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Location Choice by Households and Polluting Firms: An Evolutionary Approach

By B.R. Dijkstra and F.P. De Vries

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Abstract

This paper examines several policy regimes to deal with the problem that households suffer from environmental damage by firms in the same region. Taxation gives firms and households an incentive to stay away from each other. Laissez faire (compensation) only gives households (firms) an incentive to stay away from firms (households). We employ an evolutionary framework to analyze migration movements in the course of time, since firms and households will not relocate immediately in response to payoff differentials. We find that taxation creates the right incentives to reach a local welfare maximum. However, compensation may lead to a better outcome than taxation.

Outline

Non-technical summary

We usually think of polluting firms as causing pollution damage, and of households living nearby as victims of this damage. However, in this paper we recognise the reciprocal nature of local pollution: Local pollution only occurs when firms and households are located close to each other. We cannot see one actor as the culprit and the other as the victim.

We analyse a model with two regions (A and B), where there is only pollution damage when households and firms are in the same region. The optimal solution is that households (the largest group) are predominantly in A (the largest region). Because damage occurs when the two groups are in the same region, it is optimal to have at least partial segregation. That is, the optimum features either only households in A, only firms in B, or both. There may however also be another local optimum with firms predominantly in A.

We discuss the effects of three policy regimes: laissez faire, taxation and compensation. Under laissez faire, the government does not intervene. This means that households have an incentive to stay away from firms, because they are harmed by pollution. Firms, on the other hand, have no reason to stay away from households. Under taxation, firms have to pay a tax to the government according to the damage they "cause" (loosely speaking). Again, households stay away from firms, but now firms also stay away from households, because they are taxed. Finally, under compensation, firms stay away from households since they have to compensate households for the damage. Households have no reason to stay away from firms, because they are completely compensated for the pollution damage.

We take an evolutionary approach to analyze the location decisions by households and firms. When households can get a higher payoff in A than in B, they don't move immediately from B to A. Rather, there will be a stream of migration in the course of time until the payoff in both regions is equal.

We find that taxation gives just the right location incentives. Since pollution damage occurs when firms and households are in the same location, firms should be discouraged to locate near households and households should stay away from firms. As a result, taxation always leads to at least a local welfare optimum. Laissez faire and compensation, however, can also lead to a local welfare optimum. All that is needed is that the group that is in both regions takes pollution damage into account.

Our most important finding is that while taxation always leads to at least a local welfare optimum, compensation can outperform taxation. There are initial location patterns that evolve only to the "bad" local optimum under taxation, but to the "good" global optimum under compensation.

This result implies that policymakers should be aware of the effect of their environmental policy on migration decisions by households and firms and the long-run geographical distribution that will evolve. Taxation may look like a better instrument than compensation, because it gives households an incentive to stay away from firms. However, taxation may set the economy on a migration path toward an inferior location pattern.

1 Introduction

Environmental problems occur on different geographical scales: local, national, transboundary and even global. Depending on the nature of the problem, there may be several ways of dealing with it: reducing emissions, taking protective measures to limit the damage, or moving polluters and (potential) victims away from each other. Our paper focuses on the latter remedy. Needless to say, we don't wish to suggest that segregation is the only, or the preferable answer to all environmental problems. But in some cases, where economic activities cause local damage to other activities (like agriculture or recreation) or to human health, segregation may be effective.

In environmental economics, a polluter's decision where to produce subject to the strictness of environmental policy has become an important research area.[1] However, not only polluters can move to a region with more lenient environmental policy. Victims of pollution can also move to a region with better environmental quality. Presumably, environmental quality will be better in a region with less polluters. Conversely, polluters will cause less environmental damage to victims in a sparsely populated region, so that environmental policy in this region can be more lenient. Thus, one might expect polluters and victims to segregate as a response to the environmental problem.

The tendency to segregate depends, however, on the environmental policy regime. When firms are taxed according to environmental damage, firms and households will have an incentive to stay away from each other. Under the alternative regime of laissez faire, households still have an incentive to stay away from firms, but firms have no incentive to stay away from households. Some segregation will still take place, because households moving to the region with less firms will bid up land prices and thus crowd out firms. However, there will be less segregation under laissez faire than under taxation. Finally, when firms have to compensate households for environmental damage, firms have an incentive to stay away from households, but households have no incentive to stay away from firms. Again, there will be less segregation than under taxation.

Whereas complete segregation would eliminate the environmental problem, it may

[1] See Rauscher [13] [14] for overviews.

not be socially efficient. The payoff difference between the two regions under complete segregation may be so large that it is optimal to have only partial segregation: One region with only firms or households and the other region with firms as well as households. We shall see that taxation creates just the right incentives to reach a local welfare maximum. This is because environmental damage occurs when households and firms are in the same region. Therefore, firms should have an incentive to stay away from households and households should have an incentive to stay away from firms.

Since at least partial segregation is desirable, there may be multiple local welfare maxima. Likewise, since all policy regimes result in at least partial segregation, there may be multiple equilibria. In our two-region model with more households than firms, the global welfare optimum has households (the largest population) predominantly in the largest region. There may also be another local welfare optimum with firms predominantly in the largest region.

Taxation always results in a local welfare maximum, but laissez faire and compensation may also lead to this result. As long as the population located in both regions takes environmental damage into account, the local welfare maximum is implemented. Since at most one population is in both regions, there is no need for both populations to take environmental damage into account.

In order to find out which of the two local equilibria will result, we use evolutionary game theoretical concepts as introduced in biology by Maynard Smith and Price [8] and Maynard Smith [9] and applied to economics by Friedman [6] [7]. We regard an evolutionary approach as quite suitable for location decisions. When there is a payoff differential between the two regions, firms and households do not immediately move to the higher-payoff region. Rather, there will be a stream of migration in the course of time.

Our main result is that although taxation always leads to a local welfare maximum, it may not always be the best instrument. It is possible that taxation leads to the suboptimal local welfare maximum, whereas compensation results in the global optimum.

The rest of the paper is organized as follows. In Section 2, we review the literature.

Our model is introduced in Section 3. In Section 4, we determine the Nash equilibria of the three policy regimes and we determine which of the Nash equilibria are evolutionarily stable. In Section 5, we assess the outcomes of the policy regimes on welfare. Section 6 concludes the paper.

2 Review of the literature

In this review, we shall first discuss the literature on defence activities in general, including location choice. We then proceed with the literature on location choice by producers and victims of externalities.

Baumol [1] and Baumol and Oates ([2], pp. 106-8, 118-23) analyze the implementation of the welfare optimum with discrete location choice. In Chapter 4, Baumol and Oates [2] conclude that under appropriate convexity conditions, polluters should be taxed and victims should neither be compensated nor taxed. However, as Baumol [1] has shown, the externality itself may generate nonconvexities. As a result, there may be multiple local welfare maxima, some or all of them corner solutions. Baumol [1] discusses the example of location by households and smoke-emitting firms on an island separated by a ridge of mountains that prevent smoke from going from one side to the other. If the cost of smoke is high enough, there will be at least two local optima with complete segregation: households on one and firms on the other side. One of these local optima may be preferable to the other, for instance because one location offers great scenic attractions and the other is closer to raw materials. There may also be an interior maximum, if there are benefits of having firms and households on the same side.

In our model, we also have two locations for households and polluting firms. We find that there may be two local welfare maxima with at least partial segregation. As suggested by Baumol [1], we can rank these local optima. In the global optimum, the large population is predominantly located in the large region. Unlike Baumol [1] suggests, we have no interior optimum, because there is no reason for households and firms to be close to each other.

The problem with multiple local welfare maxima, as recognized by Baumol [1], is that taxation will lead toward a local optimum, but may lead away from the global optimum. Unlike the present paper, Baumol [1] and Baumol and Oates [2] do not explore the possibility that other instruments, for instance compensation of victims, may improve upon taxation.

Shibata and Winrich [15] model several specifications of victim defense activity. They point out that there can be multiple local optima, but the global optimum would depend on distributional considerations in the social welfare function, which they do not specify. In our model, by contrast, social welfare is simply the aggregate utility of all identical households, and the global optimum can be determined. Shibata and Winrich [15] also argue that if it is (locally) optimal to have only victim defense measures and no abatement by firms, laissez faire would also implement the optimum.[2] We shall encounter this argument in subsection 5.3 of our paper.

McKitrick and Collinge [10] derive a condition under which there is a unique local optimum in the presence of nonconvexities. They also discuss two strategies for implementation: an iterative tax rule and a non-iterative demand-revealing mechanism. In our paper, the iterative tax rule is to equate it to marginal damage, which is a special case of McKitrick and Collinge's [10] tax rule. Unlike McKitrick and Collinge [10], we are concerned mainly with the existence of multiple local optima, and the possibility that the iterative tax rule leads only to a local and not to the global optimum.

The literature on location choice by polluters and victims of externalities can be divided into two categories, according to the type of location choice. First, as in the present paper, the choice may be from a discrete set of regions or cities, where the location within the region or city does not matter. Secondly, the choice may be among a continuum of locations within a certain plain or city. These models explicitly take the land market into account, as does our paper.

Copeland and Taylor [5] consider a two-country two-industry world with free trade and without environmental policy. The "Smokestack" industry adds to the national stock of pollution and the "Farming" industry suffers from the national stock of pollu-

[2] Shibata and Winrich [15] claim that taxation does not lead to the optimum in this case, but Oates [12] shows that it does.

tion.[3] Pollution does not directly harm consumers. Copeland and Taylor [5] find that the diversified autarky equilibrium is unstable and there may be two stable equilibria with at least partial specialization. When one country needs to be diversified, this should be the country with the lowest labour endowment[4] or the largest regenerative capacity. However, Copeland and Taylor [5] show that the world does not necessarily evolve to the desired specialization pattern.[5]

In our model, we call the smokestack industry firms and the farming industry consumers. The dynamic adjustment process arises from the sluggish adjustment of environmental quality to emissions in Copeland and Taylor's [5] model and from the sluggish adjustment of firms' and households' location decisions to payoff differentials in our model. We also find that the interior equilibrium is unstable and the corner equilibria are stable. Unlike Copeland and Taylor [5], we do not only model laissez faire, but also taxation of polluters and compensation of victims. Finally, we also find that the world may evolve to the inefficient equilibrium.

Miyao [11] analyzes both types of location choice. First, he assumes no transportation cost. There are two populations, the members of which can either live inside the city or outside. The latter option yields an exogenously given payoff. The payoff of an agent within the city is increasing in the amount of a consumption good and the amount of residential land. Furthermore, in the case of negative intergroup externalities, payoff is decreasing in the size of the other group in the city. With positive intragroup externalities, an agent's payoff is increasing in the size of the own group in the city. Unsurprisingly, Miyao [11] derives the same qualitative results for both kinds of externalities. A mixed-city Nash equilibrium, with both populations in the city, is unstable and the two Nash equilibria with a single population in the city are stable.

Miyao [11] also analyzes the case with transportation cost within the city. Then an agent must also decide where to live in the city. Miyao [11] finds that this has

[3] Unteroberdoerster [16] adds transboundary pollution to Copeland and Taylor's [5] model.

[4] This is because the industries will be smaller in the country with the low labour supply, and thus the externality is smaller.

[5] As Copeland and Taylor [5] already note, even when the optimal specialization pattern is achieved, it may not implement the first best. The Smokestack industry will emit too much in the diversified country, because there is no environmental policy.

a stabilizing effect on location choice. The mixed city can now be a stable Nash equilibrium.

Like Miyao [11], we examine a negative intergroup externality and we only endogenize location choice, from which land size and the extent of the externality follow. However, whereas the externality is always reciprocal in Miyao [11], we let the direction of the externality depend on environmental policy. With taxation, the externality is reciprocal. With laissez faire, the firms confer a negative externality upon the households. With compensation, the households confer a negative externality on the firms. Furthermore, whereas Miyao's [11] model features one location and an exogenously given outside option, our model features two locations. Thus, we endogenize the outside option. Analogous to Miyao [11], we find that a Nash equilibrium with households and firms in both regions is unstable.

3 The model

3.1 Introduction

In our review of the literature, we have seen that there are no contributions that relate directly to our subject of location decisions by households and polluting firms under different policy regimes. We shall therefore set up our own model in this section, keeping it as simple as possible. As we shall see in subsection 3.4, environmental damage is a factor that influences location decisions of some populations under some policy regimes. However, environmental damage is not always a driving force. We therefore need at least one other factor that influences the location decision. This will be the land market: Firms and households prefer to locate in the region with the lowest ground prices. A household's utility is linearly separable in the consumption good, land size and pollution.

There are two populations: households h and firms f. There are N_h households and N_f firms. Let $n_f = N_f/N_h$. For the sake of concreteness, we only analyze the case where $n_f < 1$: there are less firms than households.

There are two regions, $z = A, B$. Denote by s_k^A the fraction of population k ($k = h, f$) located in region A. There is a fixed area of land in either region that can be occupied. We denote the inverse of the location size by D^z. Region A is larger: $D^A < D^B$.

In this section we discuss production by firms and consumption by households (subsection 3.2), the land market (3.3), pollution and environmental policy (3.4).

3.2 Firms and households

The firms in region z produce a homogeneous good x with land g^z and a firm-specific indivisible factor F. The production technology features constant returns to scale and thus diminishing marginal returns to land. The production x_f^z of x by a firm in region z is then given by:

$$x_f^z = \phi(g^z) \qquad \phi'(g^z) > 0 \qquad \phi''(g^z) < 0 \tag{1}$$

Since good x is chosen as the numeraire, $\phi(g^z)$ is also the firm's revenue.

The utility from consumption for household H in region z is given by:

$$u_H^z = x_H + m_H u(g^z/m_H) \qquad m_H > 0 \qquad u' > 0 \qquad u'' < 0 \tag{2}$$

where x_H is the household's consumption of x and $m_H u(g^z/m_H)$ its utility from land. We assume that the payoff function $u(g^z)$ from land equals the firm's production function $\phi(g^z)$ of land. Thus, the firm's production function (1) becomes:

$$x_f^z = u(g^z)$$

The assumption implies that one firm's demand for land equals the demand by m_H households. We can then scale household size such that one firm's demand for land equals one household's demand for land. Let there be M_H households H with utility from consumption given by (2). Then there are $N_h \equiv M_H/m_H$ households h with utility from consumption given by:

$$u_h^z = x_h + u(g^z) \tag{3}$$

The market clearing condition for good x is:

$$x_h = n_f \left[s_f^A u(g^A) + (1 - s_f^A) u(g^B) \right] \tag{4}$$

The LHS of (4) gives a household's consumption of x. The RHS represents the firms' production in regions A and B respectively, normalized by the number of households N_h.

Households derive income from the ownership of land and firm shares and possibly from the redistribution of tax revenues or compensation of environmental damage. While all households have identical tastes, they may differ in their incomes. However, we shall assume that each household has enough income to consume at least some x. Then all households in region z will occupy the same area of land g^z.

3.3 Land

The land market in both regions is competitive which means that the whole area will always be rented out to occupants. As we have seen in subsection 3.2, a household's utility as well as a firm's revenue from land in z is given by $u(g^z)$.

Given that a household is in area z, its land size is determined by:

$$\max_{g^z} u(g^z) - p^z g^z, \tag{5}$$

where p^z is the rental price of land in area z. The solution to (5) is:

$$u'(g^z) = p^z. \tag{6}$$

Since all occupants (households and firms) have the same demand function, the total area is distributed equally among them. Denoting the inverse of region z's size by D^z, this implies that the area g^z per occupant in region z is given by the inverse of the population density d^z:

$$g^A = \frac{1}{d^A} = \frac{1}{D^A N_h (n_f s_f^A + s_h^A)} \qquad g^B = \frac{1}{d^B} = \frac{1}{D^B N_h [n_f(1 - s_f^A) + (1 - s_h^A)]}. \tag{7}$$

Substituting (6) and (7) into (5), we find for the net payoff from land in region z:

$$\begin{aligned} \Pi^A(s_f^A, s_h^A) &= \pi(d^A) = u\left(g^A\right) - \frac{u'\left(g^A\right)}{D^A N_h (n_f s_f^A + s_h^A)} \\ \Pi^B(s_f^A, s_h^A) &= \pi(d^B) = u\left(g^B\right) - \frac{u'\left(g^B\right)}{D^B N_h [n_f(1 - s_f^A) + (1 - s_h^A)]} \end{aligned} \tag{8}$$

with g^A and g^B given by (7). We will refer to Π^z as the consumer surplus (for households) or operating profit (for firms) from occupying land in region z. Consumer surplus or operating profit is a function Π^z of the population shares in A. The function $\Pi^A(s_f^A, s_h^A)$ is decreasing in both arguments. Conversely, the function $\Pi^B(s_f^A, s_h^A)$ is increasing in both arguments. Consumer surplus can also be written as a function π of population density d^z, with $\pi'(d^z) < 0$.

3.4 Pollution and environmental policy

Households suffer from pollution by firms in the same region. A household's payoff is linearly decreasing in total regional emissions. Emissions are caused by the firms' use of the fixed production factor F. Emissions per firm, independent of its location, are denoted by e. Firms cannot decrease their emissions by reducing output or taking abatement measures.

We consider three environmental policy regimes:

- Laissez-faire: no environmental policy. Households tend to stay away from firms, because they are harmed by the firms' pollution. Firms, on the other hand, have no incentive to stay away from households;
- Taxation: firms are taxed for the total damage they inflict upon households.[6] The tax revenues are distributed in lump-sum fashion among households. Households tend to stay away from firms (because of the pollution) and firms tend to stay away from households (because they are taxed for the damage they cause). Thus, households' and firms' incentives are symmetric.
- Compensation: firms fully compensate households for the damage they inflict upon them. Firms tend to stay away from households, because they have to compensate households for the damage they cause. Households, on the other hand, have no incentive to stay away from firms. They are fully compensated for the pollution damage they suffer from firms. Thus, compensation is the mirror image of laissez-faire, with interchanged incentives for households and firms.

[6] Note that average damage equals marginal damage, so that this tax can be seen as a Pigouvian tax.

4 Policy Equilibria

In this section, we determine the Nash and evolutionary equilibria of the three policy regimes. In a Nash equilibrium, no one has an incentive to move. Thus means we need to determine the loci, where a population is indifferent between the two locations. For corner solutions, with one or both populations in one location only, we also have to determine whether this population wants to stay there. An evolutionary equilibrium is a stable Nash equilibrium. Thus, in order to find the evolutionary equilibria, we have to look at the phase diagram to see whether populations move toward the Nash equilibrium. The loci and the dynamics are given by:

- ff' : firms, taking environmental damage into account, are indifferent between A and B. This applies to taxation and compensation.

$$\Pi^A(s_f^A, s_h^A) - eN_h s_h^A = \Pi^B(s_f^A, s_h^A) - eN_h(1 - s_h^A) \tag{9}$$

  When the LHS is larger (smaller) than the RHS, firms move to A (B).

- hh' : households, taking environmental damage into account, are indifferent between A and B. This applies to laissez faire and taxation.

$$\Pi^A(s_f^A, s_h^A) - en_f N_h s_f^A = \Pi^B(s_f^A, s_h^A) - en_f N_h(1 - s_f^A) \tag{10}$$

  When the LHS is larger (smaller) than the RHS, households move to A (B).

- dd' : the population that only takes density into account, is indifferent between A and B. This applies to firms under laissez faire and to households under compensation. The condition is $\Pi^A(s_f^A, s_h^A) = \Pi^B(s_f^A, s_h^A)$, or substituting (8):

$$D^A\left(n_f s_f^A + s_h^A\right) = D^B\left[n_f(1 - s_f^A) + 1 - s_h^A\right]. \tag{11}$$

  When the LHS is smaller (larger) than the RHS, the population moves to A (B).

Figures 1 to 3 show the phase diagrams for the three policy regimes. The locus dd' is always linear. For simplicity, the lines ff' and hh' are also drawn as linear.

For each policy regime, there are two possibilities: either the loci intersect (and they do so once), or they don't. These possibilities are shown in the right and left-hand panel, respectively of Figures 1 to 3. If the loci don't intersect for a given policy regime, there is one Nash equilibrium, which is in a corner. If the loci intersect, there are two additional Nash equilibria: one in the opposite corner and one interior.

Let us now state this result formally.[7] Qualitatively, there are seven different location configurations, which we shall refer to with shorthand notation like (f, fh). This means: firms in A and firms and households in B. The configurations can be classified into three types. Type FH comprises $(f, h), (fh, h)$ and (f, fh). Type HF comprises $(h, f), (fh, f)$ and (h, fh). The mixed type consists of (fh, fh) only.

Proposition 1 *Under laissez faire, there are three Nash equilibria (one FH, one HF and one mixed), if and only if:*

$$n_f D^B < (2 + n_f) D^A \tag{12}$$

If and only if (12) is not satisfied, there is a unique Nash equilibrium which is of the FH type.

Proposition 2 *Under taxation, there are three Nash equilibria (one FH, one HF and one mixed), if and only if:*

$$\Pi^A\left(1, \frac{1}{2} + \frac{1}{2}n_f\right) - eN_h n_f < \Pi^B\left(1, \frac{1}{2} + \frac{1}{2}n_f\right) \tag{13}$$

If and only if (13) is not satisfied, there is a unique Nash equilibrium which is of the HF type.

Proposition 3 *Under compensation, there are three Nash equilibria (one FH, one HF and one mixed), if and only if:*

$$D^B < (1 + 2n_f) D^A \tag{14}$$

If and only if (14) is not satisfied, there is a unique Nash equilibrium which is of the HF type.

[7] All proofs are in the Appendix.

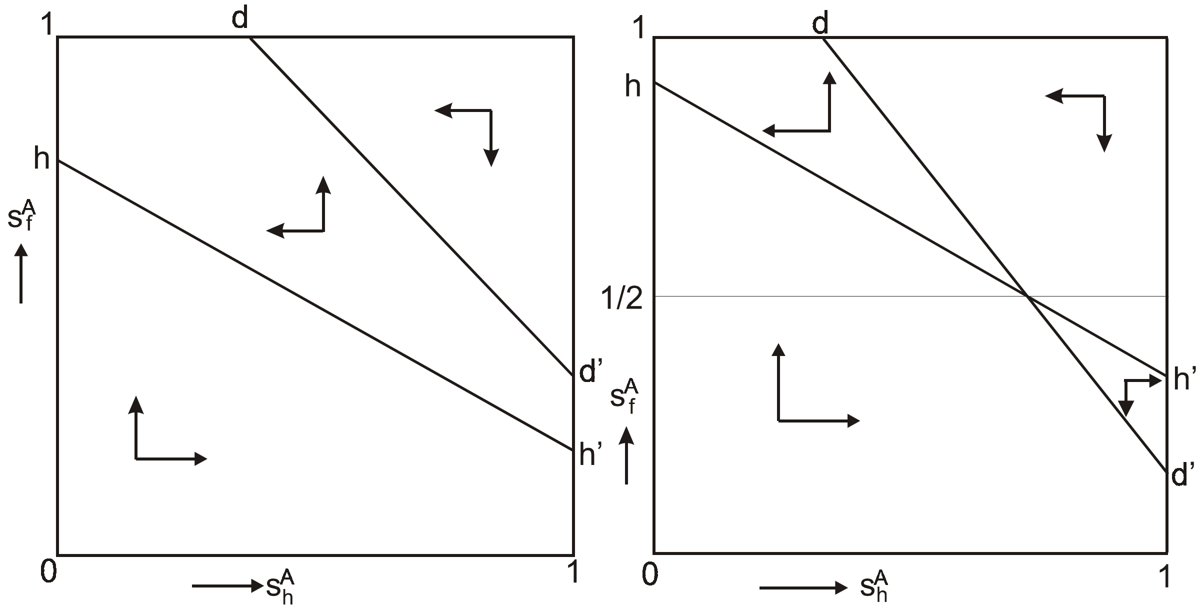

Figure 1: Phase portraits laissez faire. Left: one equilibrium, right: multiple equilibria.

As we can see from the phase diagrams, the corner NE are evolutionarily stable and the interior NE are not:

Proposition 4 *For all policy regimes, a Nash equilibrium is an evolutionary equilibrium if and only if it is a corner Nash equilibrium.*

Let us now discuss the outcome for laissez faire with the aid of Figure 1. The discussion for taxation and compensation is similar.

From Figure 1 it is clear that there is an FH equilibrium (in the upper left hand corner) when point h is to the left of point d. In point d, firms are indifferent between A and B. All firms are in A and households are in A and B so that density is equal and firms are indifferent between A and B. In point d, households prefer the clean region B. For households to be indifferent, there should be more households in B and less in A. Thus h is to the left of d.

There is an HF equilibrium (in the lower right hand corner) under laissez faire when point h' is above or to the right of point d'. Point d' can be either on the $s_f^A = 0$ or on the $s_h^A = 1$ axis. In point d' on the $s_f^A = 0$ axis, all firms are in B and households are in A and B so that density is equal and firms are indifferent between A and B.

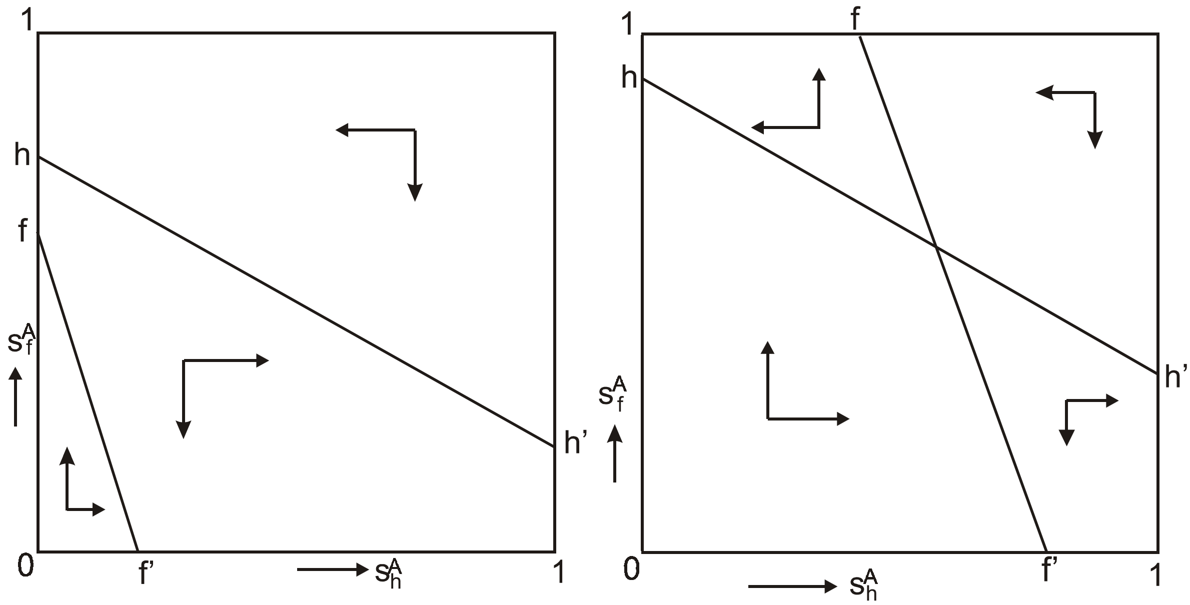

Figure 2: Phase portraits taxation. Left: one equilibrium, right: multiple equilibria.

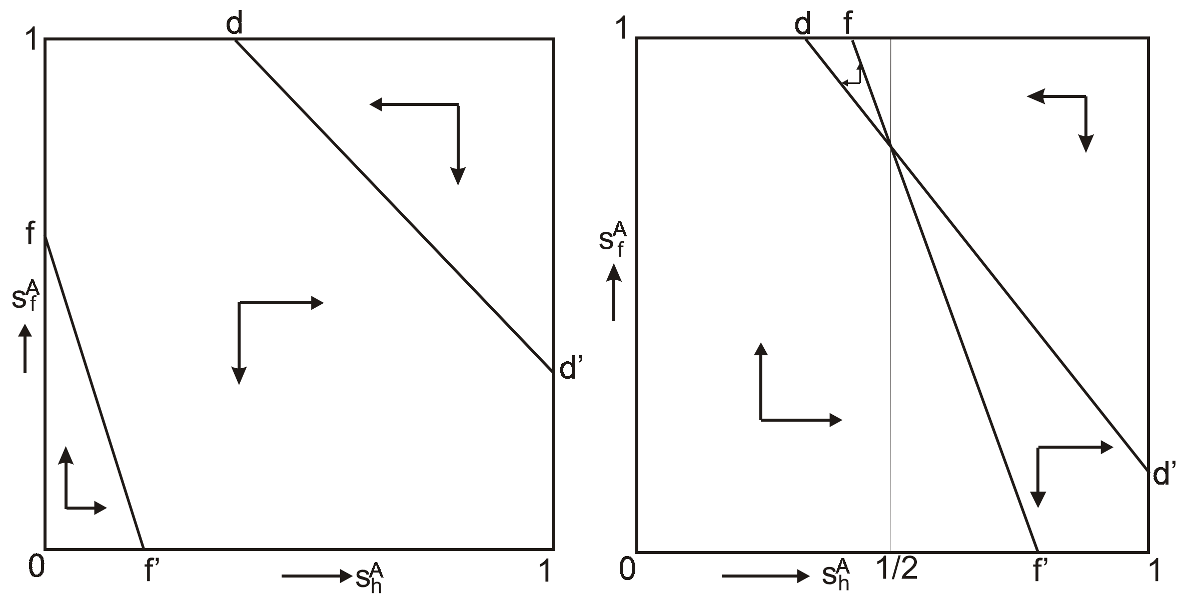

Figure 3: Phase portraits compensation. Left: one equilibrium, right: multiple equilibria.

Then households prefer the clean region B. For households to be indifferent, there should be more households in A. Thus h' is to the right of d' and there is always an HF equilibrium when d' is on the $s_f^A = 0$ axis.

In point d' on the $s_h^A = 1$ axis (as in Figure 1), all households are in A and firms are in A and B so that density is equal in A and B and firms are indifferent. In point d', when there are less (more) firms in A than in B, households prefer A (B) and h' is below (above) d'. Thus, there is not always an HF equilibrium under laissez faire.

Finally, it is clear from Figure 1 that there is an interior Nash equilibrium if and only if there is an HF equilibrium. The interior equilibrium is unstable because the hh' curve is flatter than the dd' curve. To understand why hh' is flatter than dd', let us consider what happens when, starting from the interior NE, we move a number of households from A to B. That is: we move horizontally to the left from the intersection of hh' and dd'. The question is how many firms we have to move from B to A in order to make households and firms indifferent between A and B again. That is: how far do we have to move up to reach hh' or dd' again. For firms, it is just a matter of restoring equal density in both regions. For households, however, the movement of firms does not only increase density in A compared to B, but it also increases pollution in A compared to B. Thus less firms need to move from A to B to make households indifferent than to make firms indifferent. In terms of Figure 1, this means that hh' is flatter than dd'.

5 Welfare analysis

5.1 Introduction

In this section, we shall analyze the welfare performance of the three policy regimes. The question is which policy regime leads to the best equilibrium in terms of welfare. In subsection 5.2, we determine the welfare optima. We shall see that the first order conditions are identical to the loci for taxation. Thus, taxation always results in at least a local welfare optimum.

However, as we shall see in subsection 5.3, laissez faire and compensation can also lead to a local welfare optimum in some cases. As long as the population that is in both regions takes environmental damage into account, an evolutionary equilibrium is a local welfare optimum.

Finally, in subsection 5.4, we address the question whether another policy regime can lead to a better outcome than taxation. We shall see that compensation may outperform taxation.

5.2 Welfare optima

In this subsection we shall identify the welfare optima. Aggregate per capita welfare is:

$$\begin{aligned} W(s_f^A, s_h^A) &= s_h^A u(g^A) + (1 - s_h^A)u(g^B) + n_f \left[s_f^A u(g^A) + (1 - s_f^A)u(g^B) \right] \\ &\quad - N_h n_f e s_f^A s_h^A - N_h n_f e(1 - s_f^A)(1 - s_h^A). \end{aligned} \tag{15}$$

The first two terms on the RHS of (15) represent the household's utility of land in regions A and B, respectively. The third term is the household's utility from the consumption good x, which by (3) equals its consumption x_h. By the market clearing condition (4), per capita consumption of x must equal its per capita production. The last two terms reflect the household's damage from emissions by firms in regions A and B, respectively.

Taking the first derivatives of W with respect to s_f^A and s_h^A yields, from (15), (7) and (8):

$$\frac{\partial W}{\partial s_f^A} = n_f \left[\Pi^A(s_f^A, s_h^A) - eN_h s_h^A - \Pi^B(s_f^A, s_h^A) + eN_h(1 - s_h^A) \right] = 0 \tag{16}$$

$$\frac{\partial W}{\partial s_h^A} = \Pi^A(s_f^A, s_h^A) - eN_h n_f s_f^A - \Pi^B(s_f^A, s_h^A) + eN_h n_f(1 - s_f^A)u(g^A) = 0 \tag{17}$$

We see that the first order conditions for s_f^A and s_h^A correspond to the conditions (9) for firms and (10) for households to be indifferent between A and B under taxation. Furthermore, when welfare is increasing in s_f^A (s_h^A), firms (households) will be moving to A under taxation. Our findings from section 4 about the Nash and evolutionary equilibria under taxation can then be translated into welfare terms as follows:

Proposition 5 *1. When there is an interior solution to the first order conditions (16) and (17), it is a saddle point.*

2. There is always a (local) welfare maximum HF.

3. There may be an additional local welfare maximum FH.

The close connection between taxation and welfare can be interpreted as follows. Environmental damage occurs when firms and households are in the same location. Thus, firms as well as households should have an incentive to stay away from each other. These are exactly the incentives that taxation provides.

When both HF and FH are local welfare maxima, it is best to have the largest group in the largest region. Therefore households should be in A and firms in B rather than the other way around:

Proposition 6 *HF is the global welfare maximum.*

5.3 Local assessment of policy regimes

In this subsection, we shall see whether the evolutionary equilibria of the policy regimes correspond to a local welfare maximum. We already know that taxation always results in a local welfare maximum. However, laissez faire and compensation may also lead to a welfare maximum. This will happen when either the two populations are completely separated or the population that is in both regions takes environmental damage into account.

With laissez faire, only households take environmental damage into account. Laissez faire always has an equilibrium FH, which is either (f, h) or (fh, h). This equilibrium corresponds to the local (suboptimal) welfare maximum FH, if it exists. There may also be an evolutionary HF equilibrium. When this is (h, f) or (h, fh), it will correspond to the global welfare maximum. When the laissez faire equilibrium is (fh, f), it deviates from the global optimum. This is because the firms consider both locations, and they do not take environmental damage into account. Thus s_f^A will be higher than optimal.

With compensation, only firms take environmental damage into account. Compensation always has an equilibrium HF. This corresponds to the global optimum when the equilibrium is (h, f) or (fh, f). When the compensation equilibrium is (h, fh), it deviates from the global optimum. This is because the households consider both locations, and they do not take environmental damage into account. Compensation may also have an evolutionary FH equilibrium, which will always be (fh, h). This equilibrium never corresponds to the local optimum, because the households do not take environmental damage into account.

5.4 Global assessment of policy regimes

We now know that taxation always results in a welfare maximum and that compensation and laissez faire may also lead to a welfare maximum. The question we address in this subsection is: Are there cases in which laissez faire or compensation outperforms taxation? This would happen when taxation leads to the suboptimal local welfare maximum FH and the other instrument results in a better HF.

It is easily seen that taxation is always better than laissez faire.[8] The interesting comparison is between compensation and taxation. We will only compare evolutionary equilibria, because these are the only equilibria that a system can evolve to. We know from Propositions 2 and 3 that taxation and compensation have either one or two evolutionary equilibria. That means we have to distinguish three situations:

1. Taxation and compensation have only one equilibrium.

2. One policy regimes has two evolutionary equilibria, the other has only one.

3. Both policy regimes have two evolutionary equilibria.

In case 1, taxation yields the global welfare maximum. Compensation results in the global welfare maximum when $D^A < n_f D^B$. Thus, taxation is always at least as good as compensation, and sometimes even better.

[8]This can be checked by going through the steps detailed below for the comparison between compensation and taxation. Note that the difference between compensation and laissez faire is due to our assumption that there are more households than firms (or more precisely, households have higher aggregate demand for land). If there were more firms than households, the results would be the other way around.

In case 2, there will be multiple evolutionary equilibria with taxation (the global HF and the local FH welfare maximum), whereas there is only one equilibrium (the global welfare maximum HF) with compensation:

Lemma 7 *When there is a single evolutionary equilibrium (EE) under taxation, there can be two EE under compensation. However, when there is a single EE under compensation, there is also a single EE under taxation.*

This implies that there are initial states that lead to the local welfare maximum HF under taxation, but to FH under compensation. As we know from subsection 5.3, compensation implements the global optimum if households are only located in region A. But even if compensation does not implement the global optimum, welfare in HF under compensation may still be higher than in FH under taxation. Thus, there are initial states from which compensation leads to a better outcome than taxation.

Intuitively, the reason why there may be an FH equilibrium under taxation, but not under compensation, is the following. Because points d and f in Figures 2 and 3 are always on the $s_f^A = 1$ axis, the FH equilibrium is either (f, h) or (fh, h). Thus FH is an equilibrium if and only if all firms want to remain in A. With compensation, households are not bothered by the firms' pollution, so that there will be more households in A than with taxation. This makes A a less pleasant place for firms, both because of the higher land rents and the higher payments for pollution. Thus, the conditions for an FH equilibrium to exist are stricter under compensation.

Finally, we look at case 3, where both taxation and compensation have multiple equilibria. The question is whether there are initial states that evolve toward FH under taxation and toward HF under compensation. In that case, as explained above, there are circumstances under which welfare in the equilibrium with compensation is higher than with taxation.

If we make an integral picture which includes all loci of the three policy regimes, we get a picture as given in Figure 4.[9] Under taxation, a starting point in the area $rfvh$ results in the suboptimal FH equilibrium r. Under compensation, a starting point in

[9] The arrows are valid for taxation and compensation, but not necessarily for laissez faire.

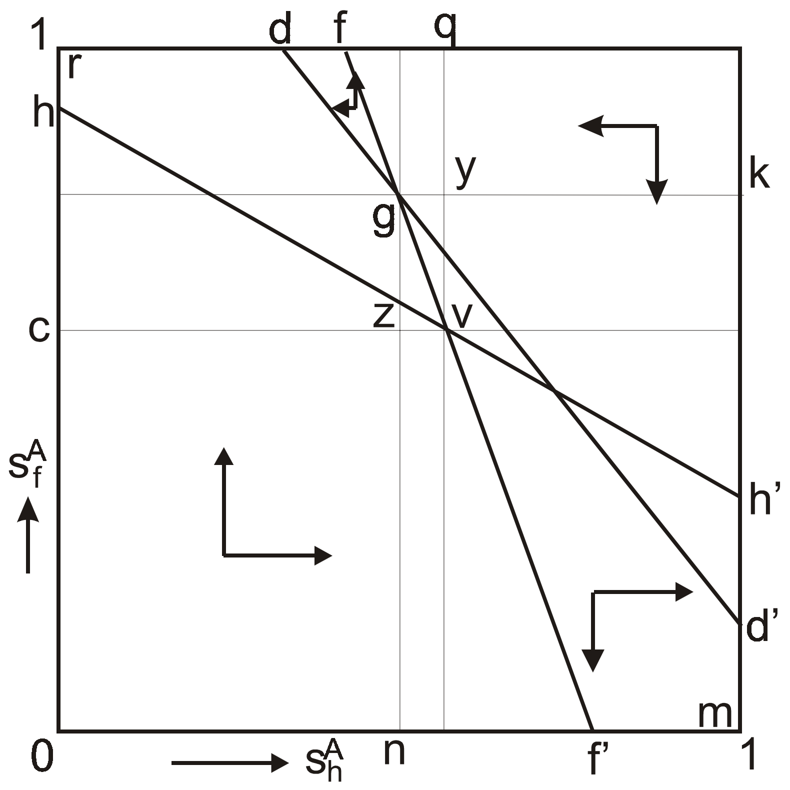

Figure 4: Overall phase portrait

the area $mf'gd'$ results in the optimal HF equilibrium m. We see that there is no overlap between these two areas.

However, we can actually say something about a larger area. For instance, look at a starting point in the area chv under taxation. We know firms as well as households will start moving from B to A. At some point in time, the system will reach the line hv, where households are indifferent between B and A. Then it enters the area $rfvh$, where households move from A to B, and firms still move from B to A, until the equilibrium r is reached. A starting point in the area cvh must result in r, because the dynamics can never cross the cv line. Thus, they must eventually enter the $rfvh$ area, and $rfvh$ results in r.

Applying the above reasoning, we can be sure that all initial states in the area $rqvc$ evolve toward the bad equilibrium r under taxation. Under compensation, all initial states in the area $gkmn$ will evolve toward the good equilibrium m. Note that there is an overlap between the areas $gkmn$ and $rqvc$, consisting of $gyvz$. Initial states in this area will evolve toward the global welfare maximum under compensation, but only toward the local maximum under taxation. Thus, when the starting point is in the area $gyvz$, compensation leads to a better outcome than taxation.

The proof that there always exists an area $gyvz$ which evolves to r under taxation and m under compensation is straightforward. Note that the corner points g and v are always on ff'. All we need to show is that point g is to the left of point v. These points are the mixed equilibria of compensation and taxation, respectively. As the proofs of Propositions 2 and 3 show, the mixed equilibrium has $s_h^A = \frac{1}{2}$ under compensation (point g) and $s_h^A > \frac{1}{2}$ under taxation (point v). Intuitively, the reason is as follows.

Consider the mixed equilibrium under compensation. To keep households indifferent between the two locations, they should have the same density. Firms are interested in density and compensation payments. Since both regions have the same density, they should also have the same level of compensation payment per firm. This means that the number of households should be the same in both regions. Thus, in the interior Nash equilibrium g under compensation, half of the households is in A.

Under taxation, both firms and households take density and pollution into account. In terms of density, one region will be more attractive than the other, and equally so to firms and households. This means that in terms of pollution, this region must be equally unattractive for firms and households. Thus, the difference in the number of firms between A and B should equal the difference in the number of households. There must be more households and firms in A than in B, since otherwise, density as well as pollution would be higher in B. Thus, in the interior Nash equilibrium v under taxation, more than half of the households is in A.

6 Conclusion

We have modelled location choice by households and firms, where households suffer from pollution by firms in the same region. Since households and firms will not move immediately in response to payoff differences, we have used an evolutionary approach. We have studied three policy regimes. Under taxation, firms and households have an incentive to stay away from each other. Under laissez faire, households have an incentive to stay away from firms, but firms do not have an incentive to stay away from households. Finally, under compensation, firms have an incentive to stay away from households, but households don't have an incentive to stay away from firms.

There is a close association between taxation and welfare. This is because damage arises when firms and households are in the same region. Thus, one would want firms to stay away from households and households to stay away from firms. These are exactly the incentives that taxation creates.

Although taxation always leads to a local welfare maximum, this does not imply that taxation is always the best instrument. Laissez faire and compensation may also lead to welfare maxima. This is because the maximum is always a corner solution: at least one population locates in only one region. Only the population that is in both regions should take environmental damage into account. In fact, it is possible that compensation leads to the global welfare maximum, whereas taxation only leads to the local optimum.

Building our model, we have had to make some special assumptions that it would be worthwhile to relax. We could allow for firms to reduce their emissions by reducing output and possibly by reducing emissions per unit of output as well, and for households to take other defensive measures than moving away from the polluted region. With taxation, firms would take the optimal abatement measures and households would take the optimal defensive measures. With laissez faire, households would take defensive measures, but firms would not undertake abatement. With compensation, firms would abate, but households would not take defensive measures. Compensation still implements the global optimum as long as firm and households are completely separated. Also, compensation could still be better than taxation if compensation resulted in the optimal segregation pattern and taxation did not.

An interesting development of the model would be the application of the Coase [4] theorem. According to the Coase theorem, welfare will be maximized as long as property rights are assigned. The result does not depend on who has the property rights. In our laissez faire scenario, firms have the right to pollute. With compensation, households have the right to clean air. However, these scenarios did not always lead to the local welfare optimum. This is not so strange, because Coase [4] envisaged that voluntary payments from one population to another would take place in order to implement the optimum. Under laissez faire, households would have to pay firms to stay away from them. Under compensation, firms would have to pay households. Until now, we have not taken this possibility into account.

One might wonder how voluntary transfers arise and develop in an evolutionary world. It seems plausible that they can only arise in an evolutionary equilibrium, for two reasons. The first is that it facilitates looking forward. In order to understand the use of voluntary transfers, an agent must be able to predict what will happen without transfers, and how transfers can improve upon that. Out of equilibrium, the world is constantly changing. That makes it difficult to look forward. In an evolutionary equilibrium, nothing changes, so that conditions are favourable for someone to get the idea that nothing will change in the future without voluntary transfers. Secondly, in an evolutionary equilibrium, agents will start to identify with their current residence and start wondering how they can make it a more pleasant place. On the other hand, when an agent has recently moved and observes others moving, he will not feel very attached to his residence.

7 Appendix

7.1 Proof of Proposition 1

7.1.1 FH equilibrium

The FH equilibrium cannot be (f, fh) because density would be higher in B and firms would want to move to A. The FH equilibrium is (f, h) if households want to stay in B. If they don't, there is an equilibrium (fh, h), because when households are indifferent between A and B, density is higher in B. Then firms don't want to move to B.

7.1.2 Mixed equilibrium

Firms and households are indifferent between A and B if (11) and (10) hold, respectively. Both equations can only be satisfied simultaneously if $s_f^A = 0.5$. Substituting this into (11) and solving for s_h^A:

$$s_h^A = \frac{(2+n_f)D^B - n_f D^A}{2(D^A + D^B)}. \tag{18}$$

We see that $s_h^A < 1$ only if condition (12) holds.

7.1.3 HF equilibrium

We know that an FH equilibrium always exists and there is either no or one mixed equilibrium. It then follows from Figure 1 that there is an HF equilibrium if and only if there is a mixed equilibrium, i.e. condition (12) holds.

7.2 Proof of Proposition 2

7.2.1 HF equilibrium

The HF equilibrium is (h, f) if firms will stay in B and households will stay in A. If firms don't want to stay in B in (h, f), there will be an equilibrium (fh, f) with firms indifferent between A and B:

$$\Pi^A(s_f^A, 1) - eN_h = \Pi^B(s_f^A, 1) \tag{19}$$

Households prefer to stay in A in (fh, f) if:

$$\Pi^A(s_f^A, 1) - eN_h n_f s_f^A > \Pi^B(s_f^A, 1) - eN_h n_f (1 - s_f^A)$$

Substituting (19), this inequality becomes $1+n_f > 2n_f s_f^A$, which is always satisfied.

If households don't want to stay in A in (h, f), there will be an equilibrium (h, fh) with households indifferent between A and B:

$$\Pi^A(0, s_h^A) = \Pi^B(0, s_h^A) - eN_h n_f \tag{20}$$

Note that $s_h^A > \frac{1}{2}$, because if $s_h^A \leq \frac{1}{2}$, density would be lower in the larger region A, so that households would prefer the low-density, clean region A to the high-density, dirty region B.

Firms prefer to stay in B in (h, fh) if:

$$\Pi^A(0, s_h^A) - eN_h s_h^A < \Pi^B(0, s_h^A) - eN_h(1 - s_h^A) \tag{21}$$

Substituting (20), inequality (21) holds if $s_h^A > \frac{1}{2} - \frac{1}{2}n_f$. Since $s_h^A > \frac{1}{2}$, this inequality is always satisfied.

7.2.2 Mixed equilibrium

Firms and households are indifferent between A and B if (9) and (10) hold, respectively. Then:

$$2s_h^A - 1 = n_f(2s_f^A - 1) \tag{22}$$

It is clear from (22) that s_h^A is between s_f^A and $\frac{1}{2}$. However, when $s_f^A \leq s_h^A \leq \frac{1}{2}$, the LHSs of (9) and (10) exceed the RHSs. In this case, A would be the low-density and the low-pollution region. Thus, in the mixed type equilibrium, $s_f^A > s_h^A > \frac{1}{2}$. Then A is the high-pollution, low-density region. For a mixed equilibrium to exist, firms should prefer to move to B when they are all in A. From (9) and (22) with $s_f^A = 1$, this will happen if and only if condition (13) holds.

7.2.3 FH equilibrium

We know that an HF equilibrium always exists and that there is either no or one mixed equilibrium. It is then clear from Figure 2 that there is an FH equilibrium if and only if there is a mixed equilibrium, i.e. condition (13) holds.

7.3 Proof of Proposition 3

7.3.1 HF equilibrium

The HF equilibrium is (h, f) if firms will stay in B and households will stay in A. If firms don't want to stay in B, there will be an equilibrium (fh, f). Households will remain in A in (fh, f), because density is lower in A.

If households don't want to stay in A in (h, f), there will be an equilibrium (h, fh) with households indifferent and thus density equal in A and B:

$$\Pi^A(0, s_h^A) = \Pi^B(0, s_h^A) \tag{23}$$

The solution is:

$$s_h^A = \frac{(1+n_f)D^B}{D^A + D^B} > \frac{1}{2}$$

The inequality follows from $D^B > D^A$. Firms prefer to stay in B:

$$\Pi^A(0, s_h^A) - eN_h s_h^A < \Pi^B(0, s_h^A) - eN_h(1 - s_h^A)$$

Substituting (23), the inequality holds when $s_h^A > \frac{1}{2}$, which is the case.

7.3.2 Mixed equilibrium

Firms and households are indifferent between A and B if (11) and (10) hold, respectively. Both equations can only be satisfied simultaneously if $s_h^A = 0.5$. Substituting this into (11) and solving for s_f^A:

$$s_f^A = \frac{(1 + 2n_f)D^B - D^A}{2n_f(D^A + D^B)}.$$

We see that $s_f^A < 1$ only if condition (14) holds.

7.3.3 FH equilibrium

We know that an HF equilibrium always exists and that there is either no or one mixed equilibrium. It is then clear from Figure 3 that there is an FH equilibrium if and only if there is a mixed equilibrium, i.e. condition (14) holds.

7.4 Proof of Proposition 4

Let us first look at stability of the interior NE. As is clear from Figures 1 to 3, the interior NE is unstable when the loci for firms is steeper than the loci for households.[10] The loci are determined by $\Delta U_k^\rho \equiv U_k^A - U_k^B$ for $k = f, h$ and regime ρ is laissez faire λ, taxation τ or compensation κ. The slope of the loci ds_f^A/ds_h^A follows from the total differentiation with respect to s_h^A:

$$\frac{\partial U_k^A}{\partial s_f^A}\frac{ds_f^A}{ds_h^A} + \frac{\partial U_k^A}{\partial s_f^A} = \frac{\partial U_k^B}{\partial s_f^A}\frac{ds_f^A}{ds_h^A} + \frac{\partial U_k^B}{\partial s_f^A}$$

or:

$$\frac{ds_f^A}{ds_h^A} = -\frac{\partial \Delta U_k^\rho / \partial s_h^A}{\partial \Delta U_k^\rho / \partial s_f^A}$$

[10] See Chiang [3], 640-3, for a rigorous underpinning.

Taking into account that the loci always have negative slope, the loci for firms is steeper than the loci for households in regime ρ when:

$$\delta^\rho \equiv \frac{\partial \Delta U_f^\rho}{\partial s_f^A}\frac{\partial \Delta U_h^\rho}{\partial s_h^A} - \frac{\partial \Delta U_f^\rho}{\partial s_h^A}\frac{\partial \Delta U_h^\rho}{\partial s_f^A} < 0$$

The payoff differences between the two locations are, from (8):

$$\begin{aligned}
\Delta U_h^\lambda &= \Delta U_h^\tau = \pi(d^A) - \pi(d^B) + eN_h n_f(1 - 2s_f^A) \\
\Delta U_f^\tau &= \Delta U_f^\kappa = \pi(d^A) - \pi(d^B) + eN_h(1 - 2s_h^A) \\
\Delta U_h^\kappa &= \Delta U_f^\lambda = \pi(d^A) - \pi(d^B)
\end{aligned}$$

The derivatives of the payoff differences with respect to s_f^A and s_h^A are, using (7):

$$\begin{aligned}
\frac{\partial \Delta U_f^\rho}{\partial s_f^A} &= \frac{\partial \Delta U_h^\kappa}{\partial s_f^A} = n_f N_h D\pi' < 0 \\
\frac{\partial \Delta U_h^\rho}{\partial s_h^A} &= \frac{\partial \Delta U_f^\lambda}{\partial s_h^A} = N_h D\pi' < 0 \\
\frac{\partial \Delta U_h^\lambda}{\partial s_f^A} &= \frac{\partial \Delta U_h^\tau}{\partial s_f^A} = N_h n_f D\pi' - 2eN_h^2 n_f < 0 \\
\frac{\partial \Delta U_f^\tau}{\partial s_h^A} &= \frac{\partial \Delta U_f^\kappa}{\partial s_h^A} = N_h D\pi' - 2eN_h^2 < 0
\end{aligned} \tag{24}$$

with $D \equiv D^A + D^B$. We then find:

$$\begin{aligned}
\delta^\lambda &= \delta^\kappa = 2F_f' F_f' N_h n_f De\pi' < 0 \\
\delta^\tau &= F_f' F_f' N_h[2De(1 + n_f)\pi' - 4e^2 n_f] < 0
\end{aligned}$$

This implies that any interior NE is unstable.

Let us now look at the stability of NE at the corners and the edges of the state space. It is easily seen that all corner NE (f, h) and (h, f), with complete segregation, are stable. This is because the conditions for a corner NE already stipulate that both populations prefer to stay in their present location. For NE at the edge, with partial segregation, the population that is in one location should prefer to stay there. For the population k that is in both locations, we have to check whether $\partial F_k^\rho / \partial s_k^A \leq 0$. It is clear from (24) that this is the case.

7.5 Proof of Lemma 7

When there are two EE under taxation and one under compensation, condition (13) for an FH equilibrium under taxation:

$$\Pi^A\left(1, \frac{1}{2} + \frac{1}{2}n_f\right) - eN_hn_f < \Pi^B\left(1, \frac{1}{2} + \frac{1}{2}n_f\right)$$

is satisfied, whereas the condition (14) for an FH equilibrium under compensation is not:

$$\Pi^A\left(1, \frac{1}{2}\right) > \Pi^B\left(1, \frac{1}{2}\right) \tag{25}$$

The LHS of (25) exceeds the LHS of (13), whereas the RHS of (25) is below the RHS of (13). Thus, it is possible for (13) and (25) to be satisfied simultaneously. However, it is not possible for neither (13) nor 25) to be satisfied simultaneously, i.e. for there to be one EE under taxation and two under compensation.

7.6 Proof of Proposition 6

First, we will show that (f, h) is worse than HF. We shall see that:

$$u\left(\frac{1}{D^AN_h}\right) + n_fu\left(\frac{1}{D^BN_hn_f}\right) > n_fu\left(\frac{1}{D^AN_hn_f}\right) + u\left(\frac{1}{D^BN_h}\right) \tag{26}$$

The expression on the LHS of (26) is aggregate per capita welfare in (h, f) and the expression on the RHS is aggregate welfare in (f, h). Inequality (26) can be rewritten as:

$$u\left(\frac{1}{D^AN_h}\right) - n_fu\left(\frac{1}{D^AN_hn_f}\right) > u\left(\frac{1}{D^BN_h}\right) - n_fu\left(\frac{1}{D^BN_hn_f}\right) \tag{27}$$

The expression on the LHS of (27) is the increase in aggregate welfare derived from occupying region A, when the firms move out and the households move in. Due to the concavity of $u(g)$, an increase in the number of occupants increases total welfare. In Figure 5, this increase is denoted by JK. On the RHS of (27) is the decrease in aggregate welfare derived from occupying region B, when the households move out and the firms move in. This decrease is given by LM in Figure 5. As Figure 5 shows,

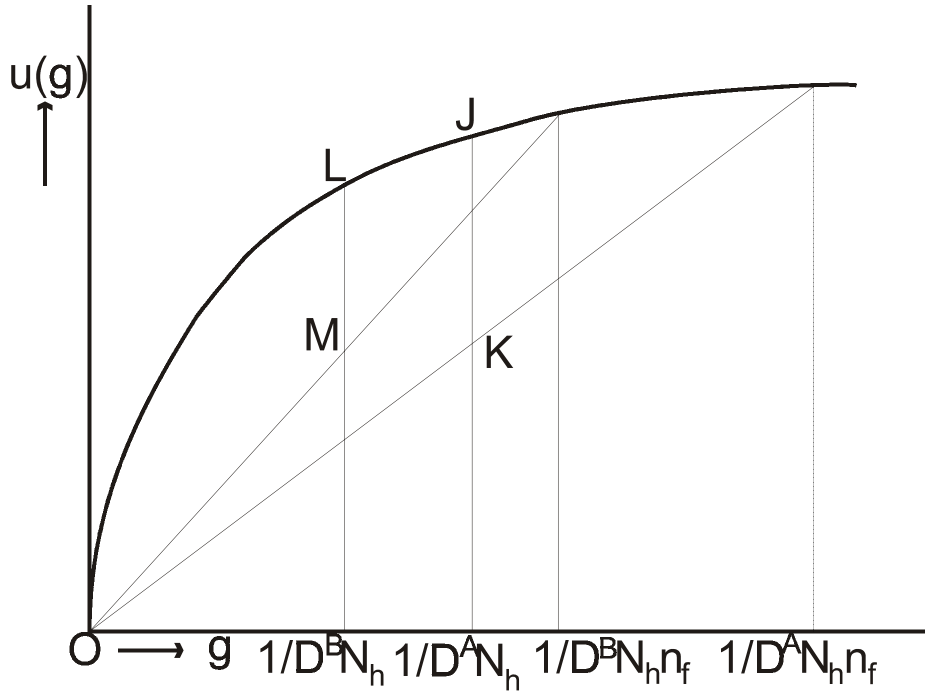

Figure 5: Comparing aggregate payoff from land in (h, f) and (f, h).

$JK > LM$. Formally, inequality (27) follows from $D^B > D^A$ and

$$\frac{\partial \left[u(g) - n_f u\left(\frac{g}{n_f}\right) \right]}{\partial g} = u'(g) - u'\left(\frac{g}{n_f}\right) > 0$$

The inequality follows from $n_f < 1$ and $u''(g) < 0$.

Secondly, we will see that there are always constellations with a higher welfare than (fh, h). Note that with (fh, h), there are $N_h n_f$ firms in A, $s_h^A N_h$ households in A and $(1 - s_h^A)N_h$ households in B. Per capita damage from pollution is $eN_h n_f s_h^A$. There are three possibilities:

1. $n_f + s_h^A < 1 - s_h^A$. In this case, density is higher in B. Welfare can then be increased by exchanging the occupants of A and B. Pollution damage will remain the same. As our previous discussion of (26) has shown, aggregate welfare from land will increase, because the large group is brought to the large region.

2. $1 - s_h^A < n_f + s_h^A < 1$. Welfare can be increased by having $N_h(n_f + s_h^A)$ households in A and $N_h(1 - n_f - s_h^A)$ households and all $N_h n_f$ firms in B. Note that density

in both regions remains the same. However, pollution damage per capita has decreased from $eN_h n_f s_h^A$ to $eN_h n_f(1 - n_f - s_h^A)$.

3. $n_f > 1 - s_h^A$. Then welfare is higher in an alternative scenario with all households in A, $N_h(n_f - 1 + s_h^A)$ firms in A and $N_h(1 - s_h^A)$ firms in B. Again, density remains unchanged, but pollution damage has decreased by:

$$eN_h \left[n_f s_h^A - n_f + 1 - s_h^A\right] = eN_h(1 - n_f)(1 - s_h^A) > 0$$

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