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Environmental attitudes and impacts of privatization on R&D, environment and welfare in a mixed duopoly

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ABSTRACT

We introduce the environmental attitudes of the public firm into a polluting mixed duopoly and then examine the effects of privatization on the environmental R&D (ER&D), the environmental quality and the social welfare. The government levies an exogenous environmental tax on pollution and both firms adopt the cleaner production technology to reduce emissions. We mainly find that, when the public firm cares less about the environment, privatization can induce both firms' ER&D and better the environment. However, the opposite may appear when the public firm cares much for the environment. In addition, whether privatization improves or reduces the social welfare in the case of high marginal environmental damage depends on the environmental attitudes of the public firm and the environmental tax rates.

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1. Introduction

With the deterioration of the environment and the enhancement of people's environmental awareness, more and more governments pay attention to the environmental issues. In many countries, the highly polluting industries usually include both public and private firms (Xing et al., 2019). For example, they coexist in petrochemical industries of India and China. Since the 1980s, privatization (or partial privatization) of state-owned firms has been a feature of the government policy in many countries (Pal and Saha, 2015; Wang and Wang, 2009). Our first objective is to analyze the effect of privatizing public firms on the environmental R&D (Henceforth ER&D in short), environment and social welfare.

Some empirical studies have investigated the environmental attitudes of public firms. Fryxell and Lo (2001) show that managers in Chinese state-owned firms care more about the environment than their counterparts in private firms do. However, state-owned firms have a high degree of autonomy in many countries. It follows that some of them do not pay as much attention to the environment as

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the government does (Pal and Saha, 2015; Xu et al., 2016). Serious environmental pollution events caused by state-owned enterprises often occur in some countries (Xie et al., 2012)¹. Practical evidences indicate that state-owned enterprises even pay less attention to the environment than private enterprises in some pollution industries.² Our second objective is to examine how the environmental attitudes of public firms affect the relationship between privatization and ER&D (environment or social welfare).

We consider a two-stage game in a polluting mixed duopoly with an exogenous environmental tax in this study. Firms adopt the cleaner production technology to reduce emissions. In the first stage, each firm invests in ER&D to reduce pollution emissions. In the second stage, firms determine their quantities and compete in product market. We mainly find that: (i) when the public firm cares less (much) for the environment, privatization can (cannot) boost both public and private firms' ER&D efforts simultaneously; (ii) when the public firm cares less for the environment, privatization can improve the environment regardless of the size of marginal environmental damage and the rate of environmental tax; (iii) when the public firm cares much for the environment, privatization causes a poorer (may lead to a better) environment if the marginal environmental damage is high and the environmental tax is low (high); (iv) when the public firm cares less (much) for the environment, privatization can enhance (reduce) the social welfare in the case of high marginal environmental damage and high (low) environmental tax.

The paper is organized as follows. Section 2 reviews the literature. Section 3 describes the basic model. Section 4 (section 5) gives the ER&D efforts, environmental damage and social welfare in equilibrium before (after) privatization. Section 6 compares the results in sections 4 and 5. Section 7 discusses the situations that the environmental tax rates and the public firm's environmental attitudes are endogenous respectively. Finally, section 8 presents conclusions.

2. Literature review

As people attach importance to the environment, more mixed oligopoly studies incorporate environment issues into their analysis (Xing et al., 2019). In addition, privatization is not only a realistic policy in polluting mixed oligopolies, but it is also concerned by theoretical research (Xing, 2019).

Several scholars have examined the effects of privatization on the environmental R&D and/or the environmental quality. The related studies mainly involve two pollution abatement technologies: end-of-pipe and cleaner production (Skea, 1995). Haruna and Goel (2019), Pal and Saha (2015), Xing et al. (2020) and Xing et al. (2019) assume that firms use the end-of-pipe technology and it can be promoted by undertaking ER&D. Haruna and Goel (2019) find that privatization reduces ER&D and worsens the environment with an endogenous environmental tax and research spillovers. Pal and Saha (2015) also consider the endogenous environmental tax, but they think that privatization will improve the environment if the public firm cares about the environment. Xing et al. (2020) consider the exogenous environmental tax, but find that privatization increases the total ER&D if the tax rate is high. Under the

ER&D subsidy policy, Xing et al. (2019) get different conclusions from that of Haruna and Goel (2019), and show that if the public firm does not care (extremely cares) for the environment, privatization increases (decreases) the total ER&D and improves the environment in both situations.

Tsai et al. (2016) think that the end-of-pipe technology can decrease a firm's gross emissions but may not affect this firm's output, however the cleaner production technology can generate less emissions per unit of output and thus make the firm's output and abatement decisions interweave. Pal and Saha (2015) and Haruna and Goel (2019) give the optimal environmental tax rate by maximizing the social welfare (i.e., the environmental tax is endogenous). However, it is hard for policy makers to get the optimal environmental tax rate that maximizes the social welfare in reality. In many developing countries, the environmental tax rates are usually low and far below the optimal level of society. In this situation, the exogenous environmental tax may be more practical. Unlike Pal and Saha (2015), Haruna and Goel (2019) and Xing et al. (2019), Tsai et al. (2016) take into account the cleaner production technology and an exogenous environmental tax. They find that in a mixed duopoly privatization can improve the ER&D level of one firm at most, and it may cause a poorer environment if the marginal environmental damage is high and the environmental tax is low.³

Some other scholars have investigated the effects of privatizing a public firm on the social welfare in polluting mixed duopoly. Pi et al. (2013) find that privatization exerts no impacts on the social welfare without considering the environmental policies and emission reduction. Wang et al. (2009) and Ferreira and Ferreira (2013) assume that each firm adopts pollution abatement technologies in response to the environmental tax, and they come to a different conclusion from that of Pi et al. (2013). Wang et al. (2009) think that the social welfare can be enhanced by implementing partial-privatization policy, whereas Ferreira and Ferreira (2013) show that privatization leads to a reduction in the social welfare. Ohori (2004) considers an international mixed duopoly with environmental tax and tariff and finds that privatization decreases the social welfare.

Empirical evidences showed that there are significant differences in the public firms' concern for the environment in the same pollution industry in different countries (Hettige et al., 1996; Ohori, 2006a; Pal and Saha, 2015; Chang et al., 2015; Xing et al., 2019). Public firms do not pay much attention to the environment in many developing countries, and they usually care less for the environment than similar firms in developed countries. When firms use the cleaner production technology in a polluting mixed duopoly, the environmental attitudes of the public firm can affect its (or its rival's) output and ER&D decisions and then affect the environmental quality and the social welfare. Therefore, privatizing the public firm that cares much for the environment or does not care much for the environment in a mixed duopoly, its effects on the private (or public) firm's ER&D incentives, the environment and the social welfare may not be the same.

For the above reasons, this study introduces the environmental attitudes of the public firm into the mixed duopoly model and examines the effect of privatization on the ER&D, the environment and the social welfare. It shows that, in the situation of

exogenous environmental tax, the effects of privatization on them depend on how much the public firm cares for the environment. Privatization can induce both firms' ER&D and better the environment if the public firm cares less for the environment, and the opposite may appear if it cares much for the environment. This result is different from that of Tsai et al. (2016), Haruna and Goel (2019), Pal and Saha (2015) and Xing et al. (2019). Tsai et al. (2016) think that privatization cannot simultaneously catalyze both public and private firms' ER&D efforts; Haruna and Goel (2019) show that privatization always decreases ER&D and worsens the environment; and Pal and Saha (2015) and Xing et al. (2019) find that privatization always better the environment if the public firm pays full attention to the environment. In addition, this study also shows that privatization can improve or reduce the social welfare depending on how much the public firm cares for the environment and how much the government imposes the environmental tax. Obviously, this result is different from that of Pi et al. (2013), Wang et al. (2009), Ferreira and Ferreira (2013) and Otori (2004). Similar to the result of this study, Xing et al. (2019) also find that privatization can improve or reduce the social welfare. However, they do not consider the cleaner production technology and the environmental tax policy.

3. The model

We consider a Cournot duopoly market that consists of firm 0 and firm 1. The former is a public (or private) firm and the latter is a private firm. They produce homogeneous goods. The inverse market demand is given by: $P(Q) = a - Q = a - (q_0 + q_1)$, in which q_i denotes the firm i 's output ($i = 0, 1$), Q denotes the total output and a denotes the market size ($a \geq Q$). The production cost function for firm i is quadratic and has the following form: $C(q_i) = cq_i + q_i^2/2$.⁴

Production generates pollution and producing one unit of output leads to one unit of pollution. Each firm uses the cleaner production technology in pollution abatement and they can improve the level of this technology with the help of ER&D. The pollution caused by firm i after ER&D is given by⁵: $E_i = (1 - r_i)q_i$, where r_i denotes the firm i 's ER&D effort ($0 \leq r_i \leq 1$). The corresponding ER&D expenditure of firm i is: $I(r_i) = \frac{1}{2}r_i^2$. The environmental damage function is described by⁶:

$$D(E) = d \sum_{i=0}^1 (1 - r_i)q_i \quad (1)$$

In (1), $E = E_0 + E_1$ denotes the total pollution and d measures the marginal environmental damage ($d > 0$).⁷ In order to correct pollution externality, the government implements the environmental tax policy (Haruna and Goel, 2019). The environmental tax payment paid by firm i after ER&D is: $T_i = t(1 - r_i)q_i$, where t stands for the tax rate ($t > 0$).⁸ It is worth noting that Tao et al. (2019) compare the efficiency of unit and ad valorem taxation in the mixed duopoly.

The profit function for firm i can be expressed as:

$$\begin{aligned} \pi_i = & P(Q)q_i - C(q_i) - I(r_i) - T_i = (a - q_i - q_j)q_i - \left(cq_i + \frac{1}{2}q_i^2 \right) \\ & - \frac{1}{2}r_i^2 - t(1-r_i)q_i, \quad i = 0, 1, \quad i \neq j \end{aligned} \quad (2)$$

The social welfare comprises the consumer surplus ($CS = \frac{1}{2}Q^2$), the producer surplus ($\Pi = \sum_{i=0}^1 \pi_i$) and the environmental tax revenues ($T = \sum_{i=0}^1 T_i$), less the environmental damage ($D(E)$), which is given by⁹:

$$SW = \frac{1}{2}Q^2 + \sum_{i=0}^1 \pi_i + \sum_{i=0}^1 T_i - D(E) = aQ - \frac{1}{2}Q^2 - \sum_{i=0}^1 C(q_i) - \sum_{i=0}^1 I(r_i) - D(E) \quad (3)$$

Poyago-Theotoky (1998) points out that the distinguishing feature between private and public firms lies in their different objectives. A private firm usually aims to profit maximization. However, a public firm is generally assumed to pursue the maximization of the social welfare in most of the mixed oligopoly literature related to the environment. Some scholars argue that a public firm may not pursue the goal of maximizing the social welfare (Wang and Wang, 2009; Pal and Saha, 2015; Xing et al., 2019; Xing et al., 2020). Moreover, several empirical studies indicated that the environmental attitudes of public firms differ greatly in the same polluting industries across countries (Hettige et al., 1996; Ohori, 2006b; Chang et al., 2015). Therefore, we introduce a parameter into the objective function of the public firm to measure its environmental attitude. We assume that the objective function of the public firm is as follows¹⁰:

$$\begin{aligned} \Psi = & \frac{1}{2}Q^2 + \sum_{i=0}^1 \pi_i + \sum_{i=0}^1 T_i - kD(E) = \int_0^Q P(z)dz - \sum_{i=0}^1 C(q_i) - \sum_{i=0}^1 I(r_i) - kD(E) \\ = & aQ - \frac{1}{2}Q^2 - \sum_{i=0}^1 C(q_i) - \sum_{i=0}^1 I(r_i) - kD(E) \end{aligned} \quad (4)$$

In (4), k ($0 \leq k \leq 1$) is used to represent the degree of concern on the environment by the public firm. In this study, we use the parameter k to measure the attitude of the public firm toward the environment. The larger k is, the more the public firm pays attention to the environment. On the contrary, the smaller k is, the less the public firm pays attention to the environment. If $k = 1$, the public firm extremely cares for the environment and aims to maximize the social welfare. In this case, the public firm pursues the same objective as the government. If $k = 0$, the public firm does not care for the environment at all. Moreover, if $0 < k < 1$, the public firm cares about the environment, but cares less about it than the government. Note that the environmental tax revenues are balanced by the environmental tax payments of firms, and therefore, the term related to the tax does not appear in Eq. (4) (Kato, 2011). This implies that the environmental tax does not directly affect the public firm's

output (or ER&D) decisions. However, it may indirectly affect them through the private firm's output (or ER&D). In the model of Tsai et al. (2016), they assume that the public firm maximizes the social welfare. Obviously, the objective function of the public firm in their study is a special case of this study (i.e., $k = 1$).

The game of this model has two stages. In the first (second) stage, firms choose ER&D efforts (outputs) simultaneously and independently. We will start by solving the mixed duopoly in section 4, in which firm 0 is not privatized, and then we will solve the pure duopoly in section 5, in which firm 0 is privatized.

4. Mixed duopoly

Firm 0 is entirely public owned and pursues the maximization of Ψ in this section. However, firm 1 pursues the maximization of its profits (i.e., π_1). Obviously, two firms have different objectives in this situation. We start our analysis with the output stage. The first-order conditions are:

$$\frac{\partial \Psi}{\partial q_0} = P(Q) - C'(q_0) - k(1-r_0)D'(E) = w - kd(1-r_0) - 2q_0 - q_1 = 0 \quad (5)$$

$$\frac{\partial \pi_1}{\partial q_1} = P(Q) + P'(Q)q_1 - C'(q_1) - T_1' = w - t(1-r_1) - q_0 - 3q_1 = 0 \quad (6)$$

where $w = a - c$. Note that we assume $a > c$. Obviously, the second-order conditions are satisfied because $\frac{\partial^2 \Psi}{\partial q_0^2} = -2 < 0$ and $\frac{\partial^2 \pi_1}{\partial q_1^2} = -3 < 0$. Solving (5) and (6), we obtain the outputs for public and private firms:

$$q_0^* = \frac{3[w - kd(1-r_0)] - [w - t(1-r_1)]}{5} \quad (7)$$

$$q_1^* = \frac{2[w - t(1-r_1)] - [w - kd(1-r_0)]}{5} \quad (8)$$

Now, we go on to consider the ER&D stage. The first-order conditions are as follows:

$$\begin{aligned} \frac{\partial \Psi(r_0, r_1)}{\partial r_0} &= \underbrace{[-P'(Q^*)q_1^* - (1-r_1)(kD'(E^*) - t)]}_{\text{strategic effect}} \frac{\partial q_1^*}{\partial r_0} + \underbrace{kD'(E^*)q_0^* - I'(r_0)}_{\text{environmental effect}} \\ &= \frac{kd}{25} [9w - 16kd(1-r_0) + (2t + 5kd)(1-r_1)] - r_0 = 0 \end{aligned} \quad (9)$$

$$\begin{aligned} \frac{\partial \pi_1(r_0, r_1)}{\partial r_1} &= \underbrace{P'(Q^*)q_1^* \frac{\partial q_0^*}{\partial r_1}}_{\text{strategic effect}} + \underbrace{tq_1^* - I'(r_1)}_{\text{tax-saving effect}} \\ &= \frac{6t}{25} [w - 2t(1-r_1) + kd(1-r_0)] - r_1 = 0 \end{aligned} \quad (10)$$

Because $0 < t < d < 1$ and $0 \leq k \leq 1$, $\frac{\partial^2 \Psi}{\partial r_0^2} = \frac{16}{25}k^2d^2 - 1 < 0$ and $\frac{\partial^2 \pi_1}{\partial r_1^2} = \frac{12}{25}t^2 - 1 < 0$. It follows that the second-order conditions are satisfied. Tsai et al. (2016) also consider the strategic effect and environmental effect (the strategic effect and tax-saving effect) for the public (private) firm and analyze their effects on the public (private) firm's ER&D decisions. However, the strategic effect and environmental effect for the public firm in this study is different from that of Tsai et al. (2016) because they have one more parameter k in this study (see (9)).

Solving (9) and (10), we obtain the equilibrium ER&D efforts for public and private firms:

$$r_0^* = \frac{kd[(45-24t^2-6kdt)w - (55kd-36kdt^2 + 6k^2d^2t-10t)]}{125 - 60t^2 + 36k^2d^2t^2 - 6k^3d^3t - 80k^2d^2} \quad (11)$$

$$r_1^* = \frac{6t[5(1-k^2d^2)w - (10t-6k^2d^2t + k^3d^3-5kd)]}{125 - 60t^2 + 36k^2d^2t^2 - 6k^3d^3t - 80k^2d^2} \quad (12)$$

According to (1, 3, 7, 8, 11) and (12), we can derive the outputs for public and private firms, the environmental damage and the social welfare in equilibrium:

$$q_0^* = \frac{(50-30t^2 + 6k^2d^2t^2 - 6k^3d^3t - 5k^2d^2)w - (-25t - 30kdt^2 + 10k^2d^2t - 15k^3d^3 + 75kd)}{125 - 60t^2 + 36k^2d^2t^2 - 6k^3d^3t - 80k^2d^2} \quad (13)$$

$$q_1^* = \frac{5[5(1-k^2d^2)w - (10t-6k^2d^2t + k^3d^3-5kd)]}{125 - 60t^2 + 36k^2d^2t^2 - 6k^3d^3t - 80k^2d^2} \quad (14)$$

$$D^* = \frac{d \left[\begin{aligned} & [(125-25k^2d^2-60t^2-10kdt) - kd(45-24t^2-6kdt)w] \times [(50-30t^2 + 6k^2d^2t^2 - \\ & 6k^3d^3t - 5k^2d^2)w - (-25t - 30kdt^2 + 10k^2d^2t - 15k^3d^3 + 75kd)] + [(125-80k^2d^2 \\ & - 30kdt) - 30t(1-k^2d^2)w] \times [25(1-k^2d^2)w - 5(10t-6k^2d^2t + k^3d^3-5kd)] \end{aligned} \right]}{(125-60t^2 + 36k^2d^2t^2 - 6k^3d^3t - 80k^2d^2)^2} \quad (15)$$

$$SW^* = \frac{\left[\begin{aligned} & 5[(-10k^2d^2 + 6k^2d^2t^2 + 10-6t^2)w + 5t-6kdt^2-4k^2d^2t + 10kd-2k^3d^3] \times [(75-30t^2-30k^2d^2 + 6k^2d^2t^2 - \\ & 6k^3d^3t)w - 50kd-25t + 30kdt^2 + 20k^2d^2t + 10k^3d^3] + 5[(50-30t^2 + 6k^2d^2t^2 - 6k^3d^3t - 5k^2d^2)w - (-25t - \\ & 30kdt^2 + 10k^2d^2t - 15k^3d^3 + 75kd)] \times [5(1-k^2d^2)w - (10t-6k^2d^2t + k^3d^3-5kd)] - 0.5k^2d^2[(45-24t^2-6kdt)w \\ & - (55kd-36kdt^2 + 6k^2d^2t-10t)]^2 - 18t^2[5(1-k^2d^2)w - (10t-6k^2d^2t + k^3d^3-5kd)]^2 - d[(125-25k^2d^2-60t^2 \\ & - 10kdt) - kd(45-24t^2-6kdt)w] \times [(50-30t^2 + 6k^2d^2t^2 - 6k^3d^3t - 5k^2d^2)w - (-25t - 30kdt^2 + 10k^2d^2t - 15k^3d^3 \\ & + 75kd)] - d[(125-80k^2d^2-30kdt) - 30t(1-k^2d^2)w] \times [25(1-k^2d^2)w - 5(10t-6k^2d^2t + k^3d^3-5kd)] \end{aligned} \right]}{(125-60t^2 + 36k^2d^2t^2 - 6k^3d^3t - 80k^2d^2)^2} \quad (16)$$

Note that in order to guarantee $0 \leq r_i^* \leq 1$ and $q_i^* \geq 0$ ($i = 0, 1$), the parameters need to satisfy the following inequality $\max\{w_1, w_3, w_5, 0\} \leq w \leq \min\{w_2, w_4\}$ in this section, in which $w_1 = \frac{55kd-36kdt^2+6k^2d^2t-10t}{3(15-8t^2-2kdt)}$, $w_2 = \frac{5(25-2kdt-5k^2d^2-12t^2)}{3kd(15-8t^2-2kdt)}$ (if $0 < k \leq 1$ and $w_2 = +\infty$ if $k = 0$), $w_3 = \frac{10t-6k^2d^2t+k^3d^3-5kd}{5(1-k^2d^2)}$, $w_4 = \frac{25-6kdt-16k^2d^2}{6t(1-k^2d^2)}$ and $w_5 = \frac{5(-5t-6kdt^2+2k^2d^2t-3k^3d^3+15kd)}{50-30t^2+6k^2d^2t^2-6k^3d^3t-5k^2d^2}$.

5. Pure duopoly

Firm 0 is completely privatized in this section (after privatization). Both firms aim to maximize their profits. First, we consider the output stage. Firm i maximizes π_i with respect to q_i . The first-order conditions for maximization are:

$$\frac{\partial \pi_i}{\partial q_i} = P(Q) + P'(Q)q_i - C'(q_i) - T_i' = w - t(1 - r_i) - 3q_i - q_j = 0, i = 0, 1, i \neq j \quad (17)$$

Obviously, the second-order conditions are satisfied because $\frac{\partial^2 \pi_i}{\partial q_i^2} = -3 < 0$ ($i = 0, 1$). Solving (17), we obtain the outputs for public and private firms:

$$q_i^\# = \frac{3[w - t(1 - r_i)] - [w - t(1 - r_j)]}{8}, i = 0, 1, i \neq j \quad (18)$$

Now, we continue to consider the ER&D stage. The first-order conditions are given by:

$$\frac{\partial \pi_i(r_0, r_1)}{\partial r_i} = P'(Q^\#)q_i^\# \frac{\partial q_j^\#}{\partial r_i} + \underset{\text{strategic effect}}{tq_i^\#} - \underset{\text{tax-saving effect}}{I'(r_i)} = \frac{9t}{64} [2(w - t) - tr_j + 3tr_i] - r_i = 0, i = 0, 1, i \neq j \quad (19)$$

Because $0 < t < d < 1$, $\frac{\partial^2 \pi_i}{\partial r_i^2} = \frac{27}{64}t^2 - 1 < 0$ ($i = 0, 1$). It follows that the second-order conditions are satisfied. Solving (19), we get the equilibrium ER&D efforts for public and private firms:

$$r_0^\# = r_1^\# = \frac{9t(w - t)}{32 - 9t^2} \quad (20)$$

Using (1, 3, 18) and (20), we can derive the outputs for public and private firms, the environmental damage and the social welfare in equilibrium:

$$q_0^\# = q_1^\# = \frac{8(w - t)}{32 - 9t^2} \quad (21)$$

$$D^\# = \frac{16d(w - t)(32 - 9tw)}{(32 - 9t^2)^2} \quad (22)$$

$$SW^\# = \frac{(w - t)[(320 - 225t^2 + 144dt)w + 192t + 81t^3 - 512d]}{(32 - 9t^2)^2} \quad (23)$$

Note that in order to ensure $0 \leq r_i^\# \leq 1$ and $q_i^\# \geq 0$, the parameters need to meet $t \leq w \leq \frac{32}{9t}$ in this section.

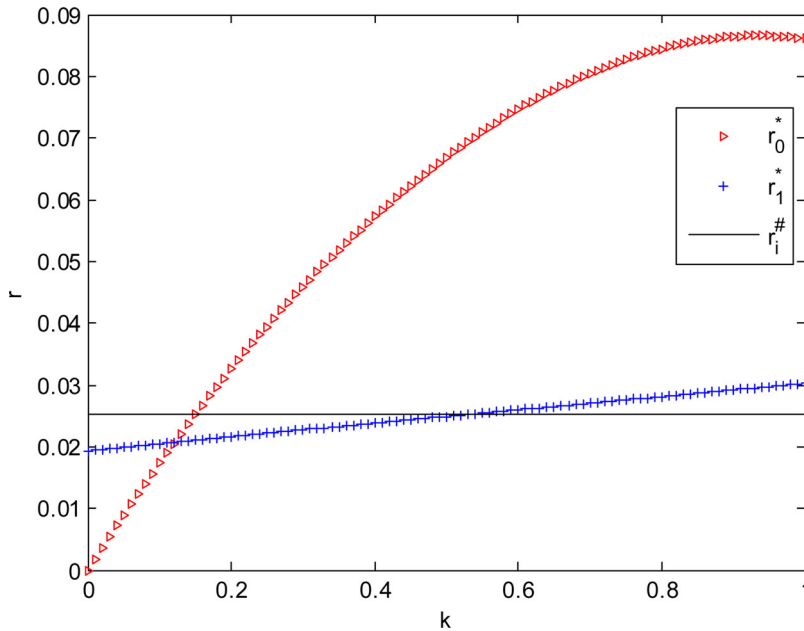


Figure 1. The equilibrium ER&D efforts in the mixed and private duopoly if the environmental tax is low (given $a = 1.5$, $c = 0.5$, $t = 0.1$ and $d = 0.5$). Source: Authors' Calculations.

6. Comparisons

We compare the private (or public) firm's ER&D efforts, the environmental damage and the social welfare in the mixed duopoly and in the private duopoly, and further investigate the effects of privatizing the public firm on them. Combining the requirements for parameters in sections 4 and 5, we assume that the parameters satisfy $\underline{w} \leq w \leq \bar{w}$ in this section, where $\underline{w} = \max\{w_1, w_3, w_5, t\}$ and $\bar{w} = \min\{w_2, w_4, \frac{32}{9t}\}$.

Proposition 1. There exist thresholds \underline{k} and \bar{k} of k ($0 < \underline{k} \leq \bar{k} < 1$) such that (i) when k is smaller than \underline{k} (i.e., $0 \leq k < \underline{k}$), privatization can promote both public and private firms' ER&D efforts simultaneously; and (ii) when k is larger than \bar{k} (i.e., $\bar{k} < k \leq 1$), privatization cannot promote both public and private firms' ER&D efforts simultaneously.

Proof. See Appendix A.

Tsai et al. (2016) find that privatization cannot simultaneously catalyze both public and private firms' ER&D efforts, and Haruna and Goel (2019) think that privatization leads to a reduction in ER&D. However, their result may not be true if we introduce the public firm's environmental attitudes into the mixed duopoly. In the studies of Tsai et al. (2016) and Haruna and Goel (2019), they assume that the public firm is a welfare-maximizer. This implicitly states that the public firm extremely cares about the environment. That is, $k = 1$ in their studies. Proposition 1 indicates that, if the public firm does not care much about the environment (i.e., k is small enough), privatization can boost the ER&D efforts of both public and private firms at the same time (see Figures 1 and 2). Therefore, when we examine the effect of privatizing the

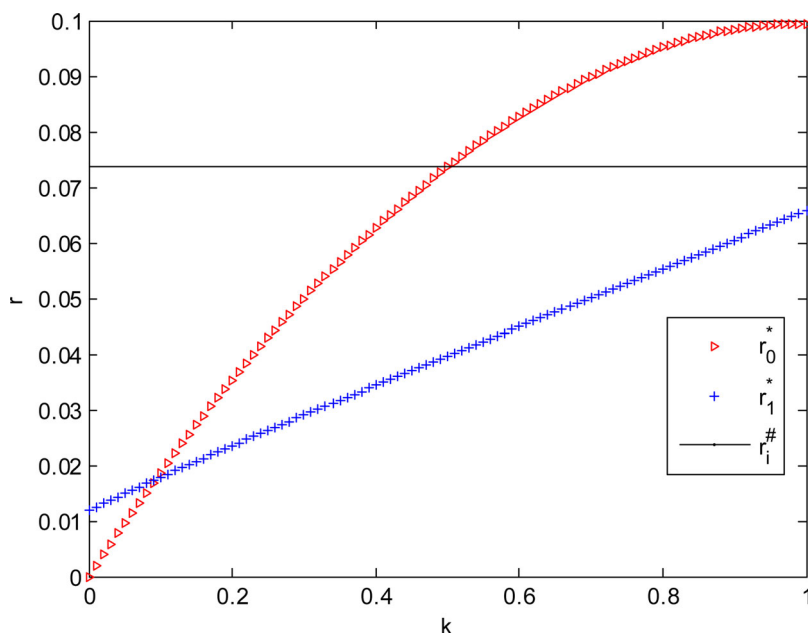


Figure 2. The equilibrium ER&D efforts in the mixed and private duopoly if the environmental tax is high (given $a = 1.5$, $c = 0.5$, $t = 0.45$ and $d = 0.5$). Source: Authors' Calculations.

public firm on the private (or public) firms' ER&D in a mixed oligopoly, we should take into account the attitudes of public firms towards the environment. Note that Haruna and Goel (2019) assume that firms use the end-of-pipe technology and the environmental tax is endogenous. However, firms use the cleaner production technology and the environmental tax is exogenous in this study.

The intuition of Proposition 1 is as follows. First, we consider the part (i). For firm 1, given t , if the public firm does not care much for the environment (i.e., k is small enough), privatization increases its output (i.e., $q_1^* < q_1^{\#}$) because of a weaker competition in the pure duopoly. Thus, privatization enhances the firm 1's tax-saving effect. This increases the firm 1's ER&D incentives. It follows that privatization can catalyze the firm 1's ER&D efforts. For firm 0, in the mixed duopoly the environmental tax does not directly affect its ER&D decisions, so there is no the tax-saving effect. However, there are the environmental effect and the strategic effect for it in the mixed duopoly. Obviously, the environmental effect is weak (because the term $kD'(E^*)q_0^* - I'(r_0)$ is small) if the public firm does not care much for the environment. Moreover, the strategic effect ($[-P'(Q^*)q_1^* - (1-r_1)(kD'(E^*) - t)](\partial q_1^*/\partial r_0)$) is also weak (because $|\partial q_1^*/\partial r_0| = kd/5$ is small) if k is sufficiently small. Thus, the ER&D incentives for firm 0 are low in the mixed duopoly. For firm 0, the environmental effect disappears in the pure duopoly, but the tax-saving effect appears. Given t , if k is sufficiently small, the tax-saving effect (the strategic effect) for firm 0 in the pure duopoly dominates the environmental effect (the strategic effect) for it in the mixed duopoly. It follows that privatization increases the firm 0's ER&D efforts. Second, we consider the part (ii). When the public firm cares much for the environment (i.e., k is large enough), privatization cannot promote both public and private firms' ER&D

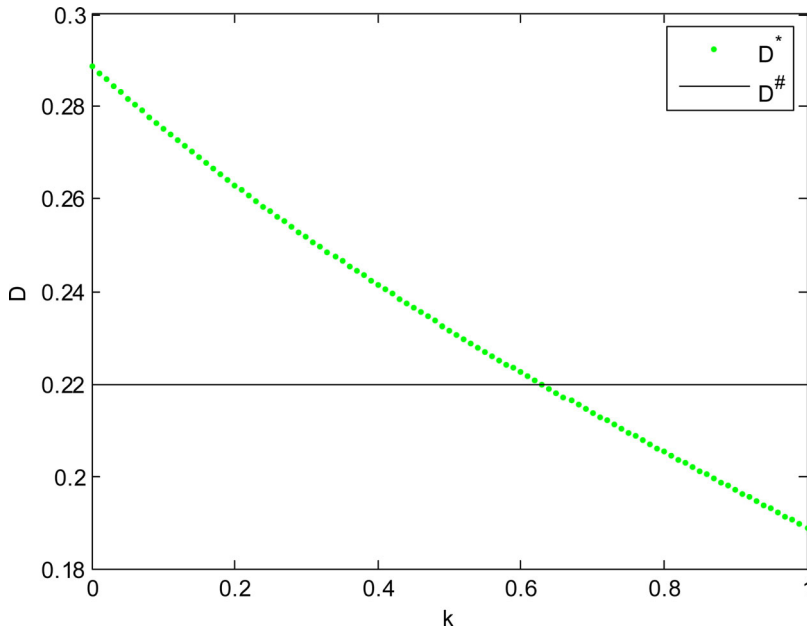


Figure 3. The environmental damage in the mixed and private duopoly if the environmental tax is low (given $a = 1.5$, $c = 0.5$, $t = 0.1$ and $d = 0.5$). Source: Authors' Calculations.

efforts simultaneously. The reasons can be similarly given as in Propositions 2, 3 and 4 of Tsai et al. (2016).

Proposition 2. There exist thresholds k_{\leftrightarrow} and \bar{k} of k ($0 < k_{\leftrightarrow} \leq \bar{k} < 1$) such that (i) when k is smaller than k_{\leftrightarrow} (i.e., $0 \leq k < k_{\leftrightarrow}$), privatization can improve the environment (even if d is high and t is not sufficiently high); and (ii) when k is larger than \bar{k} (i.e., $\bar{k} < k \leq 1$), privatization can deteriorate the environment if d is high and t is not sufficiently high, but it may improve the environment if both d and t are high.

Proof. See Appendix B.

The first part of Proposition 2 shows that, when the public firm does not care much for the environment (i.e., k is small enough), privatization can improve the environment, even if the marginal environmental damage is high and the environmental tax is not very high (see Figure 3). This is different from the results of Tsai et al. (2016) and Haruna and Goel (2019). Tsai et al. (2016) think that if the marginal environmental damage is high, privatization may further worsen the environment unless the environmental tax is very high. Haruna and Goel (2019) find that privatization causes a worse environment. The second part of Proposition 2 indicates that, when the public firm cares much for the environment (i.e., k is large enough), privatization makes the environment worse if the marginal environmental damage is high and the environmental tax is not high enough (see Figure 3), and it may improve the environment if both the marginal environmental damage and the environmental tax are high (see Figure 4). Therefore, when we investigate the effect of privatization on the environment in a mixed oligopoly, we should consider the public firms'

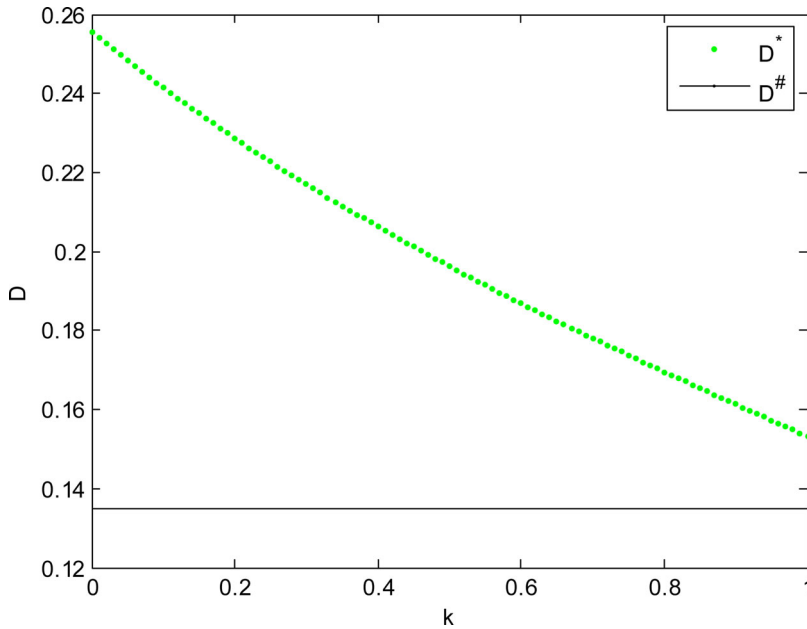


Figure 4. The environmental damage in the mixed and private duopoly if the environmental tax is high (given $a = 1.5$, $c = 0.5$, $t = 0.45$ and $d = 0.5$). Source: Authors' Calculations.

environmental attitudes and the environmental tax rates. Moreover, Pal and Saha (2015) consider the end-of-pipe technology and the endogenous environmental tax, and Xing et al. (2019) consider the end-of-pipe technology and the endogenous environmental R&D subsidy. They find that privatization always better the environment if the public firm pays full attention to the environment. Obviously, the results of this study are different. Thus, when we examine the effect of privatization on the environment, we should distinguish the types of pollution abatement technologies and environmental policies.

The intuition of Proposition 2 is as follows. First, we consider the part (i). Given t , when the public firm does not care much about the environment (i.e., k is small enough), privatization leads to a weaker competition. It follows that firm 1 produces less in the mixed duopoly than in the pure duopoly (i.e., $q_1^* < q_1^\#$). That is, privatization leads to an increase of its output. Moreover, firm 0 considers the consumer surplus when deciding on the output in the mixed duopoly, but does not consider it in the pure duopoly. If the public firm does not care much about the environment, its output is more in the mixed duopoly than in the pure duopoly. It follows that privatization reduces the firm 0's output (i.e., $q_0^* > q_0^\#$). Because the effect of privatization on the firm 0's output dominates its effect on the firm 1's output. Thus, privatization reduces the total output (i.e., $q_0^* + q_1^* > q_0^\# + q_1^\#$). According to the part (i) of Proposition 1, privatization can catalyze both public and private firms' ER&D efforts if k is sufficiently small. It follows that unit output of firms generates less pollution in the pure duopoly than in the mixed duopoly. Thus, the environmental damage is lower in the pure duopoly than in the mixed duopoly. That is, privatization helps to k reduce the environmental damage. Second, we consider the part (ii). If k is large

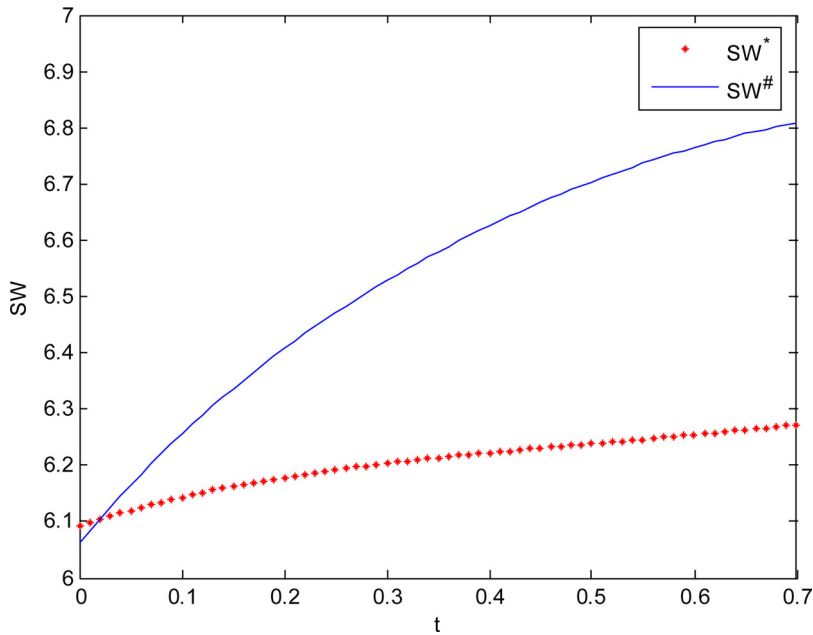


Figure 5. The social welfare in the mixed and private duopoly if the public firm cares less for the environment (given $a = 5.5$, $c = 0.5$, $k = 0.1$ and $d = 0.7$). Source: Authors' Calculations.

enough, when firm 0 determines output and ER&D, it will fully consider their effects on the overall environment in the mixed duopoly. However, it pursues profit maximization and doesn't care about the environment in the pure duopoly. Although after privatization firm 0 takes into account the environmental tax, the pollution externality is poorly internalized by the environmental tax if d is high and t is not high. In this situation, the effect of firm 0's output and ER&D changes due to privatization on the environment may dominate the effect of firm 1's output and ER&D changes due to privatization on the environment. Thus, privatization may deteriorate the environment if k is sufficiently large, d is high and t is not sufficiently high. Moreover, the pollution externality of private firms can be mostly internalized by the environmental tax if both d and t are high. In this situation, privatization may improve the environment even if firm 0 cares much about the environment in the mixed duopoly.

Proposition 3. In the case of high marginal environmental damage (i.e., d is high), there exist thresholds \hat{k} and \bar{k} of k ($0 < \hat{k} \leq \bar{k} < 1$) such that (i) when k is smaller than \hat{k} (i.e., $0 \leq k < \hat{k}$), privatization can improve the social welfare if t is high, and the opposite may appear if t is low; and (ii) when k is larger than \bar{k} (i.e., $\bar{k} < k \leq 1$), privatization can reduce the social welfare if t is low, and the opposite may appear if t is high.

Proof. See Appendix C.

Proposition 3 implies that, in a highly polluting mixed duopoly (i.e., d is high), whether privatization leads to an increase (or a reduction) in the social welfare depends on the environmental attitudes of the public firm and the environmental tax

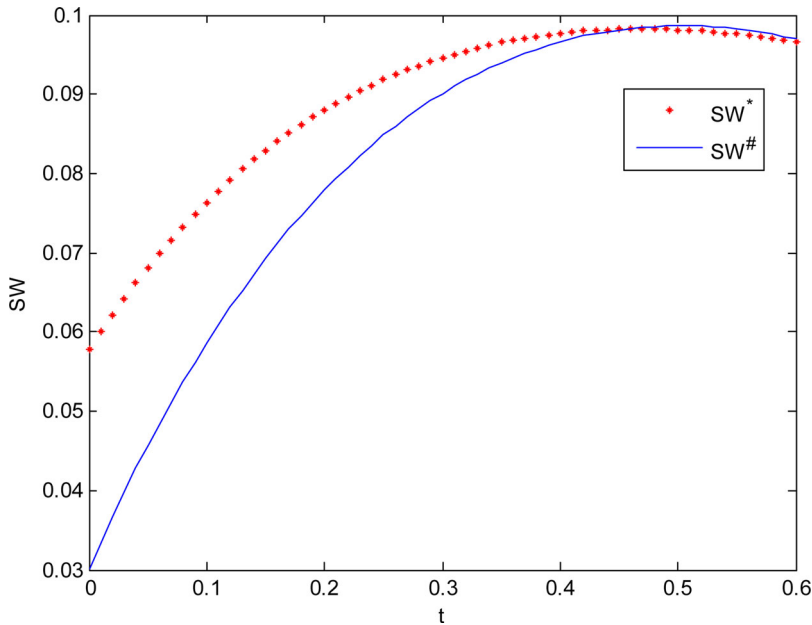


Figure 6. The social welfare in the mixed and private duopoly if the public firm cares much for the environment (given $a = 1.7$, $c = 0.5$, $k = 0.9$ and $d = 0.7$). Source: Authors' Calculations.

rates. For example, if the environmental tax is high (low), privatizing a public firm which cares less (much) about the environment will lead to an increase (a reduction) in the social welfare (see Figures 5 and 6). Therefore, when policy makers examine the effect of privatization on the social welfare, they should not ignore the factors of the public firms' environmental concerns and the environmental tax rates. Xing et al. (2019) assume that firms use the end-of-pipe technology and the government subsidizes the environmental R&D, and find that privatization always decreases the social welfare if the public firm is very concerned about the environment. Obviously, the results of this study are different. We find that privatization may increase the social welfare even if the public firm cares much for the environment.

The reason for Proposition 3 is as follows. According to (3), the social welfare consists of the consumer surplus, the producer surplus, the total environmental tax revenues and the environmental damage. In the case of high marginal environmental damage, the production of firms has great impacts on the environment. First, we consider part (i). If k is small and t is high, when deciding on output the public firm cares less for the environment, whereas the private firm cares much for its pollution due to high environmental tax burden. It follows that privatization can reduce the total output¹¹ and thus can decrease the consumer surplus. Using the part (i) of Proposition 2, privatization can reduce the environmental damage if the public firm cares less for the environment. Obviously, privatization can also decrease the total environmental tax revenues in this situation.¹² Moreover, privatization can increase the producer surplus. The reason is as follows. When k is small and t is high, firm 0 obtains more profit in the pure duopoly than in the mixed duopoly because it pays more attention to its own profits in the pure duopoly, and firm 1 obtains more profit

in the pure duopoly than in the mixed duopoly because of weaker competition in the pure duopoly. It follows that privatization can increase the producer surplus. When k is small and t is high, the effect of privatization on the producer surplus and the environmental damage exceeds that on the consumer surplus and the total environmental tax revenues. It follows that privatization improves the social welfare. Moreover, if the public firm cares less for the environment, the effect of privatization on the environmental damage weakens with a decrease of the environmental tax rate. Thus, privatization may reduce the social welfare if k is small and t is low.

Now, we consider part (ii). If k is large and t is low, when deciding on output the public firm cares much for the environment, but the private firm cares less for its pollution due to low environmental tax burden. It follows that privatization can increase (reduce) the total output if w is small (large)¹³. Thus, privatization can also increase (reduce) the consumer surplus if w is small (large). Using the part (ii) of [Proposition 2](#), privatization can increase the environmental damage if the public firm cares much for the environment and the environmental tax is low. Obviously, privatization can also increase the total environmental tax revenues in this situation. Moreover, privatization can increase the producer surplus. The reason is as follows. When k is large and t is low, firm 0 obtains more profit in the pure duopoly than in the mixed duopoly because it pays more attention to its own profits in the pure duopoly, and firm 1 obtains less (more) profit in the pure duopoly than in the mixed duopoly if w is small (large). Obviously, privatization can increase the producer surplus if w is large. In addition, the effect of privatization on the firm 0's profit dominates that on the firm 1's profit if w is small. It follows that privatization can also increase the producer surplus if w is small. Thus, privatization can increase the producer surplus. When k is large and t is low, the effect of privatization on the environmental damage (the consumer surplus and the environmental damage) exceeds that on the consumer surplus, the producer surplus and the total environmental tax revenues (the producer surplus and the total environmental tax revenues) if w is small (large). It follows that privatization reduces the social welfare. Moreover, if the public firm cares much for the environment, the effect of privatization on the environmental damage weakens with an increase of the environmental tax rate. Thus, privatization may increase the social welfare if k is large and t is high.

7. Discussion

7.1. When the environmental tax rate is endogenous

An important assumption in the basic model is that the environmental tax rate is exogenous. That is, natural question on this study is an endogenous environmental tax issue. In the literature of environmental tax in a mixed market, some scholars consider the effects of an optimal tax and the privatization policy on the environment and the social welfare (Wang and Wang, 2009; Ohori, 2014; Pal and Saha, 2015; Xu and Lee, 2018). In this section, we add a stage before environmental R&D, in which the government chooses the optimal environmental tax.

The government maximizes the social welfare (16) ((23)) with respect to t . Then, we can solve the optimal environmental tax rate t^* ($t^\#$) in the mixed (pure) duopoly.

Because the expressions of t^* and $t^\#$ are too long, we will not give them here. With the help of numerical analysis, we find that: (i) if k is small (large), privatization can (cannot) promote both public and private firms' ER&D efforts simultaneously; (ii) if k is small, privatization can improve the environment; and if k is large, privatization can improve or deteriorate the environment¹⁴; (iii) in the case of high d , if k is small, privatization can improve the social welfare; and if k is large, privatization can improve or reduce the social welfare¹⁵. Compared with the main findings in section 6, [propositions 1](#) and [2](#), and the part (ii) of [proposition 3](#) still hold. It is worth noting that when the environmental tax rate is endogenous, privatization certainly improves the social welfare if k is small and d is high. This result is different from that in the part (i) of [proposition 3](#). The reason is that if the environmental tax rate is endogenous, the optimal tax rate cannot be small enough in the case of high d in both mixed duopoly and pure duopoly. It follows that the result (when k is small, privatization may reduce the social welfare if t is low) in the part (i) of [proposition 3](#) does not appear in the situation of endogenous tax.

7.2. When the degree of concern on the environment by the public firm is endogenous

We assume that the degree of the environmental attitude of the public firm (i.e., k) is exogenous in the basic model. With the increase of environmental pressure, the government may hope that public firms can play a better role as a model in the implementation of environmental social responsibility. If the government can force public firms to consider the environmental damage from the perspective of welfare maximization, the situation of endogenous k appears. In this section, we add a stage before environmental R&D, in which the public firm chooses k to maximize the social welfare.

The public firm maximizes the social welfare (16) with respect to k . Then, we can solve the optimal degree of the public firm's environmental attitude (k^*) in the mixed duopoly. With the help of numerical analysis, we find that: (i) privatization cannot promote both public and private firms' ER&D efforts simultaneously; (ii) privatization can deteriorate the environment if d is high and t is low, but it may improve the environment if both d and t are high¹⁶; (iii) privatization can reduce the social welfare if d is high and t is low, but it may increase the social welfare if both d and t are high¹⁷. Compared with the main findings in section 6, the part (ii) of [propositions 1](#), [2](#) and [3](#) still holds. However, the results of the part (i) of [propositions 1](#), [2](#) and [3](#) do not appear in the situation of endogenous k . The reason is as follows. When k is endogenous, its optimal value is either equal to 1 or close to 1. Obviously, the situation that the public firm cares less about the environment will not appear in the case of endogenous k . Thus, the results of the part (i) of [propositions 1](#), [2](#) and [3](#) may not appear.

8. Conclusion

Focusing on the role of the environmental attitudes of the public firm, we have reconsidered the effects of privatization on the environmental R&D, the environment

and the social welfare in a mixed duopoly with an exogenous environmental tax. We mainly find that, if the public firm cares much for the environment, privatization can reduce at least one firm's ER&D efforts, and can worsen the environment if the marginal environmental damage is high and the environmental tax is not high. However, if the public firm cares less for the environment, privatization can boost both public and private firms' ER&D efforts, and can help to improve the environment (even if the marginal environmental damage is high and the environmental tax is not high). In addition, in the case of high marginal environmental damage, whether privatization improves or reduces the social welfare depends on the environmental attitudes of the public firm and the environmental tax rates.

The policy implication is as follows. Given the environmental tax rate, when a ready-for privatizing public firm that cares less about the environment, privatization will not only boost the firms' ER&D efforts but also help to reduce the environmental damage. In many developing countries, the public firms usually care less for the environment in highly polluting industries. In this situation, privatization of public firms can be used as a policy tool to achieve the dual goals of promoting the ER&D and improving the environment. Nevertheless, policy makers should be aware that privatization may cause a loss of social welfare if the environmental taxes are low.

We use a simplest framework to investigate the effects of privatization on the environmental R&D, the environment and the social welfare in a mixed duopoly. Several extensions may be possible: (i) the government not only imposes the environmental taxes on the firm's pollution but also subsidizes its environmental R&D activities; and (ii) the firms do not compete in production (Cournot competition), but in price (Bertrand competition) in product market. However, these extensions need to do more work and are a task that remains for future research.

Notes

1. See the notice on completing the commitment of listed environmental protection verification and rectification within a time limit issued by the Ministry of environmental protection of the people's Republic of China in 2010.
2. Hettige et al. (1996) show that some state-owned enterprises have higher pollution intensity than private enterprises in pulp and paper industries of Bangladesh, Indonesia, India and Thailand.
3. Some scholars analyze the factors influencing the adoption of a clean technology (Gil-Moltó and Varvarigos, 2013; Bréchet and Meunier, 2014). However, their studies do not involve privatization.
4. It is worth noting that we consider the increasing marginal costs, which is different from the constant marginal cost of Tsai et al. (2016), but consistent with most mixed oligopoly literature (See Gil-Moltó et al. (2011), Haruna and Goel (2019), Xing et al. (2019) and so on).
5. Note that the environmental R&D does not necessarily affect the marginal production costs and thus it is different from the cost-reducing R&D (d'Aspremont and Jacquemin, 1988; Chen and Nie, 2014; Yang and Nie, 2015; Xing, 2018).
6. The function form of environmental damage is similar to that of Ben Youssef and Dinar (2011), Song and Sun (2012) and Tsai et al. (2016).
7. For the convenience of analysis, we assume that d is not very large and satisfies $0 < d < 1$ in this study.

8. We assume $0 < t < d$ in this study. It is generally believed that the environmental tax rate should be lower than the marginal environmental damage in an imperfect market structure (Ohori, 2006a; Tsai et al., 2016). It is unrealistic to over-correct the environmental distortion. For example, Ohori (2014) and Pal and Saha (2015) find that the optimal environmental tax is always strictly lower than the marginal environmental damage in the mixed duopoly.
9. See Wang and Wang (2009), Tsai et al. (2016) and Haruna and Goel (2019).
10. Pal and Saha (2015), Xing et al. (2019) and Xing et al. (2020) also introduce the public firm's environmental concern into their studies. However, Pal and Saha (2015) and Xing et al. (2019) only consider two special situations (i.e., $k = 1$ and $k = 0$), and Xing et al. (2020) do not consider the situation of $k = 0$. Moreover, they consider the end-of-pipe technology but not the cleaner production technology.
11. Because privatization can decrease (increase) the firm 0's (firm 1's) output, and the effect of privatization on the firm 0's output exceeds that on the firm 1's output.
12. Because both of the environmental damage ($D(E) = d(E_0 + E_1)$) and the total environmental tax revenues ($T = t(E_0 + E_1)$) are determined by the total pollution.
13. Because privatization can increase (decrease) the firm 0's output and can decrease (increase) the firm 1's output if w is small (large), and the effect of privatization on the firm 0's output exceeds that on the firm 1's output.
14. For example, when $k = 1$, $w = 1$ and $d = 0.5$, privatization improves the environment; and when $k = 1$, $w = 1$ and $d = 0.9$, privatization deteriorates the environment.
15. For example, when $k = 1$, $w = 1$ and $d = 0.5$, privatization reduces the social welfare; and when $k = 1$, $w = 1$ and $d = 0.9$, privatization increases the social welfare.
16. For example, when $d = 0.5$, $t = 0.45$ and $w = 1$, privatization improves the environment.
17. For example, when $d = 0.9$, $t = 0.85$ and $w = 1$, privatization increases the social welfare.
18. For example, $k_5 = \frac{t}{d}$ meets the requirements.

Disclosure statement

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Appendix

Appendix A.

Proof of Proposition 1: (i) Obviously, both r_0^* and $r_0^\#$ are continuous functions of k on interval $[0, 1]$, and $r_0^* = 0 < r_0^\#$ if $k = 0$. Thus, there exists k_1 ($0 < k_1 < 1$) making that $r_0^* < r_0^\#$ for all $k \in [0, k_1)$. Now we set $G(w) = r_1^*|_{k=0} - r_1^\#|_{k=0}$ and can prove $G(\underline{w}) < 0$ and $G(\bar{w}) < 0$. Thus, $G(w) < 0$ (i.e., $r_1^*|_{k=0} < r_1^\#|_{k=0}$) for all $w \in [\underline{w}, \bar{w}]$ because of $G(w)$ is a linear function of w . Because r_1^* and $r_1^\#$ are continuous functions of k on interval $[0, 1]$, and $r_1^* < r_1^\#$ if $k = 0$, there exists k_2 ($0 < k_2 < 1$) making that $r_1^* < r_1^\#$ for all $k \in [0, k_2)$. In summary, when $k \in [0, \underline{k})$ ($\underline{k} = \min\{k_1, k_2\}$), $r_0^* < r_0^\#$ and $r_1^* < r_1^\#$; (ii) We set $L = r_0^* - r_0^\#$. Obviously, $L(w)$ is a linear function of w . Then, we can prove $L(\bar{w})_{k=1} > 0$ and $L(w_0')_{k=1} = 0$ ($w_0' = \frac{90kdt^3 - 320kdt + 192k^3d^3t - 927k^2d^2t^2 + 1760k^2d^2 + 540t^4 - 1125t^2}{3(-391kdt^2 + 480kd + 72kdt^4 - 90k^2d^2t^3 + 176k^2d^2t + 180t^3 - 375t + 18k^3d^2t^2)}$). Thus, $L(w)_{k=1} > 0$ if $w \in (w', \bar{w}]$ ($w' = \max\{\underline{w}, w_0'\}$) because $L(w)_{k=1}$ is also a linear function of w . L is a continuous function of k on interval $[0, 1]$. Thus, there exists k_3 ($0 < k_3 < 1$) making that, for all $k \in (k_3, 1]$, $L(w) > 0$ if $w \in (w', \bar{w}]$. Moreover, we set $H = r_1^* - r_1^\#$. Obviously, $H(w)$ is a linear function of w . Then, we can prove $H(\underline{w})_{k=1} > 0$, $H(\bar{w})_{k=1} < 0$ and $H(w'')_{k=1} = 0$ ($w'' = \frac{265t - 144k^2d^2t + 90kdt^2 - 320kd + 64k^3d^3}{90t^2 - 55 - 18k^2d^2t^2 - 80k^2d^2 + 18k^3d^3t}$). Thus, $H(w)_{k=1} > 0$ if $w \in [\underline{w}, w'')$ because $H(w)_{k=1}$ is also a linear function of w . H is a continuous function of k on interval $[0, 1]$. Thus, there exists k_4 ($0 < k_4 < 1$) making that, for all $k \in (k_4, 1]$, $H(w) > 0$ if $w \in [\underline{w}, w'')$. Note that $H(w'') = 0$. Further, we can prove that there exists k_5 ($0 < k_5 < 1$) making that $w' \leq w''$ for all $k \in (k_5, 1]$ ¹⁸. In summary, when $\bar{k} < k \leq 1$

($\bar{k} = \max\{k_3, k_4, k_5\}$), at least one of $L(w) > 0$ and $H(w) > 0$ is established. This implies that it is impossible for $L(w) < 0$ and $H(w) < 0$ (i.e., $r_0^* < r_0^\#$ and $r_1^* < r_1^\#$) to appear at the same time if $\bar{k} < k \leq 1$.

Appendix B.

Proof of Proposition 2: Setting $N = D^* - D^\#$, $N(w)$ is a quadratic function of w . Obviously, $N'(w) = \partial N / \partial w$ is a linear function of w . (i) We can prove that $N'(\underline{w})_{k=0} > 0$ and $N'(\bar{w})_{k=0} > 0$. Thus, $N'(w)_{k=0} > 0$ for all $w \in [\underline{w}, \bar{w}]$. Because $N'(w)_{k=0} > 0$ in $[\underline{w}, \bar{w}]$ and $N(\underline{w})_{k=0} > 0$, $N(\bar{w})_{k=0} > 0$ for all $w \in [\underline{w}, \bar{w}]$. Obviously, N is a continuous function of k on interval $[0, 1]$. Combining with $N(w)_{k=0} = (D^* - D^\#)_{k=0} > 0$, there exists a k_{\leftarrow} ($0 < k_{\leftarrow} < 1$) making that $D^* > D^\#$ for all $k \in [0, k_{\leftarrow}]$. (ii) First, we consider the situation that d is high enough and t is not high. There is a unique point w''' that makes $N'(w''') = 0$. We can prove that $N(\underline{w})_{k=1} < 0$, $N(\bar{w})_{k=1} < 0$ and $N(w''')_{k=1} < 0$. Because $N(w)$ is a quadratic function of w , $N(w)_{k=1} < 0$ for all $w \in [\underline{w}, \bar{w}]$. Moreover, N is a continuous function of k on interval $[0, 1]$. Combining with $N(w)_{k=1} = (D^* - D^\#)_{k=1} < 0$, there exists a \hat{k} ($0 < \hat{k} < 1$) making that $D^* < D^\#$ for all $k \in (\hat{k}, 1]$. Second, we consider the situation that both d and t are high enough. In this case, $D^* > D^\#$ may appear if k is large enough. For example, given $w = 1.5$, $d = 0.9$ and $t \in [0.8, 0.9)$, when $0.9 < k \leq 1$, $D^* > D^\#$.

Appendix C.

Proof of Proposition 3: Setting $M = SW^* - SW^\#$, $M(w)$ is a quadratic function of w . There is a unique point w'''' that makes $M'(w''''') = 0$ ($M'(w) = \partial M / \partial w$). (i) First, we consider the situation that both d and t are high enough. We can prove that $M(\underline{w})_{k=0} < 0$, $M(\bar{w})_{k=0} < 0$ and $M(w''''')_{k=0} < 0$. Because $M(w)$ is a quadratic function of w , $M(w)_{k=0} < 0$ for all $w \in [\underline{w}, \bar{w}]$. Moreover, M is a continuous function of k on interval $[0, 1]$. Combining with $M(w)_{k=0} = (SW^* - SW^\#)_{k=0} < 0$, there exists a k ($0 < k < 1$) making that $SW^* < SW^\#$ for all $k \in [0, k)$. Second, we consider the situation that d is high enough and t is low enough. In this case, $SW^* > SW^\#$ may appear if k is small enough. For example, given $w = 23$ and $d = 0.9$, when $k = 0.1$, $SW^* > SW^\#$ for all $t \in [0, 0.15]$; (ii) First, we consider the situation that d is high enough and t is low enough. We can prove that $M(\underline{w})_{k=1} > 0$, $M(\bar{w})_{k=1} > 0$ and $M(w''''')_{k=1} > 0$. Because $M(w)$ is a quadratic function of w , $M(w)_{k=1} > 0$ for all $w \in [\underline{w}, \bar{w}]$. Moreover, M is a continuous function of k on interval $[0, 1]$. Combining with $M(w)_{k=1} = (SW^* - SW^\#)_{k=1} > 0$, there exists a \hat{k} ($0 < \hat{k} < 1$) making that $SW^* > SW^\#$ for all $k \in (\hat{k}, 1]$. Second, we consider the situation that both d and t are high enough. In this case, $SW^* < SW^\#$ may appear if k is large enough. For example, given $w = 1.2$ and $d = 0.9$, when $k = 0.9$, $SW^* < SW^\#$ for all $t \in [0.7, 0.9)$.