation (3c) is rewritten as

$$a_{Z1}X_1 + a_{Z2}X_2 = Z \qquad (3c')$$

In reference to (12) and (3c'), equation (3a') is rewritten as

$$(a_{L1}+ea_{Z1})X_1 + (a_{L2}+ea_{Z2})X_2 = L_0 \qquad (3a'')$$

Hence the existence of pollution is seen to increase the economy's overall labour requirement by the amount $ea_{Z1}Y_1$ for sector 1, and by $ea_{Z2}Y_2$ for sector 2. As to factor intensity, we assume the "strong factor intensity condition" introduced by Batra and Casas (1976, p26):

$$a_{K1}/a_{K2} > a_{Z1}/a_{Z2} > (a_{L1}+ea_{Z1})/(a_{L2}+ea_{Z2}) \qquad (13)$$

which is rewritten as,

$$a_{K1}/a_{Z1} > a_{K2}/a_{Z2} \quad \text{and} \quad a_{K1}/(a_{L1}+ea_{Z1}) > a_{K2}/(a_{L2}+ea_{Z2})$$

$$(a_{L2}+ea_{Z2})/a_{K2} > (a_{L1}+ea_{Z1})/a_{K1} \quad \text{and} \quad (a_{L2}+ea_{Z2})/a_{Z2} > (a_{L1}+ea_{Z1})/a_{Z1}$$

implying that sector 1 is strongly intensive in the use of exactly one factor of capital, and that sector 2 is strongly intensive in labour.

Let "t" be the rate of pollution compensation, imposed by the regional government, per unit of pollution output. Then, the profit for the j-th sector is written as,

$$P_jX_j - (\ w(a_{Lj}+ea_{Zj}) + a_{Kj}r + tea_{Zj}\ )X_j$$

and the equation (4) is rewritten as,

$$(a_{Lj}+ea_{Zj})w + a_{Kj}r = P_j - tea_{Zj} \quad \text{for} \quad j=1,2 \qquad (4')$$

Pollution related compensation is usually related to 1) cost of medical treatment, 2) compensation for disability(earnings lost), 3) reimbursement for pain and suffering, and 4) reimbursement for property damage (see for example, Gresser et al (1981,p295). Thus, the terms $ea_{Zj}w$ and tea_{Zj} in (4') correspond to 2) and 3) for the case of health damage, and to 2) and 4) for such natural resouce damages as the pollution damage on ground-water resource, respectively. When we express the unit production function for the j-th product as,

$$f^j(a_{Lj}, a_{Kj}, a_{Zj}) = 1 \qquad (14)$$

we may then calculate the slope of the level surface of the production function based on the profit maximization conditions:

$$P_j \partial f^j / \partial a_{Lj} = w \qquad (15a)$$

$$P_j \partial f^j / \partial a_{Kj} = r \qquad (15b)$$

$$P_j \partial f^j / \partial a_{Zj} = e(t+w) \qquad (15c)$$

From (15), it is clear that the slope of the level surface is unchanged under the proportional change in w,r, and t. Thus, input-output coefficient function (5) is rewritten as,

$$a_{ij} = a_{ij}(w,r,t;e) \quad \text{for} \quad i=L,K;\ j=1,2 \qquad (5')$$

which is homogeneous of degree zero in input prices, r and w, and the rate of damage compensation, t.

The set of equations (3a"),(3b),(3c'),(4') and (5') describes the production side of the economy. As to the demand side, we employ the usual assumption that the country is small and faces exogenously given world prices.

Equipped with this structure, we can rewrite equation (6),(7) and (8). First of all, equation (6) is rewritten as follows:

$$\begin{aligned} &(\lambda_{L1}+\lambda_{Z1})X_1^* + (\lambda_{L2}+\lambda_{Z2})X_2^* \\ &\quad = L_0^* - (\lambda_{L1}a_{L1}^* + \lambda_{Z1}a_{Z1}^* + \lambda_{L2}a_{L2}^* + \lambda_{Z2}a_{Z2}^* + (\lambda_{Z1}+\lambda_{Z2})e^*) \\ &\lambda_{K1}X_1^* + \lambda_{K2}X_2^* = K^* - (\lambda_{K1}a_{K1}^* + \lambda_{K2}a_{K2}^*) \end{aligned} \qquad (6')$$

where the notations are slightly modified to $\lambda_{ij}=a_{ij}X_j/h_i$ (i=L,K; $h_i=L_0$,K) and $\lambda_{Zj}=ea_{Zj}X_j/L_0$. It is noted that the relationships hold as follows, $\lambda_{L1}+\lambda_{Z1}+\lambda_{L2}+\lambda_{Z2}=1$ and $\lambda_{K1}+\lambda_{K2}=1$. Equation (7) is rewritten as,

$$P_j^* = (\theta_{Lj}+\theta_{Zj})w^* + (\theta_{Zj}+\theta_{tj})e^* + \theta_{tj}t^* + \theta_{Kj}r^* \quad \text{for} \quad j=1,2 \qquad (7')$$

where

$\theta_{Zj} = wea_{Zj}/P_j$: the distributive share of the cost of labour damage in the j-th sector

$\theta_{tj} = tea_{Zj}/P_j$: the distributive share of the cost of damage compensation in the j-th sector

$\theta_{Lj}+\theta_{Kj}+\theta_{Zj}+\theta_{tj} = 1$ for j=1,2

Final set of equations, (8), is rewritten as (see Appendix 1 for derivation):

$$\begin{aligned}
a_{Lj}^* &= \theta_{Kj}\sigma_{KL}^j(r^* - w^*) + (B'')\theta_{Zj}\sigma_{ZL}^j(t^* - w^*) \\
a_{Kj}^* &= \theta_{Kj}\sigma_{KK}^j(r^* - w^*) + (B'')\theta_{Zj}\sigma_{ZK}^j(t^* - w^*) \\
a_{Zj}^* &= \theta_{Kj}\sigma_{KZ}^j(r^* - w^*) + (B'')\theta_{Zj}\sigma_{ZZ}^j(t^* - w^*) \qquad (8')
\end{aligned}$$

, where

$$(B'') = t/(t+w) > 0$$

Our purpose in this section is to investigate the backward incidence of the damage compensation policy. However, the control variable for the regional government is not the pollution level, Z, but the damage compensation rate, "t". In order to express the impact of the changing "t" on factor prices, w and r, and pollution level, Z, we may rewrite (6'),(7'), and (8') into the following equation, which corresponds to equation (10) in section 2 :

$$\begin{pmatrix} \theta_{L1}+\theta_{Z1} & \theta_{K1} & 0 \\ \theta_{L2}+\theta_{Z2} & \theta_{K2} & 0 \\ -(C1) & -(C2) & (A) \end{pmatrix} \begin{pmatrix} w^* \\ r^* \\ Z^* \end{pmatrix} = \begin{pmatrix} -\theta_{t1} \\ -\theta_{t2} \\ (C3) \end{pmatrix} t^* \qquad (10')$$

where we assumed $P_1^*=P_2^*=K^*=L_0^*= e^*= 0$ (see Appendix 2 for derivation). Thus we may solve equation (10') as follows:

$$Z^* = t^* \left((C1)(D1)+(C2)(D2)+(C3)(D3) \right)/(A)|\theta| \qquad (16)$$

$$w^* = t^* (A)(D1)/|\theta| \qquad (17)$$

$$r^* = t^* (A)(D2)/|\theta| \qquad (18)$$

where

$$\left.\begin{aligned}
(D1) &= \theta_{K1}\theta_{t2} - \theta_{K2}\theta_{t1} > 0 \\
(D2) &= (\theta_{L2}+\theta_{Z2})\theta_{t1} - (\theta_{L1}+\theta_{Z1})\theta_{t2} > 0 \\
(D3) &= (\theta_{L1}+\theta_{Z1})\theta_{K2} - \theta_{K1}(\theta_{L2}+\theta_{Z2}) < 0 \\
(A) &= \lambda_{K2}(\lambda_{L1}+\lambda_{Z1})-\lambda_{K1}(\lambda_{L2}+\lambda_{Z2}) < 0 \\
|\theta| &= (A)(D3) \\
&= (A)rw((a_{L1}+ea_{Z1})a_{K2}-(a_{L2}+ea_{Z2})a_{K1}))/P_1P_2 > 0
\end{aligned}\right\} \qquad (19)$$

The sign of (D1),(D2),(D3),(A) and $|\theta|$ in equation (19) are obtained from equation (13). Thus we may easily conclude that the increase in the damage compensation rate (t) leads to the decrease in the wage rate and in the rental on capital. This result is the major difference between the model in section 2 and the model in this section. In reference to Figure 1, both the unit cost curve for sector 1 and that for sector 2 shift, in response to the increase in the compensation rate, toward the origin with the consequent decrease in "w" and "r". This is the main reason why we are unable to obtain such a clear result as in the modified Yohe model, concerning the effects on the sector outputs and the pollution level.

Based on Appendix 3, we can summarize our main result in this section as follows: if sector 2 does not generate any pollutant ($a_{Z2}= 0$) and labour input and pollution input are complementary to each other in the production process ($\sigma_{ZL}\leq 0$), then the increase in the pollution damage compensation rate leads to the decrease in the total amount of pollution, and expansion in the labour intensive industry sector at the expense of the capital intensive industry sector.

4. Summary of the results

Table 1 compares the results obtained in section 2 and 3. In Section 2 we extended the Yohe Model so as to include the nonlinear damage funciton, whereas in Section 3 we extended the Batra-Casas Model to include the linear damage function. As it is well known from existing literature in the field of international trade, if the number of factors exceeds the number of goods, then the comparative statics results for market equilibrium solutions depend on the substitutability of production factors (see Woodland(1982, p94). Diewert and Woodland(1977, p386) showed that the increase in the substitutability of production factors leads to the decrease in the response of factor rewards to the change in the endowment. This seems to be the main reason why in the Yohe Model the range of factor substituability is assumed to be limited. This limited range of substitutability simplifies the input-output coefficient function (compare equations (8) and (8')) and consequently, contributes to the derivation of clear policy implication for pollution control policy. The introduction of nonlinear damage function in the Yohe Model limited the applicability of his Propositions 1 and 3, whereas his Proposition 3 was relaxed to include the case of regional income growth. This is mainly due to the introduction of damage function which forces to bend down the unit cost curve for sector 1 in Figure 1. Especially the modified versions of Propositons 1 and 3 show that the efficacy of price mechanism in pollution control is expected for equations (8) and (8')) and consequently, contributes to the derivation of clear policy implication for pollution control policy. The introduction of nonlinear damage function in the Yohe Model limited the applicability of his Propositions 1 and 3, whereas his Proposition 3 was relaxed to include the case of regional income growth. This is mainly due to the introduction of damage function which forces to bend down the unit cost curve for sector 1 in Figure 1. Especially the modified versions of Propositons 1 and 3 show that the internal solution with X_1, X_2 > 0 for the national income maximum is expected for the case of convex damage function with low level of initial pollution . For, though the situation depicted in Figure 1 holds for the convex damage function with low level of pollution or for the concave damage function with high level of pollution, the latter case may not genetrate any internal solution, due to Proposition 3.

The original Batra-Casas Model generates 8 theorems, four of which are related to region specific factors. One of the remaining four theorems, theorem 1, says that an increase in the supply of a factor always lowers the reward of that factor at constant commodity prices. Due to the assumption of linear damage function, the profit maximization condition (7') does not contain pollution variable, Z, and consequently, the modified Batra-Casas Model in Section 3 becomes essentially a two-good and two-factor model. Therefore changes in factor supplies of original labour (L_0) and capital (K) have no effect on factor prices, w and r. This is the reason why we do not have a counterpart to Batra-Casas's Theorem 1.

Although they allow the substitution relationships among all three factors, they somehow put stricter restraint on the factor substitution by introducing the concept of "strong" factor intensity. We introduced a linear damage function into their model. Linearity assumption is the price we pay to investigate the comparative statics of the pollution compensation rate. The results summarized in Table 1 is acceptable. In case of the compensation policy, the national income is defined to as

$$Y = w(L_0 - eZ) + (w+t)eZ + rK$$
$$= wL_0 + teZ + rK$$

and consequently we obtain $Y^* = \theta_t Z^*$. Thus the effect on the national income is reasonable. As to the effects on the factor prices and sector outputs, if we assume that sector 1 is strongly capital intensive and sector 2 is strongly labour intensive, we are unable to say that the increase in damage compensation rate necessarily leads to the decrease in polluting sector outputs as well as pollution, unless we further assume that only sector 1 is the polluting sector and $\sigma_{LZ} \leq 0$.

Thus, we can now further understand that if such a tragedy as the Minamata Mercury Pollution had happened in a competitive small country, and if we heroically assumed the health damages were reversible, then the damage compensation policy may lead to the decrease in pollution as well as pollution damage.

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Appendix 1 Derivation of equation (8')

Totally differentiating eqs. (14) and (15) with respect to w, we obtain

$$\begin{pmatrix} 0 & f_1 & f_2 & f_3 \\ f_1 & f_{11} & f_{12} & f_{13} \\ f_2 & f_{21} & f_{22} & f_{23} \\ f_3 & f_{31} & f_{32} & f_{33} \end{pmatrix} \begin{pmatrix} (\partial p_j/\partial w)/p_j \\ \partial a_{Lj}/\partial w \\ \partial a_{Kj}/\partial w \\ \partial a_{Zj}/\partial w \end{pmatrix} = \begin{pmatrix} 0 \\ 1/p_j \\ 0 \\ e/p_j \end{pmatrix} \tag{S1}$$

where $f_{hk}=\partial^2 f_j/\partial a_h \partial a_k$ for $h,k=L_j,K_j,Z_j$. Then we get from eq. (S1)

$$\partial a_{Lj}/\partial w = \begin{pmatrix} 0 & f_2 & f_3 \\ f_2 & f_{22} & f_{23} \\ f_3 & f_{32} & f_{33} \end{pmatrix} /p_j(F) + \begin{pmatrix} 0 & f_2 & f_3 \\ f_1 & f_{12} & f_{13} \\ f_2 & f_{22} & f_{23} \end{pmatrix} e/p_j(F)$$

$$= F_{11}/p_j(F) + F_{31}e/p_j(F)$$

$$= a_{Lj}\theta_{Lj}\sigma^j_{LL}/p_j f_{Lj} + ea_{Zj}\theta_{Lj}\sigma^j_{ZL}/p_j f_{Lj} \tag{S2}$$

$$\partial a_{Kj}/\partial w = F_{12}/p_j(F) + eF_{32}/p_j(F)$$

$$= a_{Kj}\theta_{Lj}\sigma^j_{LK}/p_j f_{Lj} + ea_{Kj}\theta_{Zj}\sigma^j_{ZK}/p_j f_{Lj} \tag{S3}$$

$$\partial a_{Zj}/\partial w = F_{13}/p_j(F) + eF_{33}/p_j(F)$$

$$= a_{Zj}\theta_{Lj}\sigma^j_{LZ}/p_j f_{Lj} + ea_{Zj}\theta_{Zj}\sigma^j_{ZZ}/p_j f_{Zj} \tag{S4}$$

, where (F) is the matrix determinant of eq. (S1). F_{hk} is the minor of the element f_{hk} and is the partial elasticity of substitution, σ^j_{hk} is defined to be

$$F_{hk} = a_h(F)\theta_k\sigma^j_{hk}/f_k$$

$$= a_k(F)\theta_h\sigma^j_{hk}/f_h \tag{S5}$$

Similarly, totally differentiating eq. (14) and (15) with respect to r, we obtain

$$\partial a_{Lj}/\partial r = F_{21}/p_j$$

$$= a_{Lj}\theta_{Kj}\sigma^j_{KL}/p_j f_{Kj} \tag{S6}$$

$$\partial a_{Kj}/\partial r = a_{Kj}\theta_{Kj}\sigma^j_{KK}/p_j f_{Kj} \tag{S7}$$

$$\partial a_{Zj}/\partial r = a_{Zj}\theta_{Kj}\sigma^j_{KZ}/p_j f_{Kj} \tag{S8}$$

Finally, totally differentiating eq. (14) and (15) with respect to t, we get

$$\partial a_{Lj}/\partial t = eF_{31}/p_j(F)$$
$$= ea_{Lj}\theta_{Zj}\sigma^j_{ZL}/p_j f_{Zj} \tag{S9}$$

$$\partial a_{Kj}/\partial t = eF_{32}/p_j(F)$$
$$= ea_{Kj}\theta_{Zj}\sigma^j_{ZK}/p_j f_{Zj} \tag{S10}$$

$$\partial a_{Zj}/\partial t = eF_{33}/p_j(F)$$
$$= ea_{Zj}\theta_{Zj}\sigma^j_{ZZ}/p_j f_{Zj} \tag{S11}$$

Now we are ready to derive the equation (8'). Since the derivation procedure is the same, we here derive only the first equation of (8'). From equation (5') we derive

$$a^*_{Lj} = (da_{Lj}/d\tau)/a_{Lj}$$
$$= (\partial a_{Lj}/\partial w)(dw/d\tau)(w/w)(1/a_{Lj})$$
$$+ (\partial a_{Lj}/\partial r)(dr/d\tau)(r/r)(1/a_{Lj})$$
$$+ (\partial a_{Lj}/\partial t)(dt/d\tau)(t/t)(1/a_{Lj}) \tag{S12}$$

, where τ is used to differentiate time from compensation rate t. From equations (S2),(S6), and (S9), we obtain

$$a^*_{Lj} = (w^*w/a_{Lj})((a_{Lj}\theta_{Lj}\sigma^j_{LL}+ea_{Zj}\theta_{Lj}\sigma^j_{ZL})/(p_j f_{Lj}))$$
$$+ (r^*r/a_{Lj})((a_{Lj}\theta_{Kj}\sigma^j_{KL})/(p_j f_{Kj}))$$
$$+ (t^*t/a_{Lj})((ea_{Lj}\theta_{Zj}\sigma^j_{ZL})/(p_j f_{Zj})) \tag{S13}$$

Using equation (15),

$$a^*_{Lj} = w^*(\theta_{Lj}\sigma^j_{LL} + (ea_{Zj}\theta_{Lj}\sigma^j_{ZL}/a_{Lj})) + r^*\theta_{Kj}\sigma^j_{KL}$$
$$+ (t/(t+w))t^*\theta_{Zj}\sigma^j_{ZL} \tag{S14}$$

Since the input-output coefficient funciton is homogeneous of degree zero with respect to w,r,t, we obtain

$$w\,\partial a_{Lj}/\partial w + r\,\partial a_{Lj}/\partial r + t\,\partial a_{Lj}/\partial t = 0$$

,which is rewritten by using (S2),(S6) and (S9) as follows

$$(\sigma^j_{LL}+(ea_{Zj}\sigma^j_{ZL}/a_{Lj}))\theta_{Lj} + \theta_{Kj}\sigma^j_{KL} + (B'')\sigma^j_{ZL}\theta_{Zj} = 0 \qquad \text{(S15)}$$

, where (B") = t/(t+w). Now substituting (S15) into (S14), we obtain the first equation of equation set (8').

Appendix 2 Derivation of equation (10')

Solving equation (6') simultaneously for X_1^* and X_2^* without the assumption of zero percentage rate of growth for r, w, and e, gives

$$X_1^* = (-(\lambda_{L2}+\lambda_{Z2})(K^*+\beta_k)+\lambda_{K2}(L_0^*+\beta_L+\beta_Z-(\lambda_{Z1}+\lambda_{Z2})e^*))/(A)$$

$$X_2^* = ((\lambda_{L1}+\lambda_{Z1})(K^*+\beta_k)-\lambda_{K1}(L_0^*+\beta_L+\beta_Z-(\lambda_{Z1}+\lambda_{Z2})e^*))/(A) \qquad \text{(Q1)}$$

, where

$$(A) = \lambda_{K2}(\lambda_{L1}+\lambda_{Z1})-\lambda_{K1}(\lambda_{L2}+\lambda_{Z2}) < 0$$

$$\beta_L = -(\lambda_{L1}a_{L1}^*+\lambda_{L2}a_{L2}^*)$$

$$\beta_K = -(\lambda_{K1}a_{K1}^*+\lambda_{K2}a_{K2}^*)$$

$$\beta_Z = -(\lambda_{Z1}a_{Z1}^*+\lambda_{Z2}a_{Z2}^*) \qquad \text{(Q2)}$$

In order to express the change in the total amount of pollution in terms of the change in input prices and damage compensation rate, we totally differentiate equation (3c') as follows:

$$Z^* = \lambda_{T1}X_1^* + \lambda_{T2}X_2^* + \lambda_{T1}a_{Z1}^* + \lambda_{T2}a_{Z2}^* \qquad \text{(Q3)}$$

where

$$\lambda_{Tj} = a_{Zj}X_j/Z \quad \text{for} \quad j=1,2$$

Assuming $K^*=0$ and substituting (Q1) into (Q3), we obtain

$$\begin{aligned}(A)Z^* = {} & (A)(\lambda_{T1}a_{Z1}^* + \lambda_{T2}a_{Z2}^*) \\ & + (\beta_k(\lambda_{T2}(\lambda_{L1}+\lambda_{Z1})-\lambda_{T1}(\lambda_{L2}+\lambda_{Z2})) \\ & + (\lambda_{T1}\lambda_{K2}-\lambda_{T2}\lambda_{K1})(L_0^*+\beta_L+\beta_Z) + e^*(B3) \qquad \text{(Q4)}\end{aligned}$$

where

$$(B3) = (\lambda_{T2}\lambda_{K1}(\lambda_{Z1}+\lambda_{Z2})-\lambda_{T1}\lambda_{K2}(\lambda_{Z1}+\lambda_{Z2})) < 0$$

Substituting (8') and (Q2) into (Q4), we get as follows;

The first term in the RHS of equation (Q4) excluding (A)

$$\begin{aligned}& = (\lambda_{T1}\theta_{K1}\sigma_{KZ}^1+\lambda_{T2}\theta_{K2}\sigma_{KZ}^2)(r^*-w^*) \\ & \quad + (\lambda_{T1}\theta_{Z1}\sigma_{ZZ}^1+\lambda_{T2}\theta_{Z2}\sigma_{ZZ}^2)(B'')(t^*-w^*) \qquad \text{(Q5)}\end{aligned}$$

The second term in the RHS of equation (Q4)

$$= -\left((B1)(\lambda_{K2}\theta_{K2}\sigma^2_{KK}+\lambda_{K1}\theta_{K1}\sigma^1_{KK})\right)(r^*-w^*)$$
$$-\left((B1)(\lambda_{K2}\theta_{Z2}\sigma^2_{ZK}+\lambda_{K1}\theta_{Z1}\sigma^1_{ZK})\right)(B'')(t^*-w^*) \qquad (Q6)$$

where $(B1) = \lambda_{T2}(\lambda_{L1}+\lambda_{Z1})-\lambda_{T1}(\lambda_{L2}+\lambda_{Z2}) < 0$

The third term in the RHS of equation (Q4)

$$= L_0^*(B2) + w^*(B2)(\lambda_{L1}\theta_{K1}\sigma^1_{KL}+\lambda_{L2}\theta_{K2}\sigma^2_{KL}+\lambda_{Z1}\theta_{K1}\sigma^1_{KZ}+\lambda_{Z2}\theta_{K2}\sigma^2_{KZ})$$
$$+ w^*(B2)(B'')(\lambda_{L1}\theta_{Z1}\sigma^1_{ZL}+\lambda_{L2}\theta_{Z2}\sigma^2_{ZL}+\lambda_{Z1}\theta_{Z1}\sigma^1_{ZZ}+\lambda_{Z2}\theta_{Z2}\sigma^2_{ZZ})$$
$$- r^*(B2)(\lambda_{L1}\theta_{K1}\sigma^1_{KL}+\lambda_{L2}\theta_{K2}\sigma^2_{KL}+\lambda_{Z1}\theta_{K1}\sigma^1_{KZ}+\lambda_{Z2}\theta_{K2}\sigma^2_{KZ})$$
$$- t^*(B2)(B'')(\lambda_{L1}\theta_{Z1}\sigma^1_{ZL}+\lambda_{L2}\theta_{Z2}\sigma^2_{ZL}+\lambda_{Z1}\theta_{Z1}\sigma^1_{ZZ}+\lambda_{Z2}\theta_{Z2}\sigma^2_{ZZ}) \qquad (Q7)$$

where $(B2) = \lambda_{T1}\lambda_{K2} - \lambda_{T2}\lambda_{K1} < 0$

Substituting (Q5),(Q6),(Q7) into (Q4), and combining with equation (7'), we obtain equation (10'). Especially, the last equation of (10') is written as

$$(A)Z^* = (C1)w^* + (C2)r^* + (C3)t^* + (B2)L_0^* + (B3)e^* \qquad (10')$$

where (C1) is the sum of the following terms;

σ^1_{KZ} $(-(A)\lambda_{T1}\theta_{K1}+(B'')(B1)\lambda_{K1}\theta_{Z1}+(B2)\lambda_{Z1}\theta_{K1})$

σ^2_{KZ} $(-(A)\lambda_{T2}\theta_{K2}+(B'')(B1)\lambda_{K2}\theta_{Z2}+(B2)\lambda_{Z2}\theta_{K2})$

σ^1_{ZZ} $(B'')(-(A)\lambda_{T1}\theta_{Z1}+(B2)\lambda_{Z1}\theta_{Z1})$

σ^2_{ZZ} $(B'')(-(A)\lambda_{T2}\theta_{Z2}+(B2)\lambda_{Z2}\theta_{Z2})$

σ^1_{KK} $(B1)\lambda_{K1}\theta_{K2} > 0$

σ^2_{KK} $(B1)\lambda_{K2}\theta_{K2} > 0$

σ^1_{KL} $(B2)\lambda_{L1}\theta_{K1} < 0$

σ^2_{KL} $(B2)\lambda_{L2}\theta_{K2} < 0$

σ^1_{ZL} $(B'')(B2)\lambda_{L1}\theta_{Z1} \geq 0$ if $\sigma^1_{ZL} \leq 0$

σ^2_{ZL} $(B'')(B2)\lambda_{L2}\theta_{Z2} \geq 0$ if $\sigma^2_{ZL} \leq 0$

, (C2) is the sum of the folowing terms;

σ^1_{KZ} $((A)\lambda_{T1}\theta_{K1}-(B2)\lambda_{Z1}\theta_{K1})$

σ^2_{KZ} ($(A)\lambda_{T2}\theta_{K2} - (B2)\lambda_{Z2}\theta_{K2}$)

σ^1_{KK} ($-(B1)\lambda_{K1}\theta_{K1}$) < 0

σ^2_{KK} ($-(B1)\lambda_{K2}\theta_{K2}$) < 0

σ^1_{KL} ($-(B2)\lambda_{L1}\theta_{K1}$) > 0

σ^2_{KL} ($-(B2)\lambda_{L2}\theta_{K2}$) > 0

and (C3) is the sum of the following terms;

σ^1_{ZZ} (B")($(A)\lambda_{T1}\theta_{Z1} - (B2)\lambda_{Z1}\theta_{Z1}$)

σ^2_{ZZ} (B")($(A)\lambda_{T2}\theta_{Z2} - (B2)\lambda_{Z2}\theta_{Z2}$)

σ^1_{ZK} (B")($-(B1)\lambda_{K1}\theta_{Z1}$ > 0

σ^2_{ZK} (B")($-(B1)\lambda_{K2}\theta_{Z2}$ > 0

σ^1_{ZL} (B")($-(B2)\lambda_{L1}\theta_{Z1}$ ≤ 0 if $\sigma^1_{ZL} \leq 0$

σ^2_{ZL} (B")($-(B2)\lambda_{L2}\theta_{Z2}$ ≤ 0 if $\sigma^2_{ZL} \leq 0$

Appendix 3 The sign condition of equation (16)

In order to investigate the sign condition of the RHS of eauation (16), we rewrite it as follows:

$$Z^* = (\lambda_{T1} a^*_{Z1} + \lambda_{T2} a^*_{Z2}) + \beta_k (B1)/(A) + (\beta_L + \beta_Z)(B2)/(A) \qquad \text{(R1)}$$

where we assumed $L^*_0 = e^* = K^* = 0$. We now check the sign of each term on the RHS of equation (R1):

$$\lambda_{T1} a^*_{Z1} + \lambda_{T2} a^*_{Z2} = (r^*-w^*)(\lambda_{T1}\theta_{K1}\sigma^1_{KZ} + \lambda_{T2}\theta_{K2}\sigma^2_{KZ})$$
$$+ (B'')(t^*-w^*)(\lambda_{T1}\theta_{Z1}\sigma^1_{ZZ} + \lambda_{T2}\theta_{Z2}\sigma^2_{ZZ})$$
$$< 0 \quad \text{if} \quad r^* - w^* < 0 \qquad \text{(R2)}$$

Here we used the relationship that $t^* - w^* > 0$ if $t^* > 0$. From equation (17), we get the following equality:

$$|\theta|(t^*-w^*) = (\ |\theta| - (A)(D1)\ )t^*$$
$$= (A)t^*(\theta_{K2}-\theta_{K1}) > 0 \qquad \text{(R3)}$$

where we used (13) and $\theta_{Lj}+\theta_{Kj}+\theta_{Zj}+\theta_{tj}=1$ for j=1,2. Since sector 1 is assumed to be strongly capital intensive, we know that $t^*-w^* > 0$.

As to the sign conditions of the second and the third terms on the RHS of equation (R1), we obtain as follows:

$$\beta_L + \beta_Z = -(r^*-w^*)(\lambda_{L1}\theta_{K1}\sigma^1_{KL} + \lambda_{L2}\theta_{K2}\sigma^2_{KL} + \lambda_{Z1}\theta_{K1}\sigma^1_{KZ} + \lambda_{Z2}\theta_{K2}\sigma^2_{KZ})$$
$$- (t^*-w^*)(B'')(\lambda_{L1}\theta_{Z1}\sigma^1_{ZL} + \lambda_{L2}\theta_{Z2}\sigma^2_{ZL} + \lambda_{Z1}\theta_{Z1}\sigma^1_{ZZ} + \lambda_{Z2}\theta_{Z2}\sigma^2_{ZZ})$$
$$> 0 \quad \text{if} \quad r^*-w^* < 0 \ \text{and} \ \sigma^j_{ZL} \leq 0 \qquad \text{(R4)}$$

$$\beta_k = -(r^*-w^*)(\lambda_{K1}\theta_{K1}\sigma^1_{KK} + \lambda_{K2}\theta_{K2}\sigma^2_{KK})$$
$$- (t^*-w^*)(B'')(\lambda_{K1}\theta_{Z1}\sigma^1_{ZK} + \lambda_{K2}\theta_{Z2}\sigma^2_{ZK})$$
$$< 0 \quad \text{if} \quad r^*-w^* < 0 \qquad \text{(R5)}$$

Thus, if r^*-w^* is negative, then the first and second terms of the RHS of equation (R1) become negative. From equations (18) and (19), we get the following equality:

$$|\theta|(r^*-w^*)/(\ (A)t^*\ ) = D2 - D1$$

$$= (et/P_1P_2)\left(w\left((a_{L2}+ea_{Z2})a_{Z1}-(a_{L1}+ea_{Z1})a_{Z2}\right) - r(a_{K1}a_{Z2} - a_{K2}a_{Z1}) \right) \quad \text{(R6)}$$

The strong factor intensity assumption, equation (13), says that the sign of (r^*-w^*) is indeterminate.

However when we assume that sector 2 does not generate any pollution , we obtain that

$$\lambda_{t2} = \theta_{t2} = 0 \quad \text{(R7)}$$

In this case we get a happy result from (17), (19) and (R6) that (D1)<0, (B2) > 0, $w^*>0$, $t^*-w^*>0$, and $r^*-w^*< 0$, and consequently that the RHS of equations (R1) and (16) becomes negative as $t^* > 0$.

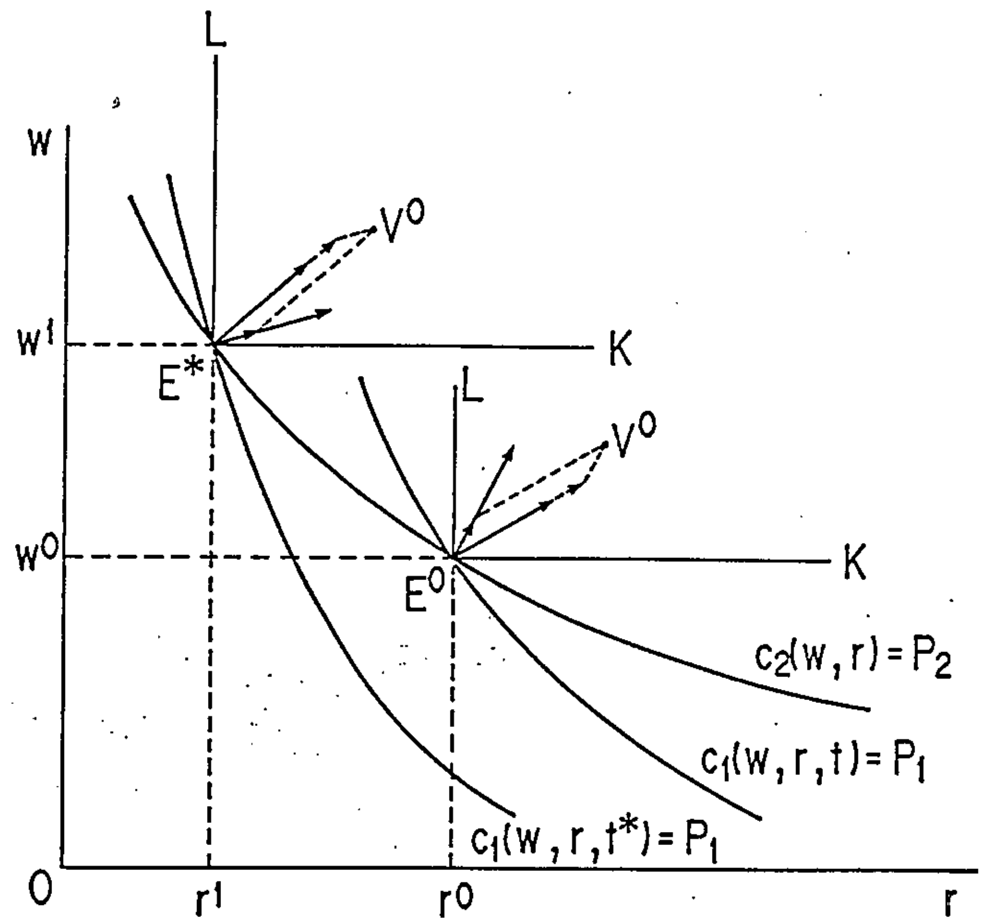

Figure 1 Factor price and sector output responses to an increase in the emissions tax rate from t to t^*

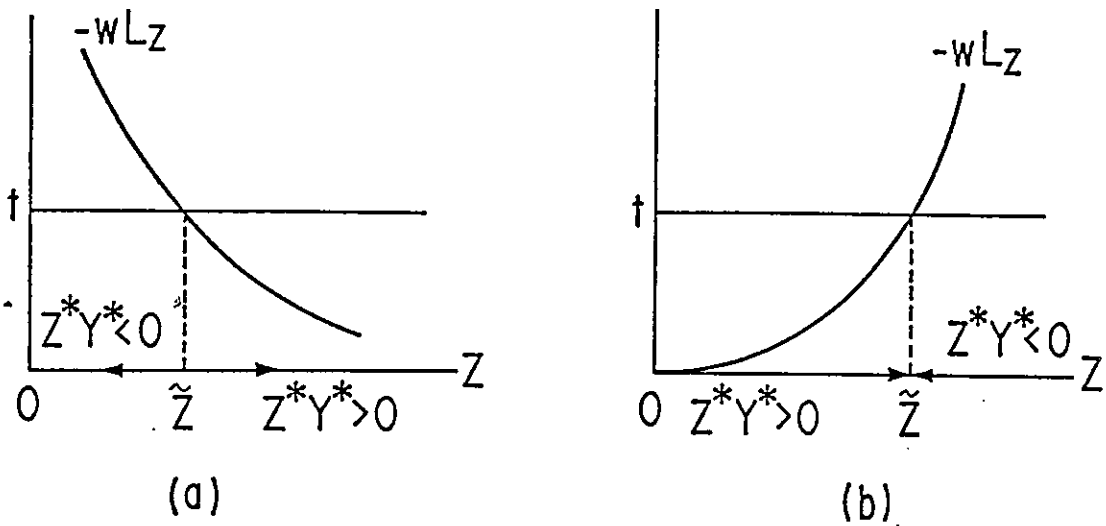

Figure 2 Stability of pollution control policy for the cases of concave and convex damage function

Table 1   Assumptions and conclusions of the two models

The Model in Section 2 (The Yohe Model with nonlinear damage function)	The Model in Section 3 (The Batra-Casas Model with a linear damage function)
Main Assumptions	**Main Assumptions**
1. Substitutability Sector 1 — K and L, K and Z Sector 2 — K and L	1. Substitutability Sector 1, Sector 2 — K and L, K and Z, L and Z
2. Polluting Sector Sector 1	2. Polluting Sector both Sector 1 and Sector 2
3. Type of Environmental Policy Pollution control policy (policy parameter= amount of emitted pollutants, Z)	3. Type of Environmental Policy Damage compensation policy (policy parameter= the compensation rate, t)
Main Conclusions	**Main Conclusions**
1. (Modified version of Yohe's Proposition 1) If $(a_{K2}/a_{L2}) < (a_{K1}/(a_{L1}+a_{Z1}L_Z)$ is satisfied, then $Z^*w^* < 0$, $Z^*r^* > 0$, $Z^*t^* < 0$	1. (Modified version of Batra-Casas's Theorem 2a) If Sector 1 is strongly capital intensive and Sector 2 is strongly labour intensive, then $t^*w^* < 0$ and $t^*r^* < 0$ Furthermore, if sector 2 does not generate any pollution and $\sigma^j_{ZL} \leq 0$, then $t^*Z^* < 0$.
2. (Modified version of Yohe's Proposition 2) If $t + wL_Z \geq 0$ then $Y^*Z^* \geq 0$	2. (Modified version of Batra-Casas's Theorem 5) $Y^*t^* < 0$ holds unconditionally.
3. (Modified version of Yohe's Proposition 3 or that of Batra-Casas's Theorem 6) If the same assumption in 1. holds, then $X_1^*Z^* > 0$ and $X_2^*Z^* < 0$	3. (Modified version of Batra-Casas's Theorem 6) If the same assumption in 1. holds, then $X_1^*t^* < 0$ and $X_2^*t^* > 0$