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Is Environmental Tax Harmonization Desirable in Global Value Chains?*

Haitao Cheng[†] Hayato Kato[‡] Ayako Obashi[§]

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Abstract

The spatial unbundling of parts production and assembly currently characterizes globalization, leading to the worldwide dispersion of pollution. We consider socially optimal (cooperative) environmental taxes in a two-country model of global value chains in which the location of both parts and assembly can differ. When unbundling costs are so high that parts and assembly must collocate in the pre-globalized world, pollution is spatially concentrated, and harmonizing environmental taxes maximizes global welfare. In contrast, with low unbundling costs triggering the dispersion of parts and thus pollution throughout the world as today, harmonization fails to maximize global welfare. Similar results hold when the two countries non-cooperatively choose their environmental taxes.

Keywords: Environmental policy; Fragmentation; Emission tax competition; International coordination; Trade in parts and components

JEL classification: F18; F23; Q56; Q58.

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1 Introduction

Globalization since the late twentieth century features not just declining barriers to trade and factor mobility, but also the lowering of costs for coordinating activities within organizations. This spatial separation of production stages, which Baldwin (2016) refers to as the *second unbundling*, has significant implications for the environment as well as trade.¹ This is because it may promote the relocation of polluting industries to countries with lax environmental standards, an issue known as the pollution haven hypothesis (Markusen et al., 1995; Levinson and Taylor, 2008).

One measure taken to act against the harmful impact of unbundling production processes could be the a harmonization of environmental standards among countries (Sterner and Köhlin, 2003). Equalizing regulations among countries does not distort the location decisions of firms and may mitigate the divergence of environmental quality. However, harmonization may be too naive a policy to address individual environmental impacts given country heterogeneity.

We aim to evaluate the effectiveness of environmental tax harmonization using a two-country model of global value chains à la Baldwin and Venables (2013), where firms produce a final good through assembling the chain of many parts. Specifically, we characterize the socially optimal environmental taxes (or cooperative equilibrium) that maximize global welfare and compare them with harmonized taxes. In the pre-globalized world where all production processes collocate, i.e., before the second unbundling, environmental taxes do nothing to improve the global environment. Setting an equal tax between countries maximizes the global welfare by not distorting efficient locations. However, in the globalized world where assembly and parts can be spatially unbundled, i.e., after the second unbundling, environmental taxes can reduce global environmental damage by avoiding the concentration of polluting processes. The simple harmonization is almost never desirable and a more careful coordination is necessary.

This result is about whether socially optimal and harmonized taxes coincide. One interested in the need for policy coordination (not just simple harmonization) may also question whether socially optimal taxes coincide with noncooperative taxes. We show that this is more likely to hold before the second unbundling than in the globalized world. This is because prior to the second unbundling, there is little scope for governments to manipulate the location of parts through environmental taxes. Each government then lacks a strong incentive

¹The first unbundling refers to the spatial separation of consumption and production owing to the development of the steam engine in the Industrial Revolution.

to set specific tax rates so that it realizes the socially optimal taxes in the noncooperative equilibria. As a result, the equilibrium tax rates chosen by each country do not differ much from the socially optimal tax rates. The second unbundling, however, makes the location of parts more sensitive to environmental taxes and thus tax competition leads to equilibrium tax rates different to the socially optimal tax rates. Our conclusion that current globalization calls for more careful policy coordination beyond simple harmonization has implications for the experiences of earlier member states of the European Union (EU) prior to 2004, i.e., the EU 15, and the newer member states among the Central and Eastern European (CEE) countries since 2004.

Some studies have investigated the environmental impact of mobile firms, but the production structure in their models is generally too simple to cover fragmentation (Pflüger, 2001; Zeng and Zhao, 2009; Ishikawa and Okubo, 2017; Forslid et al., 2017; Ikefuji et al., 2016; Voßwinkel and Birg, 2018).² Pflüger (2001), for example, examines the effect of pollution taxes on the international relocation of monopolistically competitive firms. By extending Pflüger’s model to incorporate transboundary pollution, Ishikawa and Okubo (2017) reveal that trade liberalization may increase global pollution through firm relocation from a country with stringent regulation to a country with lax regulation. Voßwinkel and Birg (2018) examine non/cooperative environmental policies in an oligopolistic competition setting with a specific focus on the quality of difference of goods. In contrast to these studies where the vertical linkages between sectors are ignored, we consider a so-called *spider* structure, comprising multiple limbs (parts) coming together to make up a body (assembly).

The studies closest to ours are Hamilton and Requate (2004); and Wan et al. (2018), which examine unilaterally optimal taxes and Nash equilibrium taxes in two-country models with vertically linked sectors.³ Both these studies assume that upstream firms produce polluting inputs and are taxed/subsidized by their local government, as do we. However, unlike the current paper, they also consider international trade in only final goods, which corresponds to the pre-globalized situation in our analysis. To describe the global value chains in the present world, we allow for trade in both inputs and assembly relocation.

Using Baldwin and Venables (2013)’s framework, Obashi (2019) characterizes optimal combinations of trade instruments and finds that policy prescriptions proposed by traditional

²Using an evolutionary game approach, Dijkstra and De Vries (2006) conclude that environmental taxation may induce polluting firms to stay away from consumers. However, in contrast to our analysis, their focus is on the spatial unbundling of consumption and production, not the spatial unbundling of production itself.

³See also Wan and Wen (2017). Some studies consider a wider variety of policy tools, including border tax adjustments as well as emission taxes, although they do not allow for vertical linkages (Lai and Hu, 2008; Yomogida and Tarui, 2013; Keen and Kotsogiannis, 2014; Sanctuary, 2018; Ogawa and Yanase, 2019).

trade models are not sufficient to achieve the social optimum. Although environmental issues were outside the scope of Obashi (2019), her study and ours should be seen as complements as both emphasize that the evolution of global value chains significantly changes policy design.

The remainder of the paper is structured as follows. Section 2 presents the model and analyzes the location patterns of parts given assembly location and environmental taxes. Section 3 allows for endogenous assembly location and examine socially optimal taxes in the pre-globalized world and Section 4 does this for the globalized world. Section 5 confirms that our main result holds in different settings. The final section discusses implications for the real world.

2 The model

Consider a world with two countries, N and S . The two countries have equal population with unit mass. Each individual inelastically supplies one unit of labor. There are three types of goods: a final good, a range of parts (intermediate inputs), and a numéraire good. The numéraire good is produced using labor and is costlessly traded, which equalizes its international price. With choice of units, the wage rates in both countries are equal to unity. Each part can be produced using labor in both countries and can be internationally traded. Parts production generates local pollution and is thus taxed by the domestic government. A single final good producer (assembler) locates in N or S and assembles the range of parts into one unit of the good. As in Baldwin and Venables (2013), the two countries differ in two ways: (i) only N consumes the final good and (ii) the average cost of producing parts is lower in S than in N .

To describe the second unbundling, we distinguish between two types of frictions. If the assembler is located in S , it must pay *trade costs* to export the final good to N . If the locations of parts and assembly differ, the assembler must pay additional *unbundling costs* to import parts from abroad. Unbundling costs include communication costs between headquarters and foreign suppliers as well as physical transportation costs.⁴

⁴As discussed shortly, we assume that both trade costs and unbundling/communication costs increase proportionally to quantity. There is no general agreement about how to model communication costs (Gokan et al., 2019). Whether communication costs affect the fixed or variable costs of trade depends on the role of communications in transactions. The increased use of the Internet (e.g., Freund and Weinhold, 2004), for example, facilitates the search for trading partners and thus solely affects the fixed costs. However, in the manufacturing activities, the downstream and upstream production processes need to interact to coordinate the specification of a customized product and the timing of delivery, which would primarily affect variable costs. Considering these interactions between headquarters and distant plants, some studies model

2.1 Preferences

The utility of the representative consumer in $i \in \{N, S\}$ is

$$U_i = \tilde{u}\mathbf{1}_i + X_i - D(e_i), \quad (1)$$

where X_i is the consumption of the numéraire good, and e_i is the pollution level. $\mathbf{1}_i$ takes one if $i = N$ and zero if $i = S$. The consumer in N obtains \tilde{u} from consuming one unit of the final good. The disutility from pollution is expressed as $D(e_i) = \gamma e_i^2/2$ with $\gamma > 0$. The budget constraint is

$$p\mathbf{1}_i + X_i = 1 + t_i e_i + \bar{X}, \quad (2)$$

where p is the final good's price and t_i is the environmental tax by i per unit of pollution. The income consists of wage ($w_i = 1$), the redistribution of tax revenues ($t_i e_i$), and the initial endowment of the numéraire (\bar{X}). \bar{X} ensures positive consumption of the numéraire. Substituting (2) into (1) yields the indirect utility V_i .

2.2 Sourcing decision

The assembler first chooses where to locate and then from which country to source parts. Here, we consider the sourcing decision of the assembler given its location.

Letting z be the index of parts from the set $Z = [\underline{b}, \bar{b}]$, the unit cost of any part $z \in Z$ is unity if it is produced in N . If a part $z \in Z$ is produced in S , on the other, its unit cost is $b(z) = z$ with $0 < \underline{b} < 1 < \bar{b}$. Thus N has a comparative advantage in parts $b \in [1, \bar{b}]$, while S has it in parts $b \in [\underline{b}, 1)$. S has an average cost advantage over N , i.e., $\beta \equiv 1 - (\underline{b} + \bar{b})/2 > 0$.⁵ Producing one unit of each part generates one unit of local pollution.

The assembler produces one unit of the final good by assembling one unit of each part. When parts cross the border, additional unbundling costs θ arise. The sourcing decision is on a parts basis by comparing the international cost difference. Supposing the assembler is

communication costs as an iceberg cost proportional to the firm's output (Duranton and Puga, 2005; Fujita and Thisse, 2006. Indeed, Fink et al. (2005) find that communication costs exert a significant impact on the variable costs of trade, thereby affecting trade patterns, especially for differentiated goods. We follow the latter modeling strategy for communication costs.

⁵The average cost of parts in S is $\frac{1}{\bar{b}-\underline{b}} \int_{\underline{b}}^{\bar{b}} \tilde{b} d\tilde{b} = \frac{1}{\bar{b}-\underline{b}} \cdot \frac{\bar{b}^2 - \underline{b}^2}{2} = \frac{\bar{b} + \underline{b}}{2}$, while that in N is $\frac{1}{\bar{b}-\underline{b}} \int_{\underline{b}}^{\bar{b}} 1 d\tilde{b} = 1$.

in N , a part z is sourced there if

$$\begin{aligned} \underbrace{1 + t_N}_{\text{Cost in } N} &< \underbrace{b(z) + \theta + t_S}_{\text{Cost in } S}, \\ \rightarrow b(z) &> b_N \equiv \min[\max\{\underline{b}, 1 - \theta + \Delta t\}, \bar{b}], \\ \text{where } \Delta t &\equiv t_N - t_S. \end{aligned}$$

The inequality is likely to hold if S 's cost is high (high $b(z)$), N 's tax compared with S 's is low (low Δt), and unbundling costs are high (high θ).

Supposing the assembler is in S , a part z is produced there if

$$\begin{aligned} \underbrace{1 + \theta + t_N}_{\text{Cost in } N} &> \underbrace{b(z) + t_S}_{\text{Cost in } S}, \\ \rightarrow b(z) &< b_S \equiv \max[\min\{\bar{b}, 1 + \theta + \Delta t\}, \underline{b}], \end{aligned}$$

which can be interpreted analogously.

When unbundling costs are sufficiently high, the two *unbundling thresholds* degenerate, i.e., $b_N = \underline{b}$ and $b_S = \bar{b}$, and all parts colocate with assembly. Specifically, supposing $\theta > \bar{\theta} \equiv \max\{1 - \underline{b} + \Delta t, \bar{b} - 1 - \Delta t\}$, Fig. 1 draws such a region (\mathcal{NS} in the figure) given assembly location and taxes.⁶ The co-location motive of the assembler to save unbundling costs is so strong that neither comparative advantage nor environmental taxes matter. The parts and assembly are spatially bundled in the pre-globalization world.

When unbundling costs are sufficiently low, the two unbundling thresholds do not degenerate. The location of some parts is dictated by comparative advantage and taxes, not by the colocation motive. Supposing $\theta < \underline{\theta} \equiv \min\{1 - \underline{b} + \Delta t, \bar{b} - 1 - \Delta t\}$, Fig. 2 depicts the sourcing pattern.⁷ Unlike Fig. 1, there are two other regions in Fig. 2, \mathcal{N} and \mathcal{S} . Parts in \mathcal{N} , for example, are those in which N has a very strong comparative advantage, and are always produced in N . As low unbundling costs also make the assembler aware of taxes, the tax difference now matters for its sourcing decision. The spatial unbundling captures the current globalization. In what follows, we separately present the analysis of the two cases.

The key mechanism here is that stringent environmental regulations would relocate the dirtiest parts of the production process to countries with less strict policies, which Cherni-wchan et al. (2017) refer to as the pollution offshoring hypothesis. If this hypothesis holds,

⁶Note that $b_N = \underline{b}$ holds if $\underline{b} > 1 - \theta + \Delta t$; $b_S = \bar{b}$ holds if $\bar{b} < 1 + \theta + \Delta t$. These conditions lead to $\theta > \max\{1 - \underline{b} + \Delta t, \bar{b} - 1 - \Delta t\}$, which is equivalent to $\Delta t \in (\bar{b} - \theta - 1, \underline{b} + \theta - 1)$.

⁷This condition is equivalent to $\Delta t \in (\underline{b} + \theta - 1, \bar{b} - \theta - 1)$.

domestic firms become cleaner. This is not because they have reduced the emission intensity of their own activities, but because they have shifted the dirtiest parts of their production out of the country. There are some empirical evidences to support the pollution offshoring hypothesis. For example, Cherniwchan (2017) found that the emission intensities of the US manufacturing plants fell in part due to changes in their access to dirtier intermediate inputs in Mexico following trade liberalization through the North American Free Trade Agreement (NAFTA).⁸

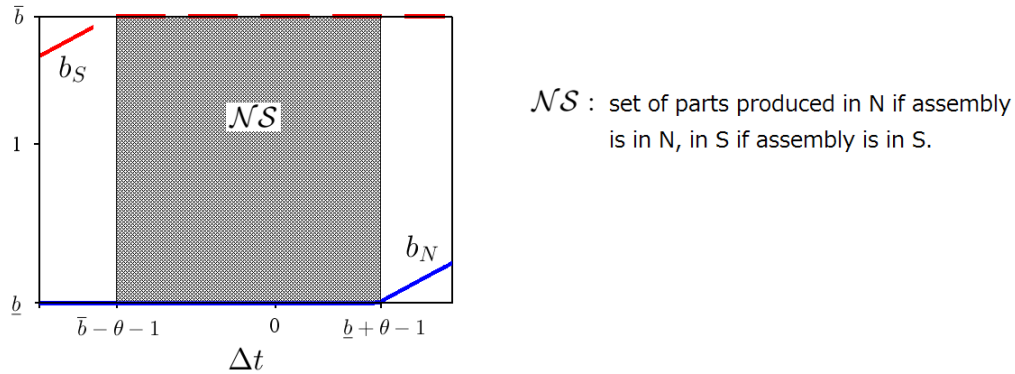


Fig. 1. Sourcing pattern under high unbundling costs.

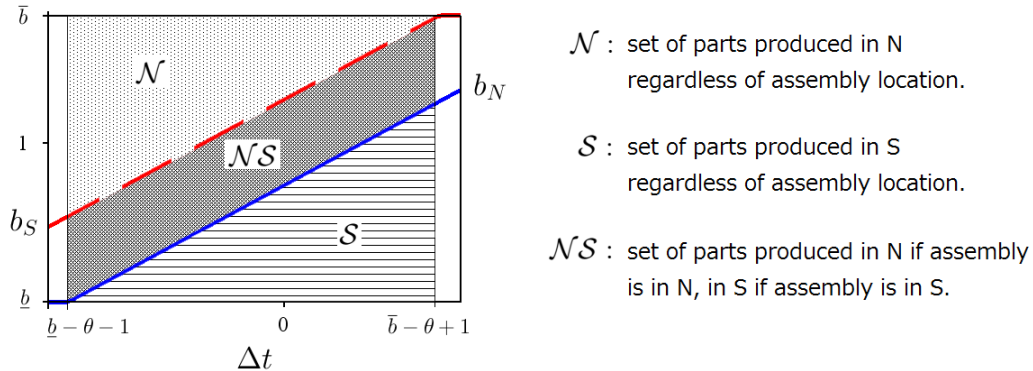


Fig. 2. Sourcing pattern under low unbundling costs.

⁸The empirical literature is yet to reach a consensus. For instance, Shapiro and Walker (2018) found that fragmenting production or offshoring was unlikely to account for a large share of the reductions in emissions intensities in US manufacturing production.

3 High unbundling costs: colocation of parts and assembly

We consider here the case where unbundling costs are high: $\theta > \bar{\theta}$ so that parts and assembly are spatially bundled. We first characterize the assembly location for the given taxes and then derive the socially optimal taxes.

3.1 Assembly location

Let C_i be the total costs of producing one unit of the final good, given assembly in $i \in \{N, S\}$. Noting $b_N = \underline{b}$, we have

$$\begin{aligned} C_N &= \underbrace{\int_{\underline{b}}^{b_N} (\tilde{b} + \theta + t_S) d\tilde{b}}_{\text{Parts from } S} + \underbrace{\int_{b_N}^{\bar{b}} (1 + t_N) d\tilde{b}}_{\text{Parts from } N} \\ &= (\bar{b} - \underline{b})(1 + t_N). \end{aligned} \quad (3)$$

Similarly, noting $b_S = \bar{b}$, we have

$$\begin{aligned} C_S &= \tau + \underbrace{\int_{\underline{b}}^{b_S} (\tilde{b} + t_S) d\tilde{b}}_{\text{Parts from } S} + \underbrace{\int_{b_S}^{\bar{b}} (1 + \theta + t_N) d\tilde{b}}_{\text{Parts from } N} \\ &= \tau + (\bar{b} - \underline{b}) \left(\frac{\underline{b} + \bar{b}}{2} + t_S \right), \end{aligned} \quad (4)$$

where trade costs τ enter since the good crosses the border. All parts are sourced locally and thus θ does not appear here.

The assembler chooses the location that yields the lower C_i . Assembly takes place in N if

$$\begin{aligned} \Delta C &\equiv C_N - C_S = -\tau + (\bar{b} - \underline{b}) (\beta + \Delta t) \leq 0, \\ &\rightarrow \tau \geq \tau^* \equiv (\bar{b} - \underline{b}) (\beta + \Delta t), \end{aligned} \quad (5)$$

where $\beta \equiv 1 - (\underline{b} + \bar{b})/2$,

High trade costs ensure the assembler prefers the proximity to consumers. As seen from the switching point τ^* , below which assembly takes place in S , the assembler is more likely to

locate in N as N 's tax becomes lower (lower Δt) and/or N 's parts are more costly (higher β). This tendency is magnified by the total number of parts: $\bar{b} - \underline{b}$.

3.2 Social optimum

Environmental taxes potentially affect pollution arising from dirty parts production via two channels. First, as discussed in Section 2.2, a tax increase in one country makes its production cost of parts higher, inducing the assembler to change the sourcing pattern. The assembler sources more parts from the other country than before, where more pollution and environmental damage occur. Second, as discussed in Section 3.1, taxes affect the assembler's location choice through changes in the switching point, τ^* , and may lead to a discontinuous jump in pollution. If an increase in t_N makes τ^* higher than the exogenously given trade costs, τ , the assembler moves from S to N and brings N a discontinuous increase in pollution due to the colocation motive of parts and assembly.

Under high unbundling costs, however, the first channel, i.e., the assembler's sourcing decision, is ineffective. The colocation motive is so strong that the unbundling thresholds degenerate ($b_N = \underline{b}$; $b_S = \bar{b}$), implying that environmental taxes affect pollution only through the second channel, i.e., the assembler's location decision.

The social/global welfare W is the sum of each country's indirect utility V_i . Using (1) to (4), we have

$$W = \begin{cases} W|_{A=N} = \sum_{i=N,S} V_i|_{A=N} = u - (\bar{b} - \underline{b}) - (\gamma/2)(\bar{b} - \underline{b})^2 & \text{if } \tau \geq \tau^* \\ W|_{A=S} = \sum_{i=N,S} V_i|_{A=S} = u - \tau - (1/2)(\bar{b} - \underline{b})(\underline{b} + \bar{b}) - (\gamma/2)(\bar{b} - \underline{b})^2 & \text{if } \tau < \tau^* \end{cases},$$

where $u \equiv \tilde{u} + 2(1 + \bar{X})$,

and where the subscript $A = i \in \{N, S\}$ indicates the assembler's location. Since all parts co-locate with assembly, the pollution level in i is $e_i = \bar{b} - \underline{b}$ if the assembler is in i and it is $e_i = 0$ otherwise. We do not examine each component of the social welfare here, but details about the final good's price and the environmental damage are in Appendix A1.

Surprisingly, taxes do not enter in W . Since the unbundling thresholds degenerate, the environmental damage does not depend on taxes: $D(e_i) = (\gamma/2)(\bar{b} - \underline{b})^2$. Higher taxes improve welfare by raising tax revenues, while they reduce welfare by raising the final good's price. These two counteracting effects offset each other.⁹ Taxes thus affect parts location

⁹For example, if assembly takes place in N , the sum of the consumer surplus and tax revenues in the

only through changes in assembly location. The social planner cannot manipulate τ^* directly, but can do so indirectly by changing taxes.

Noting that τ^* depends on the tax difference, not individual levels, the planner chooses Δt to attain $\max\{W|_{A=N}, W|_{A=S}\}$ by (indirectly) manipulating the switching point τ^* . The optimal tax difference for any trade costs turns out to be $\Delta t = 0$, as Fig. 3 illustrates.¹⁰ That is, the planner should not intervene in the assembler's location choice. If the location of assembly were manipulated, comparative advantage would be distorted and thus the total cost would not be minimized. In addition, assembly location affects *local* environmental damage, but does not affect *global* environmental damage, since the assembler sources all parts locally. The planner is thus unable to reduce the global damage by changing assembly location. The planner fully respects the cost-minimization location choice of the assembler by setting the tax difference to zero. The socially optimal switching point then becomes $\hat{\tau}^* \equiv \tau^*|_{\Delta t=0} = \beta(\bar{b} - \underline{b})$.

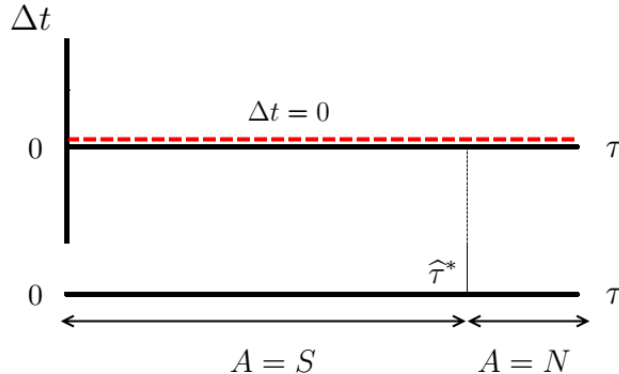


Fig. 3. Socially optimal tax harmonization (dashed line) and assembly location under high unbundling costs.

Proposition 1. *Under high unbundling costs, environmental tax harmonization, i.e., $t_N = t_S$, always maximizes social welfare for any level of trade costs.*

world is

$$\begin{aligned} (\tilde{u} - C_N) + t_N(\bar{b} - \underline{b}) &= \tilde{u} - (\bar{b} - \underline{b})(1 + t_N) + t_N(\bar{b} - \underline{b}) \\ &= \tilde{u} - (\bar{b} - \underline{b}), \end{aligned}$$

which is independent of taxes. The same argument holds if assembly takes place in S . See Appendix A1 for the exact welfare expressions.

¹⁰All proofs of the propositions are in Appendix A2. Given τ , there may be other optimal tax differences than $\Delta t = 0$ (see Fig. A2). But only $\Delta t = 0$ maximizes social welfare for any τ .

4 Low unbundling costs: separation of parts and assembly

We turn to the case where unbundling costs are low: $\theta < \underline{\theta}$. Low unbundling costs allow parts and assembly to locate in different countries, capturing the second unbundling.

4.1 Assembly location

As Fig. 2 suggests, the two unbundling thresholds are within the interval of $[\underline{b}, \bar{b}]$. The total cost of the final good in each location is respectively

$$C_N = \underbrace{\left(\theta + t_S + \frac{b + b_N}{2}\right)}_{\text{Parts from } S} (b_N - \underline{b}) + \underbrace{(1 + t_N)(\bar{b} - b_N)}_{\text{Parts from } N}, \quad (6)$$

$$C_S = \tau + \underbrace{\left(t_S + \frac{b + b_S}{2}\right)}_{\text{Parts from } S} (b_S - \underline{b}) + \underbrace{(1 + \theta + t_N)(\bar{b} - b_S)}_{\text{Parts from } N}, \quad (7)$$

where $b_N = 1 - \theta + \Delta t$ and $b_S = 1 + \theta + \Delta t$. Assembly takes place in N if

$$\begin{aligned} \Delta C \equiv C_N - C_S &= -\tau + 2\theta \left(1 - \frac{b + \bar{b}}{2} + \Delta t\right) \leq 0, \\ \rightarrow \tau &\geq \tau^{**} \equiv 2\theta(\beta + \Delta t). \end{aligned}$$

Unlike τ^* defined in (5), τ^{**} depends on θ . Lower unbundling costs make the colocation of parts and assembly less important, whereas they make the proximity to the consumer in N more important. A lower θ decreases τ^{**} , making the assembler more likely to locate in N .

4.2 Social optimum

In contrast to the case of high unbundling costs, environmental taxes affect pollution through both the assembler's sourcing and location decisions. A tax increase in one country leads to the offshoring of dirty parts production and may reduce pollution there without losing out the assembler. In the globalized world, taxes are more effective in reducing pollution than in the pre-globalized world. We thus expect that there is a need for more careful tax coordination than with just simple harmonization.

With low unbundling costs, we use (1), (2), (6), and (7) to express the social welfare as

$$W = \begin{cases} W|_{A=S} = \sum_{i=N,S} V_i|_{A=S} & \text{if } \tau < \tau^{**} \\ W|_{A=N} = \sum_{i=N,S} V_i|_{A=N} & \text{if } \tau \geq \tau^{**} \end{cases},$$

$$W|_{A=S} = u - \left[\tau + \frac{1}{2}(\underline{b} + b_S)(b_S - \underline{b}) + (1 + \theta)(\bar{b} - b_S) \right] - \frac{\gamma}{2}[(\bar{b} - b_S)^2 + (b_S - \underline{b})^2],$$

$$W|_{A=N} = u - \left[\left(\theta + \frac{\underline{b} + b_N}{2} \right) (b_N - \underline{b}) + (\bar{b} - b_N) \right] - \frac{\gamma}{2}[(\bar{b} - b_N)^2 + (b_N - \underline{b})^2].$$

Unlike the case of high unbundling costs, the tax difference Δt affects not just the switching point τ^{**} but the unbundling thresholds b_i . The planner chooses Δt to maximize W by (indirectly) manipulating b_i as well as τ^{**} . Although we do not look at each component of welfare here, one can find the details about the final good's price and the environmental damage in Appendix A1.

Formally, we can the socially optimal tax difference as follows and is illustrated in Fig. 4.¹¹

$$\Delta t = \begin{cases} \Delta t|_{A=S} \equiv -\frac{2\gamma(\beta + \theta)}{2\gamma + 1} & \text{if } \tau < \tau^a \\ \Delta \hat{t} + \varepsilon & \text{if } \tau^a \leq \tau < \hat{\tau}^{**} \\ \Delta \hat{t} \equiv \frac{\tau}{2\theta} - \beta & \text{if } \hat{\tau}^{**} \leq \tau < \tau^b \\ \Delta t|_{A=N} \equiv \frac{2\gamma(\theta - \beta)}{2\gamma + 1} & \text{if } \tau \geq \tau^b \end{cases},$$

where $\tau^a \equiv \frac{2\theta(\beta - 2\gamma\theta)}{2\gamma + 1}$, $\hat{\tau}^{**} \equiv \frac{2\beta\theta}{2\gamma + 1}$, $\tau^b \equiv \frac{2\theta(2\gamma\theta + \beta)}{2\gamma + 1}$,

and $\varepsilon > 0$ is a sufficiently small constant.¹² $\hat{\tau}^{**}$ is the socially optimal switching point.

The socially optimal tax difference would be zero if there were no environmental damage $\gamma = 0$. The planner intervenes solely for reducing the global environmental damage. Since the global damage becomes more severe as pollution is more spatially concentrated, the planner aims to diversify the location of parts. The optimal tax difference is thus set to make the distribution of parts production more equal.¹³

As trade costs τ fall, more parts are shifted from N to S because (i) S 's cost advantage

¹¹For τ^a to be positive, the sensitivity of environmental damage is assumed not to be too large: $\gamma < \bar{\gamma} \equiv \beta/(\bar{b} - \underline{b})$.

¹²In Fig. 4, we ignore ε . $\Delta t|_{A=N}$ can be negative if θ is low enough.

¹³It can be checked that the socially optimal unbundling threshold b_i is closer to the middle point of the range $(\underline{b} + \bar{b})/2$ than the unbundling threshold under no taxes.

begins to matter and (ii) the assembler moves from N to S . To avoid the concentration of pollution, N 's tax compared with S 's is set higher than before and thus the optimal tax difference decreases with τ . The simple harmonization is no longer desirable except for a special case at which the optimal tax difference coincides with zero.

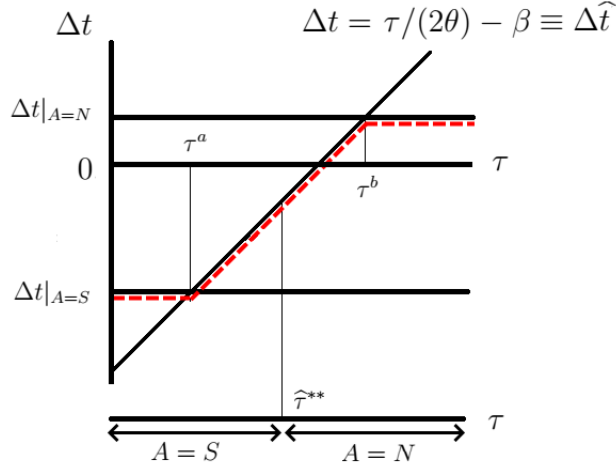


Fig. 4. Socially optimal tax difference (dashed line) and assembly location under low unbundling costs.

Proposition 2. *Under low unbundling costs, environmental tax harmonization never maximizes social welfare except for a specific level of trade costs.*

5 Extensions

5.1 Environmental damage function

We assumed a convex form of the environmental damage function, i.e., $D(e_i) = \gamma e_i^2/2$, which is fairly common in the literature (e.g., Ulph, 1996; Copeland and Taylor, 2005, Ch. 2). Our main results, Propositions 1 and 2, do not depend on the specific form of damage function, as we argue below.

Under high unbundling costs, where all parts production colocalizes with assembly, pollution occurs only in the country with assembly. The levels of pollution and environmental damage are then independent of taxes. Therefore, the social planner does not care about the

function form of $D(\cdot)$. Regardless of whether it is convex or concave, the harmonized tax rates are also socially optimal ones.

Under low unbundling costs, the tax difference does affect which parts are produced in which country, even when it does not change assembly location. In this case, the harmonized tax rates can generally never be the socially optimal ones no matter what the function form of $D(\cdot)$ may be. For illustration, consider a situation where θ is close to zero and γ is so high that the planner cares solely about the environmental damage. The sum of the environmental damage in each country is given by $(\gamma/2)[D(e_N) + D(e_S)] = (\gamma/2)[D(\bar{b} - b) + D(b - \underline{b})]$, where $b \simeq 1 + \Delta t$ is the unbundling threshold below (above) which parts are produced in S (N). The planner attempts to minimize this by altering the unbundling threshold b through changes in the tax difference $\Delta t \equiv t_N - t_S$.

If $D(\cdot)$ is convex, as assumed in the main analysis, the global damage is minimized when b is at the middle point: $(\underline{b} + \bar{b})/2$.¹⁴ The socially optimal tax difference must satisfy $b = 1 + \Delta t = (\underline{b} + \bar{b})/2$, or $\Delta t = \beta \equiv 1 - (\underline{b} + \bar{b})/2 > 0$. The harmonized tax rates would lead to too much pollution in S .

If $D(\cdot)$ is concave, the global damage is minimized when b is at either of the endpoints: \underline{b} or \bar{b} .¹⁵ The socially optimal tax difference must be either $\Delta t = 1 - \underline{b} > 0$ or $\Delta t = 1 - \bar{b} < 0$ to induce all parts production to take place in one country. Tax harmonization that allows for the diversification of parts production is then poor policy.

5.2 Nash equilibrium vs. social optimum

The focus of this paper is on whether the harmonization policy maximizes social welfare. We could also ask whether decentralized policies chosen by noncooperative governments, i.e., Nash equilibrium policies, lead to the socially optimal outcome. Here, we here intuitively argue that the Nash equilibrium tax difference is more likely to differ from the socially optimal one under low unbundling costs than under high unbundling costs. Our main finding carries over: globalization calls for more careful international coordination than a simple harmonization rule. The full characterization of Nash equilibria is relegated to Appendices A3 and A4.

¹⁴The FOC for the minimization problem is $-D'(\bar{b} - b) + D'(b - \underline{b}) = 0$, noting that the SOC is satisfied because of the convexity of $D(\cdot)$: $D''(\bar{b} - b) + D''(b - \underline{b}) > 0$. From the FOC, we have $D'(\bar{b} - b) = D'(b - \underline{b})$, or $b = (\underline{b} + \bar{b})/2$.

¹⁵This result comes from the fact that the SOC for the minimization problem is not satisfied: $D''(\bar{b} - b) + D''(b - \underline{b}) < 0$.

5.2.1 High unbundling costs

We consider the governments' incentive to deviate from the harmonized tax rates: $t_N = t_S$, which maximizes social welfare (see Proposition 1). Since the unbundling thresholds degenerate under high unbundling costs, i.e., $b_N = \underline{b}$; $b_S = \bar{b}$, the levels of pollution and environmental damage are independent of taxes. The governments can then do little to reduce local pollution and thus do not tend to prefer specific tax rates.

If trade costs are sufficiently high such that $\tau \geq \hat{\tau}^*$, assembly takes place in N (see Section 3). In this case, government S does not wish to challenge government N over assembly by reducing t_S because attracting assembly by the reduced t_S would not bring with it much tax revenue. As there are neither assembly nor tax revenues in S , government S does not have any incentive to raise t_S , either. Government N is also unwilling to change t_N because t_N does not enter its objective function.¹⁶ The harmonized tax rates are then indeed Nash-equilibrium ones.

If $\tau < \hat{\tau}^*$, where assembly takes place in S , government S has an incentive to set t_S higher than t_N because by doing so S can increase tax revenues while not inducing assembly relocation. The Nash equilibrium tax difference can never be zero.

In sum, if $\tau \geq \hat{\tau}^*$, the harmonized tax rates are the Nash equilibrium ones as well as the socially optimal ones.

5.2.2 Low unbundling costs

Under low unbundling costs, the unbundling thresholds do not degenerate, i.e., $b_N = 1 - \theta + \Delta t$; $b_S = 1 + \theta + \Delta t$. The country without assembly also suffer environmental damage from dirty input production, implying that both governments, regardless of hosting assembly, can affect the level of pollution through taxes. They want to choose a specific tax rate that maximizes their national welfare, which is in stark contrast to the case of high unbundling costs.

A tax increase by government $i \in \{N, S\}$ causes the relocation of parts and thus pollution to $j \neq i$. Government j then wishes to increase its tax rate as well to prevent environmental damage. That is, the two countries' tax rates are strategic complements: both governments wish to change their tax rates in the same direction.¹⁷ Therefore, irrespective of the level

¹⁶An increase in t_N has a positive effect on tax revenues and a negative effect on the consumer surplus, which cancel each other. Therefore, t_N does not matter for government N 's welfare.

¹⁷The strategic complementarity leads to a race to the top, in which each country's tax rate at the Nash equilibrium is higher than their rate at the social optimal. The argument here assumes that the governments emphasize environmental damage, i.e., a high γ . If instead γ is low and thus the governments emphasize tax

of trade costs, the Nash equilibrium tax difference is in general different from the socially optimal one in such a way that the former is smaller than the latter.

6 Concluding discussion

Desirable environmental policies may drastically change before and after the current globalization characterized by the spatial unbundling of production processes. In the pre-globalized world, environmental tax harmonization avoids distorting efficient location choices and maximizes global welfare, despite heterogeneity between countries. In the globalized world, however, it leads to the excessive spatial concentration of pollution and (almost) never maximizes global welfare. The second unbundling may then call for careful international coordination beyond simple harmonization.

We can relate these findings to the experience of countries in the European Union (EU). From the 1970s onward, the EU sought to harmonize environmental policies among its member states. Holzinger et al. (2008) confirm that some 40 environmental measures converged across 24 advanced economies, including the EU 15, between 1970 and 2000. In addition, Arbolino et al. (2018) analyze the diffusion process of environmental policies and find that achievements of the environmental policy objectives of one country converged to the corresponding performance of the other country within the EU 15 from 2000 to 2014. These studies suggest that harmonization was dominant between member states with similar characteristics (EU 15) and/or in periods covering years prior to the second unbundling (1970-1990).¹⁸

However, it would be difficult to achieve a common goal through harmonized policies if there are significant disparities in social and economic status among countries. In this regard, Andonova and VanDeveer (2012) examine environmental policies in the CEE in the process of EU accession and show that considerable divergence in environmental practices and institutions persists. Furthermore, as international fragmentation of production or offshoring expands, less developed nations would be reluctant to raise environmental standards to the level of stringency level closer to those of the advanced economies because in a world of liberalized trade and investment they fear losing the interest of foreign investors. Although environmental policy is not a sole determinant of comparative advantage, it does matter at the margin, particularly for countries whose competitiveness depends on producing at low cost production, as in our theoretical framework (World Bank, 2020, Ch.5).

revenues, the complementarity results in a race to the bottom.

¹⁸According to Baldwin (2016), the second unbundling accelerated from around 1990 (p.5).

Lastly, we highlight two important issues that have not been addressed in the current paper. First, it would be worthwhile investigating how we should coordinate environmental and trade policies such as import tariffs (Lai and Hu, 2008; Yomogida and Tarui, 2013; Keen and Kotsogiannis, 2014; Sanctuary, 2018; Ogawa and Yanase, 2019). In the age of the second unbundling, the location of parts is sensitive to the international cost differences generated by both policy measures. Key questions would be as follows. Which measure is effective for the global environment? Are tariffs necessary as border tax adjustments given different emission taxes at home and abroad? Second, it would also be interesting to consider pollution emitted during the transportation of goods, considering its importance among all sources of pollution (Abe et al., 2014; Ishikawa and Tarui, 2018).¹⁹ Transportation pollution is particularly relevant in *snake*-style production, in which parts move sequentially from upstream to downstream with value added at each stage. The snake-style production tends to generate more pollution than the spider-style production we consider in this paper, because parts produced in one country can be shipped multiple times before they reach the final stage. Incorporating these aspects into our model would lead to greater externalities and thus larger deviations between harmonized and socially optimal taxes. We leave these issues for future research.

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¹⁹For example, greenhouse gas (GHG) emissions from transportation account for 28.9 percent of total US GHG emissions in 2017, making it the largest contributor to US GHG emissions. Source: U.S. Environmental Protection Agency (<https://www.epa.gov/ghgemissions/sources-greenhouse-gas-emissions>, accessed on March 23, 2020).

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Appendix to “Is Environmental Tax Harmonization Desirable in Global Value Chains?”

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A1 Final good’s price and environmental damage

High-unbundling-cost case. From the discussion in Section 3.1, we obtain the final good’s price as

$$p = \min \{C_N, C_S\} = \begin{cases} C_N = (\bar{b} - \underline{b})(1 + t_N) & \text{if } \tau \geq \tau^* \\ C_S = \tau + (\bar{b} - \underline{b}) [(\underline{b} + \bar{b})/2 + t_S] & \text{if } \tau < \tau^* \end{cases},$$

which is shown in Fig. A1. We note that assembly takes place in $A = N$ ($A = S$) if $\tau \geq \tau^*$ ($\tau < \tau^*$).

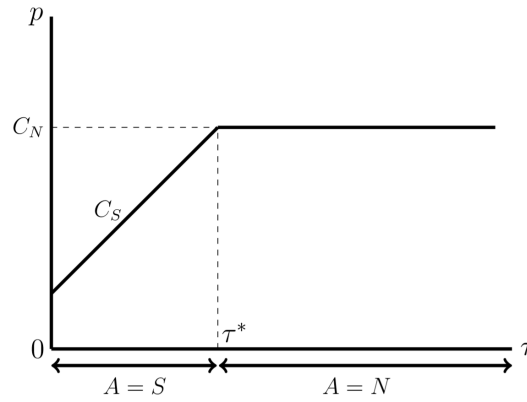


Fig. A1. Final good’s price under high unbundling costs.

The environmental damage in each country is

$$D(e_N) = \begin{cases} (\gamma/2)(\bar{b} - \underline{b})^2 & \text{if } \tau \geq \tau^* \\ 0 & \text{if } \tau < \tau^* \end{cases},$$

$$D(e_S) = \begin{cases} 0 & \text{if } \tau \geq \tau^* \\ (\gamma/2)(\bar{b} - \underline{b})^2 & \text{if } \tau < \tau^* \end{cases}.$$

The sum of the two equals

$$D(e_N) + D(e_S) = (\gamma/2)(\bar{b} - \underline{b})^2 \quad \text{for any } \tau.$$

These are illustrated in Fig. A2.

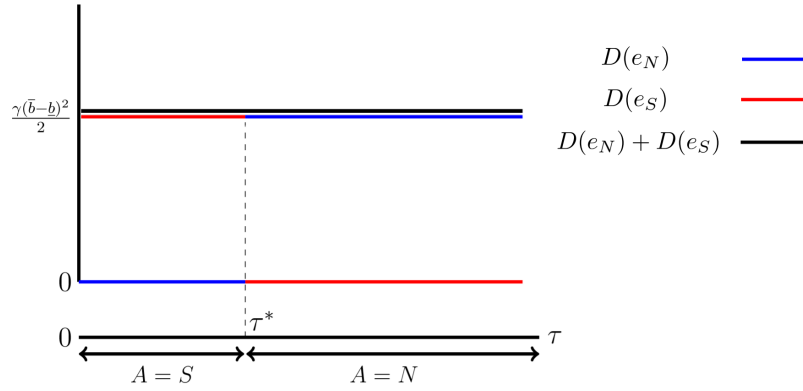
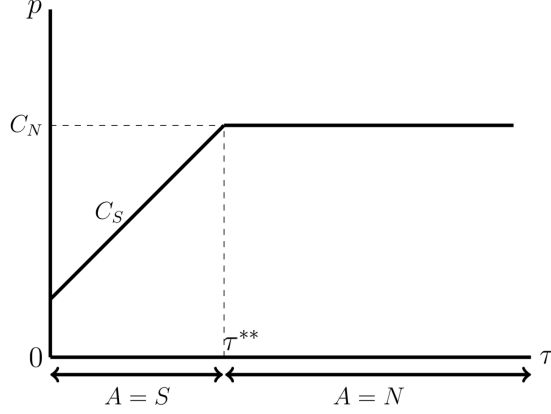


Fig. A2. Environmental damage under high unbundling costs.

Low-unbundling-cost case. From the discussion in Section 4.1, we obtain the final good's price as

$$p = \min \{C_N, C_S\} = \begin{cases} C_N = \underbrace{\left(\theta + t_S + \frac{b + b_N}{2}\right) (b_N - \underline{b})}_{\text{Parts from } S} + \underbrace{(1 + t_N)(\bar{b} - b_N)}_{\text{Parts from } N} & \text{if } \tau \geq \tau^{**} \\ C_S = \tau + \underbrace{\left(t_S + \frac{b + b_S}{2}\right) (b_S - \underline{b})}_{\text{Parts from } S} + \underbrace{(1 + \theta + t_N)(\bar{b} - b_S)}_{\text{Parts from } N} & \text{if } \tau < \tau^{**} \end{cases},$$

which is shown in Fig. A3. We note that assembly takes place in $A = N$ ($A = S$) if $\tau \geq \tau^{**}$ ($\tau < \tau^{**}$).



Fig, A3. Final good's price under low unbundling costs.

The environmental damage in each country is

$$D(e_N) = \begin{cases} D(e_N)|_{A=N} = (\gamma/2)(\bar{b} - b_N)^2 & \text{if } \tau \geq \tau^{**} \\ D(e_N)|_{A=S} = (\gamma/2)(\bar{b} - b_S)^2 & \text{if } \tau < \tau^{**} \end{cases},$$

$$D(e_S) = \begin{cases} D(e_S)|_{A=N} = (\gamma/2)(b_N - \underline{b})^2 & \text{if } \tau \geq \tau^{**} \\ D(e_S)|_{A=S} = (\gamma/2)(b_S - \underline{b})^2 & \text{if } \tau < \tau^{**} \end{cases}.$$

The global damage is then

$$D(e_N) + D(e_S) = \begin{cases} [D(e_N) + D(e_S)]|_{A=N} = (\gamma/2) [(\bar{b} - b_N)^2 + (b_N - \underline{b})^2] & \text{if } \tau \geq \tau^{**} \\ [D(e_N) + D(e_S)]|_{A=S} = (\gamma/2) [(\bar{b} - b_S)^2 + (b_S - \underline{b})^2] & \text{if } \tau < \tau^{**} \end{cases}.$$

We note the following:

$$\begin{aligned} D(e_N)|_{A=N} &> D(e_N)|_{A=S}, \\ D(e_S)|_{A=N} &< D(e_S)|_{A=S}, \\ D(e_N)|_{A=S} - D(e_S)|_{A=S} &= -\gamma(\bar{b} - \underline{b})(\beta + \Delta t + \theta) < 0, \\ D(e_S)|_{A=N} - D(e_N)|_{A=S} &= \gamma(b_N - \underline{b} + \bar{b} - b_S)(\beta + \Delta t) > 0, \\ D(e_S)|_{A=S} - D(e_N)|_{A=N} &= \gamma(b_S - \underline{b} + \bar{b} - b_N)(\beta + \Delta t) > 0, \\ [D(e_N) + D(e_S)]|_{A=S} - [D(e_N) + D(e_S)]|_{A=N} &= \gamma(b_S - b_N)(b_N + b_S - \bar{b} - \underline{b}) \\ &= 4\gamma\theta(\beta + \Delta t) > 0. \end{aligned}$$

Although the inequalities above unambiguously hold, we still need to check the relationship

between the two countries' pollution levels when the assembly is in N :

$$D(e_N)|_{A=N} - D(e_S)|_{A=N} = -\gamma(\bar{b} - \underline{b})(\beta + \Delta t - \theta).$$

Country N 's pollution level tends to be lower when country S 's average cost advantage is larger (higher β); the tax difference is larger (high Δt); and the unbundling costs are lower (lower θ). Depending on the sign of $\beta + \Delta t - \theta$, the environmental damage is illustrated in Figs A4 and A5.

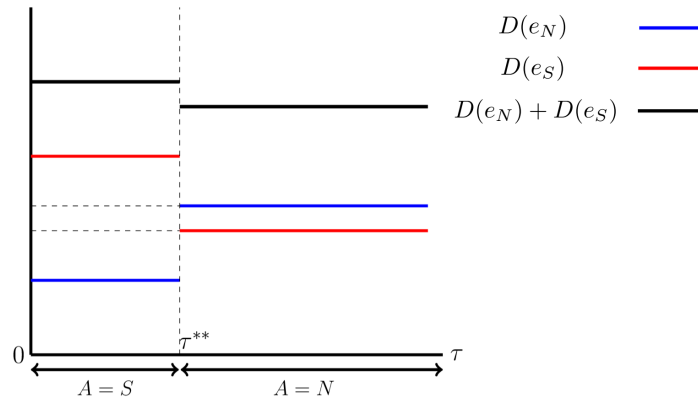


Fig. A4. Environmental damage under low unbundling costs if $\beta + \Delta t - \theta < 0$.

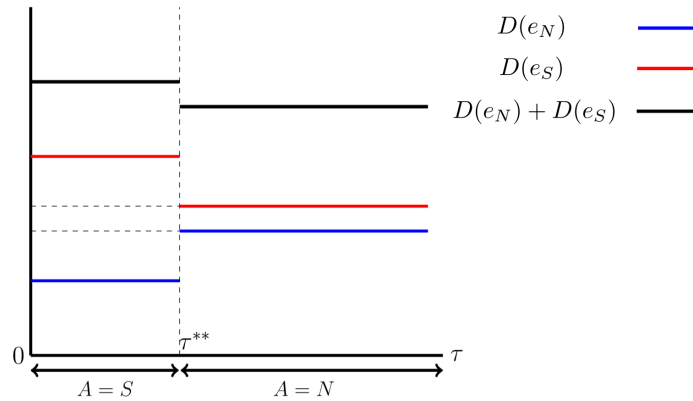


Fig. A5. Environmental damage under low unbundling costs if $\beta + \Delta t - \theta > 0$.

A2 Proofs of propositions

A2.1 Proof of Proposition 1

From (1), (2), (3), and (4), the indirect utility of the representative agent in each country is given by

$$V_N = \begin{cases} V_N|_{A=S} = \tilde{u} - C_S + 1 + \bar{X} & \text{if } \tau < \tau^* \\ V_N|_{A=N} = \tilde{u} - C_N + t_N(\bar{b} - \underline{b}) - (\gamma/2)(\bar{b} - \underline{b})^2 + 1 + \bar{X} & \text{if } \tau \geq \tau^* \end{cases},$$

$$V_S = \begin{cases} V_S|_{A=S} = t_S(\bar{b} - \underline{b}) - (\gamma/2)(\bar{b} - \underline{b})^2 + 1 + \bar{X} & \text{if } \tau < \tau^* \\ V_S|_{A=N} = 1 + \bar{X} & \text{if } \tau \geq \tau^* \end{cases},$$

where $C_S = \tau + (\bar{b} - \underline{b})/[(\bar{b} + \underline{b})/2 + t_S]$; $C_N = (\bar{b} - \underline{b})(1 + t_N)$; $\tau^* \equiv (\bar{b} - \underline{b})(\beta + \Delta t)$; $\beta \equiv 1 - (\underline{b} + \bar{b})/2$. The social welfare is defined by the sum of each country's indirect utility:

$$W = \begin{cases} W|_{A=S} = V_N|_{A=S} + V_S|_{A=S} = u - \tau - (1/2)(\bar{b} - \underline{b})(\underline{b} + \bar{b}) - (\gamma/2)(\bar{b} - \underline{b})^2 & \text{if } \tau < \tau^* \\ W|_{A=N} = V_N|_{A=N} + V_S|_{A=N} = u - (\bar{b} - \underline{b}) - (\gamma/2)(\bar{b} - \underline{b})^2 & \text{if } \tau \geq \tau^* \end{cases},$$

where $u \equiv \tilde{u} + 2(1 + \bar{X})$,

as given in the main text.

Taxes do not enter the expressions of social welfare and only affect the location decision of the assembler. The social planner thus chooses the assembly location through taxes that gives the higher social welfare. A simple comparison of welfare between the two locations reveals

$$\max\{W|_{A=N}, W|_{A=S}\} = \begin{cases} W|_{A=S} = u - \tau - (\bar{b} - \underline{b})(\underline{b} + \bar{b})/2 - (\gamma/2)(\bar{b} - \underline{b})^2 & \text{if } \tau < \hat{\tau}^* \\ W|_{A=N} = u - (\bar{b} - \underline{b}) - (\gamma/2)(\bar{b} - \underline{b})^2 & \text{if } \tau \geq \hat{\tau}^* \end{cases},$$

where $W|_{A=N} = W|_{A=S}$ holds at $\hat{\tau}^* \equiv \beta(\bar{b} - \underline{b})$.

To see the results intuitively, it is helpful to illustrate the assembly location pattern in the (τ, Δ) plane, as Fig. A6 shows. The upward-sloping line is the cost-indifference one: $\tau = \tau^*$, or equivalently, $\Delta t = \tau/(\bar{b} - \underline{b}) - \beta$, which represents N 's maximum tax rate that keeps assembly there. The social planner should set taxes so that the assembly locates in N

if $\tau \geq \hat{\tau}^*$ and it locates in S otherwise. The optimal tax difference is thus

$$\Delta t \begin{cases} > \tau/(\bar{b} - \underline{b}) - \beta & \text{if } \tau < \hat{\tau}^* \\ \leq \tau/(\bar{b} - \underline{b}) - \beta & \text{if } \tau \geq \hat{\tau}^* \end{cases},$$

which is represented by the shaded area in Fig. A7. As is clear from Fig. A7, only the tax harmonization $\Delta t = 0$ (dashed line) maximizes the social welfare for any level of trade costs.

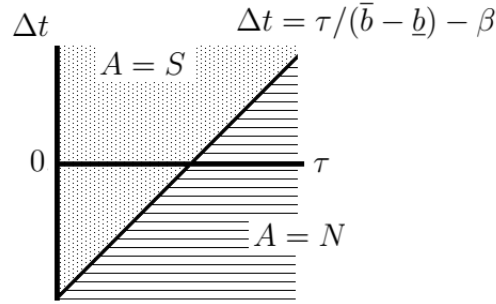


Fig. A6. Location of assembly under high unbundling costs.

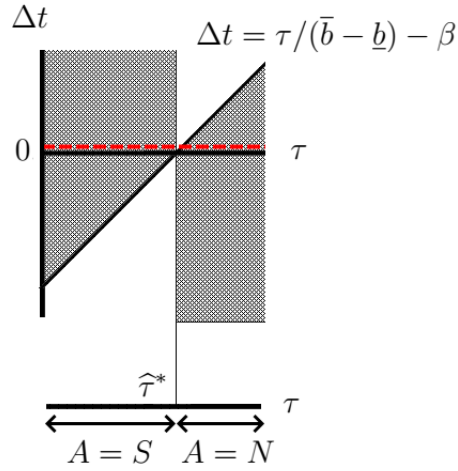


Fig. A7. Socially optimal tax difference (shaded area) and assembly location under high unbundling costs.

A2.2 Proof of Proposition 2

We first derive the unconstrained socially optimal taxes given the location of assembly. With low unbundling costs, the indirect utility of the representative agent in each country is given

by

$$V_N = \begin{cases} V_N|_{A=S} = \tilde{u} - C_S + t_N(\bar{b} - b_S) - (\gamma/2)(\bar{b} - b_S)^2 + 1 + \bar{X} & \text{if } \tau < \tau^{**} \\ V_N|_{A=N} = \tilde{u} - C_N + t_N(\bar{b} - b_N) - (\gamma/2)(\bar{b} - b_N)^2 + 1 + \bar{X} & \text{if } \tau \geq \tau^{**} \end{cases},$$

$$V_S = \begin{cases} V_S|_{A=S} = t_S(b_S - \underline{b}) - (\gamma/2)(b_S - \underline{b})^2 + 1 + \bar{X} & \text{if } \tau < \tau^{**} \\ V_S|_{A=N} = t_S(b_N - \underline{b}) - (\gamma/2)(b_N - \underline{b})^2 + 1 + \bar{X} & \text{if } \tau \geq \tau^{**} \end{cases},$$

where C_i is defined in (6) and (7); and $\tau^{**} \equiv 2\theta(\beta + \Delta t)$; $b_N = 1 - \theta + \Delta t$; $b_S = 1 + \theta + \Delta t$.

The social welfare is defined by the sum of the two country's indirect utility:

$$W = \begin{cases} W|_{A=S} = \sum_{i=N,S} V_i|_{A=S} & \text{if } \tau < \tau^{**} \\ W|_{A=N} = \sum_{i=N,S} V_i|_{A=N} & \text{if } \tau \geq \tau^{**} \end{cases},$$

$$W|_{A=S} = u - \left[\tau + \frac{1}{2}(\underline{b} + b_S)(b_S - \underline{b}) + (1 + \theta)(\bar{b} - b_S) \right] - (\gamma/2)[(\bar{b} - b_S)^2 + (b_S - \underline{b})^2],$$

$$W|_{A=N} = u - \left[\left(\theta + \frac{\underline{b} + b_N}{2} \right) (b_N - \underline{b}) + (\bar{b} - b_N) \right] - (\gamma/2)[(\bar{b} - b_N)^2 + (b_N - \underline{b})^2],$$

as given in the text.

For the social welfare level at each assembly location, the first-order conditions give

$$\frac{dW|_{A=S}}{dt_N} = -\frac{dW|_{A=S}}{dt_S} = 0,$$

$$\rightarrow (t_N - t_S)|_{A=S} = -\frac{2\gamma}{2\gamma + 1}(\theta + \beta) \equiv \Delta t|_{A=S},$$

$$\frac{dW|_{A=N}}{dt_N} = -\frac{dW|_{A=N}}{dt_S} = 0,$$

$$\rightarrow (t_N - t_S)|_{A=N} = \frac{2\gamma}{2\gamma + 1}(\theta - \beta) \equiv \Delta t|_{A=N}.$$

Since $dW|_{A=i}/dt_N$ and $(-dW|_{A=i}/dt_S)$ are collinear, what matters for the social welfare maximization is the tax difference and not the absolute levels of taxes.

We then allow for endogenous assembly location and see how it affects the optimal taxes. As in Appendix A2.1, it is helpful to consider in the $(\tau, \Delta t)$ plane. The upward-sloping line in Fig. A8 is the cost-indifference line: $\tau = \tau^{**}$, or equivalently, $\Delta t = \tau/(2\theta) - \beta \equiv \hat{\Delta t}$. Putting the unconstrained maximizers derived before into the plane, we can obtain Fig. A9 and identify that there are three cases to be considered. Letting τ^a (or τ^b) be the intersection of the cost-indifference line and $\Delta t|_{A=S}$ (or $\Delta t|_{A=N}$), the three cases are characterized as

follows.

Case (i) $\tau < \tau^a$. The social optimum will be either the constrained maximum with assembly in N , $W|_{A=N, \Delta t = \Delta \hat{t}}$, or the unconstrained maximum with assembly in S , $W|_{A=S, \Delta t = \Delta t|_{A=S}}$.

Case (ii) $\tau^a \leq \tau < \tau^b$. The social optimum will be either the constrained maximum with assembly in N , $W|_{A=N, \Delta t = \Delta \hat{t}}$, or the constrained maximum with assembly in S , $W|_{A=S, \Delta t = \Delta \hat{t} + \varepsilon}$.

Case (iii) $\tau \geq \tau^b$. The social optimum will be either the unconstrained maximum with assembly in N , $W|_{A=N, \Delta t = \Delta t|_{A=N}}$, or the constrained maximum with assembly in S , $W|_{A=S, \Delta t = \Delta \hat{t} + \varepsilon}$.

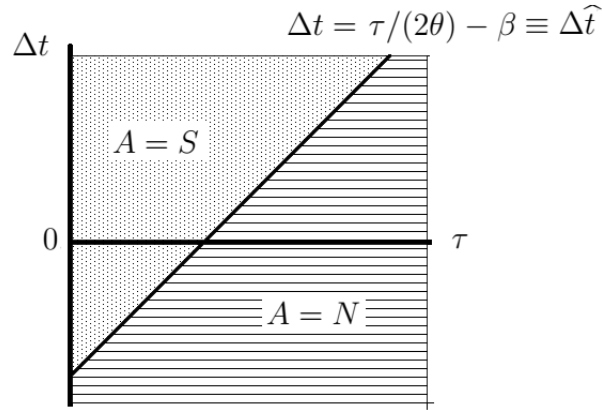


Fig. A8. Location of assembly under low unbundling costs.

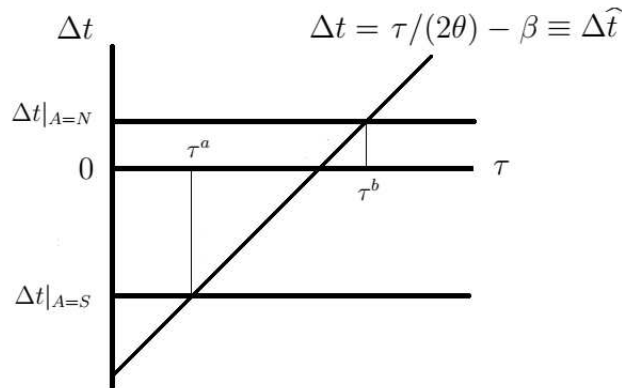


Fig. A9. Unconstrained optimal tax differences under low unbundling costs.

For the latter reference, it is informative here to compare the constrained maxima between the two locations.

$$\begin{aligned} W|_{A=N, \Delta t=\Delta\hat{t}} - W|_{A=S, \Delta t=\Delta\hat{t}+\varepsilon} &= \tau + \beta(b_N - b_S) + 2[\theta + \gamma(b_N - b_S)][1 - (b_N + b_S)/2 - \beta] \\ &= \tau(2\gamma + 1) - 2\beta\theta, \end{aligned}$$

noting that ε is sufficiently small. On $\Delta t = \Delta\hat{t}$, it holds that $b_N - b_S = -2\theta$ and $b_N + b_S = 2(1 + \Delta\hat{t})$. We thus have $W|_{A=N, \Delta t=\Delta\hat{t}} \geq W|_{A=S, \Delta t=\Delta\hat{t}+\varepsilon}$ if $\tau \geq \hat{\tau}^{**} \equiv 2\beta\theta/(2\gamma + 1)$ and $W|_{A=N, \Delta t=\Delta\hat{t}} < W|_{A=S, \Delta t=\Delta\hat{t}+\varepsilon}$ otherwise. It can be also checked that $\tau^a < \hat{\tau}^{**} < \tau^b$.

With these in hand, we will derive the socially optimal taxes in each case.

Case (i) $\tau < \tau^a$. In this case, we have

$$W|_{A=S, \Delta t=\Delta t|_{A=S}} > W|_{A=S, \Delta t=\Delta\hat{t}} > W|_{A=N, \Delta t=\Delta\hat{t}}.$$

The socially optimal outcome is the unconstrained maximum with assembly in S .

Case (ii) $\tau^a \leq \tau < \tau^b$. As $\hat{\tau}^{**}$ is in between τ^a and τ^b , this case is further divided into two subcases.

Case (ii-a) $\tau^a \leq \tau < \hat{\tau}^{**}$. We have

$$W|_{A=S, \Delta t=\Delta\hat{t}+\varepsilon} > W|_{A=N, \Delta t=\Delta\hat{t}}.$$

The socially optimal outcome is that assembly takes place in S and the tax difference is set at $\Delta t = \Delta\hat{t} + \varepsilon$.

Case (ii-b) $\hat{\tau}^{**} \leq \tau < \tau^b$. We have

$$W|_{A=N, \Delta t=\Delta\tilde{t}} \geq W|_{A=S, \Delta t=\Delta\hat{t}+\varepsilon}.$$

The socially optimal outcome is that assembly takes place in N and the tax difference is set at $\Delta t = \Delta\tilde{t}$.

Case (iii) $\tau \geq \tau^b$. In this case, we have

$$W|_{A=N, \Delta t=\Delta t|_{A=N}} > W|_{A=N, \Delta t=\Delta\hat{t}} > W|_{A=S, \Delta t=\Delta\hat{t}+\varepsilon}.$$

The socially optimal outcome is the unconstrained maximum with assembly in N .

In sum, the socially optimal tax difference is

$$\Delta t = \begin{cases} \Delta t|_{A=S} = -\frac{2\gamma(\beta + \theta)}{2\gamma + 1} & \text{if } \tau < \tau^a \\ \Delta \hat{t} + \varepsilon & \text{if } \tau^a \leq \tau < \hat{\tau}^{**} \\ \Delta \hat{t} = \frac{\tau}{2\theta} - \beta & \text{if } \hat{\tau}^{**} \leq \tau < \tau^b \\ \Delta t|_{A=N} = \frac{2\gamma(\theta - \beta)}{1 + 2\gamma} & \text{if } \tau \geq \tau^b \end{cases},$$

where $\tau^a \equiv \frac{2\theta(\beta - 2\gamma\theta)}{2\gamma + 1}$, $\hat{\tau}^{**} \equiv \frac{2\beta\theta}{2\gamma + 1}$, $\tau^b \equiv \frac{2\theta(2\gamma\theta + \beta)}{2\gamma + 1}$,

as given in the main text.

A3 Nash equilibrium outcome under high unbundling costs

As noted in Appendix A2.1, under high unbundling costs, the indirect utility of the representative agent in each country is given by

$$V_N = \begin{cases} V_N|_{A=S} = \tilde{u} - C_S + 1 + \bar{X} & \text{if } \tau < \tau^* \\ V_N|_{A=N} = \tilde{u} - C_N + t_N(\bar{b} - \underline{b}) - (\gamma/2)(\bar{b} - \underline{b})^2 + 1 + \bar{X} & \text{if } \tau \geq \tau^* \end{cases},$$

$$V_S = \begin{cases} V_S|_{A=S} = t_S(\bar{b} - \underline{b}) - (\gamma/2)(\bar{b} - \underline{b})^2 + 1 + \bar{X} & \text{if } \tau < \tau^* \\ V_S|_{A=N} = 1 + \bar{X} & \text{if } \tau \geq \tau^* \end{cases},$$

where $C_N = (\bar{b} - \underline{b})(1 + t_N)$; $C_S = \tau + (\bar{b} - \underline{b})[(\underline{b} + \bar{b})/2 + t_S]$; $\tau^* \equiv (\bar{b} - \underline{b})(\beta + \Delta t)$. The unbundling thresholds degenerate: $b_N = \underline{b}$; $b_S = \bar{b}$.

(i) First, we investigate S 's best responses given N 's pollution tax. Evaluating the switching point τ^* at taxes making the locations indifferent to S (i.e., $V_S|_{A=S} = V_S|_{A=N}$), we get the threshold tax rate: $\hat{t}_N = \tau/(\bar{b} - \underline{b}) - \beta + (\gamma/2)(\bar{b} - \underline{b})$.

If $t_N \in [0, \hat{t}_N]$, S imposes a pollution tax satisfying $t_S \geq t_N - \tau/(\bar{b} - \underline{b}) + \beta$ so as to induce $A = N$ and $V_S|_{A=N} = 0$. Or else, S 's welfare is negative ($A = S$, $V_S|_{A=S} < 0$).

If $t_N \in (\widehat{t}_N, \infty)$, S imposes a pollution tax satisfying $t_S < t_N - \tau/(\bar{b} - \underline{b}) + \beta - \varepsilon$ so as to induce $A = S$ and positive welfare where ε is a sufficiently small constant.

(ii) Second, we investigate N 's best responses given S 's pollution tax. Similarly, evaluating the switching point τ^* at taxes making the locations indifferent to N (i.e., $V_N|_{A=S} = V_N|_{A=N}$), we get the threshold tax rate: $\widehat{t}_S = -\tau/(\bar{b} - \underline{b}) + \beta + (\gamma/2)(\bar{b} - \underline{b})$.

If $t_S \in [0, \widehat{t}_S)$, then $V_N|_{A=S} > V_N|_{A=N}$ holds. N imposes $t_N > t_S + \tau/(\bar{b} - \underline{b}) - \beta$ and chooses $A = S$.

If $t_S \in [\widehat{t}_S, \infty)$, then $V_N|_{A=S} < V_N|_{A=N}$ holds. N imposes $t_N < t_S + \tau/(\bar{b} - \underline{b}) - \beta$ and chooses $A = N$.

(iii) Third, we combine (i) and (ii) together to get the Nash equilibria as follows.

If $\tau/(\bar{b} - \underline{b}) - \beta < 0$, or $\tau < \widehat{\tau}^*$, both locations can be the Nash equilibria, i.e., $A^{NE} \in \{N, S\}$. The Nash equilibrium tax differences at $A^{NE} = N$ are $\Delta t^{NE} < 2[\tau/(\bar{b} - \underline{b}) - \beta]$, and those at $A^{NE} = S$ are $\Delta t^{NE} = \tau/(\bar{b} - \underline{b}) - \beta$.

If $\tau/(\bar{b} - \underline{b}) - \beta = 0$, or $\tau = \widehat{\tau}^*$, the tax differences and the assembly location at the Nash equilibria are respectively $\Delta t^{NE} \leq 0$ and $A^{NE} = N$.

If $\tau/(\bar{b} - \underline{b}) - \beta > 0$, or $\tau > \widehat{\tau}^*$, the tax differences and the assembly location at the Nash equilibria are respectively $\Delta t^{NE} < \tau/(\bar{b} - \underline{b}) - \beta$ and $A^{NE} = N$.

From Appendix A2, we can see that the Nash equilibria coincides with the socially optimal outcomes for $\tau \geq \widehat{\tau}^*$, which are shown in Fig. A10.

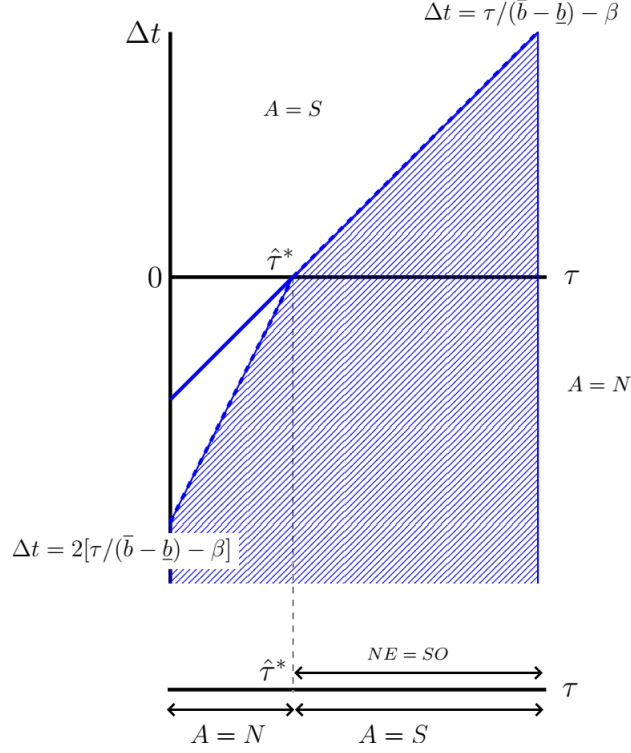


Fig. A10. Nash equilibrium tax difference (shaded area and $\Delta t = \tau/(\bar{b} - \underline{b}) - \beta$) and assembly location under high unbundling costs

A4 Nash equilibrium outcome under low unbundling costs

As noted in Appendix A2.2, the indirect utility of the representative agent in each country is given by

$$V_N = \begin{cases} V_N|_{A=S} = \tilde{u} - C_S + t_N(\bar{b} - b_S) - (\gamma/2)(\bar{b} - b_S)^2 + 1 + \bar{X} & \text{if } \tau < \tau^{**} \\ V_N|_{A=N} = \tilde{u} - C_N + t_N(\bar{b} - b_N) - (\gamma/2)(\bar{b} - b_N)^2 + 1 + \bar{X} & \text{if } \tau \geq \tau^{**} \end{cases},$$

$$V_S = \begin{cases} V_S|_{A=S} = t_S(b_S - \underline{b}) - (\gamma/2)(b_S - \underline{b})^2 + 1 + \bar{X} & \text{if } \tau < \tau^{**} \\ V_S|_{A=N} = t_S(b_N - \underline{b}) - (\gamma/2)(b_N - \underline{b})^2 + 1 + \bar{X} & \text{if } \tau \geq \tau^{**} \end{cases},$$

where C_i is defined in (6) and (7); and $\tau^{**} \equiv 2\theta(\beta + \Delta t)$; $b_N = 1 - \theta + \Delta t$; $b_S = 1 + \theta + \Delta t$.

(i) First, we derive the best responses of each country with exogenous assembly location.

N 's best response given t_S and $A = N$ is

$$\tilde{t}_N^{BR}(t_S)|_{A=N} \equiv t_N = \frac{\gamma}{1+\gamma}t_S + \frac{\gamma}{1+\gamma}(\bar{b} - 1 + \theta).$$

N 's best response given t_S and $A = S$ is

$$\tilde{t}_N^{BR}(t_S)|_{A=S} \equiv t_N = \frac{\gamma}{1+\gamma}t_S + \frac{\gamma}{1+\gamma}(\bar{b} - 1 - \theta).$$

S 's best response given t_N and $A = N$ is

$$\tilde{t}_S^{BR}(t_N)|_{A=N} \equiv t_S = \frac{1+\gamma}{2+\gamma}t_N + \frac{1+\gamma}{2+\gamma}(1 - \theta - \underline{b}).$$

S 's best response given t_N and $A = S$ is

$$\tilde{t}_S^{BR}(t_N)|_{A=S} \equiv t_S = \frac{1+\gamma}{2+\gamma}t_N + \frac{1+\gamma}{2+\gamma}(1 + \theta - \underline{b}).$$

(ii) Second, we allow for endogenous location and derive S 's best response with endogenous assembly given t_N .

$$t_S^{BR}(t_N) = \begin{cases} \tilde{t}_S^{BR}(t_N)|_{A=N} & \text{if } t_N < \hat{t}_N^* \\ t_S|_{A=S} = t_N - \tau/(2\theta) + \beta & \text{if } \hat{t}_N^* \leq t_N \leq t_N^1, \\ \tilde{t}_S^{BR}(t_N)|_{A=S} & \text{if } t_N > t_N^1 \end{cases}$$

where $\hat{t}_N^* = \tau(2+\gamma)/(2\theta) + (3+\gamma)\theta + (\gamma/2)(\bar{b}-\underline{b}) + (\bar{b}-1) - \sqrt{2(2+\gamma)\tau + 2\theta(2+\gamma)(\bar{b}-\underline{b} + 2\theta)}$ is the switching point of assembly location at which S is indifferent to where assembly takes place; $t_N^1 = (2+\gamma)[\tau/(2\theta) - \gamma] + (1+\gamma)(1 + \theta - \underline{b})$.²⁰ It is illustrated in Fig. A11.

²⁰We need to assume that $\theta < (\bar{b} - \underline{b})/2(1 + \gamma)$ to avoid the case where the switching point falls between the two exogenous best response lines. The assumption is reasonable since we restrict our attention to the case of low unbundling costs.

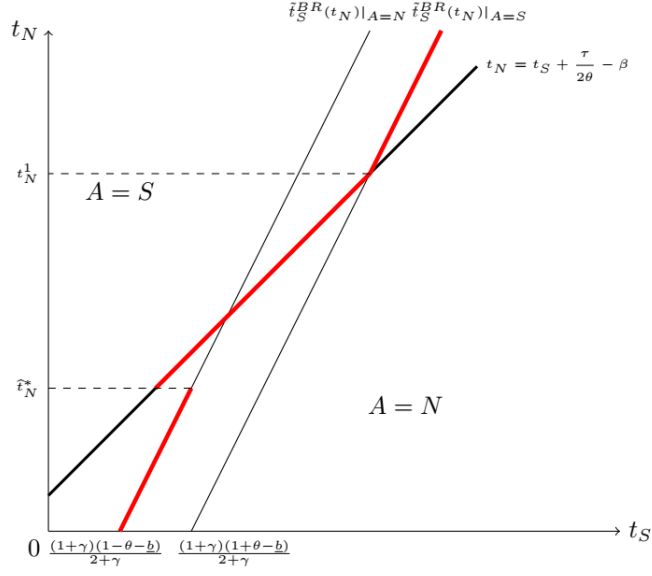


Fig. A11. S 's best response with endogenous assembly location (red curve).

(iii) Third, we allow for endogenous location and derive N 's best response given t_S .

$$t_N^{BR}(t_S) = \begin{cases} \tilde{t}_N^{BR}(t_S)|_{A=S} & \text{if } t_S < t_S^1 \\ t_N|_{A=S} \equiv t_S + \tau/(2\theta) - \beta & \text{if } t_S^1 \leq t_S \leq \hat{t}_S^* \\ t_N|_{A=N} \equiv t_S + \tau/(2\theta) - \beta & \text{if } \hat{t}_S^* < t_S \leq t_S^2 \\ \tilde{t}_N^{BR}(t_N)|_{A=N} & \text{if } t_S > t_S^2 \end{cases},$$

where $\hat{t}_S^* \equiv \gamma(\bar{b} - 1) - (1 + \gamma)[\tau/(2\theta) - \beta]$ is the switching point of assembly location at which N is indifferent to where assembly takes place; $t_S^1 \equiv \gamma(\bar{b} - 1 - \theta) - (1 + \gamma)[\tau/(2\theta) - \beta]$; $t_S^2 \equiv \gamma(\bar{b} - 1 + \theta) - (1 + \gamma)[\tau/(2\theta) - \beta]$. Note that $\hat{t}_S^* = (t_S^1 + t_S^2)/2$. N 's best response is illustrated in Fig. A12.

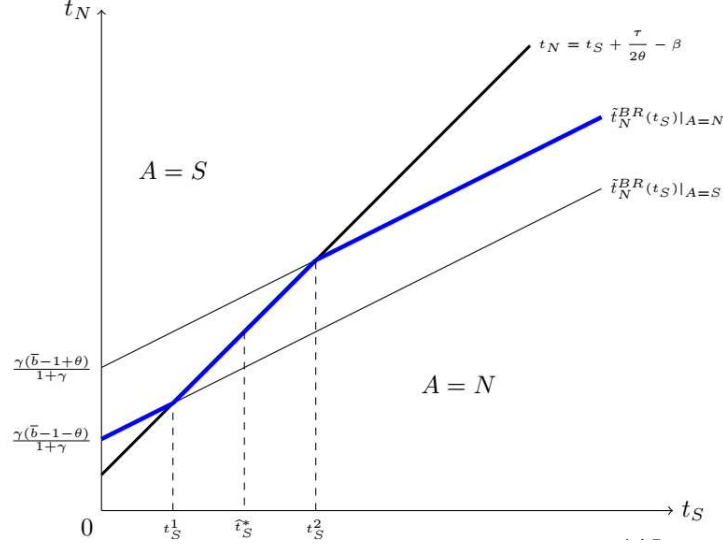


Fig. A12. S 's best response with endogenous assembly location (blue curve).

(iv) Fourth, we derive Nash equilibria with endogenous assembly location. We only need to combine the best responses of the two countries together and then to see whether there exist intersections or overlapping lines. Fig. A13 draws the cost-indifference line at $\tau = 0$, i.e., $\tau^{**} \equiv 2\theta(\beta + \Delta t) = 0$, or $t_N = t_S - \beta$. Note that the cost-indifference line locates above the intersection of $\tilde{t}_N^{BR}(t_S)|_{A=S}$ and $\tilde{t}_S^{BR}(t_N)|_{A=S}$. Therefore, there are two types of Nash equilibria depending on τ : one characterized by the cost-indifference line; the other by the intersection of $\tilde{t}_N^{BR}(t_S)|_{A=N}$ and $\tilde{t}_S^{BR}(t_N)|_{A=N}$, i.e., point B .

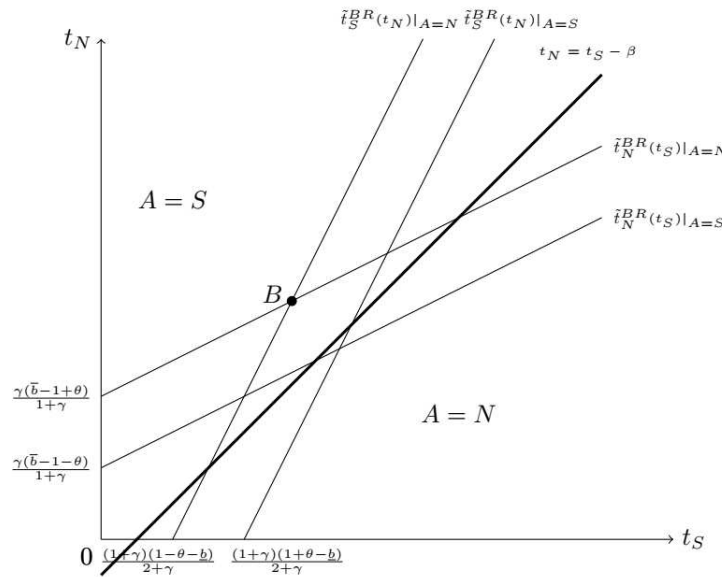


Fig. A13. Cost-indifference line at $\tau = 0$.

We have seen that N is indifferent to where assembly takes place if $t_N = t_N^*$, so is S at $t_S = \widehat{t}_S^*$, or equivalently $t_N = \widehat{t}_N^{**} \equiv \widehat{t}_S^* + \tau/(2\theta) - \beta$. Noting that the two countries' switching points are \widehat{t}_N^* and \widehat{t}_N^{**} , the two switching points are equalized at²¹

$$\tau_1 \equiv \frac{\theta \left[\sqrt{\theta(2+\gamma)\{2\gamma^2(\theta + \bar{b} - \underline{b}) + \gamma(2 + 2\bar{b} - 4\underline{b} + \theta)\} + 2(1 - \underline{b}) - (\gamma^2 + 3\gamma + 1)\theta - (\bar{b} - 1)(1 + \gamma)} \right]}{(1 + \gamma)^2}.$$

Then, for $\tau < \tau_1$, the Nash equilibria occur on the cost-indifference line where $\Delta t|_{A=S}^{NE} = \tau/(2\theta) - \beta$ (see Fig. A15). At point B , N 's and S 's pollution taxes are

$$t_N^B = \frac{\gamma(2 + \gamma)}{2(1 + \gamma)}(\bar{b} - 1 + \theta) + \frac{\gamma}{2}(1 - \theta - \underline{b}),$$

$$t_S^B = \frac{\gamma^2}{2}(\bar{b} - 1 + \theta) + \frac{1 + \gamma}{2}(1 - \theta - \underline{b}).$$

Equalizing t_N^B and \widehat{t}_N^* gives

$$\tau_2 \equiv \frac{2\theta \sqrt{2\theta(1 + \gamma) [\gamma^2(\bar{b} - \underline{b}) + \gamma(\theta + 1 + 2\bar{b} - 3\underline{b})] + 2(1 - \underline{b}) - \theta(2\gamma^2 + 3\gamma + 2) - (\bar{b} - 1)(2 + \gamma)}}{(1 + \gamma)(2 + \gamma)}$$

Then, for $\tau > \tau_2$ the Nash equilibrium occurs at point B where $\Delta t|_{A=N}^{NE} = \gamma(\bar{b} - 1 + \theta)/[2(\gamma + 1)] - (1 - \theta - \underline{b})/2$ (see Fig. A18).

For $\tau_1 \leq \tau \leq \tau_2$, there are two possible cases: (a) both countries still impose pollution taxes along the cost-indifference line, but they choose different assembly locations (see Fig. A16); (b) their best-response curves have neither intersections nor overlapping parts (see Fig. A17). In both cases, there is no Nash equilibrium.

To conclude, we have

$$\Delta t^{NE} = \begin{cases} \Delta t|_{A=S}^{NE} \equiv \tau/(2\theta) - \beta & \text{if } \tau < \tau_1 \\ \text{No Nash equilibrium} & \text{if } \tau_1 \leq \tau \leq \tau_2, \\ \Delta t|_{A=N}^{NE} \equiv \gamma(\bar{b} - 1 + \theta)/[2(\gamma + 1)] - (1 - \theta - \underline{b})/2 & \text{if } \tau > \tau_2 \end{cases}$$

which is shown in Fig. A14. The Nash equilibria coincides with the socially optimal outcomes only for $\tau \in (\tau^a, \widehat{\tau}^{**})$, which is narrower than $\tau \geq \widehat{\tau}^*$. We can thus conclude that the

²¹It can be checked that $\partial \widehat{t}_N^*/\partial \tau > 0$; $\partial \widehat{t}_N^{**}/\partial \tau < 0$; and $\widehat{t}_N^* < \widehat{t}_N^{**}$ holds at $\tau = 0$.

decentralized policy outcomes are more likely to deviate from the socially optimal ones in the age of the second unbundling.

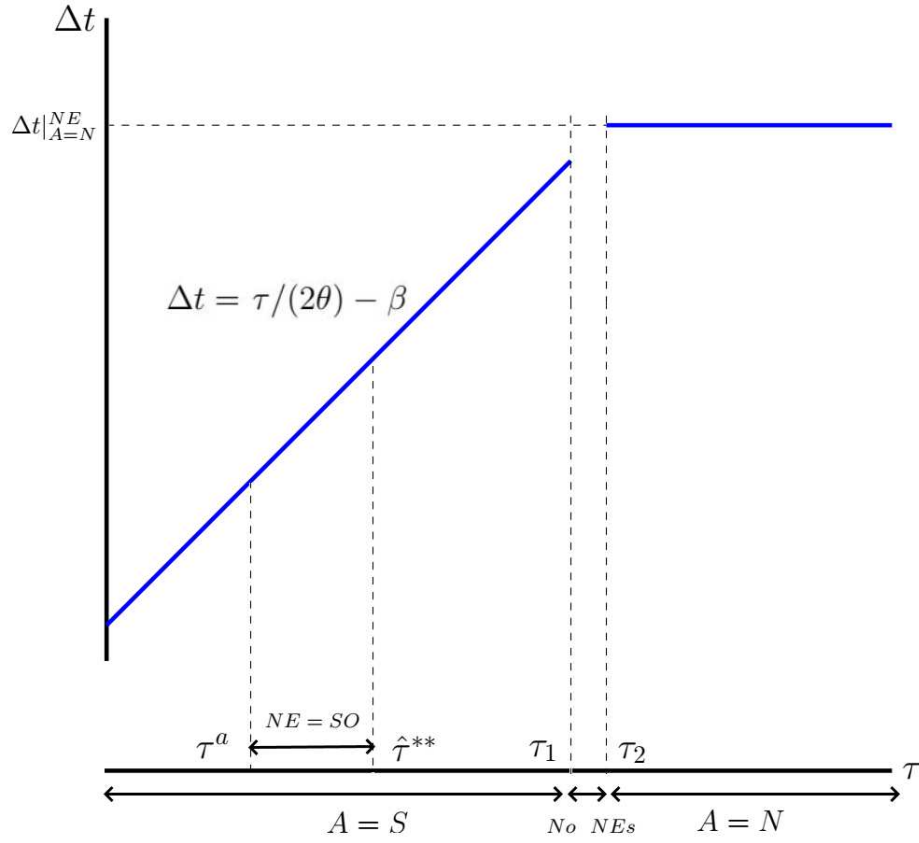


Fig. A14. Nash equilibrium tax difference (blue line) and assembly location under low unbundling costs.

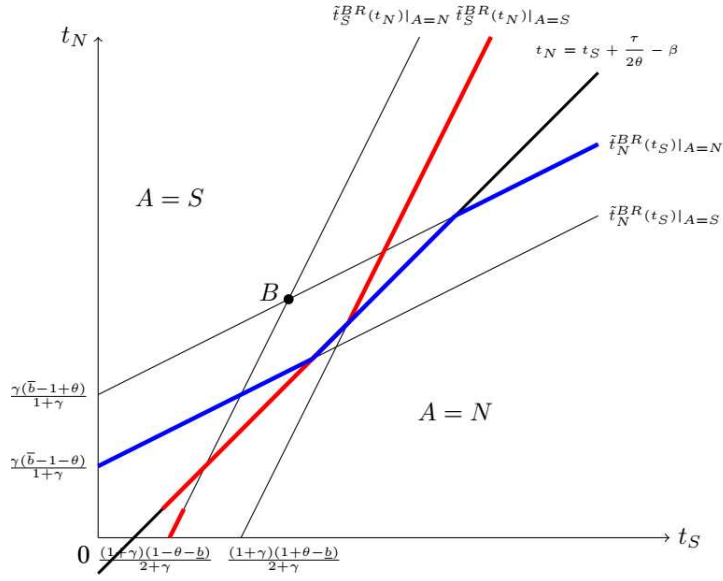


Fig. A15. Nash equilibrium for $\tau < \tau_1$.

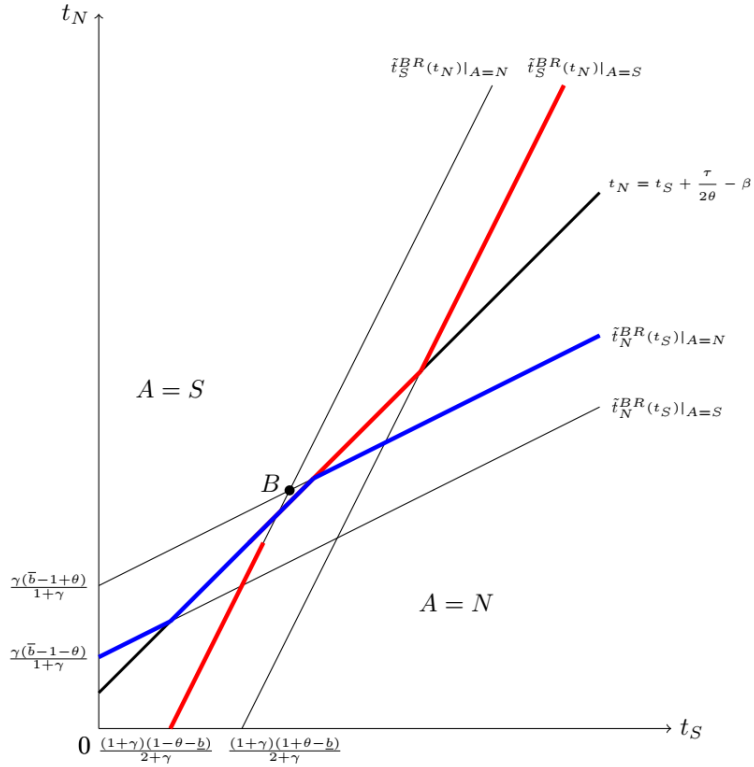


Fig. A16. Case (a) for $\tau_1 \leq \tau \leq \tau_2$: overlapping line with different assembly location.

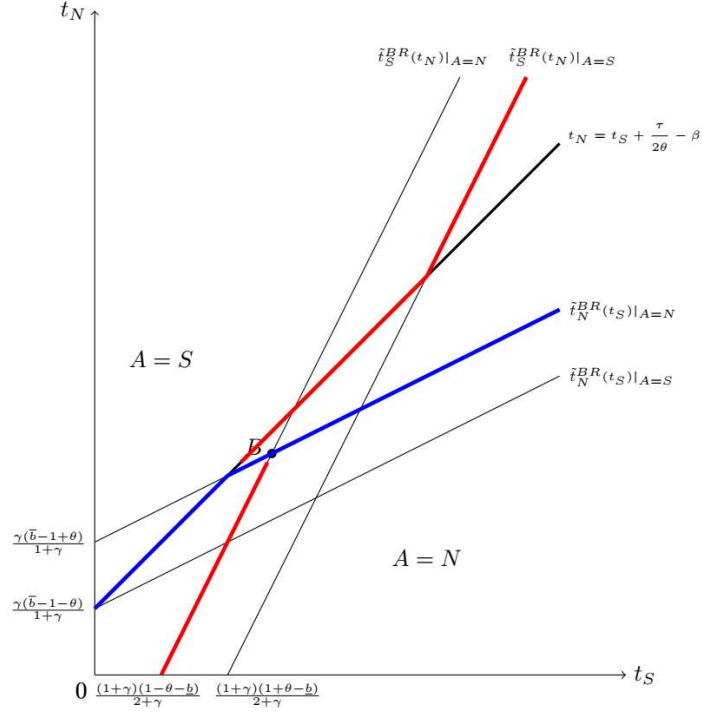


Fig. A17. Case (b) for $\tau_1 \leq \tau \leq \tau_2$: no intersections.

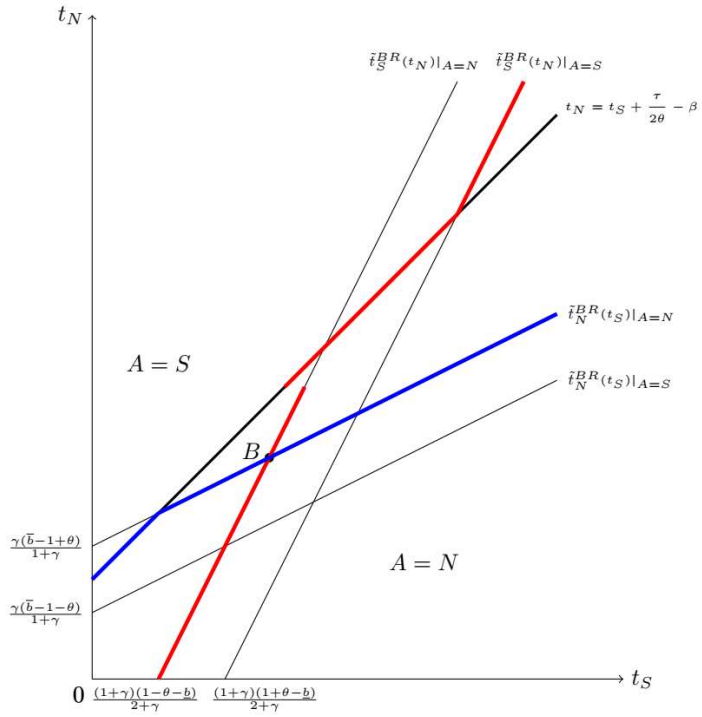


Fig. A18. Nash equilibrium for $\tau > \tau_2$.