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HOW DOES ENVIRONMENTAL REGULATION SHAPE ECONOMIC DEVELOPMENT? A TAX COMPETITION MODEL OF CHINA

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How Does Environmental Regulation Shape Economic Development?

A Tax Competition Model of China

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Abstract

We propose a novel theoretical framework to study how environmental regulation shapes economic development in a developing country such as China. We develop a dynamic tax competition model in which local governments, located in development zones, use variation in taxes to attract workers to their jurisdictions. Their objective is to maximize tax revenue less local health costs that are proportional to local pollution. Our main result is that competition generates a reallocation of productive factors when national regulation is introduced. Local governments in more productive regions set greater production taxes than in other regions. This makes workers and output to shift from more to less developed regions of the country.

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1 Introduction

The impact of environmental regulation on microeconomic outcomes has been widely studied in the economic literature. Studies show that environmental regulation affects: i) firms' competitiveness (Jaffe et al. (1995), Berman and Bui (2001), Alpay et al. (2002), Greenstone et al. (2012), Xie et al. (2017) and Lanoie et al. (2011)); ii) firm's structure and market power (Becker and Henderson (2000) and Fowlie et al. (2016)); iii) health outcomes (Hansman et al. (2015)); and iv) corruption levels (Duflo et al. (2013) and Oliva (2015)). However, the more general question of how environmental regulation influences spatial development inside a country has been left aside.

Our paper investigates how environmental regulation shifts labor force, output and productivity in a context of tax competition between units organized in a federal structure. We develop a model in which local governments compete for unskilled labor through production taxes. They seek to maximize local revenue minus health costs that are proportional to local pollution. Changes in the national pollution standard—introduced by the national government—will alter relative health costs, and will change the outcome of the dynamic game local governments play.

This investigation is motivated by the regional disparities and the political economy of China. The country's regional divide between coastal and inland provinces has persisted since at least the 19th century (Bergère (1989)). Modern economic activity emerged in coastal cities—such as Shanghai and Guangzhou—but failed to spread industrialization to the underdeveloped interior. Concentration of economic activities was accelerated in the end of the 1970s, after the 1978 economic reforms (Jia and Chao (2016)). As a result of these reforms, mobility of capital and labour increased between provinces, allowing the Chinese economy to take-off. From 1978 to 2009, China's GDP *per capita* has grown by an average 8.77% per year; and total factor productivity, one of the main drivers of this growth, has grown, on average, 3.8% on the period of 1978-2005 (Jia and Chao (2016) and Bosworth and Collins (2008))[1].

Although, during this period, economic development was unprecedented, inland provinces provided inputs for coastal cities' development without reaping the social and economic benefits of national growth. Regional disparities then widened even more from the early 1990s to the 2000s, when they peaked, in 2004 (Houkai (2014)). Today, the coastal region produces half of China's GDP, and has the most efficient and technologically advanced share of Chinese firms (Lemoine and Traeger (2014)).

Workforce, one of the most important productive inputs in the coun-

[1] Total factor productivity growth seem to account for 40% of China's GDP growth in the period 1978-2005 (Bosworth and Collins (2008)).

try, has been following closely output share[2]. Since the 1980s, and more intensely after the *hukou* system was relaxed, workers tended to migrate from the West to the East (Chan (2008)). Unskilled and temporary, they move across provinces seeking better job opportunities and higher wages (Fan (2005), Liu et al. (2015) and Shen (2012)). In a country with a labor shortage, regions that are able to attract these workers can boost local economy (Knight et al. (2011)).

In parallel to the economic development, the central government has introduced sveral environmental regulations. In 1979, just one year after the economic reforms, the Chinese government issued its first main piece of national environmental regulation, the Environmental Protection Law (EPL) (Jiang et al. (2014)). This law laid out general principles of environmental protection, described key instruments for environmental management, and specified which regulations should be enforced at the national and local levels. After the EPL, a series of environmental regulations were enacted in the country, culminating in the implementation of the pollution levy system in 1996 (Jiang et al. (2014)). Today, this system is the main tool for environmental regulation in China.

The levy collected by local authorities is used to finance environmental development, administration of the program, and also subsidizes firms' pollution control projects (Wang et al. (2003)). However, the amount collected varies greatly in time and space (Wang and Wheeler (2000)). There are two reasons for that. First, there are some differences in concentration standards across provinces. Second, and most importantly for our study, part of this variation comes from differences in enforcement.

In China, local Environmental Protection Bureaus (EPBs) are responsible for collecting levies from industrial facilities (Tilt (2007)). Each EPB is free to enforce standards according to specific local socioeconomic characteristics (Zheng and Kahn (2013)). As a result of the way political incentives are structured nationally[3], this autonomy ends up being used to advance local leaders own interests. Some of them, for example, relax environmental standards to attract firms and workers to their localities.

The overall result of this institutional framework is that more stringent national environmental regulation reduces local leaders' ability to use it as a tool to attract productive inputs to their localities. Because this reduction is not homogeneous across regions, it influences the spatial distribution of resources, and have an impact on spatial economic development.

Following the literature on tax competition and federalism (Zodrow and Mieszkowski (1986), Bucovetsky (2009) and Janeba and Osterloh

[2]In 2014, 51 cities in China accumulated 20.85% of total national population. These cities also accounted for 41.60% of the country's GDP (Tao et al. (2016)).

[3]Evidence show that the central government promotes leaders on the basis of their economic performance (Wu (2010) and (Zheng et al. (2014)).

(2013)), we construct a dynamic model that captures these features of the Chinese economy. Local governments, which are located in different development zones, compete for unskilled workers through variation in production taxes. Tax reductions boost economic output by creating incentives for local firms to hire more workers. But they also increase health costs through increased local pollution. Jurisdictions are linked to the national government through a national pollution threshold that enters their optimization problem. More stringent environmental regulation—a reduced threshold—will increase local health costs, and will force local governments to increase taxes.

Our main finding is that a change in the national threshold shifts workers and output across jurisdictions. More than simply reducing total pollution, more stringent environmental regulation alters spatially the distribution of productive resources in the economy. For most parameter values, we show that output moves from most to least productive jurisdictions. This means that, in a context of tax competition and imperfect institutions, environmental regulation can be used by the central government to indirectly promote the economic development of specific regions of the country.

The next section presents the motivating evidence for our model and discusses related theoretical literature. In section 3, we introduce the first version of our model, tax competition when there is only one development zone in the economy. In section 4, we present a sequential model with many zones and jurisdictions, but abstract the actions of the national government. Section 5 outlines the national government's optimization problem. Section 6 presents our numerical simulation. We conclude the paper in section 7.

2 Motivation and Related Literature

2.1 Motivating Evidence

Our model structure is motivated by the interacting dynamics of three elements of the Chinese economy: migrants, environmental control and local leaders' set of incentives.

It is difficult to infer the exact socioeconomic characteristics of migrants in China, but recent studies show that they are mostly unskilled and temporary (Shen (2012) and Shen (2013)). Evidence from national censuses show that workers are mainly driven by economic opportunities, such as wage differentials and transportation costs, although characteristics and size of local networks also influence their decision to migrate (Liu et al. (2015) and Chan (2008)). Since at least the 1980s—and more significantly after the *hukou* system was relaxed—these unskilled workers form a floating population of cheap labor force that moves across different provinces, seeking better job opportunities (Chan (2008) and Fan (2005)). Because of historical differences in economic development, over the years, migration mostly occurred from the less developed Western part of the country to the more developed Eastern part (Lemoine et al. (2015)).

The Chinese government promotes or demotes local leaders on the basis of economic performance, and uses GDP growth as its main evaluation criterion (Wu (2010) and Zheng et al. (2014)). This reward structure increases incentives for local leaders to compete for production inputs, and to attract the greatest possible number of firms to their localities using fiscal tools. They see this floating population of unskilled workers as a chance to increase local output and boost their local economies. This is especially true in a country where there has been signs of a workforce shortage in urban centers and fast growing cities (Knight et al. (2011)).

Although, in general, local governments have little power to modify taxation—because the central government assigns fixed taxes directly to them—they can either lower taxes by granting exemptions to investors or increase revenue by fees, levies and penalties (Wang and Herd (2013)). Exemptions can be used to attract firms as well as workers—through higher wages—to their regions; whereas penalties can serve local authorities to shut down inefficient firms. Environmental enforcement has an important role here. Part of the penalties is administered because of environmental issues, such as excessive water and air pollution; and enforcement can be relaxed to make a locality more attractive to firms[4].

In China, the local authority responsible for inspecting and collecting pollution levies from industrial facilities is the Environmental Protection Bureau (EPB) (Wang et al. (2003)). It was created in 1988, together with the State Environmental Protection Agency (later replaced by the Ministry of Environmental Protection) (Jiang et al. (2014)). Today, there are around 2,500 EPBs in the country, and each one of them has autonomy to enforce environmental regulation according to the specific socioeconomic characteristics of their region (Tilt (2007) and Zheng and Kahn (2013)). Since EPB's funding comes from the local government, local leaders end up deciding how much levies to collect and when. Thus, environmental regulation becomes another tool for increasing local GDP[5]. Two empirical studies provide evidence of these dynamics. Wang and Wheeler (2000) show that collection of pollution levies is sensitive to differences in local economic development and environmental quality.

[4]Environmental regulation typically tends to increase firms' production costs (Zheng and Kahn (2013)). Because of that, lack of enforcement and control will make a locality more attractive to firms.

[5]There is evidence that local governments will favor economic growth instead of environmental quality. Wu et al. (2013), for example, show that local leaders have strongly favored investing in transportation infrastructure—which is seen as a source of economic growth—instead of environmental protection.

Wang et al. (2003) find that state owned firms and firms in bad financial situation have more bargaining power in levy payments than others.

2.2 Related Literature

The model developed in this paper builds on the tax competition literature, in the tradition of Zodrow and Mieszkowski (1986), Oates and Schwab (1988) and Bucovetsky (1991)[6]. These works developed an initial framework to analyze tax competition under federalism. Their aim was to study how public good provision is altered in the federalist setting.

Zodrow and Mieszkowski (1986) construct a model in which local governments' function is to provide a public good to citizens. They can finance this good either by taxing physical capital—perfectly mobile—or by charging a head tax on citizens. Local governments act to maximize the utility function of a representative citizen. The authors show that, when head taxes are limited, there will be an under-provision of public goods in equilibrium.

Oates and Schwab (1988) extends this framework by also considering standards for local environmental quality. In their model, local governments have two policy variables: capital tax and environmental standards. They decide the values for these two variables through a simple majority rule mechanism. They conclude that, in equilibrium, both physical capital and environmental standards will be under-provided.

Bucovetsky (1991) reconsiders the problem of competition among local governments, but allows jurisdictions to have different population sizes. Working with only 2 jurisdictions, he shows that population differences will result in taxes differences. Smaller jurisdiction will set higher capital tax than the big ones.

The main components of our model come from these three seminal papers. In our setting, jurisdictions are asymmetric in terms of productivity. They set taxes on production, and deal with environmental standards. Our model also builds upon two more recent theoretical works.

Bucovetsky (2009) studies tax competition of N asymmetric jurisdictions in terms of population size. He works with a quadratic production function to show that smaller jurisdictions will levy lower taxes. Janeba and Osterloh (2013) develop a framework in which there are two different tax competition levels. Cities compete with cities, whereas peripheries compete with peripheries. Taxes on capital are set in a multistage game: first cities compete for physical capital; then peripheries compete for the remainder. Their game is solved by backward induction.

Similar to these studies, our setting considers a N player game with a dynamic structure, solved by backward induction. However, in our

[6] See Wilson (1999) for a literature review on this topic.

case, local governments maximize tax revenues minus health costs, and not citizens' utility[7]. Moreover, we are interested in competition for unskilled workers, and not for physical capital[8].

To a lesser extent, our paper relates to the nascent literature of environmental economics that studies the effects of environmental regulation in an environment of imperfect institutions. In developing countries, regulation can create unforeseen consequences that are often undesired. Hansman et al. (2015), for instance, study the introduction of individual property rights over fish upstream in Peru. They show that piecemeal regulation[9] caused 55,000 additional respiratory hospital admissions per year. In Mexico, Oliva (2015) shows how air pollution regulation created incentives for drivers to bribe regulators, leading to greater damage to the public. She notes that "emission regulations become more prevalent in developing countries, but they may be compromised by corruption". Duflo et al. (2013) run a field experiment in Gujarat, India with third-party environmental auditors. They find that the prevalent system was largely corrupted, but that incentives for auditors can improve reporting and make regulation more effective.

A similar type of situation can also arise in developed countries. Poorly designed environmental regulation might end up contributing to environmental degradation. Becker and Henderson (2000) study plants in the US for 1963–92. They find that regulation led to a shift in industry structure to single-plant firms, resulting in more pollution. Ryan (2012) examines the welfare cost of clean air regulation in the US. He finds that regulation increased entry costs of firms, decreasing welfare. Finally, Fowlie et al. (2016) assess the implication of emissions regulation for the cement industry in the US. One of their main findings is that "emissions regulation exacerbates distortions associated with the exercise of market power in the domestic cement market".

In our case, more than simply reducing pollution, national environmental regulation changes local leaders' incentives. This will generate a spatial reallocation of productive resources, and the development of specific regions of the country.

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[7]Models in which governments behave this way are often called 'Leviathan Models' (see e.g. Oates (1985)).

[8]In this respect, our model relates to the more specific literature of labor mobility and tax competition (Wilson (1995)).

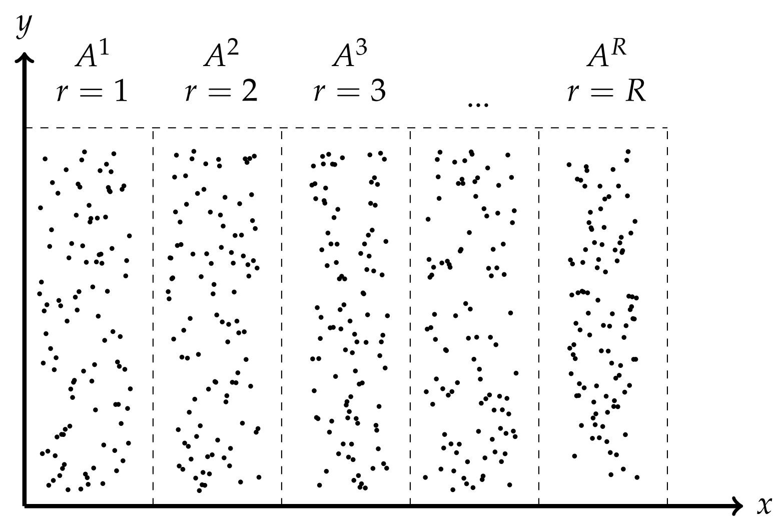
[9]Regulation that is designed from a partial equilibrium perspective, with a particular set of firms in mind.

3 Tax Competition within a Development Zone

Consider a national economy composed of many jurisdictions distributed across development zones. Each jurisdiction is composed of a local firm and a local government. Local governments are organized in a federal structure, under a national government. They have autonomy to set production taxes in their jurisdictions. Local firms can only employ local workers, L_i^r. There is no unemployment in our model, so local population of workers corresponds to total local population. We normalize national population to be equal to one, $\bar{L} = 1$.

Jurisdictions differ in terms of their vintage of immobile physical capital. Some vintages enable firms to produce more goods than others for the same quantity of labor employed. Hence, jurisdictions that have a more productive vintage also have greater productivity[10], A_i^r.

Figure 1: Spatial Setup: Development Zones



Each dashed rectangle in this diagram represents a development zone (r) composed of N jurisdictions (black dots, i). A_i^r follows a normal distribution with average equal to A^r. $A^1 > A^2 > A^3 > ... > A^R$.

Figure 1 describes the spatial setup of this economy. Each dashed

[10]Immobile financial capital has been studied, for example, in Gordon and Bovenberg (1996), Sharma (2008) and Chan et al. (2011). Gordon and Bovenberg (1996) present evidence that capital is immobile internationally and examine reasons for that. More in line with our work, Sharma (2008) investigates whether regional disparities in India are related to spatial immobility of capital. Finally, Chan et al. (2011) examine capital mobility inside China, and show that there has been increasing mobility from developed to undeveloped regions—although mobility is still low. These studies provide evidence that there is no perfect market integration across political units, and, because of that, spatial differences in productivity persist.

rectangle represents a development zone[11], r. These zones, located in the $\mathbb{R}^2$ space, are composed of N jurisdictions each, represented by black dots. A jurisdiction is identified by two coordinates, (i, r). The productivity of jurisdictions inside a zone follow a *normal* distribution[12] with average A^r. We assume that N is sufficiently large such that this distribution can be considered continuous. At this point, we do not fully characterize it, but assume that average productivities are related in the following way: $A^1 > A^2 > A^3 > ... > A^R$. Jurisdictions located in zones that are closer to the origin, $(0, 0)$, are, on average, more productive than jurisdictions located in other zones.

For reasons discussed below, the national government will consider development in a spatially restricted manner, in which jurisdictions in a given zone are developed at one time. Because of that, jurisdictions in the same zone will have similar vintages of capital, and there will be concentration of productivity in zones. This will result in the spatial distribution described above[13]. However, the spatial location of each jurisdiction inside a zone—that is, their xy coordinates—is assumed to be random[14].

In this section, we study equilibrium outcomes inside a development zone (so, we drop the r superscript). We begin by describing economic agents and by outlining the game they play. We finish by presenting three propositions that describe their optimal behavior for a given exogenous distribution of productivities.

3.1 Firms, Workers and Local Governments

There are three types of agents in our model: firms, workers and governmental units.

Firms There is one representative firm per jurisdiction that produces a common composite good with normalized price $p = 1$. Firms are im-

[11]Figure 1 presents a general diagram with R zones. In the next section, we discuss how the number of zones is determined.

[12]We choose to use normal distributions here motivated by the actual distribution of city total factor productivity (TFP) in China (Chinese Industrial Enterprises Database, 1998-2007).

[13]This spatial distribution was motivated by the current spatial distribution of TFP in China (Zhu et al. (2008) and Ke (2010)). Eastern provinces have, on average, greater TFP than Western provinces. This is a direct result of the country's historical development—discussed in the introduction, and the national government's role in this development—to be discussed in section 4.

[14]We are not interested in modelling location decisions in this paper. We assume that development zones are created in different regions of the xy space because the national government wants to promote spatial economic development. This is discussed in more detail in section 5.

mobile, and can only employ local workers. Moreover, they are obliged to use local productivity—i.e. the available vintage of capital—A_i.

They have Cobb-Douglas[15] technology such that output is given by

$$Y(A_i, L_i) = A_i(L_i)^\alpha, \tag{1}$$

where $0 < \alpha < 1$. Firms have to pay local production taxes, τ_i, to local governments.

They maximize profits subject to wages, w_i, local taxes and productivity, such that wages paid to local workers are:

$$w_i = (1 - \tau_i)\alpha A_i(L_i)^{\alpha-1} \tag{2}$$

When operating, firms emit pollution P_i, which is assumed to remain within their jurisdiction:

$$P_i = \eta Y_i, \tag{3}$$

Pollution levels increase as a fraction of local output. The constant $0 < \eta < 1$ is the coefficient of emissions per output[16].

Workers Workers maximize individual utility, $U(c_i)$, where c_i is consumption received in jurisdiction i. They have identical preferences and are mobile across jurisdictions, such that:

$$U(c_i) = U(c_j) \ \forall \ i, j. \tag{4}$$

Since they consume exactly what they receive in wages, utility equalization implies wage equalization[17].

National government The government is federal in structure, with a national government and distinct underlying jurisdictions.

The national government establishes an ambient air standard theoretically applicable across all jurisdictions[18].

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[15] We use a Cobb-Douglas type of production function for the sake of simplicity. Theoretical papers in the tax competition literature usually use quadratic production functions to derive numerical results (Bucovetsky (1991) and Bucovetsky (2009)).

[16] As in Stokey (1998), we assume that pollution is proportional to output produced. For the sake of simplicity, we assume that η does not vary across jurisdictions. This means that every jurisdiction has the same emissions technology (greater productivity does not imply greater environmental efficiency). Note that we have two different types of technology in our model: A_i and η; but, for the sake of simplicity, we only allow productivity to vary.

[17] Equation (4) is similar to the equation of equalization of capital's net of return in the first tax competition models (see e.g. Zodrow and Mieszkowski (1986)).

[18] As indicated above, local derogations from the national uniform standards may be allowed, but uniformity is the rule in order to enable uniform treatment of provinces and accounts.

It also enables transfers to local governments of resources meant to cover local health expenses[19]. This amount is assumed to be proportional to the local population and to the national pollution threshold, $\bar{P}$, established by the national government:

$$R(\bar{P}, L_i) = \phi \bar{P} L_i, \tag{5}$$

The constant $0 < \phi < 1$ converts pollution units into health cost units[20]. At this point, we do not model explicitly national government's actions. We just assume $\bar{P}$ is an exogenous variable.

Local governments The local government of each jurisdiction has revenue that comes from tax collection from firms, $\tau_i Y_i$, and from the national government's transfer. It also has a health cost function, $\phi P_i L_i$, that is a function of local pollution and population.

The optimization problem that each local government i solves is given by:

$$\underset{0 \leq \tau_i < 1}{\text{maximize}} \quad V_i = \tau_i Y_i - \phi(P_i - \bar{P}) L_i \tag{6}$$

Local governments maximize their revenue given health costs associated to pollution. Note that health costs will only be a burden for them when local pollution surpasses the national threshold, $\bar{P}$.

This setup of the local government objective function may be considered to be the net result of a federal incentive system that incentivises growth and production (e.g. via promotion of leaders) and penalises excessive pollution and its health costs (e.g. via pollution levies)[21].

The difference between local pollution levels and the national pollution threshold can be generally interpreted as the level of local tolerance towards pollution levels, relative to the regulatory norm.

[19] We assume that the national government taxes equally each local government to finance such health transfers. This tax is a fixed share of net local revenue, so we do not include it in the local governments' objective function.

[20] There is substantial research showing that pollution causes enormous health costs in China. Two important examples are: Yang et al. (2013), which find air pollution to be the fourth most important health burden in the country; and Chen et al. (2013), which find that one coal-subsidy led to a loss of 2.5 billion life years of life expectancy in Northern China. Pollution also induces direct productivity losses (Chang et al. (2016)).

[21] The central government promotes or demotes local leaders on the basis of their economic performance (Wu (2010)), and uses GDP as the main evaluation criterion (Zheng et al. (2014)). This motivates our assumption that local governments seek to maximize the difference between tax revenue and health costs. Lower production taxes will boost local output, but will also increase pollution levels that will, eventually, damage the local working force.

3.2 The Game

Here we present an illustration of the way in which tax competition might occur between local governments within the above setup. This provides a basic picture of the way these governments compete within a development zone.

- **Players**: Local Governments;
- **Actions**: $\tau_i \in [0, 1)$;
- **Payoffs**: $V(\tau_i, \tau_{-i}, A_i, A_{-i})$;
- **Time Structure**:
  - $t = 1$: N local governments set production taxes simultaneously;
  - $t = 2$: Workers migrate and wages are equalized across the zone.

Local governments seek to maximize tax revenue minus health costs, given firms and workers' behavior. After production taxes are set, migration of workers occurs and wages are equalized. We find the Subgame Perfect Equilibrium (SPE) of this game by backward induction.

We can now state our three initial propositions. These are general propositions that will hold throughout the rest of the paper[22].

Proposition 1: Taxation and Migration Local population decreases with increases in local taxes,

$$\frac{\partial L_i}{\partial \tau_i} < 0. \tag{7}$$

Proof. See Appendix.

Hence, on average, population in other jurisdictions increases when local government in i increases taxes. This demonstrates that a tax increase is always detrimental for production—because production function increases with workforce—and beneficial for health costs.

Proposition 2: Productivity and Taxation Assuming that taxes are set around zero, and productivity values are around the zone's average, A, we have that,

$$\frac{\partial \tau_i}{\partial A_i} > 0, \tag{8}$$

[22] See Appendix.

for $\frac{\phi \bar{P}}{A} < k$.

Proof. See Appendix[23].

An exogenous increase in local productivity will cause local governments to increase local taxes if the ratio between per capita national transfer and local productivity is smaller than k.

There are two ways for local governments to increase their local revenue. First, they can try to attract workers from other jurisdictions by decreasing taxes. Second, they can increase taxes when they know their high productivity compensates for a small local workforce. When productivity is small in comparison to the national transfer ($k < \frac{\phi \bar{P}}{A}$), however, it is better for the local government in i to decrease taxes—because gains from productivity are too low.

Proposition 3: Pollution and Taxation The optimal amount of taxes charged by local government in jurisdiction i is a function of current pollution within that jurisdiction and the national threshold, $\bar{P}$:

1. $\tau_i > 0$ if $P_i > \bar{P}$;
2. $\tau_i = 0$ only if $\bar{P} > P_i$.

Proof. See Appendix.

Local governments will only set positive taxes if local pollution levels surpasses the national threshold. This is because local governments benefit from low pollution levels relative to the national standard, by reason of inducing labour migration and increased production. Pollution only becomes a problem when the difference between local pollution and the national standard is high enough to make health costs positive. Then taxes may become positive, halting migration.

4 Dynamic Tax Competition – Multiple Development Zones

In the previous section, we show how local governments within a given development zone compete through local taxes to attract labour, production, and hence tax revenues. As production and pollution escalate, local governments in more productive jurisdictions tax more, and low productivity jurisdictions produce more.

[23] $k = \frac{(1-\alpha)N^{1-\alpha}}{1+\alpha}$. To obtain these results we need τ_i to be around zero and A_i to be around A.

We now allow for the national government to have an active role in our game. It will decide whether to finance the construction of new jurisdictions, that is, a new development zone. If the national government decides to finance a new zone, then workers migrate to the new jurisdictions. Production follows labour, and—because productivity in these jurisdictions is lower on average—average pollution in this economy decreases. In other words, the creation of a new zone diffuses production, and pollution, nationally.

On the other hand, if the national government decides not to finance new capital, the national threshold, $\bar{P}$, is adjusted so that it is equal to the average pollution in the economy[24]. This change in regulation decreases $\bar{P}$ and forces firms in existing zones to reduce production. This ends up decreasing national pollution.

We begin this section by modelling the decision problem of the national government. We then describe the dynamic game we study. We finish by stating two propositions that describe the impact of changes in the national threshold on local tax rates.

National government The national government solves the following problem,

$$\underset{a=\{1,0\}}{\text{minimize}} \quad P^{av}(a) + a \cdot c \cdot A^{R+1} \tag{9}$$

where $c \cdot A^{R+1}$ is the cost of financing a new development zone and $P^{av}(a)$ is the function that describes the average local pollution in this economy[25]. National government's possible actions are: to finance a new zone $a = 1$, or not, $a = 0$.[26]

The expression above describes a cost minimization problem between i) the cost of pollution and ii) the cost of spatial economic development. Average pollution is a decreasing function of a; with more development zones, production diffuses nationally and average pollution decreases. The cost of financing new capital, however, is positive and proportional to the average vintage of capital, A^{R+1}, that will be financed. The relationship, $A^1 > A^2 > ... > A^{R+1}$, holds, such that jurisdictions in earlier

[24]This is so assuming that the initial exogenous value of the national threshold, $\bar{P}$, is high compared to the actual average level of pollution. This assumption is motivated by the fact that only in recent years the Chinese government started to consider environmental quality a problem (Zheng et al. (2014)).

[25]Note that R refers to the total number of development zones in this economy. The subscript r refers to the zone number, $r = \{1, 2, ..., R\}$.

[26]Here, we assume that the national government knows in advance the outcome of the simultaneous game played by local governments—that is, it knows the exact tax distribution for any number of development zones.

zones are, on average, more productive than in newer zones[27].

Hence, the national government will choose to finance a new development zone as long as,

$$|\Delta P^{av}(a)| > c \cdot A^{R+1}, \tag{10}$$

that is, reduction in average pollution is greater that the cost of new jurisdictions. If the national government chooses not to finance a new zone, the national threshold, $\bar{P}$, is adjusted to be equal the average pollution in the country[28]:

$$\bar{P} = P^{av}(R) \tag{11}$$

The idea here is to capture in a very simplified way the trade-off the national government might face between promoting spatial economic growth and decreasing national pollution. By financing new capital, the national government increases national output and allows investments to reach once undeveloped regions. However, at the same time, this increases pollution and health costs in these areas[29].

4.1 The Game

The game we develop in this section is similar to the one presented in section 3, but played several times by different sets of players—local governments in different development zones. It is the national government that will allow a new set of jurisdictions to play the game by financing a new development zone.

Figure 2 describes our game. Suppose that, initially, there is only one development zone in the economy we described in the previous section,

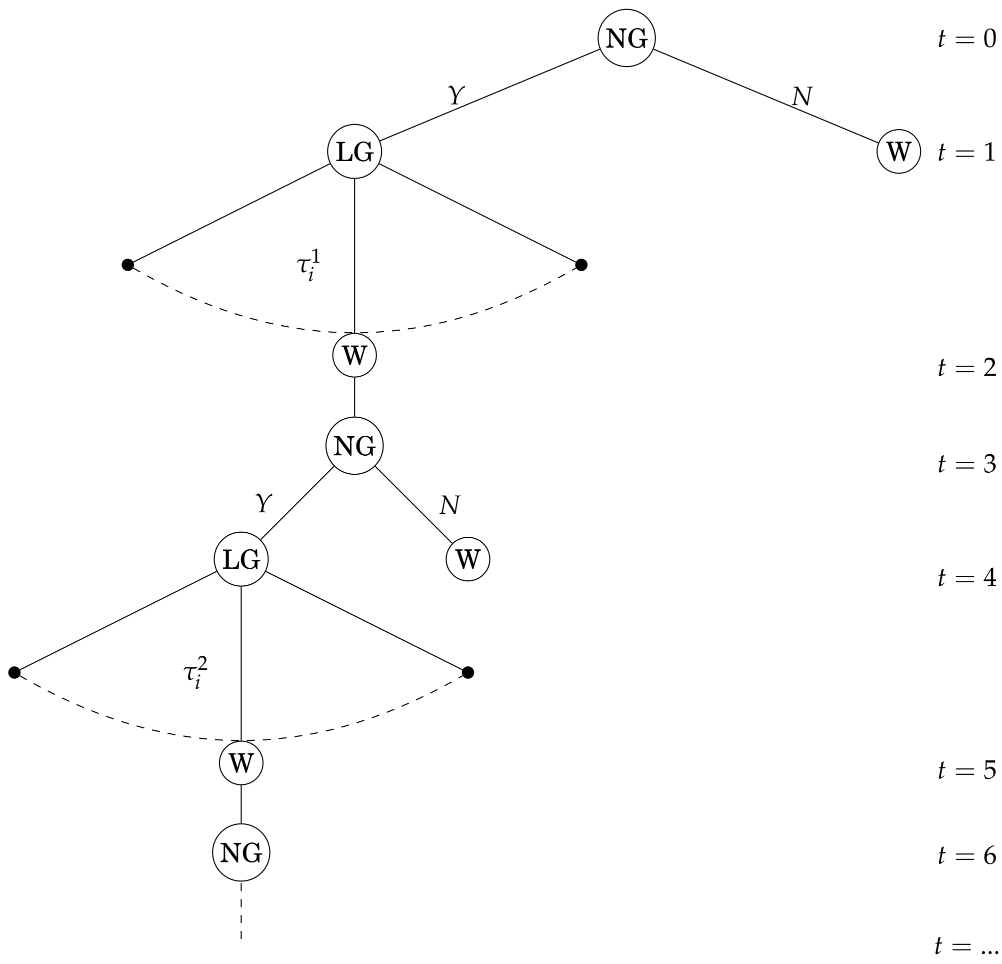
[27]Three elements of the Chinese economy suggest that both spatial economic development and environmental quality enter the central government's objective function. (1) China has maintained a government-dominated financial system for, at least, the last four decades (Boyreau-Debray and Wei (2005) and Megginson et al. (2014)). This has enabled the central government to have a decisive role in the country's development path. (2) The Chinese government has adopted development strategies that tended to reallocate capital from more productive regions towards less productive ones (Boyreau-Debray and Wei (2005), Lin and Liu (2006) and Chan et al. (2011)). One of its objective was to "Develop the West", that is, to promote the development of hinterland provinces. (3) In recent years, the central government has been showing signs that environmental goals, such as pollution reduction, are part of its development strategy (**?**).

[28]The national government will not choose to reduce the national threshold straight away because this generates an increase in the average level of taxes and a reduction in national production, $\frac{\partial Y_i}{\partial \tau_i} < 0$. A more stringent environmental regulation will be its last resource to reduce average pollution.

[29]This framework also indicates that an important determinant of the national government's problem would be the respective shapes of the aggregate health costs and aggregate production functions.

zone $r = 1$. Repeatedly, the national government (NG) has to decide whether to finance the creation of new capital, that is, new jurisdictions. As described in figure 1, these jurisdictions will form a new development zone, characterized by a productivity distribution (with average A^r). Every time a new zone is financed, all local governments (LG)—in all zones—set production taxes simultaneously. Workers (W), then, migrate nationally until wages are equalized. The game ends when the national government decides not to finance a new development zone, and $\bar{P}$ is adjusted.

Figure 2: Game Tree



NG: National Government decides whether it creates a new zone, $a \in \{Y, N\}$. If $a = N$, $\bar{P}$ is updated.
LG: All local governments set production taxes—or update them, $\tau_i^r \in [0, 1)$.
W: Workers migrate and wages are equalized across the economy, $w_i^r = w_j^r$, $\forall i, j, r$.
The variable t refers to time period.

4.2 The effect of Environmental Regulation on Local Tax Rates

Instead of solving for the SPE of this game—this can be done by backward induction over pairs of periods—we present two propositions that, together, describe what happens to local tax rates when there are variations in $\bar{P}$.

We wish to show how changes in the national threshold—that is, variations in the stringency of environmental regulation—influence the spatial movement of labour and production.

Proposition 4: Optimal Taxes across Zones Assuming that taxes are set around zero, and productivity values of jurisdictions in a zone are near the average value, A^r, we have that,

$$\frac{\partial \tau_i^r}{\partial A_i^r} > 0, \tag{12}$$

if $k_1 < \frac{\phi \bar{P}}{A^r} < k_2$.

Proof. See Appendix[30].

This means that jurisdictions in zones with greater average productivity will set greater taxes than other jurisdictions. Note that we considered the special case in which jurisdictions have productivity values that are near their zones' average[31], and taxes are low.

Exogenous variations in productivity can have different effects in taxation—and in local population. It all depends on the ratio between the national threshold ($\bar{P}$) and productivity values across zones. If, for example, we have low average productivity values, high coefficient of health costs and high threshold value, local governments in productive zones will most likely decrease taxes to attract workers to their jurisdictions.

This leads to our second proposition, which describes how changes in the national threshold changes optimal taxes and, ultimately, drive workers' migration and changes production in this economy.

Proposition 5: Impact of National Threshold A decrease in the national threshold, $\bar{P}$, will increase average taxes in zone r:

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[30] $k_1 = \frac{1}{(N\theta^r)^{1-\alpha}}$ and $k_2 = \frac{(1+\alpha)(N\theta^r)^{1-\alpha}}{(1+\alpha)}$; $\theta^r = 1 + \sum_{h=1}^{r-1} \left(\frac{A^r}{A^h}\right)^{\frac{1}{\alpha-1}}$.

[31] This has the implication that, for our results to hold in our numerical simulation, we will need to use normal distributions of productivity that have small variance.

$$\frac{\partial \bar{\tau}^r}{\partial \bar{P}} < 0 \tag{13}$$

Proof. See Appendix.

A reduction in the national threshold means that local governments in a zone receive reduced transfers from the national government. Their tolerance towards pollution, then, decreases, and their willingness to tax increases. Jurisdictions that are on the verge of setting positive taxes will do so, after a decrease in $\bar{P}$.

Given that the national threshold determines the stringency of the environmental legislation in this economy, we can also conclude that a more stringent national standard will make local governments to increase production taxes.

As showed in proposition 4, earlier development zones—i.e. zones with greater average productivity—will increase taxes more than newer zones when $\bar{P}$ decreases (for the conditions specified in that proposition). This will make wages in these zones decrease more as well, and will drive workers to newer—and less productive—places. Production in these newer zones will then increase, and average national pollution will decrease.

This demonstrates that a more stringent national standard will drive workers and, ultimately, shift production from more productive regions to the interior of this economy. On a more general level, our model shows that, in a context of tax competition and imperfect institutions, national environmental standards have an impact that is not only limited to environmental quality. Environmental regulation can generate a spatial reallocation of productive resources, and can change development outcomes.

5 Simulation

In this section, we simulate the game described in figure 2. The simulation shows how the interaction between environmental regulation and health costs shape economic development in a context of tax competition between local governments within a federal structure. This interaction, together with the cost of financing new capital, determines whether new economic zones are created, and undeveloped regions are explored.

5.1 Parameters

Table 1 specifies the parameter values we used for our simulation.

Table 1: Parameter values for the Simulation

Parameter	Value	Description
N	50	Number of jurisdictions in each development zone
$\bar{L}$	1	Total Population
Production Parameters		
A^1	$\mathcal{N}(6,1)$	Productivity of the first zone
α	0.3	Labour elasticity
Environmental Parameters		
η	0.2	Emissions per output (intensity)
ϕ	0.5	Health Costs per Pollution Emitted
$\bar{P}$	10	National Threshold
c	1.1%	Cost of Capital

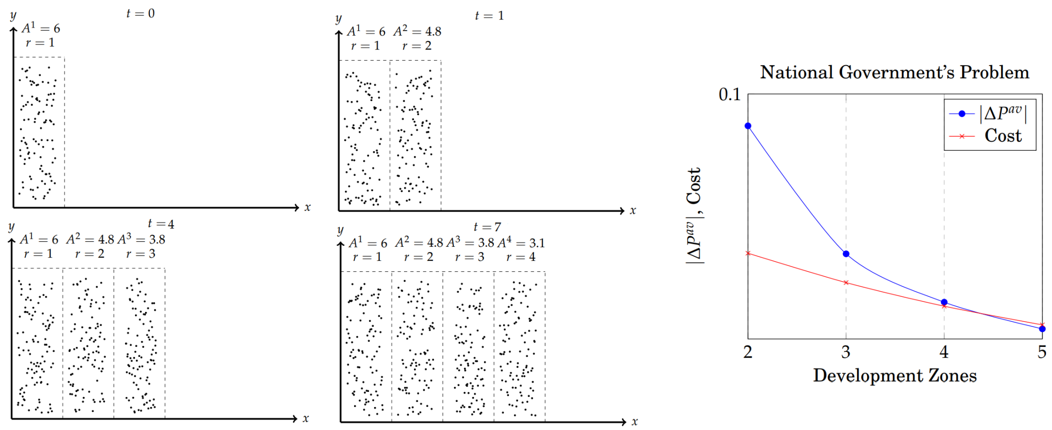
No attempt has been made to calibrate our model. We are only interested in illustrating qualitative dynamics in this paper. With this is mind, we choose parameter values such that the general pattern described by our model is clearly illustrated in our simulation.

Our results are sensitive to the productivity profile we choose—that is, average productivity in development zones. This happens because local productivity is proportional to local pollution, and the difference between local pollution and the national threshold will determine tax differences across jurisdictions. To keep differences in taxes across development zones relatively low, we set average productivity to decrease following the equation: $A^r = A^1 \cdot 0.8^{r-1}$, where A^1 is the average productivity of the first zone.

5.2 Results

Figure 3 shows this economy's geography over time and the national government's decision problem[32]. The game ends with four development zones, after the national government chooses not to finance the fifth one, at $t = 10$ (the fourth zone is created at $t = 7$). Note that all zones have the same number of jurisdictions, 50.

Figure 3: Simulation: Development Zones



Evolution of this economy over time. Initially, there is one development zone, with average productivity equal to 6.0. As the game continues, new jurisdictions are created and four development zones are established ($t = 7$). The game ends at $t = 10$, after the national government decides not to finance the fifth zone. Note that the position of each jurisdiction inside a development zone is random. The graph in the right hand-side depicts the national government's decision problem. The blue curve is the absolute reduction in average pollution as a function of the number of development zones. The red curve is the cost of financing a new development zone. When $|\Delta P^{av}| < Cost$, the national government stops financing new zones.

For the parameters we chose, the reduction in average local pollution becomes smaller than the cost of financing the fifth zone, so that the national government stops at four development zones. There would be further spatial development in this economy if the cost of financing new capital was smaller, or if the quality of capital decreased quicker with respect to the zone number. In other words, we would have further spatial expansion if it was cheaper to diffuse production spatially.

Figure 4, 5 and 6 present the evolution of the national spatial distributions of taxes, local population and local output over time, before the national threshold $\bar{P}$ is adjusted.

Figure 4 describes how production taxes change as the number of development zones increases. We show tax increments for each jurisdiction

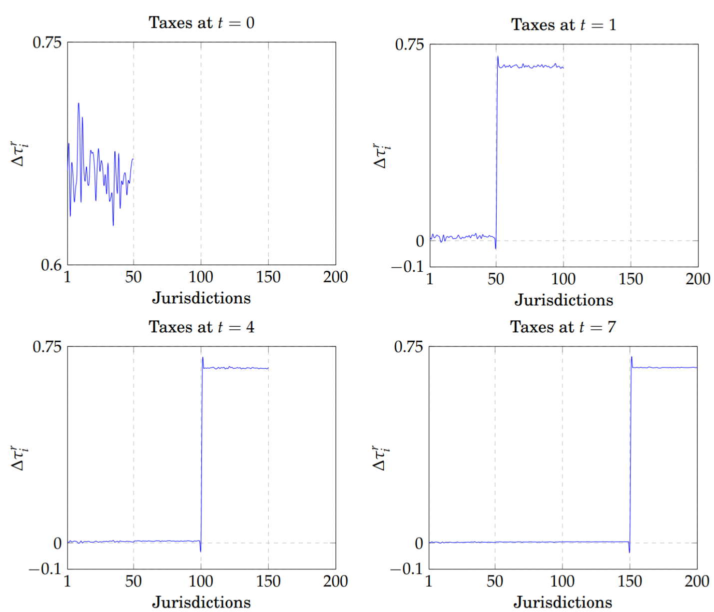
[32]We use *Matlab* to run the simulations. To solve the constrained linear system, we employ the function *lsqlin*.

over time. As the number of development zones increases, jurisdictions in older zones practically do not change their initial rate of taxes.

In absolute terms, local governments in older zones set greater taxes than governments in newer ones. Moreover, the national average level of taxes increases with the total number of zones in the economy. We see that by comparing tax averages over time. There is an increase in average taxes—from $t = 0$ (one zone) to $t = 7$ (four zones)—of approximately 2.1%. The reason behind this is that, as the number of jurisdictions and zones increase, the effect of an increase in taxes in the local population is smaller—going to zero when $NR \to \infty$.

Productivity and taxes determine how workforce and output are distributed within and across zones in this economy. As the graphs for workforce show in figure 5, increments in local workforce distribution are a function of tax distribution. Although workforce of jurisdictions of earlier development zones is always greater than in more recent zones, we see that they lose workers as new zones are created. When the national government finances a new zone, it also promotes migration of workers from earlier to newer regions in the economy.

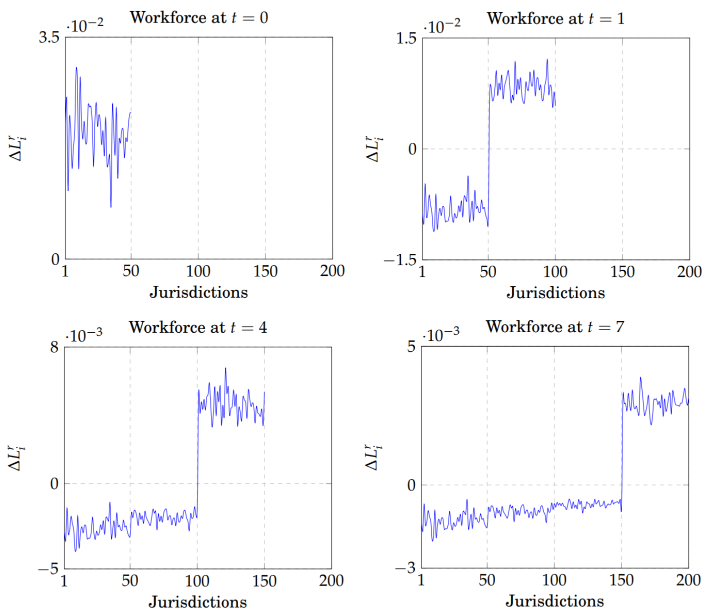
Figure 4: Simulation – Evolution of Tax Distribution across Jurisdictions



Tax increments, $\Delta\tau_i^r$, of each jurisdiction before the national threshold $\bar{P}$ is adjusted. At $t = 1$, there is one development zone. At $t = 7$, there are four zones.

Since local output is an increasing function of local workforce, we observe a similar pattern for the national distribution of output. As figure 6 shows, productivity and tax differences also determine output distribution nationally. The first development zone has the greatest population share and, also, the greatest output share relatively to other zones, approximately 39% of total national production. But this zone loses output in comparison to jurisdictions in more recent zones, as spatial economic development evolves in the country.

Figure 5: Simulation – Evolution of Workforce Distribution

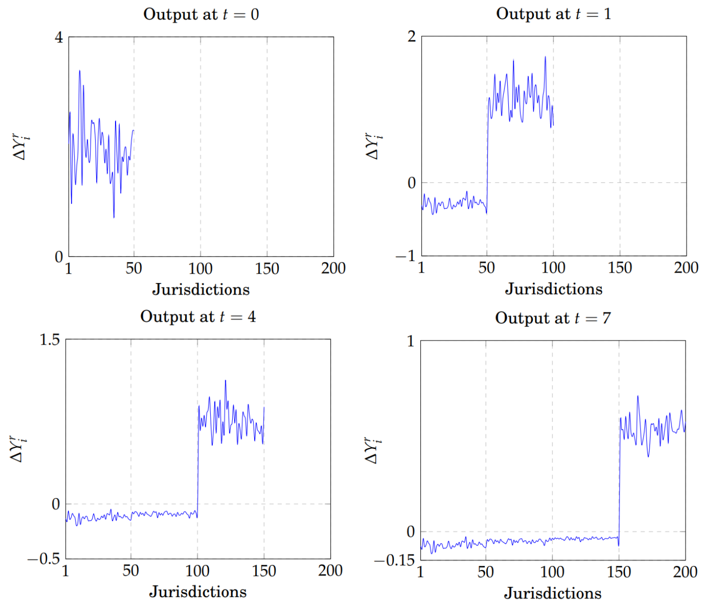


Workforce increments, ΔL_i^r, of each jurisdiction before the national threshold $\bar{P}$ is adjusted. At $t = 1$, there is one development zone. At $t = 7$, there are four zones.

At $t = 10$, after the national governments decides not to finance a new zone, a new national threshold is set. This new threshold is equal to the average local pollution in the country, with four development zones. For the set of parameters we use, $\bar{P}$ goes from 10 to 0.2. This severe reduction results in an average increase in taxes of approximately 4%.

As we discussed previously, a reduction in the national pollution threshold means a more stringent national environmental regulation. The amount transferred to local governments for health expenses is reduced, prompting them to increase production taxes to keep revenue levels. A way to interpret this increase in taxes is to think that local governments increase enforcement of environmental regulation—for example, in order to reduce direct health expenses or to send away dirty and inefficient industries.

Figure 6: Simulation – Evolution of Output Distribution



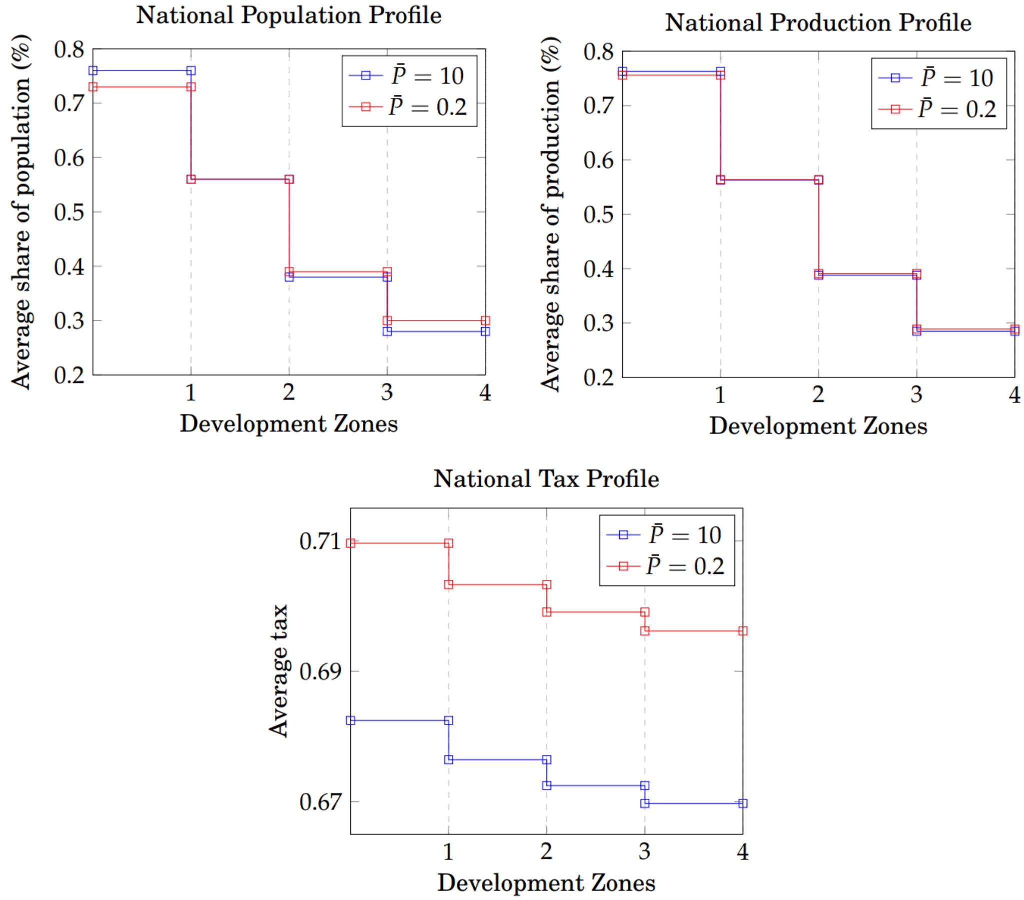
Output increments, ΔY_i^r, of each jurisdiction before the national threshold $\bar{P}$ is adjusted. At $t = 1$, there is one development zone. At $t = 7$, there are four zones.

Figure 7 compares these two situations: i) in blue, we present average optimal taxes, local population and local output for each zone at $t = 10$, with the old $\bar{P}$; ii) in red, we present these variables again, but for the new value of $\bar{P}$.

Optimal taxes increase in all four development zones after the threshold is adjusted. The average increase in the first zone is approximately 1% greater than the average increase in the fourth one. Zones that have greater average productivity increase taxes more than other zones. This has an impact in local population and local output.

As figure 7 shows, workers leave the most productive zone and migrate to newer zones. The fourth development zone has an average increase of local population of around 0.5%, whereas the first zone has an average decrease of approximately 0.3%. This movement of workers changes the national distribution of output. There is an increase in average output of zones 3 and 4; and total production in the first development zone falls. For our parameter values, the average output increase in the fourth zone is of approximately 0.2%. This zone receives the greatest number of migrants, and has the greatest increase in output.

Figure 7: Population, Production and Tax Profiles



These three graphs show the national profile of population, production and taxes for each development zone. We show the average jurisdiction share in each zone of total population and production before and after $\bar{P}$ is adjusted; and the average tax local governments set in each zone. Jurisdictions in zones 3 and 4 experience an increase in output and population shares.

5.3 Discussion

This section simulates the dynamic game we presented in figure 2. Local governments in different development zones, connected through free flows of workers, set production taxes simultaneously every time new jurisdictions are created. These governments seek to maximize revenue less health costs that are proportional to local pollution. They receive transfers from the national government, which decides whether to keep financing new development zones.

Tax competition between local governments determines the distribution of workers in space. This distribution, in turn, determines how output is distributed within and across development zones. Local governments' responses to changes in environmental regulation is a function of their level of tolerance towards pollution—that is, the difference between local pollution and the national threshold.

Our results demonstrate two things. First, the creation of new zones is partly determined by the outcome of the tax competition game. The reduction in average local pollution brought by the creation of a new zone is a function of the way workers are distributed spatially. If, for example, less productive jurisdictions were somehow able to retain more workers than more productive ones, reduction in average pollution would fall, and fewer development zones would be financed.

Second, workers and production shift from more to less productive regions when there is a change in national environmental regulation. A more stringent regulation changes the outcome of the tax competition game. The increase in taxes in undeveloped jurisdictions is smaller than in developed ones. Workers then migrate to interior zones, and production shifts to this region of the country.

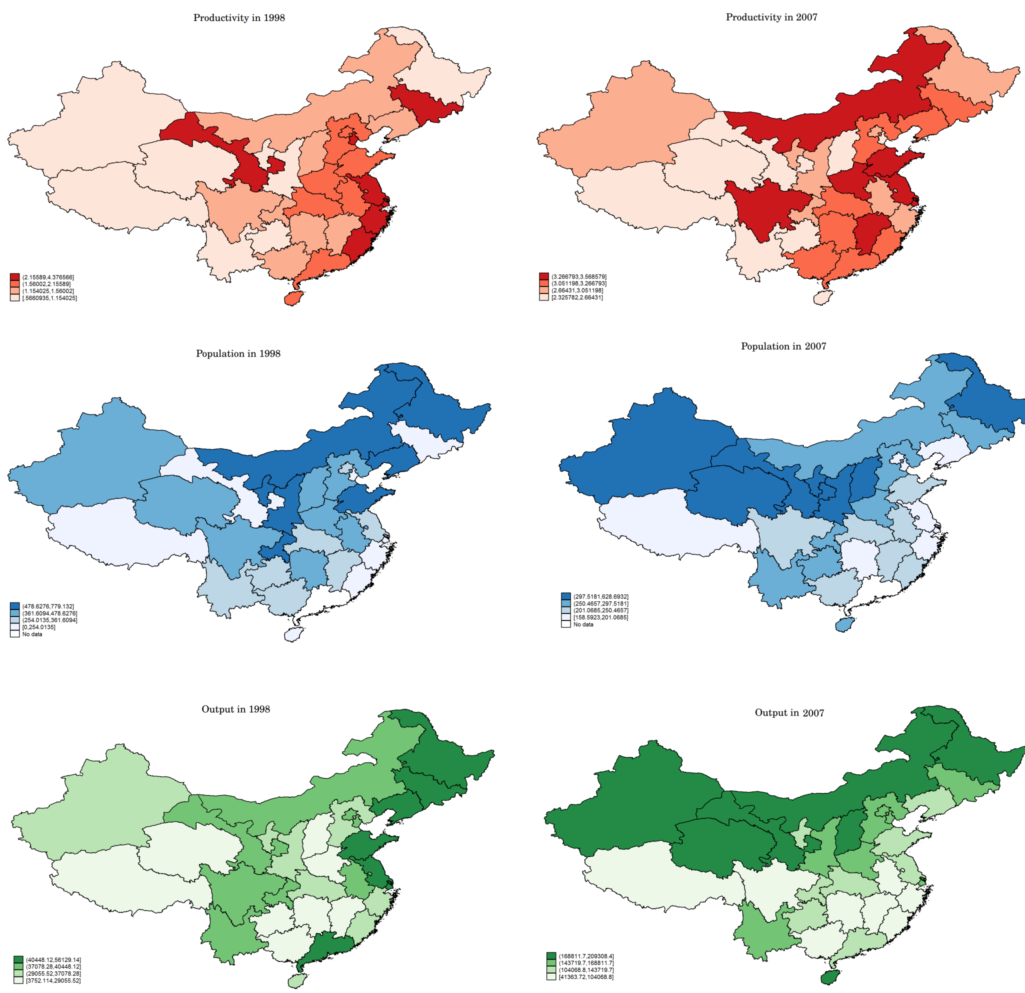
Therefore, the interaction between environmental regulation and imperfect institutions will determine the distribution of productivity and production in this economy. This, ultimately, will shape spatial economic development in the country.

Figure 8 presents distributions of productivity (red), workforce (blue) and output (green) by Chinese provinces in 1998 and in 2007. Darker colors mean higher concentrations of these variables. To calculate these figures, we used the Chinese Industrial Enterprise Database (CIED), which includes financial and operational information on firms with sales above 5 million RMB per year.

We see a clear shift in workforce and production over time. In 2007, hinterland provinces in the north of China concentrated most of output and labour share. This shows that, as our model posits, there was some kind of movement from the coast to the interior of the country in these nine years. The shift in productivity is less accentuated. But it also happened in a fashion that is somewhat similar to the one described by our model. In 1998, coastal provinces concentrated the most productive firms—that is, the most productive vintages of capital. In 2007, central provinces right next to coastal ones, increased their productivity levels, and some of them became the most productive in the country.

From 1998 to 2007, the Chinese central government introduced several new environmental regulations (Jiang et al. (2014)). From 1996 to 2013, for example, a series of new national pollution standards for different products in different industries were published and turned effective (Chinese Ministry of Environment). These standards most likely affected employment and production trends of firms surveyed in the CIED. Our model offers a framework to understand how the introduction of these environmental regulations might have contributed to the spatial configuration we see in figure 8. According to our results, part of the shift in these productive inputs, and in technology, might have been caused by the introduction of more stringent regulation.

Figure 8: Spatial Distribution of Productivity, Workforce and Output in China (1998 and 2007)



These six maps show the spatial distribution of TFP, workforce and output by province. The maps on the left hand-side depict these distributions in 1998, while the maps on the right hand-side show the same distributions for 2007. Darker colors mean greater concentration. Source: Chinese Industrial Enterprise Database.

6 Conclusion

Our theoretical analysis demonstrates that, in a context of tax competition and imperfect institutions, environmental regulation can reshape the spatial distribution of productive resources. This will also change the spatial pattern of economic development in a country.

In the case studied here, we see resources moving from more to less productive regions. Moreover, our analysis also shows that, if the national government faces an environmental–economic growth trade-off, it will finance development in undeveloped regions of the country until pollution reduction is equal to financing costs. This means that the national government will diffuse production into several development zones, before it adjusts the stringency of environmental regulation.

These findings provide evidence of the indirect spatial impact of environmental regulation. They contribute to the economic literature that studies the unforeseen consequences of environmental regulation (Hansman et al. (2015), Oliva (2015) and Duflo et al. (2013)). More than simply reducing pollution, regulation can redesign incentives and change economic outcomes. In a country like China, where enforcement of environmental standards varies greatly regionally, and local leaders seek promotion, environmental standards can attenuate or accentuate regional disparities.

Our results contribute to the tax competition literature in three ways. First, we introduce a model with production taxes instead of head or capital taxes (Zodrow and Mieszkowski (1986), Wilson (1986) and Wilson (1995)). Production taxes affect optimal output and employment values. Second, we show that asymmetries in terms of productivity are similar to asymmetries in terms of population size (Bucovetsky (1991) and Bucovetsky (2009)). Differences in productivity determine differences in taxes—as differences in population do for capital taxes. Finally, we construct a dynamic tax competition model with an increasing set of players (Janeba and Osterloh (2013)). We show that jurisdictions gradually increase taxes as the set of players increases.

7 Appendix

Proof of Proposition 1 We solve this first game (one urban ring) by backward induction. We start by the firm maximization problem, and wage equalization:

$$\underset{L_i}{\text{maximize}} \quad (1-\tau_i)Y_i - w_i L_i \tag{14}$$

F.O.C.: $w_i = (1-\tau_i)\alpha A_i (L_i)^{\alpha-1}$. By the fact that workers are completely mobile, we have that, $w_i = w_j \; \forall i, j$. Given that total population is normalized to 1, we have that:

$$L_i = \frac{1}{1 + \sum_{j=1}^{N-1} \left(\frac{A_i(1-\tau_i)}{A_j(1-\tau_j)}\right)^{\frac{1}{\alpha-1}}} \tag{15}$$

The derivative of this expression with respect to τ_i is negative, $\frac{\partial L_i}{\partial \tau_i} = \frac{L_i(1-L_i)}{(\alpha-1)(1-\tau_i)} < 0$. ■

Proof of Proposition 2 From local government i's F.O.C., we have that:

$$\tau_i \leq \frac{\phi(1+\alpha)\eta L_i}{\alpha} - \frac{\phi \bar{P} L_i}{\alpha Y_i} - \frac{(\alpha-1)(1-\tau_i)}{\alpha(1-L_i)}, \tag{16}$$

Taking the derivative of this expression with respect to A_i and A_j, and assuming that we are in a situation where the right hand side of this expression is greater or equal to zero, we have that,

$$\frac{\partial \tau_i}{\partial A_i} = E_1 \cdot \frac{\partial L_i}{\partial A_i} + E_2, \tag{17}$$

$$\frac{\partial \tau_j}{\partial A_j} = F_1 \cdot \frac{\partial L_i}{\partial A_j}, \tag{18}$$

where $E_1|_{\tau_i=0, A_i=A} = F_1|_{\tau_i=0, A_i=A} = \frac{-\phi \bar{P}(1+\alpha)N^\alpha}{A} < 0$ and $E_2|_{\tau_i=0, A_i=A} = \frac{\phi \bar{P}}{A^2}$, assuming that $N \gg 1$ and $\frac{\phi \bar{P}(1+\alpha)N^\alpha}{A} \gg (1-\alpha) + \phi(1+\alpha)\eta$.

Using the equation for wage equalization,

$$L_j = \left(\frac{A_i(1-\tau_i)}{A_j(1-\tau_j)}\right)^{\frac{1}{\alpha-1}} L_i \tag{19}$$

and taking its derivative with respect to A_i, we have an equation that relates $\frac{\partial \tau_i}{\partial A_i}$, $\frac{\partial \tau_j}{\partial A_i}$, $\frac{\partial L_i}{\partial A_i}$ and $\frac{\partial L_i}{\partial A_j}$.

Since total population is fixed, we also have that: $\frac{\partial L_i}{\partial A_i} + \sum_{i=1}^{N-1} \frac{\partial L_j}{\partial A_i} = 0$.

Working with all these equations, we end up with,

$$\frac{\partial \tau_i}{\partial A_i}|_{\tau_i=0,A_i=A} = \frac{AN^2(1-\alpha) - (1+\alpha)\phi\bar{P}N^{1+\alpha}}{AN(1-\alpha) - \phi\bar{P}(1+\alpha)N^{\alpha}} \tag{20}$$

This is positive if $\frac{\phi\bar{P}}{A} < \frac{(1-\alpha)N^{1-\alpha}}{1+\alpha}$.

■

Proof of Proposition 3 Rearranging the F.O.C. of the local government's optimization problem, we have that,

$$\tau_i \leq \frac{\phi[(1+\alpha)P_i - \bar{P}]}{\alpha\frac{Y_i}{L_i}} - \frac{L_i}{\alpha\frac{\partial L_i}{\partial \tau_i}}, \tag{21}$$

with equality if τ_i is positive, otherwise $\tau_i = 0$. Since the second term of the right hand side of this expression is positive, we can only have $\tau_i = 0$ if $\bar{P} > P_i$. And we just need $P_i > \bar{P}$ for $\tau_i > 0$. ■

Note that the first term of the right hand side of this expression is the contribution to the tax rate of the difference between local pollution and the national threshold scaled by output per capita. Jurisdictions where pollution levels are higher have an incentive to increase taxes.

The second term corresponds to the effect of the size of jurisdiction i on tax rates scaled by the change that a marginal increase in taxes will bring to its local population. Localities with greater population will have an incentive to increase taxes with respect to other localities.

Proof of Proposition 4 Similarly to the proof of proposition 2, we use F.O.C.'s and derive the following equations:

$$\frac{\partial \tau_i^r}{\partial A_i^r} = \frac{\partial L_i^r}{\partial A_i^r} \cdot E_1 + E_2 \tag{22}$$

$$\frac{\partial \tau_j^r}{\partial A_i^r} = \frac{\partial L_j^r}{\partial A_i^r} \cdot F_1 \tag{23}$$

$$\frac{\partial \tau_j^h}{\partial A_i^r} = \frac{\partial L_j^h}{\partial A_i^r} \cdot F_2 \tag{24}$$

Note that r refers to the last development zone built in this economy, and h refers other zones. Total population is fixed, $\sum_{h=1}^{r}\sum_{i=1}^{N} L_i^h = 1$. Using the equations for wage equalization, and after some derivation, we have that:

$$\frac{\partial L_i^r}{\partial A_i^r}|_{\tau_i=0,A_i^r=A^r} = \frac{1}{N\theta^r}\left(\frac{(\theta^r)^{-1}(1-\frac{\phi\bar{P}(N\theta^r)^{1-\alpha})}{A^R}}{(1-\alpha)A^r-\phi\bar{P}(1+\alpha)(N\theta^r)^{\alpha-1}}\right)+$$
$$\frac{1}{N\theta^r}\left(\sum_{h=1}^{r-1}\frac{(\theta^h)^{-1}\left(\frac{A^r}{A^h}\right)^{\frac{1}{\alpha-1}}(1-\frac{\phi\bar{P}(N\theta^h)^{1-\alpha})}{A^h}}{(1-\alpha)A^r-\left(\frac{A^r}{A^h}\right)^{\frac{1}{\alpha-1}}\phi\bar{P}(1+\alpha)(N\theta^h)^{\alpha-1}}\right) \tag{25}$$

Since E_1 is negative, $\frac{\partial\tau_i^r}{\partial A_i^r}$ will always be positive for $\frac{1}{(N\theta^r)^{1-\alpha}} < \frac{\phi\bar{P}}{A^r} < \frac{(1+\alpha)(N\theta^r)^{1-\alpha}}{(1+\alpha)}$, where $\theta^r = 1+\sum_{h=1}^{r-1}\left(\frac{A^r}{A^h}\right)^{\frac{1}{\alpha-1}}$.

■

Proof of Proposition 5 From proposition 3, we have the following linear system of equations (in matrix and vector form):

$$\boldsymbol{\tau} = -\boldsymbol{B_{1,2}}^{-1}\cdot\boldsymbol{B_3}(\bar{P}) \tag{26}$$

Note that $\boldsymbol{B_{1,2}}^{-1} > 0$, and that it is independent of $\bar{P}$. Thus, $\frac{\partial\tau}{\partial\bar{P}} < 0$.

■

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