Online Appendix for

"Environmental Innovation and Policy Harmonization in International Oligopoly"[*]

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Appendix: Convex environmental damages

In this appendix, we extend the model by considering convex environmental damages and compare firm incentives for environmental R&D. In our main paper, we assume that the environmental damages are linear in emissions. We show that the results obtained in the main paper qualitatively hold for the convex environmental damages.

The net benefit of country i is modified as follows:

$$W_i = \begin{cases} \pi_i + t_i(e-\epsilon_i)y_i - \delta_i\left[(e-\epsilon_i)y_i + \gamma\,(e-\epsilon_j)\,y_j\right]^2 & \text{under regime NT,} \\ \pi_i - \delta_i(a_i + \gamma\,a_j)^2 & \text{under regime NQ,} \\ \pi_i + \bar{t}\,(e-\epsilon_i)\,y_i - \delta_i\left[(e-\epsilon_i)y_i + \gamma\,(e-\epsilon_j)\,y_j\right]^2 & \text{under regime CT,} \\ \pi_i - \delta_i(\bar{a} + \gamma\,\bar{a})^2 & \text{under regime CQ,} \end{cases}$$

In the above formulation, environmental damages are quadratic in the total emissions including transboundary emissions from the foreign country. The parameter δ_i indicates the intensity of environmental damages in country i.

In the case of quadratic environmental damages, the mathematical derivation of equilibrium and its comparisons are too complex. Therefore, we simply display variables in a symmetric equilibrium and present graphical comparison results of firm incentives in each regime.[1]

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[1]The results and graphs presented here are generated by the mathematical software Mathematica 7. The detailed calculations and the accompanying Mathematica code are available upon request.

The model settings are the same as those in the main paper except for the formulation of environmental damages. Subsequently, the equilibrium levels of emission tax, emission cap, output and R&D incentives of firms in each regime, evaluated at a symmetric equilibrium, are derived by

$$t^{NT} = \frac{2(e-\epsilon)^2 \delta (1+\gamma)(2-\gamma) - 1}{(e-\epsilon)\left[2\delta (e-\epsilon)^2 (1+\gamma)(2-\gamma) + 5\right]}, \quad y^{NT} = \frac{2}{5 + 2\delta (e-\epsilon)^2 (1+\gamma)(2-\gamma)},$$

$$FI^{NT} = \frac{16e\delta \left[12 + \gamma + 4\gamma^2 + 2e^2\delta (2-\gamma)(1+\gamma)(4 - \gamma(3-2\gamma))\right]}{\left[1 + 2e^2\delta (2-\gamma)(1-\gamma)\right]\left[5 + 2e^2\delta (2-\gamma)(1+\gamma)\right]^3},$$

$$a^{NQ} = \frac{e-\epsilon}{3 + 2(e-\epsilon)^2 \delta (1+\gamma)}, \quad y^{NQ} = \frac{1}{3 + 2\delta(e-\epsilon)^2(1+\gamma)},$$

$$FI^{NQ} = \frac{2e\delta \left[2 - \gamma + 4e^2\delta (1+\gamma)(2 + \gamma + e^2\delta(2-\gamma)(1+\gamma))\right]}{\left[1 + 2e^2\delta(1-\gamma)\right]\left[3 + 2e^2\delta (1+\gamma)\right]^3},$$

$$t^{CT} = \frac{1 + 2\delta(e-\epsilon)^2 (1+\gamma)^2}{2(e-\epsilon)\left[2 + \delta(e-\epsilon)^2 (1+\gamma)^2\right]}, \quad y^{CT} = \frac{1}{2\left[2 + \delta (e-\epsilon)^2 (1+\gamma)^2\right]},$$

$$FI^{CT} = \frac{2 + 7e^2\delta(1+\gamma)^2 + 2e^4\delta^2(1+\gamma)^4}{4e\left[2 + e^2\delta(1+\gamma)^2\right]^3},$$

$$a^{CQ} = \frac{e-\epsilon}{2\left[2 + \delta (e-\epsilon)^2 (1+\gamma)^2\right]}, \quad y^{CQ} = \frac{1}{2\left[2 + \delta (e-\epsilon)^2 (1+\gamma)^2\right]},$$

$$FI^{CQ} = \frac{2 + 3e^2\delta(1+\gamma)^2\left[1 + e^2\delta(1+\gamma)^2\right]}{4e\left[2 + e^2\delta (1+\gamma)^2\right]^3}.$$

Note that the equilibrium output in each regime is necessarily positive. Unlike the case of linear environmental damages, in the case of convex environmental damages, marginal environmental damage becomes small as output decreases. Therefore, the government has no incentive to impose very stringent tax or quantity regulations that restrain production to zero.

The four panels of Figure 3 depict the comparison of firm incentives under different regimes.[2] The comparison results in the case of convex damages are qualitatively equivalent to those in the case of linear damages, except for the comparison of firm incentives between non-cooperative and cooperative tax regulations (the bottom-left panel of Figure 3). We can observe from the figure that $FI^{CT} > FI^{NT}$ holds for both extremely small δ and large δ. The intuition of the former is similar to the case of linear environmental damages, but that of the latter needs to be explained. When δ is significant, the cooperative tax rate is

[2]In the figure, ζ_i can be obtained by equating firm incentives when $\gamma = 0$ that is to be compared. For example, ζ_1 is the value of δ such that $FI^{NT}|_{\gamma=0} = FI^{NQ}|_{\gamma=0}$.

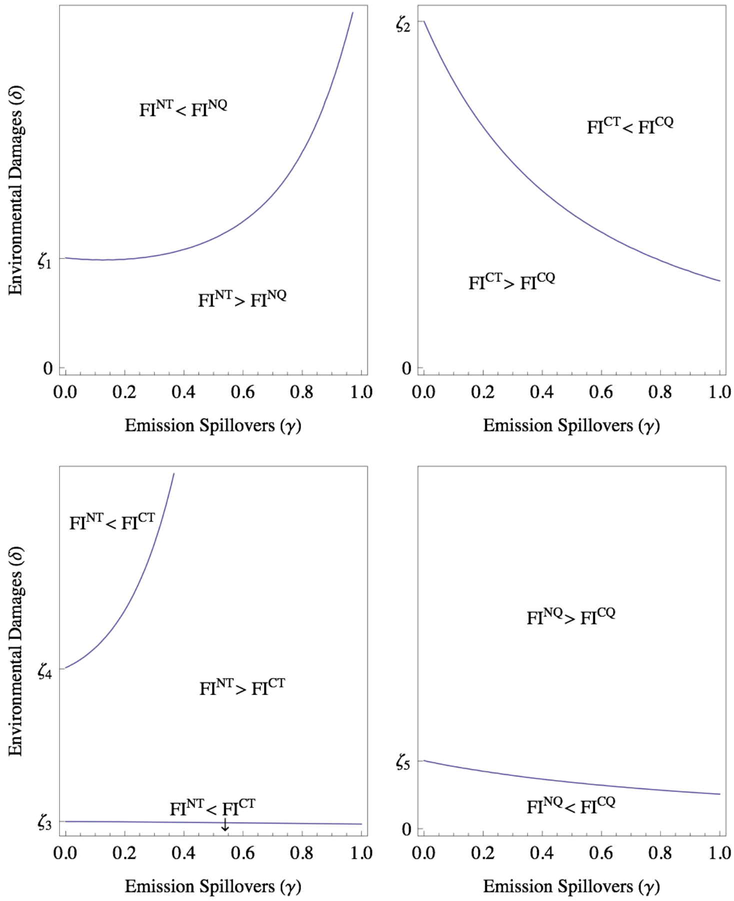

Figure 3: Comparison of firm incentives in the case of convex environmental damages

higher and thus a direct cost-reducing effect of innovation is also more significant than those under a non-cooperative tax regime. For significant environmental damages, the direct effect dominates the strategic effect of innovation, which leads to $FI^{NT} < FI^{CT}$. In the case of linear damages, for significant environmental damages, the cooperative tax is so stringent that it restrains production to zero, which is represented by the area "ruled out" in the left panel of Figure 2 in the main paper.