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“Dynamic environmental taxes in an international duopoly”

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Shuichi Ohori

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Dynamic environmental taxes in an international duopoly

Shuichi Ohori

Institute of Economic Research, Kyoto University, Japan;
Yoshida Hommachi Sakyo, Kyoto 606–8501, Japan
(ohori@kier.kyoto-u.ac.jp)

Abstract

This paper studies a dynamic game of environmental taxes between two countries in a Cournot duopoly. Based on the assumption of linear demand functions, we demonstrate that the environmental tax in the steady-state equilibrium is lower in a dynamic environmental tax game than in a static environmental one. Therefore, the dynamic behavior of the governments results in an increase in the environmental damage. Further, as a result of international cooperation on environmental taxes between two countries in the first period, there is an increase in the optimal environmental tax; this is due to the decrease in the effect of the rent-shifting.

Key words: environmental tax, dynamic programming, international duopoly

JEL classification: F18, H23, Q58

1. Introduction

There have been a substantial and growing number of disputes with regard to trade and the environment. In particular, many previous theoretical papers suggest that governments have incentives to modify environmental policies in the presence of international markets under trade liberalization. This is because governments would like home firms to gain a competitive advantage in international markets. Such a phenomenon is also referred to as "environmental dumping" or "rent-shifting", which could even result in even a "race-to-the-bottom" as governments would compete to set lower environmental standards than the marginal environmental damage costs.

Most of the theoretical analyses on this issue have been conducted under a static case of environmental policies rather than in a dynamic framework; however, the real world is not static. With respect to theoretical papers on the dynamic setting of an environmental policy, Moledina *et al.* (2003) investigated this issue with a comparison of environmental taxes and emissions permits in a dynamic setting when the regulator is not strategic. Moreover, Benford (1998) considered the optimal regulation of a persistent pollutant in a dynamic setting when the firms are not strategic. However, in general, regulators as well as firms act strategically in the dynamic world. Thus, considering a dynamic case in which both governments and firms are strategic appears to be more realistic. In addition, the environmental policies cannot be changed easily because of the complicated political processes involved. In such a situation, countries would introduce environmental policies unilaterally, and thus, the decisions would be taken sequentially. On the other hand, firms have the opportunity to act myopically because they would earn short-run profits due to the consideration given to shareholders. Hence, in this paper, we would like to focus on a case in which the behavior of governments is dynamic and that of firms is static.

This paper considers dynamic environmental tax in a steady-state equilibrium between two countries in the situation of international Cournot duopoly with two firms. Extending the study of Maskin and Tirole (1987) into our analysis, we obtain the equilibrium dynamic environmental taxes with alternating moves made by the two countries and an infinite horizon. Maskin and Tirole (1987) studied a dynamic game between two firms in a Cournot duopoly, in which the strategic variable was the output level.[1] In this paper, the strategic environmental tax setting between the two countries is considered in discrete time with an infinite horizon, and therefore, the strategic variable is the environmental tax rate. Each government sets the environmental tax in each period, taking into account the other government's reaction in the following period. On the other hand, firms myopically choose their abatement and output levels in each period in order to maximize their own profits. In this study, the problem that the two countries are confronted with is set up as a dynamic programming one. Further, we consider the case of international cooperation on environmental tax between countries. Subsequently, a comparison between dynamic, static, and cooperative environmental taxes in equilibrium can reveal the manner in which environmental policies should be introduced under trade liberalization and from the viewpoint of emission reductions.

Moreover, this paper follows Brander and Spencer's (1985) well-known analysis, where a domestic firm competes with a foreign firm in a third market. Brander and Spencer (1985) indicate that an export subsidy implemented by the domestic government results in a rent-shift from the foreign to the domestic firm. Certain previous works that adopt the third country model with the design of environmental policies, indicate that governments have incentives to set lower environmental standards than the marginal environmental damage costs.[2] In accordance with Brander and Spencer (1985), we can easily consider the dynamic environmental tax implications. Since the focus of this paper is on strategic environmental policies in international markets, following Brander and Spencer (1985) is helpful in order to grasp the fundamental nature of the problem.

The remainder of this paper is organized as follows: Section 2 explains the basic model; Section 3 includes the results of the analysis and the discussions; and Section 4 presents the concluding remarks.

2. The model

Let us consider two homogeneous firms, each located in a different country and indexed 1 and 2, respectively. It is assumed that these two countries are symmetric. The two firms produce a homogeneous good and compete in a third country's market by exporting the good to this market. The production of the homogeneous good, given by q_i $(i = 1, 2)$, causes emissions e_i, which damages only the local environment. However, each firm can prevent pollution by undertaking certain abatement measures. Thus, the emission level of each firm is given by $e_i = q_i - \theta_i$, where θ_i denotes the abatement level.

Following the basic setup of Maskin and Tirole (1987), we consider a discrete-time *Markov* equilibrium model of Cournot duopoly, in which pollution is present and the two countries act strategically. Taking into account the other country's reaction in the following period, each government non-cooperatively sets the environmental tax rate τ_i to control environmental quality. On the other hand, each firm chooses the abatement level θ_i and the output level q_i in each period in order to maximize its instantaneous profit for that period. Thus, while the countries behave in a dynamic manner, the firms are static.

In order to shapen the study, we assume that the inverse demand function is linear, i.e., $p = a - (q_1 + q_2)$, where p is the price and $a(> 0)$ denotes the choke price. The two firms share the same abatement technology represented by a quadratic abatement cost function, $ac^i = k\theta_i^2/2$ and $k > 0$. The instantaneous profit of firm i is given as[3]

$$\pi^i = pq_i - ac^i - \tau_i e_i. \tag{1}$$

The environmental damage function is given by $D^i = le_i$, where $l(\geq 1)$ denotes the marginal environmental damage and is assumed to be identical for the two countries. Futher, it is also assumed that $a > l$. Thus, the social welfare in country i is given as follows:

$$\begin{aligned} \omega^i &= \pi^i + \tau_i e_i - D^i \\ &= pq_i - \frac{k\theta_i^2}{2} - le_i. \end{aligned} \tag{2}$$

Note that according to Brander and Spencer (1985), consumer surplus is not included in the social welfare because the firms export the good to the third country, and therefore, the good is not consumed in the domestic countries.

3. Results

First let us investigate the firms' choice of the abatement and quantity levels. Differentiating (1) with respect to each abatement level and output, respectively, and after rearranging, we obtain the following:

$$\theta_i = \frac{\tau_i}{k}, \text{ and} \tag{3}$$

$$q_i = \frac{1}{3}(a - 2\tau_i + \tau_j), \tag{4}$$

where $j \neq i$. Based on (3) it can be observed that the abatement level increases with the environmental tax. Moreover, (4) implies that the environmental tax decreases the output of the domestic firm and increases that of the foreign firm. This is the standard result in most of the literature on environmental economics.

Substituting (3) and (4) into (2), we obtain the following:

$$\begin{aligned}\omega^i(\tau_i, \tau_j) &= \frac{1}{9}(a + \tau_i + \tau_j)(a - 2\tau_i + \tau_j) \\ &\quad -\frac{\tau_i^2}{2k} - \frac{l}{3k}[ka - (2k+3)\tau_i + k\tau_j]. \end{aligned} \tag{5}$$

Further, we obtain the following based on (5):

$$\frac{\partial \omega^i}{\partial \tau_i} = -\frac{1}{9k}[ka + (4k+9)\tau_i + k\tau_j - 3(2k+3)l], \tag{6}$$

$$\frac{\partial \omega^i}{\partial \tau_j} = \frac{1}{9}(2a - \tau_i + 2\tau_j - 3l), \qquad \text{and} \tag{7}$$

$$\frac{\partial^2 \omega^i}{\partial \tau_i \partial \tau_j} = -\frac{1}{9}. \tag{8}$$

At this point, we derive the equilibrium environmental tax in a static game. In order to obtain the solution, the environmental tax needs to be set such that the social welfare is maximized. By setting $\partial \omega^i / \partial \tau_i = 0$ in (6), we obtain the following equilibrium environmental tax in a static game:

$$\tau_1^{es} = \tau_2^{es} = \tau^{es} = l - \frac{k(a-l)}{5k+9}, \tag{9}$$

where es over the variable denotes the equilibrium value in a static game. According to (9), the optimal environmental tax in a static game is lower than the marginal environmental damage (thus, the Pigouvian tax). This result implies that each government has an incentive to increase the share of the domestic firm in the international market; this phenomenon has come to be known the rent-shifting effect.

Subsequently, we consider the case of international cooperation between two countries with respect to environmental taxes.[4] The objective function of the two countries is assumed to be the sum of their social welfare $\omega^i + \omega^j$. The cooperation between countries with respect to environmental tax implies that $\tau^i = \tau^j = \tau$. Differentiating $\omega^i + \omega^j$ with respect to τ yields the following first-order condition:

$$\frac{d(\omega^i + \omega^j)}{d\tau} = \frac{a}{9} - \frac{4k+9}{9k}\tau + \frac{k+3}{3k}l = 0.$$

Hence, under international cooperation between two countries, we obtain the following equilibrium environmental tax:

$$\tau^* = l + \frac{k(a-l)}{4k+9}, \tag{10}$$

where the asterisk denotes the equilibrium value in the case of international cooperation. (10) implies that the cooperative environmental tax rate in equilibrium case is higher than the marginal environmental damage cost.

On comparing (9) and (10), the following proposition is easily obtained:

Proposition 1. *In the static game, noncooperative environmental tax is lower than cooperative environmental tax, with regard to equilibrium.*

This is because the rent-shifting effect is smaller under cooperation than under noncooperation; moreover, this strategic effect is so small in the case of cooperation that it might even disappear.

Next we describe the case of a dynamic game in discrete time with an infinite horizon. The time periods are indexed by t $(= 0, 1, 2, ...)$. Let T be the time between consecutive periods. Since the governments set the discount for the future based on the same discount rate r, the discount factor can be expressed as $\delta = \exp(-rT)$, where $\delta \in (0, 1)$. The intertemporal social welfare at time t is given by

$$\sum_{t=0}^{\infty} \delta^t \omega^i(\tau_{i,t}, \tau_{j,t}),$$

where $\tau_{i,t}$ denotes the environmental tax in country i in period t.

Let us consider the timing of the environmental taxation. Country 1 sets its environmental tax in odd-numbered periods; country 2, in even-numbered periods. The environmental taxes remain fixed over two periods. It is assumed that country i's strategy relies only on the variables that directly enter the social welfare function. In other words, this game is the *Markov* strategy. Therefore, the dynamic reaction function of country 1 is $\tau_{1,2m+1} = R_1(\tau_{2,2m})$ while that of country 2 is $\tau_{2,2m+2} = R_2(\tau_{1,2m+1})$. Based on the dynamic programming formulation, there exist certain valuation functions (V_1, W_1) and (V_2, W_2) such that for any pair of environmental taxes $\{\tau_{1,2m+1}, \tau_{2,2m}\}$. Hence, the problem faced by country 1 can be expressed as follows:

$$\begin{aligned} V_1(\tau_{2,2m}) &= \max_{\tau}[\omega^1(\tau, \tau_{2,2m}) + \delta W_1(\tau)], && (11) \\ R_1(\tau_{2,2m}) &= \arg\max_{\tau}[\omega^1(\tau, \tau_{2,2m}) + \delta W_1(\tau)], \text{ and} && (12) \\ W_1(\tau_{1,2m+1}) &= \omega^1(\tau_{1,2m+1}, R_2(\tau_{1,2m+1})) + \delta V_1(R_2(\tau_{1,2m+1})). && (13) \end{aligned}$$

The same holds for country 2.

Next, we demonstrate that the equilibrium reaction functions are downward sloping.

Lemma 1. *$R_i(\tau_j) \leqq R_i(\bar{\tau}_j)$ if $\tau_j > \bar{\tau}_j$, $j \neq i$. Therefore, the equilibrium dynamic reaction functions are downward sloping.*

Proof. See Appendix A.

Since the partial derivatives of the social welfare functions (5) are linear, the following reaction functions are also linear:

$$R_1(\tau_{2,2m}) = \alpha_1 - \beta_1 \tau_{2,2m} \quad \text{and} \tag{14}$$

$$R_2(\tau_{1,2m+1}) = \alpha_2 - \beta_2 \tau_{1,2m+1}, \tag{15}$$

where $\alpha_1, \alpha_2 > 0$ and $\beta_1, \beta_2 > 0$, based on Lemma 1.

Further, using (11)–(15) and then rearranging, we obtain the following equations:

$$k - (1+\delta)(4k+9)\beta + 2\delta k\beta^2 + 2\delta(1+\delta)k\beta^3 + \delta^2 k\beta^4 = 0 \tag{16}$$

and

$$\begin{aligned} -k\alpha + [-(1+\delta)ka + 3(1+\delta)(2k+3)l - \delta k\alpha]\beta \\ +\delta k[-(1+\delta)(2a - 3l + 2\alpha) + \delta\alpha]\beta^2 - \delta^2 k\alpha\beta^3 = 0. \end{aligned} \tag{17}$$

For the details of the above calculation, see Appendix B.

Based on (16), we find the following lemma:

Lemma 2. *The real solution β of Eq. (16) is in the interval $(0,1)$, which gives rise to equilibrium reaction functions that are dynamically stable.*

Proof. See Appendix C.

Lemma 2 implies that there is one path in which the reaction functions are dynamically stable, and therefore, there exist environmental taxes in the steady state.

Based on (16) and (17), we obtain the following:

$$\alpha = \frac{(1+\beta)[-ka + 3(2k+3)l - \delta k(2a - 3l)\beta]}{5k + 9 + k\delta\beta}. \tag{18}$$

For the details of the above calculation, see Appendix D.

The equilibrium environmental tax of country i in the dynamic game is given as $\tau_i^{ed} = \alpha - \beta\tau_j^{ed} = \alpha - \beta(\alpha - \beta\tau_i^{ed})$, where ed denotes the equilibrium in the dynamic game. Therefore, replacing τ_1^{ed} and τ_2^{ed} with τ^{ed} and using (18), the steady-state equilibrium environmental tax can be represented as follows:

$$\begin{aligned} \tau^{ed} &= \frac{\alpha}{1+\beta} = \frac{-ka + 3(2k+3)l - \delta k(2a - 3l)\beta}{5k + 9 + k\delta\beta} \\ &= l - \frac{k(1+2\delta\beta)(a-l)}{5k+9+k\delta\beta}. \end{aligned} \tag{19}$$

Further, based on (9) and (19), it is clear that as $\delta \to 0$ (or $r \to \infty$), $\tau^{ed} \to \tau^{es}$. Thus, as the discount rate approximates infinity, the equilibrium environmental tax in the dynamic case converges with that in the static case.

Substituting (19) into (7), we obtain

$$\frac{\partial \omega^i}{\partial \tau_j^{ed}} = \frac{(k+2)(a-l)}{5k+9+k\delta\beta} > 0, \tag{20}$$

which is positive. This implies that an increase in the environmental tax of one country leads to an increase in the welfare of the other country. Note that the reaction functions of governments are downward sloping. Given the above, a decrease in the environmental tax set by country i will result in an increase in the environmental tax set by country j in the following period. Further, from (20), an increase in the tax in country j will leads to an increase in the welfare of country i.

Differentiating (19) with respect to δ, we have

$$\frac{d\tau^{ed}}{d\delta} = -\frac{9k(k+2)(a-l)\beta}{(5k+9+k\delta\beta)^2},$$

which is negative. Therefore, we obtain the following proposition.

Proposition 2. *The environmental tax in the steady-state equilibrium is lower in a dynamic environmental tax game than in a static environmental tax one.*

Based on Proposition 2, we find that the dynamic behavior of the governments leads to an increase in the outputs and a decrease in the abatement levels; this in turn increases the local environmental damage. Further, this implies that the rent-shifting effect is higher in the dynamic case than in the static one.

Moreover, based on Propositions 1 and 2, we also find that the international cooperation between countries in the first period leads to an increase in the optimal environmental tax, regardless of whether the game is dynamic or static.

Thus, from the viewpoint of environmental improvement, setting the environmental tax in the early periods and maintaining cooperation between countries is necessary in order to reduce or even eliminate the rent-shifting effect.

4. Concluding Remarks

This paper studies a dynamic game of environmental taxes between two countries in a Cournot duopoly wherein two countries and two firms are strategic. Based on the assumption of linear demand functions, we demonstrate that the environmental tax in the steady-state equilibrium is lower in a dynamic game than in a static game. This is because the government of each country has an incentive to set a lower environmental tax in a dynamic game rather than in a static game. Therefore, the dynamic behavior of the governments leads to an increase in the environmental damage. Further, the cooperation between countries with respect to environmental taxes in the first period leads to an increase in the optimal environmental tax. Thus, based on these conclusions, it is evident that from the viewpoint of environmental improvement, the environmental taxes should be set cooperatively in the early periods in order to decrease or even eliminate the rent-shifting effect.

The analysis conducted in this paper was based on the assumptions of a simple model and perfect information. Therefore, further study is required in the future in order to extend this simple model to the case of general demand and cost functions under the agency problem. Moreover, we need to investigate a comparison between environmental tax, emissions permits, and command-and-control policies in a dynamic setting in which both the firms and countries behave strategically.

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Notes

[1]For analyses using dynamic programming similar to Maskin and Tirole (1987), see for example, Tanaka (1994). Tanaka (1994) considered an export subsidy game under a dynamic Cournot duopoly, where the strategic variable was the output level.

[2]The third country model that incorporates the design of environmental policies has been used by Conrad (1993, 2001), Barrett (1994), Walz and Wellisch (1997), Nannerup (2001), and Ohori (2006).

[3]For simplicity, this paper overlooks the production cost. However, this does not affect our discussions in any manner.

[4]Since this paper focuses on the international cooperation at the first period, we have overlooked the cooperation in the dynamic case.

Appendix A: Proof of Lemma 1 Suppose that $\tau_1 > \bar{\tau}_1$, but $R_2(\tau_1) > R_2(\bar{\tau}_1)$. Since $R_2(\tau_1)$ is a best response to τ_1, we have

$$\omega^2(\tau_1, R_2(\tau_1)) + \delta W_2(R_2(\tau_1)) \geqq \omega^2(\tau_1, R_2(\bar{\tau}_1)) + \delta W_2(R_2(\bar{\tau}_1)).$$

Similarly, $R_2(\bar{\tau}_1)$ is a best response to $\bar{\tau}_1$ and then

$$\omega^2(\bar{\tau}_1, R_2(\bar{\tau}_1)) + \delta W_2(R_2(\bar{\tau}_1)) \geqq \omega^2(\bar{\tau}_1, R_2(\tau_1)) + \delta W_2(R_2(\tau_1)).$$

From the above two inequalities, we have

$$\omega^2(\tau_1, R_2(\tau_1)) - \omega^2(\tau_1, R_2(\bar{\tau}_1)) + \omega^2(\bar{\tau}_1, R_2(\bar{\tau}_1)) - \omega^2(\bar{\tau}_1, R_2(\tau_1)) \geqq 0,$$

which is equivalent to

$$\int_{\bar{\tau}_1}^{\tau_1} \int_{R_2(\bar{\tau}_1)}^{R_2(\tau_1)} \frac{\partial^2 \omega^2}{\partial \tau_1 \partial \tau_2} dy dx \geqq 0.$$

However, from (8), $\partial^2 \omega^2 / \partial \tau_1 \partial \tau_2$ is negative. Therefore, we show that $R_2(\tau_1) \leqq R_2(\bar{\tau}_1)$ if $\tau_1 > \bar{\tau}_1$. Following the same procedure, we obtain that $R_1(\tau_2) \leqq R_1(\bar{\tau}_2)$ if $\tau_2 > \bar{\tau}_2$. $\square$

Appendix B: Derivation of (16) and (17) Differentiating (11) with respect to environmental taxes, the first order conditions are

$$\frac{\partial \omega^1(R_1(\tau_{2,2m}), \tau_{2,2m})}{\partial \tau_1} + \delta \frac{dW_1(R_1(\tau_{2,2m}))}{d\tau_{1,2m+1}} = 0. \tag{A.1}$$

Using (14), we can rewrite (16) to the following equation:

$$\frac{\partial \omega^1(R_1(\tau_{2,2m}), R_1^{-1}(\tau_{1,2m+1}))}{\partial \tau_1} + \delta \frac{dW_1(R_1(\tau_{2,2m}))}{d\tau_{1,2m+1}} = 0. \tag{A.2}$$

Using (11), (12), and (13), we have

$$\begin{aligned} W_1(\tau_{1,2m+1}) &= \omega^1(\tau_{1,2m+1}, R_2(\tau_{1,2m+1})) \\ &\quad + \delta \omega^1(R_1(R_2(\tau_{1,2m+1})), R_2(\tau_{1,2m+1})) \\ &\quad + \delta^2 W_1(R_1(R_2(\tau_{1,2m+1}))). \end{aligned} \tag{A.3}$$

Differentiating (A.3) with respect to $\tau_{1,2m+1}$, we have

$$\begin{aligned} &\frac{dW_1(\tau_{1,2m+1})}{d\tau_{1,2m+1}} \\ = \; & \frac{\partial \omega^1(\tau_{1,2m+1}, R_2(\tau_{1,2m+1}))}{\partial \tau_1} + \frac{\partial \omega^1(\tau_{1,2m+1}, R_2(\tau_{1,2m+1}))}{\partial \tau_{2,2m+2}} \frac{dR_2(\tau_{1,2m+1})}{d\tau_1} \\ & + \delta \frac{\partial \omega^1(R_1(R_2(\tau_{1,2m+1})), R_2(\tau_{1,2m+1}))}{\partial \tau_{1,2m+3}} \frac{dR_1(R_2(\tau_{1,2m+1}))}{d\tau_{2,2m+2}} \frac{dR_2(\tau_{1,2m+1})}{d\tau_1} \\ & + \delta \frac{\partial \omega^1(R_1(R_2(\tau_{1,2m+1})), R_2(\tau_{1,2m+1}))}{\partial \tau_{2,2m+2}} \frac{dR_2(\tau_{1,2m+1})}{d\tau_1} \\ & + \delta^2 \frac{dW_1(R_1(R_2(\tau_{1,2m+1})))}{d\tau_{1,2m+3}} \frac{dR_1(R_2(\tau_{1,2m+1}))}{d\tau_{2,2m+2}} \frac{dR_2(\tau_{1,2m+1})}{d\tau_1}. \end{aligned} \tag{A.4}$$

Note that $dR_2(\tau_{1,2m+1})/d\tau_{1,2m+1} = -\beta_2$ from (15), and then substituting (A.1) into (A.4) and after rearranging, we have

$$\begin{aligned} & \frac{\partial \omega^1(\tau_{1,2m+1}, R_1^{-1}(\tau_{1,2m+1}))}{\partial \tau_{1,2m+1}} + \delta \frac{\partial \omega^1(\tau_{1,2m+1}, R_2(\tau_{1,2m+1}))}{\partial \tau_{1,2m+1}} \\ = \; & \beta_2 \delta \Big[\frac{\partial \omega^1(\tau_{1,2m+1}, R_2(\tau_{1,2m+1}))}{\partial \tau_{2,2m+2}} \\ & + \delta \frac{\partial \omega^1(R_1(R_2(\tau_{1,2m+1})), R_2(\tau_{1,2m+1}))}{\partial \tau_{2,2m+2}} \Big]. \end{aligned} \tag{A.5}$$

Note that we have $R_1^{-1}(\tau_{1,2m+1}) = (\alpha_1 - \tau_{1,2m+1})/\beta_1$, from (14). Substituting (6), (7), (14), (15) and this expression into (A.5) and after rearranging, we obtain

$$\begin{aligned} & [k - (1+\delta)(4k+9)\beta_1 + 2\delta k \beta_1 \beta_2 + 2\delta(1+\delta)k\beta_1\beta_2^2 + \delta^2 k \beta_1^2 \beta_2^2]\tau_{1,2m+1} \\ & - k\alpha_1 + [-(1+\delta)ka + 3(1+\delta)(2k+3)l - \delta k \alpha_2]\beta_1 \\ & + \delta k[-(1+\delta)(2a - 3l + 2\alpha_2) + \delta \alpha_1]\beta_1\beta_2 - \delta^2 k \alpha_2 \beta_1^2 \beta_2 = 0. \end{aligned} \tag{A.6}$$

Symmetrically, following the above same procedure for country 2's welfare maximization, we obtain

$$\begin{aligned}&[k-(1+\delta)(4k+9)\beta_2+2\delta k\beta_1\beta_2+2\delta(1+\delta)k\beta_1^2\beta_2+\delta^2k\beta_1^2\beta_2^2]\tau_{2,2m}\\&-k\alpha_2+[-(1+\delta)ka+3(1+\delta)(2k+3)l-\delta k\alpha_1]\beta_2\\&+\delta k[-(1+\delta)(2a-3l+2\alpha_1)+\delta\alpha_2]\beta_1\beta_2-\delta^2k\alpha_1\beta_1\beta_2^2=0.\end{aligned}\quad (A.7)$$

Since (A.6) and (A.7) must hold regardless of $\tau_{1,2m+1}$ and $\tau_{2,2m}$, respectively, we have

$$\begin{aligned}k-(1+\delta)(4k+9)\beta_1+2\delta k\beta_1\beta_2&\\+2\delta(1+\delta)k\beta_1\beta_2^2+\delta^2k\beta_1^2\beta_2^2&=0,\end{aligned}\quad (A.8)$$

$$\begin{aligned}-k\alpha_1+[-(1+\delta)ka+3(1+\delta)(2k+3)l-\delta k\alpha_2]\beta_1&\\+\delta k[-(1+\delta)(2a-3l+2\alpha_2)+\delta\alpha_1]\beta_1\beta_2-\delta^2k\alpha_2\beta_1^2\beta_2&=0,\end{aligned}\quad (A.9)$$

$$\begin{aligned}k-(1+\delta)(4k+9)\beta_2+2\delta k\beta_1\beta_2&\\+2\delta(1+\delta)k\beta_1^2\beta_2+\delta^2k\beta_1^2\beta_2^2&=0,\end{aligned}\quad (A.10)$$

and

$$\begin{aligned}-k\alpha_2+[-(1+\delta)ka+3(1+\delta)(2k+3)l-\delta k\alpha_1]\beta_2&\\+\delta k[-(1+\delta)(2a-3l+2\alpha_1)+\delta\alpha_2]\beta_1\beta_2-\delta^2k\alpha_1\beta_1\beta_2^2&=0.\end{aligned}\quad (A.11)$$

From symmetric relations of (A.8) and (A.10) and of (A.9) and (A.11), we have $\alpha_1=\alpha_2$ and $\beta_1=\beta_2$. Replacing α_1 and α_2 by α and β_1 and β_2 by β, respectively, equations (A.8)–(A.11) can be rewritten to the equations (16) and (17). □

Appendix C: Proof of Lemma 2 Rewriting (16) to a function, we have

$$f(\beta)=\delta^2k\beta^4+2\delta(1+\delta)k\beta^3+2\delta k\beta^2-(1+\delta)(4k+9)\beta+k. \quad (A.12)$$

Then we have

$$f'(\beta) = 4\delta^2k\beta^3+6\delta(1+\delta)k\beta^2+4\delta k\beta-(1+\delta)(4k+9), \text{ and} \quad (A.13)$$

$$f''(\beta) = 4\delta k[3\delta\beta^2+3(1+\delta)\beta+1]. \quad (A.14)$$

It is clear that $f''(\beta)>0$ since $0<\delta<1$ and $k>0$. Note that $f'(0)<0$ and $f'(1)<0$, and we have $f'(\beta)<0$ if $0<\beta<1$. We also have $f(0)>0$ and $f(1)<0$, hence the real solution of $f(\beta)=0$ is in the interval $(0,1)$. □

Appendix D: Derivation of (18) (17) can be written to

$$\alpha = \frac{(1+\delta)\beta}{E}[-ka+3(2k+3)l-\delta k(2a-3l)\beta], \quad (A.15)$$

$$\text{where } E = k[1+\delta\beta+\delta(2+\delta)\beta^2+\delta^2\beta^3]. \quad (A.16)$$

Using (16) and (A.16) and after rearranging, we obtain

$$E=\frac{(1+\delta)[5k+9+k\delta\beta]\beta}{1+\beta}. \quad (A.17)$$

Substituting (A.17) into (A.15), we obtain (18). □

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