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Spatially and Intertemporally Efficient Waste Management: The Costs of Interstate Trade Restrictions[1]

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We examine the intertemporal allocation of the solid waste of cities within the United States to spatially distributed landfills and incinerators, taking into account that capacity at existing and potential landfills is scarce. Amendments have been proposed to restrict waste flows between states by means of quotas and surcharges. We assess the aggregate surplus loss (and its regional distribution) resulting from proposed policies. In addition, we find that limitations on the size of shipments to any one state can have the perverse effect of substantially increasing interstate waste shipments as states export smaller volumes to more destinations.

Key Words: solid waste; efficiency.

INTRODUCTION

The growing trend in interstate shipments of solid waste in the United States is a topic of substantial public debate. There have been numerous Supreme Court decisions concerning the control of waste shipments in the context of the Interstate Commerce Clause and several recent congressional proposals to exempt waste generation from the jurisdiction of that clause. To date, however, very little is known

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about the effects such proposed restrictions might have on the interstate waste market.

Our research evaluates the potential economic effects of public policies proposed to restrict flows of municipal solid waste (MSW henceforth).[3] These restrictions include local or state requirements stipulating where waste must be landfilled, prohibitions on the import or export of waste across state boundaries, quantitative limits on these flows, and extra fees levied on imported waste. We focus on the aggregate surplus loss (and its regional distribution) that would result from such controls. Such losses would arise because more distant or higher-cost disposal facilities would have to be used if lower-cost choices are proscribed.

Some of the questions our paper addresses include: (1) If interstate trade in MSW is banned, what is the social surplus associated with the autarkic allocation which results? Are the changes in surplus likely to differ among regions of the country? If so, are some better off and others worse off than before the ban? (2) If interstate trade is permitted but quantities of waste imports or exports are restricted, what are the effects on the public in various regions of the country? In the associated competitive equilibrium, (3) What are the effects on producers and consumers of such quantitative restrictions? (4) If higher fees are charged for waste disposal when the waste originates outside the state, what are the economic effects on different regions of the country and on producers and consumers?

We base our approach on a central planning model of interstate waste trade developed recently by Gaudet, et al. [5]. Their model characterizes the efficient allocation over time of spatially differentiated resources in finite supply such as the nation's waste disposal facilities. We add policy constraints to their theoretical model and then implement it on the computer.

In Section 1, we offer some background information on MSW and the interstate waste market and then briefly review proposed legislative developments to restrict interstate shipments of waste and the arguments underlying the debate over them. Section 2 presents the model. We apply the model to two regions of the United States, the Northeast and Midwest. These regions account for about 80% of interstate trade by volume and involve volumes large enough to be subject to restrictions proposed in pending legislation (for example, in a recently passed Senate bill described below, two of the bill's three allowable restrictions apply only to large volumes of waste exports or imports). We also focus on waste that is landfilled, as this is the disposal method for most interstate waste. However, an important input in our model and one to which its results are sensitive is the cost of alternative disposal methods. We calibrate our model using publicly available data on waste generation, waste disposal and transportation costs, estimated demand elasticities for waste generation, and other information. We discuss these inputs to our simulation model in Section 3 and the resulting baseline simulations in Section 4; in this section we also test the sensitivity of our model to several key assumptions. We then impose various restrictions on the model to investigate the effects of several recently proposed constraints on interstate waste flows: (1) restrictions on the volume of waste exports, (2) an outright prohibition of interstate shipments,

[3]Strictly speaking, two types of such restrictions on the flow of waste are the subject of current debate: so-called flow control and restrictions specifically on *interstate* shipments of waste. Both of these restrict the flow or shipment of waste, but flow control generally refers to within-state restrictions (even though these may also impact interstate shipments). Our focus is on interstate restrictions.

(3) surcharges on imported waste, and (4) a combination of surcharges and volume-based restrictions. We estimate the effects of these restrictions on interstate waste flows, aggregate surplus loss, and the regional distribution of the changes in surplus. We also investigate the impact of such policies on producers and consumers in the associated competitive equilibrium. We present these results in Sections 4 and 5. In Section 6, we offer some conclusions about restrictions on interstate waste flow.

1. BACKGROUND—MUNICIPAL SOLID WASTE AND INCENTIVES FOR INTERSTATE WASTE TRADE

Our focus on MSW refers generally to the everyday trash generated by households. The definition of MSW varies among states and localities, but it usually includes yard trimmings (which can account for a large tonnage of waste) and excludes hazardous waste, construction and demolition debris, and industrial waste. About 210 million tons of MSW were generated in the United States during 1997 (the most recent year for which detailed data are available) or about one ton of waste per person that year. MSW generation has tended to increase about 5% per year in recent years. Historically, disposal of MSW has taken place at the nearest landfill, incinerator, or other disposal facility. For a variety of reasons, however, the amount of MSW transported across state boundaries has been increasing since the mid-1980s. According to the most recent data about interstate flows, almost all states routinely import and export some waste (47 states export waste and 44 states import waste), not just to a neighboring state but frequently much longer distances (Fig. 1).[4] This "interstate waste market" has handled an estimated 20 million tons of MSW annually in recent years (about 10% of the total MSW generated). Although this volume may seem small, the transport costs associated with it amount to about $900 million annually.[5]

The willingness to bear the transportation costs arises largely from significant differences among tipping fees (the charge per ton to unload a truck at a disposal facility) across states—much of the discussion here is based on [12]. For instance, landfill tipping fees in the mid-1990s averaged $10 in Nevada, $27 in Ohio, and $75 in New Jersey. These differences reflect several related factors, including the closing of many landfills and public opposition to expanding capacity at existing landfills or constructing new ones. For example, a trend in interstate waste transport from the Northeast to the Midwest developed during the early 1990s because of the closing of many landfills in New York and New Jersey and the inability of northeastern states to site new facilities. This caused a sharp rise in the tip fee at the remaining facilities. During 1991–1992, the tipping fee at the Fresh Kills landfill, the only disposal facility in New York City, rose from $80 to $150 per ton (it is now about $120). Tipping fees in northeastern states typically average $50 or more per ton. In contrast, the average tipping fee in midwestern states (major importers of waste) is significantly lower, averaging $25–$30 per ton. Thus, even with transportation costs, it can remain cheaper in many cases for northeastern states to export refuse to

[4]The map is for 1989–1990, but based on McCarthy [14] these flow patterns appear to have continued to the present.

[5]Authors' calculations, available from authors, are based on average volume, distance transported, and transport costs.

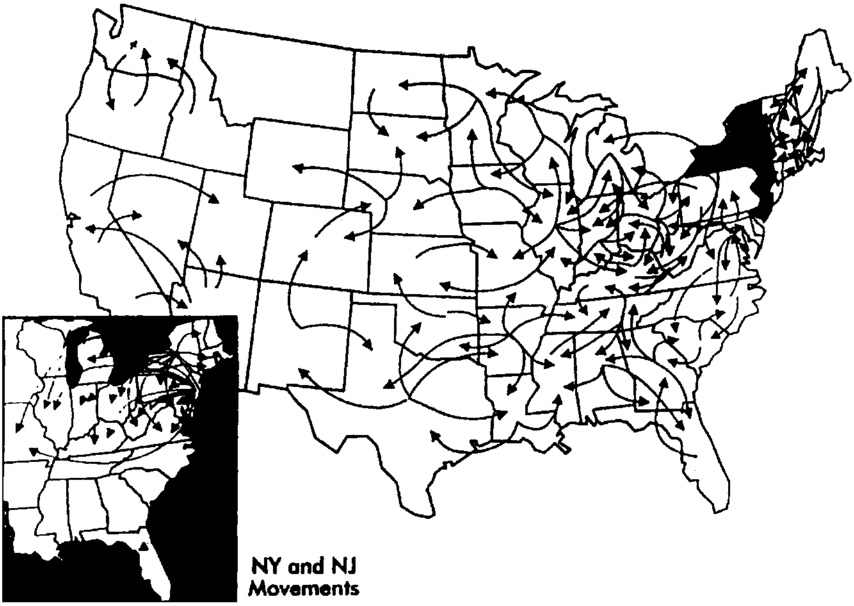

FIG. 1. Interstate flows of municipal solid waste. Source: National Solid Waste Management Association (now Environmental Industry Association), "Interstate Movement of Municipal Solid Waste," p. 3, National Solid Waste Management Association, Washington, DC (1992).

landfills in the Midwest. For example, assuming transportation costs of 10–15¢ per ton mile, the per-ton cost of shipping waste from New York to Ohio is just \$75–\$95, including Ohio's average tip fee of \$25 per ton.

The growing trend in interstate waste transport has been opposed by citizens' groups, environmental organizations, state legislators, and others. They express concern about being a "dumping ground," the impact of landfill growth on local property values, and the limited capacity of local landfills. This opposition has led many states to ban, differentially charge, or impose other restrictions on imported waste. As of 1993, 41 of the 48 contiguous states had considered or enacted legislation to restrict the flow of waste across their boundaries.

Most of these restrictions have been struck down by the courts as violations of the Interstate Commerce Clause of the United States' Constitution. When state regulations place an "undue burden" on commerce, including the trade of waste, they are deemed to be unconstitutional. In a landmark decision in May 1994, the Supreme Court ruled 6 to 3 against a municipal ordinance that MSW generated within the state of New York be managed at a designated waste processing facility financially backed by the town of Clarkstown *(Carbone, Inc. v. Town of Clarkstown)*.[6] The Court ruled that the ordinance discriminates against interstate commerce even though it prohibits waste from being sent to other local waste transfer stations as well. The Interstate Commerce Clause does, however, empower Congress to allow states to regulate commerce, and Justice Sandra Day O' Connor's concurring opinion in *Carbone* explicitly noted that it is within Congress' power to permit

[6]See *C&A Carbone v. Clarkstown*, US SupCt, No. 92-1402, 5/16/94.

local controls on waste flows. Since the mid-1990s,[7] the Congress has proposed numerous bills to allow controls. In Fall 1995, the Senate passed particularly detailed legislation, S. 534, "The Interstate Transportation of Municipal Solid Waste Act of 1995" amending the Solid Waste Disposal Act. Titles I and II of the bill attempt to affect waste flows. Title I of the bill grants state governors the authority to restrict out-of-state MSW imports to 95% of their levels in 1993 and to increasingly smaller percentages over time (ending with calendar year 2003 and each succeeding year, when the limit is to be 65% of the amount exported in 1993), provided imports exceeded 750,000 tons per year in 1993. Title I also restricts the amount of waste that exporting states may ship to any one state. The restriction is the greater of 1,400,000 tons or 90% of the amount exported to the state in 1993 and increasingly smaller amounts over time (ending with calendar year 2002 and succeeding years, when the limit is 550,000 tons). An exception to this export restriction is if landfills or incinerators in the importing state are authorized to receive out-of-state waste or have agreements with the host community that permit such imports. A third provision in the title permits importing states to collect a "cost recovery charge" not to exceed $1 per ton, for the processing or disposal of out-of-state waste.

Title III of the bill permits jurisdictions to control waste flows by requiring that they be handled (for recycling, transfer, processing, or other management) at specific waste facilities, although generally only if such controls had been operating prior to May 15, 1994 (the date of the *Carbone* decision). In most provisions of this Title, interstate flow controls may continue only until the end of the remaining life of contracts between the political subdivision and its contractors—see, e.g., [12, 24] for additional discussion of restrictions on interstate shipments. In subsequent legislative proposals, various of these quantity and surcharge provisions have been retained (see, e.g., S. 663 and its companion bill in the House of Representatives, H.R. 1190, both proposed in March 1999).

2. OVERVIEW OF THE MODEL

We turn now to the model we use to assess empirically the consequences of these proposed restrictions. We use these restrictions because they represent well the types of constraints that the Congress has debated, but our model is amenable to other formulations of constraints. In addition, since estimates of parameters associated with the landfill market differ widely, we have made the model as flexible as possible and report a variety of sensitivity tests of our empirical assumptions.

A "central planning" model such as ours has a variety of positive and normative uses.[8] Suppose first that there are significant externalities either in transporting waste or in landfilling or incinerating it. If these externalities are taken fully into account, our model can be used to compute the socially optimal plan over time and space. This would be valuable as a goal toward which regulatory policy should guide the industry.

[7]For example, draft bills on flow control/interstate transport have included a bill sponsored by Robert Smith (R, NH) and John Chafee (R, RI) in the Senate, a bill sponsored by Michael Oxley (R, OH) and Christopher Smith (R, NJ) in the House of Representatives, and a bill sponsored by Fred Upton (R, MI) in the House—see Woods [24].

[8]Nordhaus [16] used such a model to assess the distortions in the world energy market attributable to OPEC's exercise of market power.

We can also use our model to predict the welfare consequences of existing or proposed restrictions and can compare these consequences to the welfare predicted under laissez-faire on the one hand or under optimal regulation on the other. To predict the consequences of imposing specified restrictions on a competitive market in the presence of externalities, we must first draw a distinction between the allocation which arises in a competitive equilibrium and the evaluation of that allocation. External costs will be disregarded by market participants and hence will not affect the equilibrium *allocation*. On the other hand, such costs will affect our *evaluation* of that allocation. To compute the competitive allocation we assume that the planner, like the market, disregards external costs and that, like the market, the planner is constrained by the specified restrictions. To *evaluate* the welfare consequences of the resulting equilibrium, we then value the induced allocation while taking *full account* of social costs.

We were unable to find data on external costs reliable enough to reach definitive conclusions about the effects of landfill restrictions. However, positing that the external cost imposed on a city adjacent to a landfill is proportional to the activity at that landfill and to the population density of the city, we reached the tentative conclusion that the restrictions we study *reduce* aggregate surplus relative to laissez-faire and hence *a fortiori* are far from optimal. Even if further work confirmed this tentative conclusion about the effects of import restrictions and other regulations, however, no inference should be drawn about the motivation for such policies. One possibility is that the electorate in a particular state presses for such regulation to avoid the additional negative externalities the importation of out-of-state waste into in-state landfills would impose. Another possibility, which could arise even in the absence of any externalities, is that in-state voters press for import restrictions to prevent out-of-state users from bidding up in-state landfill prices.[9] Our model permits us to study the positive and normative consequences of these regulations but does not clarify what motivates them.

The computerized model we have developed determines how the capacities of landfills located in different states in the United States should be drawn down or expanded over time and which population centers these landfills—in conjunction with spatially distributed incinerators—should serve. We then use the model to calculate by how much aggregate surplus would decline with the imposition of a variety of political constraints, such as interstate restrictions under consideration in the Congress. In addition, we can quantify the distribution of these changes in surplus across states or other geographical regions and between producers and consumers of waste disposal.

The lineage of our work can be traced to Hotelling's [7] model of depletable resources—see, e.g., Salant [20] for an extensive bibliography and a nontechnical introduction to the Hotelling literature. Several authors have noted the similarity between solid waste disposal problems and the depletable resource problem first

[9]For example, Virginia may restrict inflows of waste from New York even if unrestricted trade maximizes social welfare. For out-of-state demand would bid up tip fees in Virginia and would therefore lower the equilibrium payoffs of Virginia households and businesses currently using in-state landfills. Even though these losses would, by assumption, be outweighed by the gains of New Yorkers, New Yorkers do not vote for Virginia politicians. Such politicians may find championing voters in their own state more attractive than defending the interests of New Yorkers and the limited number of Virginians who would benefit from such inflows.

studied by Hotelling, including Dunbar and Berkman [2], Chang and Schuler [1], Ready and Ready [18], and Huhtala [8]. This literature has focused on determining optimal tipping fees.

2.1. *Spatial Aspects of the Landfill Problem*

These models have not been extended explicitly to an important aspect of the solid waste industry in the United States that landfills in some parts of the country are being called upon to serve the needs of "consumers" in other parts of the country. Such an extension to a spatial dimension is necessary to evaluate restrictions that are being introduced to limit waste shipments.

Until very recently, few articles in the Hotelling literature addressed spatial aspects of resource extraction. To our knowledge there have been three key papers introducing a spatial element: Laffont and Moreaux [11], Kolstad [10], and Gaudet et al. [5]. Although only the last of these applies its results to landfills, each of them can be reinterpreted in terms of this application.

Kolstad [10], for example, can be regarded as considering the case of two landfills serving multiple cities. His approach, however, limited him to a particular spatial configuration: every city had to be located on the line segment connecting the two landfills. Gaudet et al. [5] relax this spatial restriction and hence generalize Kolstad's analysis. In their model, I landfills can be located *anywhere* (not necessarily on a line segment), J cities (represented by demand curves) can be located *anywhere* and the backstop incinerators can be located *anywhere*. Gaudet, Moreaux, and Salant [5] (hereafter GMS) then determine the solution to the planning problem (or, equivalently, the solution to the competitive equilibrium in the absence of externalities). In the solution to their planning problem, the shadow price on initial reserves in pool i has the multiplier λ_i. The multiplier on reserves in that pool at t is $\lambda_i \beta^{-t}$, where β is the discount factor ($\beta = (1+r)^{-1}$, where r is the real rate of interest). Consider city j at time t. To serve that city then at least cost, the planner would select the fill with the smallest *full* cost—taking account not merely of the transportation cost (c_{ij}) but also of the current shadow price of landfill space. In the decentralized version of this problem, title to one unit of unused space in landfill i would initially sell for λ_i. For such a riskless asset to be held, its price must rise by the rate of interest ($\beta^{-1} - 1$). A competitive operator of landfill i would be willing to collect one unit of city j's trash and transport it back to its fill for disposal at a price of $c_{ij} + \lambda_i \beta^{-t}$. The supply price offered city j net of the cost of transporting its waste to fill i is referred to as the tip fee of fill i. In GMS's unregulated case, the tip fee charged any city at time t would be $\lambda_i \beta^{-t}$. City j, of course, can be served by any of I landfills and so would face I supply prices. It would buy from the facility with the cheapest supply price. A similar story applies to each of the J cities. Ultimately, the initial prices of titles to one unit of space in each of the I fills is determined by the computer algorithm so that cumulative space used in every landfill equals its initial capacity. In the GMS model, (1) no city uses more than one landfill at the same time, (2) every patron of a given landfill is charged the same tipping fee at a given time, and (3) every tipping fee rises at the rate of interest.

Figure 2 illustrates the three best choices facing city j at time t in the GMS model. The supply price of fill 1 is smaller than the supply price of fill 2, which in turn is smaller than the supply price of the local incinerator. In this situation, city j

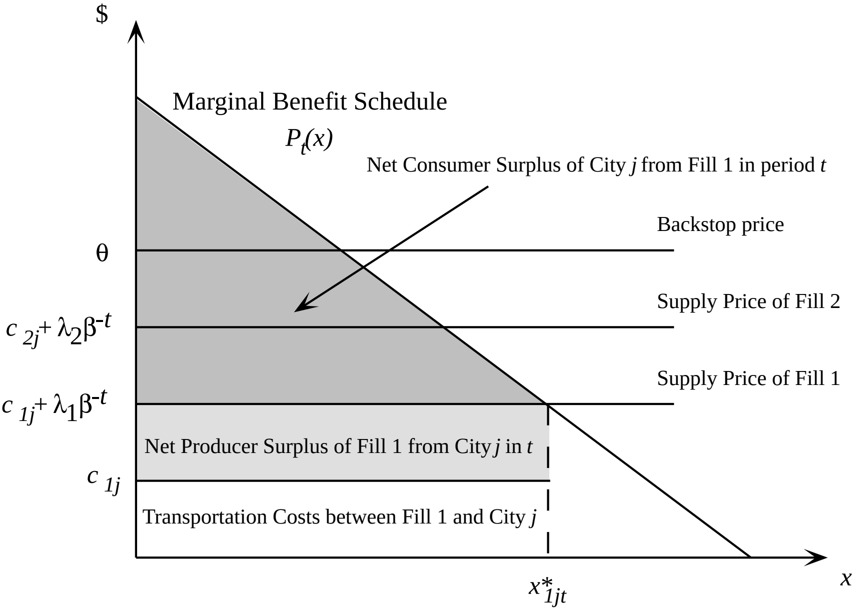

FIG. 2. GMS model in t with two landfills and one incinerator available to city j.

would ship all of its waste to fill 1. The supply prices of the other $I-3$ sources are not depicted. The price paid by city j in period t is the smallest of the supply prices—fill 1's supply price. We decompose that supply price into its transportation cost component (c_{1j}) and the "tip fee." All cities would pay this same tip fee at fill 1. The shaded areas correspond to net consumer surplus at city j and that *portion* of net producer surplus generated from fill 1's commerce with city j (revenue net of transport costs from transactions with city j but not from transactions with other cities).

The creation of space in a completely new landfill or the marginal expansion of space in an existing landfill can be accommodated easily provided that in neither case are there setup costs or other nonconvexities.[10] In the case of new landfills, the central planner would be deciding in each period which potential landfill to *develop*. The following case is trivial to implement and illustrates the strengths and weaknesses of our approach to capacity expansion. Suppose additional space can be created at constant marginal cost α but the potential cumulative expansion is limited to $\bar{A}$ units of space. This case can be implemented without change in the formulation described above. It is infeasible to use space that has not yet been created. But if expansion occurs at constant marginal cost, space will not be created until it would be used. Given this, a potential landfill can always be represented by a cost of production α and an initial size $\bar{A}$. By the same token, if this new landfill is located adjacent to an existing landfill, the planner would use the new one just

[10]Nonconvexities cause familiar problems. In the market context, competitive equilibrium may not exist [3]. The planning problem still has a global optimum but since some nonoptimal programs also solve the first-order conditions, more cases must be examined to locate the global optimum. GMS devote Section 4 of their paper to a detailed discussion of what can be said in general about the solution of the planning problem when the opening of landfills involves setup costs.

as if he were expanding the old landfill. To obtain the *full* marginal cost or supply price paid by a particular city for using an expanded landfill at date t one would add (1) the marginal cost of creating the space, α, (2) the price of a title to the unit of the newly created space being depleted, and (3) the transport cost of shipping a unit of waste between that city and landfill. If the marginal cost of creating space in a particular landfill is sufficiently large, it would never be developed (implying that $\lambda_i = 0$). If there are potential landfills in many different locations, the planner would decide which one is optimal to develop first. More generally, the planner would be deciding when to develop potential new landfills and when to expand old ones.

The marginal cost of creating additional space need not be constant. It could increase with the amount of space created in a period or could depend on the amount of space previously created. Such formulations are tractable provided the resulting planning problem remains concave.

2.2. *The Model*

Our model appends to the GMS model political constraints relevant to our policy analysis and then numerically solves for the surplus-maximizing program. The planner's problem is given by

$$\max_{x_{ijt},\, b_{jt}} \quad \sum_j \sum_t \beta^t \left\{ U_{jt}(x_{\bullet jt} + b_{jt}) - \theta b_{jt} - \sum_i c_{ij} x_{ijt} \right\} \tag{1}$$

$$\text{s.t.} \quad x_{ijt} \leq \bar{x}_{ijt} \qquad \perp \mu_{ijt}, \tag{2}$$

$$x_{i\bullet t} \leq \bar{f}_{it} \qquad \perp \eta_{it}, \tag{3}$$

$$x_{i\bullet\bullet} \leq \bar{s}_i \qquad \perp \lambda_i, \tag{4}$$

$$x_{ijt} \geq 0, \; b_{jt} \geq 0. \tag{5}$$

The notation is explained in Table I.

The GMS model would consist of the objective function (1), the reserve constraints (4), and the nonnegativity constraints (5). To these we add the following political constraints in various simulations: city–landfill interstate flow constraints (2) limiting the amount that city j can ship to landfill i at each t and constraints on the number of trucks which can access landfill i in the same day (3). The latter constraints arise either because of agreements with the surrounding community or because of physical restrictions on access.

In the presence of interstate trade restrictions, the definition of the "tip fee" charged to city j by landfill i requires some clarification. As before, the tip fee at time t is the difference between what city j pays to dispose of its waste at landfill i and the transport cost of shipping to landfill i: $P_{jt} - c_{ij}$. But the first-order conditions of the planner (or, equivalently, the equilibrium conditions in the competitive market) imply that $P_{jt} - c_{ij} = (\lambda_i^* + \mu_{ijt}^* + \eta_{it}^*)\beta^{-t}$. In the absence of interstate trade restrictions, $\mu_{ijt}^* = \eta_{it}^* = 0$ and the tip fee at t is simply the price of title at time t to one unit of space in landfill i ($\lambda_i \beta^{-t}$). However, if the planner is restricted in what can be sent from city j to landfill i at time t, then $\mu_{ijt}^* > 0$.

One way to decentralize this planning solution is by distributing $\bar{x}_{ijt}$ permits for the right to dump one unit of waste from city j in fill i at date t. Each permit would

TABLE I
Mathematical Notation

Indices	
i	Landfill index; $i \in \{1, 2, \ldots, I\}$
t	Time index; $t \in \{1, 2, \ldots, T\}$
j	City index; $j \in \{1, 2, \ldots, J\}$
S_k	Set of indices of landfills (or cities) belonging to the same federal state as landfill (or city) k
Exogenous inputs	
β	Discount factor
I	Number of landfills (sites existing at the outset or created subsequently)
J	Number of waste-generating centers (cities)
c_{ij}	Unit transportation cost from city j to landfill i
$\bar{s}_i$	Initial capacity of landfill i
θ	Unit cost of the backstop technology
$U_{jt}(Q)$	City j's utility function for disposing of Q units of waste at t
$P_{jt}(Q)$	$\equiv U'_{jt}(Q)$; city j's inverse demand for waste disposal, Q, at time t ($P_{jt}(Q)$ is *net* of unit processing costs associated with waste collection, compacting, etc.)
$D_{jt}(P)$	$\equiv P_{jt}^{-1}(Q)$; city j's demand for waste disposal at time t at price P
$\bar{f}_{it}$	Maximum amount of waste that could be shipped to landfill i from all cities at time t; it reflects the physical operational constraint of fill i
$\bar{x}_{ijt}$	An upper bound to waste shipped from city j to landfill i at time t (x_{ijt} defined below) if there are flow constraints
ε_j	An external cost (in dollars per ton)associated with disposing waste in the fill adjacent to city j
Endogenous outputs	
x_{ijt}	Amount of waste (in tons) shipped from city j to landfill i at time t
$x_{\cdot jt}$	$\equiv \sum_i x_{ijt}$; total amount of waste (in tons) shipped by city j to all landfills at time t
$x_{i\cdot t}$	$\equiv \sum_j x_{ijt}$; total amount of waste (in tons) shipped to landfill i from all cities at time t
$x_{i\cdot\cdot}$	$\equiv \sum_t \sum_j x_{ijt}$; total cumulative amount of waste (in tons) shipped to landfill i from all cities
e_{ijt}	$\equiv \sum_{j \in S_j} \sum_{i \in S_i} x_{ijt}$; exports of waste (in tons) at time t from the state where city j belongs to the state where landfill i is located
m_{it}	$\equiv \sum_{j \notin S_i} x_{ijt}$; imports of waste (in tons) at time t into the state where landfill i is located
b_{jt}	Amount of waste (in tons) of city j handled by the backstop technology at time t
η_{it}	Shadow price (in dollars per ton) associated with $\bar{f}_{it}$
μ_{ijt}	Shadow price (in dollars per ton) associated with $\bar{x}_{ijt}$
λ_i	Shadow price (in dollars per ton) associated with $\bar{s}_i$

then command a market value of μ^*_{ijt}. Alternatively, the import restriction could be implemented in a decentralized setting by charging customers in city j a tax of μ^*_{ijt} for depositing one unit of waste in fill i. Finally the government could implement the trade restriction by selling at price μ^*_{ijt} entitlements to ship one unit of waste from city j to fill i in year t. In these last two cases, city j would then choose in the equilibrium to deposit only $\bar{x}_{ijt}$ in fill i at time t. Non-source-specific restrictions on inflows to fill i could be decentralized in a similar manner.

How flow restrictions are implemented in the decentralized solution will have no effect on aggregate surplus but will affect its distribution. For example, the distribution of surplus would be affected by the manner in which the $\bar{x}_{ijt}$ permits were allocated initially; alternatively it would be affected by how the $\mu^*_{ijt}\bar{x}_{ijt}$ in fees collected were dispersed. In our simulations we assume that (1) the fee η^*_{it} is collected from all sources (and retained) by landfill i and (2) the fee μ^*_{ijt} is collected from city j by the state where landfill i is located, and it is calculated separately.

As mentioned previously, the presence of flow restrictions results in a number of phenomena which cannot arise in the GMS model.

Simultaneous Use of Several Landfills. If a *flow restriction* restricts what city j can ship to fill 1, city j might ship to fill 2 at the same time. Such simultaneous shipping never occurs in the unregulated case studied by GMS. Figure 3 depicts the choices facing city j at a given date t if it is constrained from shipping more than $\bar{x}_{1jt}$ to fill 1. The city ships as much as it is allowed ($\bar{x}_{1jt}$) to fill 1 and the remainder (x_{2jt}) to fill 2. City j pays $c_{2j} + \lambda_2\beta^{-t}$ per unit shipped to fill 2. We assume that city j pays the same price to ship to fill 1. As before the tip fee is the excess of what city j pays over the transport cost since that is what city j would have to pay to dispose of waste trucked to fill 1. In the presence of import restrictions, the final price paid by city j includes not merely the price of title to the unit of space depleted but also the *price of a permit* (or, alternatively, a fee) to ship a unit of waste from city j to fill 1.

Figure 3 depicts the two tip fees facing city j. Shaded areas correspond to net consumer surplus at city j and that portion of net producer surplus generated from

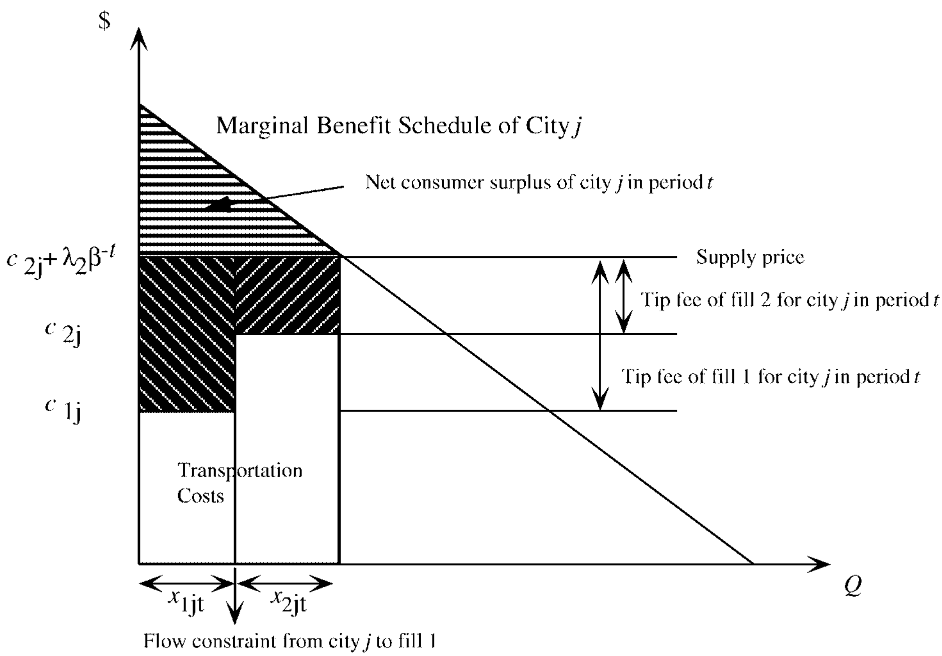

FIG. 3. GMS: city j at t with two fills and flow controls.

fill 1 and fill 2's commerce with city j. Another city, which could ship to either fill 1 or fill 2 with no flow constraints, would pay the same title price at either fill as city j in time t and hence the same tip fee at fill 2. However, the effective tip fee at fill 1 for that unconstrained city would be smaller than city j's since city j is subject to the restriction and must purchase a permit to use fill 1.

Differential Tipping Fees to Different Cities. If fill 1 also accepts waste in the same period from a second city—one which is not subject to interstate flow restrictions—then that city will pay a smaller effective tipping fee. This follows since that city purchases title to the space it depletes at the same price as city j but does not have to purchase a permit (or pay a fee) to use the fill. Such differential charges never arise in the GMS model. This difference in the tip fees charged at fill 1 does not reflect price discrimination against city j but merely the presence of binding source-specific flow restrictions in a competitive setting. Different cities shipping to the same fill and each subject to a separate source-specific flow restriction would each pay a different effective tip fee to use fill 1—all higher than the tip fee faced by an unconstrained city. On the other hand, if a set of cities were collectively constrained to ship no more than a certain amount to fill 1, then each would have to purchase the same permit price (or pay the same fee) and would therefore pay the same tip fee—once again higher than what an unconstrained city would have to pay.

Tipping Fees Rising Faster or Slower Than the Rate of Interest. Until a flow restriction binds, the tip fee grows at the rate of interest as in the GMS model. When the control first binds, however, the tip fee grows by a *larger* amount since the between-period increase in the fee reflects not merely the capital gain on the title price but also the increase in the cost of the permits to use fill 1. Since the subsequent change in the permit price can be positive or negative, the tip fees paid by cities constrained by interstate flow restrictions can grow slower or faster than the rate of interest.

3. DATA

Before describing our data in detail, we note several data-related simplifications in our simulations. The first is that we have selected as our geographic region of interest the specific portion of the waste market that accounts for the bulk of interstate shipments. This market is 14 states in the Northeast and Midwest; although this market represents only about 36% of the total volume of waste generated nationwide, it represents 75–84% of the total volume of waste shipped interstate (the range reflects differences between estimated imports and exports; see below). Table II lists these states, including the levels of their exports and imports and their trading partners as reported in published survey data. We use this information to compare our simulation results for the initial period of the operation of our model with the actual circumstances at work in the MSW market.

A second major simplification is to assume that waste is generated in one, or for geographically large states, two geographic locations in each state, and that all of the state's landfill capacity is at this location(s). For example, for New Jersey we assume that all of the state's waste is generated in Trenton and that New Jersey's entire landfill capacity is also located there. Table III lists the locations we have

TABLE II
Waste Generated, Exported, and Imported and Trading Partners, 1993

	Millions of tons per year			Shipments[a]	
	Waste generated[b]	Exports	Imports	To	From
New York	25.2	3.9	0.2	PA, OH, IL, IN	Canada
New Jersey	7.3	1.6	(neg.)	PA, VA, WV	NY
Illinois	14.7	1.0	1.0	IN, OH, WI	MO, IN, IA
Missouri	7.5	1.0	0.03	IL, KS	(?)
Pennsylvania	9.5	0.8	3.8	OH, WV, IL, IN	NJ, NY
Rhode Island	1.2	0.6	—	OH, MA	—
Ohio	17.5	0.3	1.7	MI, PA, KY,	NY, NJ, PA, RI
Virginia	7.6	0.03	1.5	NC	
West Virginia	1.7	0.1	0.5	PA,OH, KY	PA
Connecticut	2.3	—	0.8	—	(?)
Massachusetts	6.8	0.4	0.7	NH	RI, NY
New Hampshire	1.1	0.03	0.5	MA, ME	MA
Indiana	4.4	0.08	0.8	IL, OH, KY, MI	NY, NJ, IL, PA
Kansas	2.7	—	0.7	—	MO
Totals[c]	109.5	9.8	12.2		
Total as % of U.S.	36%	75%	84%		
U.S. totals	306.9	13	14.5		

Sources: Waste generated from *BioCycle*, 1994; waste exported and imported from McCarthy [13] (see also notes therein); shipment destination/origination from [13] and state data available from authors.
[a] Reflecting shortcomings in the available data, trading partners do not always match (for example, NJ reports receiving from NY but NY does not report shipping to NJ).
[b] The amount of waste generated that is landfilled varies widely across states; most waste that is exported or imported is landfilled, although there are exceptions (in Connecticut, for example, about one-third of imports go to waste-to-energy facilities (see [13] for discussion)).
[c] Exports and imports do not match for at least two reasons. One is that states in addition to those listed above export and import waste; the other is that even in nationwide data, reported exports and imports do not match—see bottom line above (see [13] for discussion).

chosen for each state (and the acronyms we use to refer to them). We make this simplification because most of the actual data we use to benchmark our simulations are reported for an entire state, not individual localities. This assumption has a potentially important implication which we discuss below in describing baseline simulation.[11]

Our third simplification concerns the inverse demand curves. As GMS discuss, a city's demand for alternatives to recycling and waste reduction (the city's demand for landfill space) can be derived from a cost-minimization problem, where waste which is not reduced or recycled must be landfilled (or incinerated). An increase in the price of landfilling (or incinerating, if it is cheaper) would result in more waste reduction and recycling and consequently less reliance on landfilling. Consequently, the derived demand for landfill space (and incineration) is downward sloping. Moreover, the increased minimized cost which would result from the increase in the landfill price can be measured as the "net consumer surplus" trapezoid under

[11] Where we have established two locations in a state, we have allocated total state waste generation between the locations based on their population. We have allocated total state landfill capacity between the two locations based on data in *Solid Waste Digest* giving landfill locations and capacities.

TABLE III
Locations and Abbreviations Used in the Model

Abbreviation	Location
NYC	New York City, NY
NYB	Buffalo, NY
NJ	Trenton, NJ
IL	Chicago, IL
MO	St. Louis, MO
PAPi	Pittsburgh, PA
PAPh	Philadelphia, PA
RI	Providence, RI
OHCl	Cleveland, OH
OHCi	Cincinnati, OH
VA	Richmond, VA
WV	Charleston, WV
CT	Hartford, CT
MA	Boston, MA
NH	Concord, NH
INI	Indianapolis, IN
ING	Gary, IN
KS	Topeka, KS

the inverse demand curve. While elegant, this approach requires the following information for *each city*[12]: (1) the cost function for recycling, (2) the cost function for waste reduction, and (3) the waste flow in the absence of waste reduction. While at least some of this information is available for Finland [8], it is not available in the United States. Therefore, in our empirical implementation of the model we chose a more practical approach which uses available information to derive the demand curve for each city.

We assume that the demand curve for every city is linear with a common slope but city-specific intercepts. (We use the quantity of waste which is actually shipped by that particular city to landfills and the price per ton paid to determine a point of each inverse demand schedule. We deduce the amount of waste landfilled by subtracting from the total waste flow for that city the amount recycled.) A common initial slope for the inverse demand curves of all cities is chosen so that the elasticities in the simulations match elasticities discussed in the empirical literature on the demand for waste disposal services (we discuss this literature below). Each inverse demand curve is assumed to pivot around its vertical intercept at 5% per year to reflect population (and income) growth.

Most of the available data that we use are quite limited for several widely recognized reasons. States have begun collecting statistics about waste generation and disposal only recently, and the types of data collected vary among states. Some jurisdictions carry out detailed surveys to determine quantities of in-state waste generation and waste imports and exports; others extrapolate using national data on waste generation per capita in their calculations. Most of our

[12]While there are virtually no data available with which to estimate the marginal costs of recycling various materials, we did use anecdotal information on such costs on an experimental basis to endogenize the choice between landfilling and recycling. We note these results in Section 5.

data are from publicly available surveys reported in the trade literature or by state agencies.[13]

There are other shortcomings in these data. For example, definitions of MSW vary among states. Some include construction and demolition debris or municipal sludge; others do not. In addition, as noted in Table II, reported volumes of imports and exports typically do not match between any pair of states (a similar problem also arises in international trade statistics on imports and exports). Usually, imports reported by the receiving state exceed exports reported by the shipping state.[14] Another problem is that data on average annual tipping fees only approximate the fees that might be charged under long-term waste management contracts and the fees charged daily in the "spot" market. The data on landfill capacity are also imperfect; estimates of landfill design capacity can change due to landfill expansion or closure or changes in operating permits, and daily operating capacity can vary for these reasons as well as those related to weather or other short-run conditions. Our sources of data and our attempts to adjust for some of their shortcomings follow below.

Demand Price Elasticities and Demand Growth Over Time. We specify linear demand functions for waste collection and disposal services for each geographic state in each time period using the following equation: $Q_{jt} = (A_j - B \cdot P_{jt})(1+g)^t$, where A_j is the waste generated in tons, B is a slope parameter, and g is the annual growth rate. Since we are only interested in *changes* in the consumer surplus, it suffices that the linear approximations to the true underlying demand functions hold around the area affected by the policy changes. The subscripts j and t refer, respectively, to the city and to the time period. The price elasticity is then

$$\xi_{jt} = -B\frac{P_{jt}}{Q_{jt}} = -\frac{A_j - Q_{jt}}{Q_{jt}}. \tag{6}$$

Demand grows over time because of growth in income and population. Estimates indicate that waste generation has been growing about 5% annually during recent years (see *BioCycle*, April 1999).[15]

We parameterize Eq. (6) such that the price elasticity is within the range of previously reported econometric estimates of the price elasticity of demand for waste collection and disposal services (see Fullerton and Kinnaman [4], Jenkins [9], Wertz [23], Morris and Byrd [15], and Skumatz and Breckinridge [22]). These estimates

[13] Several more stringent environmental regulations governing landfill operation, mandated in Subtitle D of the Resources Conservation and Recovery Act, were to have become effective during this period. The anticipated results were the closing of substandard landfills and higher operating costs at others. The trade press reports that indeed, substandard facilities did close, but these were largely small-capacity facilities. The press reports also, however, that new, large municipal facilities opened to offset the decline in aggregate capacity. More recent data, when they are available, may shed further light on the effects of Subtitle D and other changes in the disposal market.

[14] As noted by a referee, landfill operators may have an incentive to understate imports.

[15] If we were to assume that income grows at rate g and that demand growth is due solely to income growth, then the income elasticity of demand is unity. As we note above, however, we assume that our parameter g is a mix of income and population growth. Econometric estimates of income elasticities are generally small (around 0.05) although some estimates are as large as 0.2 or 0.4 (see discussion and references in Fullerton and Kinnaman [4]).

generally suggest high price–inelastic demand, on the order of −0.26 to −0.075. The price elasticities in our baseline model vary across geographic states and over time; the average across states for 1993 is −0.15. As we discussed in the preceding section, the linear inverse demand curve of each city is assumed to pivot around its vertical intercept, its elasticity at any given price will not change. However, in our simulations, the price a city pays for waste disposal rises over time and, therefore, so does the elasticity of demand. Because the most recent econometric data suggest elasticities toward the less elastic range, we also test the sensitivity of the model with less elastic demand.[16]

Operating Capacity and Backstop Costs. The operating capacity of landfills (tons per day) are statewide averages reported in various issues of *Solid Waste Digest*. We multiply the daily operating capacity by 300 to convert it to an annual measure. Incineration costs are also an input to our simulations. We use observed incinerator tipping fees as proxies for the marginal costs of our backstop technology, although the backstop can also be taken to include future landfills. We realize that estimates of capacity and incinerator tipping fees are subject to the problems noted earlier but we do not adjust for them. In cases where states do not have incinerators, we used the tipping fee at the next nearest incinerator in a neighboring state to represent the marginal cost of the cheapest incinerator available to the city (this amount generated landfill tipping fees close to actual reported fees in our baseline model; we discuss this below). We vary our assumed backstop costs in testing the sensitivity of the model.

Transportation Costs. We telephoned experts in waste hauling to obtain an estimate of transportation costs per mile per ton of waste. A consensus estimate was 11 cents, although our contacts indicated that these costs are continuing to decline. We vary this estimate between 5 and 11¢ in sensitivity tests.[17] We calculate travel distances between states using Rand McNally and American Automobile Association maps.

Discount Rate. We use 5% as the discount rate in our baseline model and use 10% in sensitivity tests.

MSW Generation, Percentage of Waste Landfilled, Landfill Capacity. Data on the annual number of tons of MSW generated by a state, the percentage landfilled, and statewide landfill capacity are from an annual nationwide survey reported in *BioCycle* magazine's assessment, "The State of Garbage in America." We use data from their 1994 survey, contained in the April 1994 issue of *BioCycle*. Some of these data are from earlier annual surveys, and data from a few states include a portion of industrial and construction/demolition waste in addition to conventionally defined MSW (see *BioCycle*, April 1994, for details). We did not attempt to adjust the data for these inconsistencies. In addition, we also used the reported data on landfill capacity remaining in the state although, as noted above, landfill capacities can be

[16]There is evidence that price elasticities can vary markedly among different types of waste but we do not take that into account (for instance, some waste is more easily recyclable; see Fullerton and Kinnaman [4] and Sigman [21] for discussion of elasticity differences).

[17]We spoke with representatives of two long-haul trucking firms and one railroad (information available upon request). Because most waste is moved by truck (only 2% is transported by rail (see Woods [25])), we use estimates of trucking costs.

altered through expansion or changes in permitting. We report in our results section the effect of allowing marginal landfill expansion to occur in our simulation.

Interstate Waste Flows. We do not use this information in our model but we do use it in evaluating our model's results. Estimates of state waste imports and exports during 1993 are from a survey by the Congressional Research Service (see McCarthy [13]) and, where available, additional data were obtained from state agencies that identify waste flows among all trading partners (these data were available from Pennsylvania, Illinois, and Indiana). A recently updated report [14] shows that interstate flows continue to follow the patterns in the earlier survey. As noted earlier, because import and export amounts generally do not match among partners, we follow the practice of studies of international trade and use import data. Our presumption is that importing states have an incentive to collect more accurate information about waste imports because of citizen opposition to these imports. (In the case of international trade statistics, import data are usually considered more reliable because trade management, such as the imposition of import tariffs and quotas, requires detailed information on quantities of imports.)

External Costs. Research to date is inconclusive on the extent to which landfills impose negative externalities on nearby communities. Two studies, in Massachusetts and California, estimate external costs in the form of air and water pollution and noise at $67 to $75 per ton—see discussion in [19]. The U.S. Environmental Protection Agency, however, argues that external effects are negligible, particularly given the extensive requirements on landfills for containment of leachate and gas (see [27, 28]). In a study of communities near landfill sites in the United Kingdom, Garrod and Willis [6] found empirically negligible external effects on home values, although the United Kingdom in 1996 imposed a tax per ton of landfilled waste ranging from $3 to $14 with the goal of, according to the legislation, fostering "an explicit environmental objective" (the legislation does not further define this objective nor does it address the nature of any externalities that decision makers consider to be associated with the objective).

If there are external costs invariant both to the level of activity at a landfill and to the source of its waste, neglecting them would not alter our results. Their inclusion would not affect the competitive allocation since they would be ignored by market participants. Moreover, they would not affect our welfare conclusions either since we restrict ourselves to reporting changes in welfare.

External costs which do vary with the level of activity at a landfill would affect our results. To illustrate how such externalities would be handled if the future data confirm that they are nonnegligible, we conduct sensitivity analysis. As suggested in Repetto et al. [19], we hypothesize that the external cost imposed on a city adjacent to a landfill is directly proportional to the tons deposited in that fill and to the population density of that city compared to the average density of all the cities. We then determine the socially optimal allocation and compare the associated net surplus to the net surplus associated with the baseline allocation after external costs are deducted. We also calculate how this maximized social surplus would be distributed in a competitive equilibrium assuming that the revenue from an optimal Pigouvian tax on users of each fill is redistributed lump sum to the victims of the pollution. Finally, we investigate the degree to which proposed policies will improve on the laissez-faire allocation given the hypothesized externalities.

4. BASELINE SIMULATION

In this section we discuss results of our baseline simulation. We describe the prices and allocations in the first year (1993) and compare them with the "real world" data. We also discuss sensitivity tests of the baseline to changes in the values of its exogenous parameters including demand elasticity, transportation costs, the discount rate, and the costs of backstop technology (incineration). We also discuss results of permitting landfills to expand by a small amount. Table IV lists the parameters we use for the baseline model.

Table V summarizes results of the baseline and, for comparison, actual data on tip fees and the value and patterns of interstate flows. The parameters we assume in the baseline generate estimated tip fees and an aggregate volume of interstate shipments that are consistent with available data. The unweighted average of our estimated tip fees is $39 compared with $41, the average in the actual data. Estimated shipments total 10.2 million tons per year, in line with actual estimates of 9.8–12.2 million tons per year (representing reported exports and imports, respectively). The pattern of trading partners and the relative volumes of waste traded among partners is also consistent with available information. As to specific volumes trading between states, experts agree that reported information on interstate flows is highly inaccurate with respect to both quantities and trading partners (moreover, as noted earlier, reported import and export data typically do not match up). For this reason, it is not clear what role the available information might play as a comparison with our simulations. In some respects, our simulated pattern of trading partners and the relative volumes of waste traded are consistent with the reported information.

TABLE IV
Baseline Parameters

City/fill	Total waste generated (million tons/year)	Fill life (yr)	Fill capacity (million tons/yr)	Landfilled (%)	Backstop cost ($/ton)
NYC	12.1	5	2.1	59	88
NYB	13.1	9	7.2	59	88
NJ	7.3	4	4.6	38	82
IL	14.7	8	14.1	78	50
MO	7.5	8	6.3	82	50
PAPI	2.0	15	10.5	68	67
PAPH	7.5	7	5	68	67
RI	1.2	15	0.8	79	50
OHCL	11.3	8	6	74	47
OHCI	6.2	8	5.6	74	45
VA	7.6	15	8.5	58	39
WVA	1.7	15	3.3	88	50
CT	2.3	4	1.1	22	70
MA	6.8	4	5.3	25	68
NH	1.1	4	1.1	65	44
INI	3.3	10	2	75	50
ING	1.1	4	2	75	50
KS	2.7	12	4.2	94	50

Note: Demand slope parameter: −0.0002 (demand elasticity: −0.15); transportation costs: 11 cents/ton/mile discount rate: 5%/year; rate of demand growth: 5%/year.

TABLE V
Baseline: Reported Values and Simulated Results for 1993

	Tip fee ($/ton)		Interstate shipments		Shipments to (from)[b]
	Reported	Simulated	Reported[a]	Simulated[a]	
NYC[c]	62.75	62.52	3.9	4.8	NJ, PAPh, **OH, VA, WV, CT, MA, IN**
NYB	62.75	52.93		0.3	PAPi
NJ	77.14	55.67	1.6	2.5 (4.6)	VA, (NYC), **PA, WV**
IL	25.17	33.29	1.0 (1.0)		**IN, WI**
MO	26.48	33.82	1		**IL, KS**
PAPi[c]	36.00	27.53	0.8 (3.9)	(2.5)	(NYB, OHCl), **WV, NJ**
PAPh	55.00	51.05		(0.2)	(NYC)
RI	48.48	44.54	0.5	(0.1)	(CT), **MA**
OHCl[c]	33.29	41.33	0.3 (1.7)	2.2	PAPi, (INI), **MI, KY, WV, NY, NJ**
OHCi	24.00	30.34		(0.3)	
VA	33.75	25.49	(1.5)	(2.5)	(NJ), **NC**
WVA	29.94	17.49	0.1 (0.5)		**KY, MD, OH, PA**
CT	65.26	50.03		0.1	**MA**
MA	55.97	42.38	0.4 (0.7)		**NH, RI, NY**
NH	41.36	36.61	0.03		**MA, ME**
INI[c]	22.81	42.26	0.08 (0.8)	0.3	OHCi, **IL, KY, MI**
ING	22.81	33.22			
KS	10.32[a]	24.87	(0.7)		**MO**
	Average Tip Fee		Total Trade Volume		
	40.74	39.14	9.8 (12.2)	10.2 (10.2)	

Source: Actual tip fee for landfills from *Solid Waste Digest*, various issues.
[a]In millions of tons per year; numbers in parentheses are imports; "reported" shipments are by state (e.g., for New York state, because the available data are not separately reported for NYV and NYB).
[b]Boldface type denotes trading partners reported in McCarthy [13] but not predicted by the simulation.
[c]States divided in model; see text.
[d]Average may be larger; *BioCycle* (1994) reports $25.

We capture the larger trades among those reported (for example, New York is the largest exporter and Pennsylvania and Virginia are among the largest importers). We also capture the largest among the reported trading partners (e.g., New York and Pennsylvania, Ohio and Indiana, Virginia and New Jersey). Some differences are that we "overpredict" imports to New Jersey and Ohio, and we "miss" some trades among small and neighboring New England states (e.g., Massachusetts, Connecticut, and Rhode Island). In general, the model yields fewer trading partners than are reported, particularly among states that trade in small volumes, than the real-world information indicates.

The model may predict fewer trading partners because of our restrictive assumption (which we made to reduce data collection requirements) about the location of waste generation and disposal. Our assumption of colocated waste generation and landfill capacity within a state means that for each state, the distance between the location of generation of waste in the state and that state's own landfill is zero. This assumption makes using a state's own landfill more attractive than interstate trade.

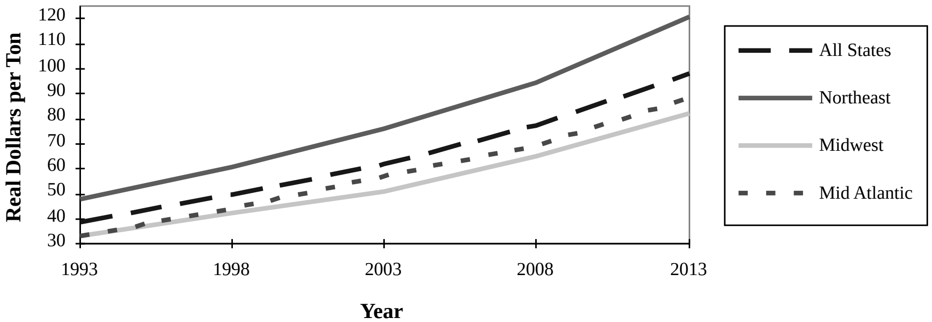

FIG. 4. Baseline: time path of tip fees (unweighted average).

In particular, the model underestimates interstate shipments:

- among states that are large or whose city/landfill sites are in the interior of the state rather than on its borders (our use of two locations in large states alleviates this problem somewhat);
- among states where there are many landfill locations throughout the state;
- among states for which reported trading partners include states outside the geographic coverage of our model (e.g., Wisconsin, Kentucky, Maryland, and Michigan); and
- among states where landfill capacity is not near the large population centers from which waste generation is assumed to originate.

Figure 4 illustrates the time path of real tip fees from 1993 to 2013 (by 2013, all sites are using their backstop technologies). The unweighted average fee for all cities increases about 163%. The largest increases are in the Northeast. Note that whereas it might be expected that the average fee should rise by the rate of interest, the tip fee is in fact the sum of shadow values on a unit of landfill capacity as well as on the operating capacity of the landfill. Thus, for instance, in the case of MO, the constraint on operating capacity does not bind in the first year of operation but does bind by the fifth year, leading to a 46% increase in the predicted tip fee. In the case of NYB, however, the operating constraint binds in the first year but not by the fifth year, leading to an increase of just 11% in the tip fee.

Figure 5 illustrates the behavior of these flows over time by indicating the number of trading partners each year and the aggregate volume of interstate shipments. Waste traded as a percentage of waste generated increases from 15% in 1993 to 33% in 1998 as states exhaust in-state landfill capacity. By 1999, these interstate flows occur among 11 different pairs of trading partners (e.g., NY–PA, NJ–VA). After 1999, more and more states begin to use their backstop technology and the volume and number of interstate trades begin to decline. By 2009, interstate flows have reached a trickle. It is not clear from debate on interstate waste whether it is the number or volume of shipments that is of most concern in the public's perception. Large numbers of small shipments may generate roadway wear and tear or congestion, say, and large shipments "use up" communities' landfill space.

Landfill Expansion. Expanding a landfill is usually quite politically controversial within the community adjacent to the fill, but municipal and state authorities sometimes amend landfill operating permits to allow some expansion—usually on the

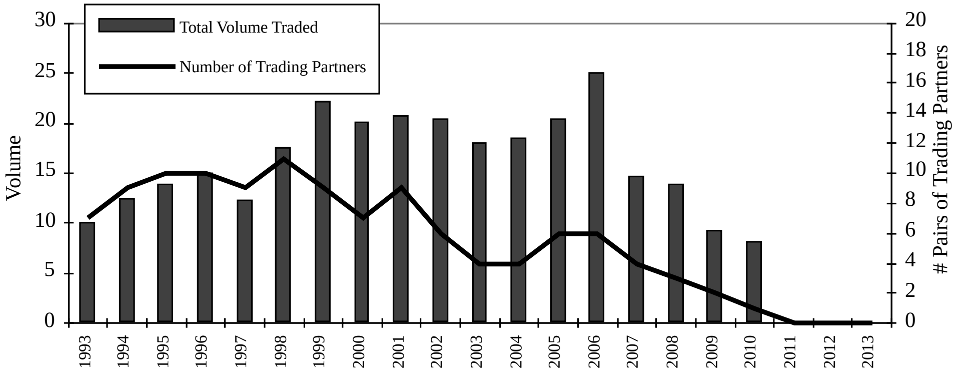

FIG. 5. Baseline: total volume and number of trades.

order of a few percent of capacity. Accordingly, we permitted our baseline model to expand landfill capacity endogenously for 4 years, under three scenarios: expansion at a marginal cost of $5, $10, and $15 per ton. In each case, we assumed that the annual capacity expansion could not exceed 2%. We find that the volume of waste traded and the number of pairs of states that trade waste are virtually unchanged. All of the landfills expand and the largest expansions take place at the large landfills in the Midwest. Figure 6 illustrates the results for expansion at $5 per ton.

4.1. *Sensitivity Simulations*

We conducted several sensitivity simulations to assess the robustness of the model to our assumed parameter values; Table VI summarizes the results—more details are available from the authors upon request. The model's predicted tip fees change only negligibly when we reduce demand elasticity, but change widely among states with the change in transportation costs. We see larger swings in surplus measures. As would be expected, discounted consumer surplus is very sensitive to the change in demand elasticity and the discount rate. Discounted producer surplus is sensitive to changes in the costs of transportation and the backstop technology. These surplus

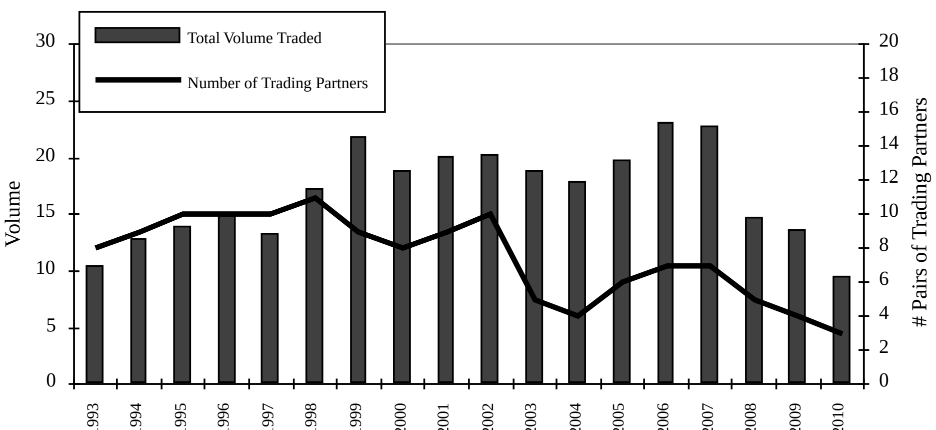

FIG. 6. Landfill expansion at $5/ton.

TABLE VI
Results of Sensitivity Tests: *Change Compared with Baseline*[a]

	Average tip fee	Volume traded (% total)	Discounted present value of surplus, 1993–2013		
			Producers	Consumers	Total
Reducing demand elasticity to −0.01 (average across states)					
1993	<5%	>10%			
2013	<5%	<5%[b]	0.9	—[c]	—[c]
Increasing the discount rate to 10%					
1993	(5–10)%	5–10%			
2013	>10%	∼	(9.2)	(191.7)	(200.9)
Reducing transportation costs to 5¢/ton/mile					
1993	∼[d]	<5%[e]			
2013	∼[f]	∼	1.5 (↓ NE, ↑ MW)	1.5	3.1
Increasing the cost of the backstop technology to $100/ton					
1993	>10%[g]	5–10%			
2013	>10%	∼	(19.2) (wide variation)	(44.9)	(25.7)

[a]Notation: numbers in parentheses represent negative figures, "(>5%)" means a decrease larger than 5% in absolute value. ∼ denotes a negligible change. Dollar figures are billions of 1993 dollars.
[b]Most states now use backstop technology.
[c]The change in consumers' surplus based on a linear approximation to the demand schedule around the baseline allocation cannot be computed here since there are different demand schedules involved.
[d]Fees decrease in the Northeast and increase in the Midwest.
[e]Largely within state.
[f]Fees increase relatively less in the Northeast than in the Midwest compared with the baseline.
[g]Fees increase in all states and double in the Midwest.
[h]We are taking into account the $12.26 billion negative externality unaccounted for previously in the baseline allocation. The consumer surplus from waste disposal ignoring the externality is $2.2 billion lower than in the baseline allocation.

effects also vary widely among geographic regions; for instance, surplus is transferred from producers in the Northeast to those in the Midwest when transportation costs decline. Perhaps most important for our focus on interstate flows, however, are the effects of the sensitivity tests on the volume traded and the number of interstate flows. Our simulations suggest that when the demand elasticity, discount rate, and transportation costs are modified, the volume traded can increase initially but there is only one additional trading partner. Over time, there is a small or negligible change in the volume traded and no change in the number of trading partners. The response to changes in transportation costs may be heavily dependent on the assumption we made to economize on data collection about the locations of landfills and of the origin of the waste generated.

As noted in Section 3, recycling can be accommodated in our model. The model can be reinterpreted to encompass the case where city j's waste stream at time t is fixed but the planner can reduce what is landfilled or incinerated by recycling at a cost a larger portion of the fixed waste stream. The utility associated with landfilling a given amount of waste is, under this interpretation, the cost which is saved from not having to recycle it. For a full discussion, see footnote 7 of GMS and the working paper to which it refers. Although we did run some simulations using this approach, we chose not to highlight them in our discussion because we judge the data obtainable on recycling costs unreliable. In particular, there are no data on marginal costs of recycling in the United States (Huhtala [8] presents some data for Finland). We approximated U.S. costs by using the reported prices offered by recyclers (by type of material—e.g., plastic or paper), from which we subtract 10%, which we assume to be their profit. We also used data on the national average percentage composition of the waste stream by type of material and assumed that the waste streams of all cities can be represented by this average. All data are from Palmer, et al. [17]. They collected information on prices from various issues of *Recycling Times* and *Resource Recycling* and report the composition of the waste stream based on Franklin Associates, *Characterization of Municipal Solid Waste in The United States*, 1992 Update (report prepared for the U.S. Environmental Protection Agency, November). Our results predicted reasonable recycling rates, ranging from 17% in KS to 25% in NYC. These rates imply a much larger percentage of waste landfilled, and a much larger quantity of waste shipped interstate than our baseline results. The results of this trial run with endogenous recycling are available from the authors. As better data become available on marginal recycling costs, we would like to do more extensive runs with recycling endogenized.

Finally, we ran simulations assuming that landfilling generates negative externalities to the inhabitants of nearby cities. We assume that the external cost at a given landfill is proportional to the population density of the city adjacent to it and to the tons of waste deposited in the landfill. We impose an average externality of \$20 per ton.[18] That is, $\varepsilon_j = \$20\times(\text{density}_j/(\text{average density}))$ is the external cost per ton imposed on inhabitants of city j because of the aggregate activity of the adjacent landfill. The planner's objective function becomes

$$\sum_j \sum_t \beta^t \left\{ (U_{jt}(x_{\cdot jt} + b_{jt}) - \varepsilon_j x_{j\cdot t}) - \theta b_{jt} - \sum_i c_{ij} x_{ijt} \right\}.$$

A Pigouvian tax can be used to decentralize this social optimum. All users of the landfill adjacent to city j would pay a tax of ε_j per ton. This would create a wedge between what these users pay to use that landfill and what the landfill receives. The social surplus in this case equals the sum of (1) net consumer surplus, (2) net

[18] As discussed, the externality varies with site in proportion to the population density of the adjacent city resulting (in the order of Table III) in an externality per ton of \$64.29, \$21.91, \$31.43, \$33.23, \$17.37, \$18.03, \$31.83, \$23.62, \$17.81, \$12.79, \$9.16, \$5.27, \$21.90, \$32.17, \$1.52, \$5.49, \$6.30, and \$5.90.

producer surplus, and (3) government tax revenues less (4) external costs. However, since the external costs are assumed to be linear, the tax revenues exactly offset the external costs. For concreteness, we assume that the revenues are paid to the victims, leaving this group unaffected.

In the presence of taxation, we redefine the tipping fee paid by city j to landfill i as the price paid by city j net of *both* the Pigouvian tax and the transportation cost. Hence, in the unregulated case, it would equal the shadow price of the resource at time t. The existence of an external cost lowers the value of additional space in the ground. Consequently, the existence of externalities causes both tipping fees and producers' rents to decrease substantially, especially in landfills situated in the Northeast. Consumer surplus from waste disposal falls but less dramatically. The number of interstate shipments also increases as the tip fees fall in the Northeast.

We can compare aggregate surplus when the externalities are taken into account to the aggregate surplus when they are ignored. During 1993–2013, \$12.26 billion (1993) dollars in external costs are imposed on consumers in the baseline allocation—i.e., the term $\sum_j \sum_t \beta^t \varepsilon_j x_{j \cdot t}$. That cost should be deducted from the aggregate surplus previously calculated for the baseline simulation. Reallocating the spatial and intertemporal allocation to take account of the hypothesized external costs turns out to raise the social surplus by \$0.23 billion. How much of this potential gain is achieved by the three restrictions simulated below? With all three policies in place, aggregate surplus *falls* relative to the baseline. Interestingly, one reason why the aggregate surplus falls is that the total amount of the externality itself increases when the three restrictions are imposed—dramatically so in some states in the Northeast. Naturally this conclusion must be regarded as speculative since it is based on hypothetical data on external costs.

5. POLICY SIMULATIONS

The primary purpose of our model is to understand the implications of various proposed policies to restrict interstate trade in MSW. In this section we consider several scenarios. We impose each of the following restrictions:

- Surcharges: a \$1 surcharge applied to each ton of imported waste.
- Quantitative restrictions: volume-based restrictions on the amount of waste exported.
- Surcharges and quantitative restrictions: a combination of a \$1 import surcharge and quantitative export restrictions.
- No trade: prohibition of any interstate shipments.

We model the first three of these policies based on provisions in the 1995 Senate bill and subsequent legislative proposals restricting waste shipments (see discussion in Section 2). Specifically, this bill proposes that importing states be permitted to levy a \$1 surcharge per ton of imports. It also proposes the requirement that exporting states in 1996 export to any one state no more than the greater of 1.4 million tons or 90% of the amount exported to the state in 1993; in 1997, the limit is the greater of 1.3 million tons or 90% of the amount exported to the state in 1993; and the limit is increasingly smaller amounts in subsequent years (with the restriction in

2002 and any year thereafter set at no more than 550,000 tons).[19] We assume that these restrictions are perfectly enforced and all tax revenue (or revenue from auctioning licenses to export or import) is redistributed to landfill owners rather than to consumers (those generating the waste). Finally, we assume in these preliminary simulations that the imposition of the new policy is perfectly anticipated.

Our primary interest is in the effects of these policies on the volume and number of interstate shipments and on changes in the size and distribution of surplus. We summarize the results in Fig. 7 and Table VII. We also have results for changes in surplus among states and for changes in tip fees, which of course drive the changes in shipments and surplus. We summarize these in the discussion below (details are available from the authors). Changes in surplus are in terms of discounted present value, in 1993 dollars.

5.1. *Surcharges*

Interstate Trade. We would expect that an import surcharge would reduce imports and the amount of waste traded among states. It would raise the prices of titles to landfill capacity sold to states which formerly exported waste and would lower the prices of titles to landfill capacity in states which formerly imported waste. When we impose a $1 surcharge on each ton of waste imported, the results are consistent with these expectations although the size of the effect is small. The percentage of waste traded declines, although by only about 4%. From Fig. 7, the total volume of waste traded and the number of pairs of states which trade each year under this policy compared with the baseline are smaller, but only slightly.

Surplus. Of all of the policy simulations, the $1 per ton surcharge yields the smallest reduction in total surplus. The reduction is about $10 million. There are larger losses in total surplus in some importing states than those in exporting states. Consumer losses are largest in the Northeast, although the largest reduction there is only about $3 per person (in NYC). Aggregate producer surplus increases about $160 million; this change in producer surplus includes the surcharge revenue (which our model ascribes to producers). Some producers in waste-importing states lose surplus even under this assumption (in OH, WV, and KS). Producers in the Northeast gain. In many cases, the within-state consumer and producer changes offset each other (the offset is realized only if the owners of disposal facilities reside in the state). Separately calculated, the surplus revenue is about $280 million.

5.2. *Volume Restrictions*: *A Cap on the Volume of Interstate Shipments Taking Effect in* 1996

In this simulation we limit the maximum number of tons that can be exported by one state to another, following the tonnage limits specified in the Senate bill. As per that bill, this upper limit took effect in 1996.

[19] It is not clear whether states may ship to states with which they did not trade prior to 1993, provided that shipments meet this quantity cap. Accordingly, we model two interpretations of the cap: (1) states are subject to the cap but may trade with any state provided the quantity satisfies the cap; and (2) states are subject to the cap and cannot ship to any state with which they did not trade in 1993.

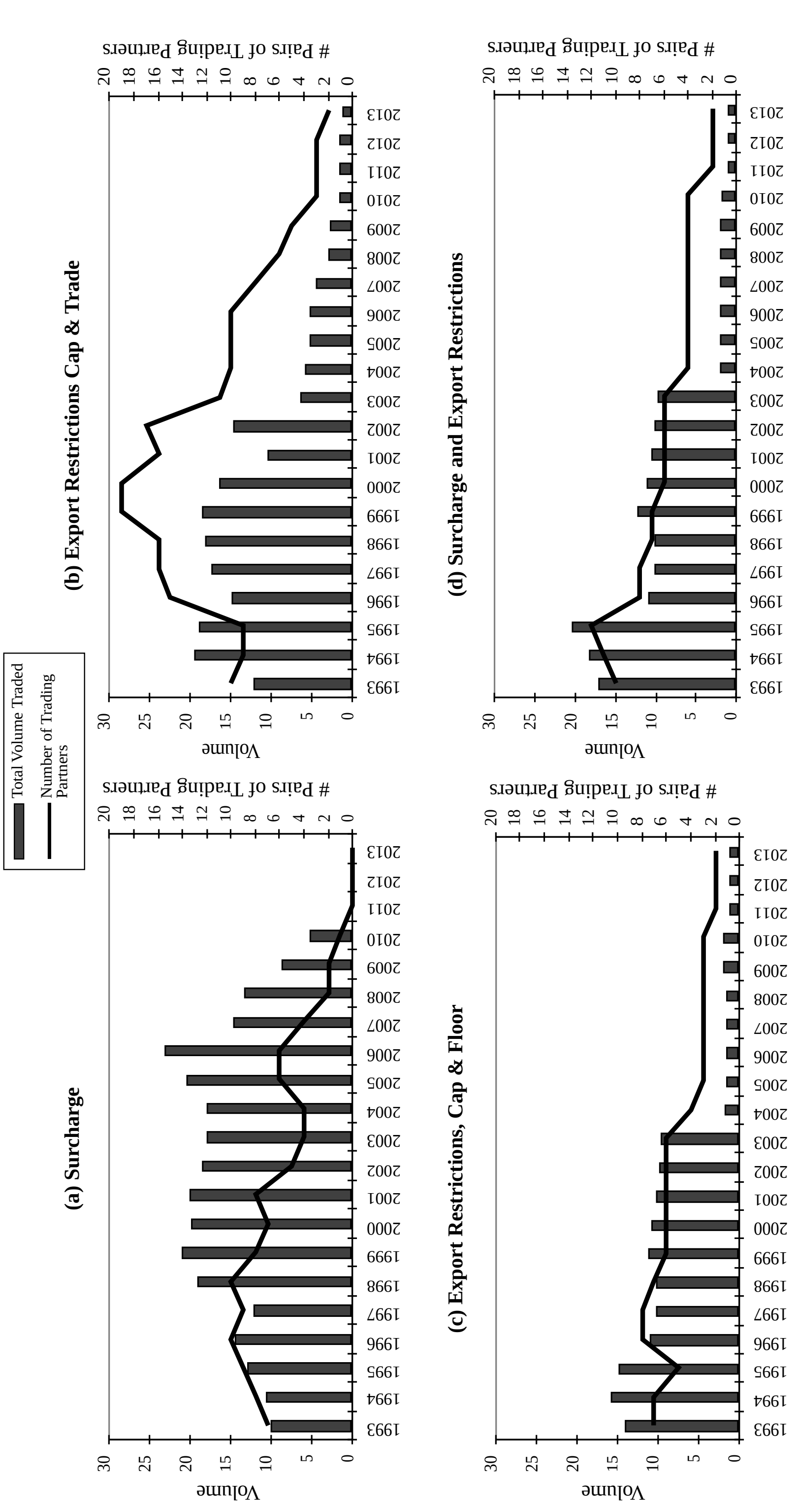

FIG. 7. Trade under policy simulations. Left scale: volume traded in millions of tons. Right scale: number of pairs of trading numbers.

TABLE VII
Policy Simulations: Surplus Effects Compared with Baseline

	Producers	Consumers	Total
Surcharge	0.16 (↓ OHCi, WV, IN)	−0.17	−0.01
Export restrictions: cap	−1.19 (↓ PA, VA)	−0.16	−1.35
Export restrictions: cap and floor	−1.75 (↓ PA, IN, VA)	−0.28	−2.03
Surcharge, cap and floor	−1.50 (↓ PA, VA, IN WV)	−0.40	−1.90
No trade	−2.47 (↓ PA, OHCi, VA, WV, IN)	−1.31	−3.78

Note: Values are reported as discounted $ (billions).

Interstate Trade. We find that tip fees increase substantially even prior to the date at which restrictions take effect. They decline in some importing states and increase in exporting states; the reduced fees in some states attract increased shipments. These changes yield interesting results in the size and patterns of trade. The total volume of traded waste decreases about 30%, but as shown in Fig. 7, the annual volume of waste traded and the number of trading partners increase throughout much of the entire time period. The increases began immediately in 1993, in anticipation of the date at which the restrictions took effect (1996). Even when the quantity traded is less than in the baseline (for example, compare the period 2003–2010), the number of trades exceeds those in the baseline, and there are more shipments of small amounts of waste.

Surplus. This restriction reduces surplus by about $1.35 billion. The largest loss is in producer surplus; aggregate loss in producer surplus is about $1.2 billion. In some waste-importing states producers lose as much as 25% (in PAPi), but in other importing states, producers gain from increased shipments (for example, in WV). Aggregate consumer surplus falls about $160 million. As in the case of the surcharge, the largest consumer surplus losses accrue in the Northeast. Consumers in some waste-importing states gain.

5.3. *Volume Restrictions*: *A Cap on the Volume of Interstate Shipments and Prohibition of New Trade with Any State*, *Taking Effect in* 1996

This simulation imposes the cap described above and prohibits any state from making any new shipments to any state with which it was not already trading in 1993. Some observers of congressional debate suggest that this combination of a cap and a floor on trade is the proper interpretation of the Senate bill.

Interstate Trade. Changes in tip fees are as in the preceding simulation, although the magnitude of the changes is less pronounced. The floor prohibiting trade among states not trading in 1993 prevents the increase in shipments of smaller volume that result when just a cap on trade is imposed. Both the number of trading partners and the quantities of waste traded are smaller than in the baseline and in any of the other policy simulations. Total waste traded falls about 50%.

Surplus. This policy results in the largest loss of surplus except for "no trade" (discussed below), on the order of \$2.03 billion. Aggregate producer and consumer surpluses both fall, about \$1.75 billion and \$28 million, respectively. The largest per capita losses in total surplus are in NYC, about \$160. Per capita losses in total surplus elsewhere are fairly small, on the order of a few dollars. The largest producer losses are in PAPi and VA (about \$1 billion) and in ING (about \$20 million). Producers gain in some states that export waste in the baseline model.

5.4. *Surcharges and Volume Restrictions*

The Senate bill permits several of its provisions to be combined. In this simulation we impose a \$1 per ton charge on imported waste, restrict the maximum volume of interstate shipments beginning in 1996, and prohibit trade between any states not already trading in 1993.

Interstate Trade. The pattern of changes in tip fees is very similar to the effects of volume restrictions. The largest difference in results between this simulation and the others is that there is a spike in the number of trading partners and waste traded in advance of 1996. Beginning in 1996, the volume and number of trades fall below the baseline. The total volume traded decreases about 45%.

Surplus. The changes in surplus are similar to the changes brought about when the cap and floor volume restrictions are imposed (recall that the surcharge-only simulation resulted in a very small change in surplus). Total surplus falls about \$2 billion; the reduction in producer surplus is smaller than that in the preceding simulation because we allow producers to keep the surplus revenues. Consumer surplus declines about \$40 million. The geographic patterns of surplus changes are similar to those generated by the cap and floor restrictions. Producers in PAPi, VA, ING, and WV incur the largest losses, as do consumers in the Northeast.

5.5. *No Trade*

Here we consider the effect of an immediate and permanent prohibition of interstate trade. Tip fees increase substantially in the Northeast and fall in some states that import waste as there is less demand for their landfill capacity. This policy yields the largest decline in producer, consumer, and total surplus. Per capita losses in total surplus range from \$370 in PAPh and \$93 in NYC to 17¢ in IL. The total surplus loss is about \$3.8 billion, roughly twice the size of the loss generated by the volume-based restrictions in the two preceding simulations.

5.6. *Summary of the Policy Simulations*

As we expected, restricting interstate trade by way of import surcharges or volume-based constraints reduces aggregate surplus, although producer surplus can increase. A \$1 per ton import surcharge generates less welfare loss than volume-based export restrictions or the combination of an import surcharge and export restrictions. Prohibiting trade altogether reduces welfare the most. Because we chose to run these simulations under the assumption that each policy is fully anticipated, our estimates of welfare loss probably understate the actual loss that would occur in the real world in which decision makers do not have perfect information.

In all cases, the reduction in the discounted total surplus is quite small—on the order of 1% and just 2% when trade is prohibited entirely. The aggregate surplus changes per capita range from 2¢ per person under a surcharge policy and $177 per person under volume-based restrictions to $350 per person if trade is prohibited entirely. Under any of the policies, however, gains or losses accruing to individual states vary markedly. In addition, different policies result in different distributional effects between consumers and producers. Under a $1 per ton import surcharge, producers in the Midwest lose, producers in the Northeast gain, and consumers in most states lose. Under export restrictions, producers gain in some states, such as West Virginia, and lose in the Northeast. Consumers gain in Pennsylvania and West Virginia and lose in some states in the Northeast.

Perhaps most important, we find that export restrictions can actually increase the number of trades as states reduce the size of shipments to any one state but increase the number of small shipments to new trading partners. Moreover, an increase in trade occurs in our model in advance of the actual date on which the restrictions take effect, largely because tip fees change in response to expected new trade patterns.

6. CONCLUSIONS

Our model of the interstate waste market is rich in detail and flexibly permits a wide variety of policy simulations. We believe that it can enrich understanding of the effects of proposed policies on the waste market, particularly since these effects can be difficult to predict across states and over time. Despite several limitations of the model, the baseline version performs well when compared to actual data.

Our model yields two sets of results. The first pertains to the effects of public policies that may affect key parameters of the waste market, such as price elasticity of demand, transportation costs, or the cost of backstop technologies. As an example, if increases in the popularity of substitutes for landfilling, such as composting, were to increase the price elasticity of demand for waste disposal, then the more likely impacts are changes in the distribution of economic surplus in the waste market rather than impacts on interstate trade. In general, we find that changes in these parameters influence distributional gains and losses rather than the magnitude of interstate shipments.

Our second set of results pertains directly to the interstate waste market. We find that policies proposed to restrict interstate waste shipments through import surcharges or volume-based restrictions reduce aggregate social welfare. However, some geographic areas, consumers, and landfill owners can bear relatively higher costs. At the same time, the surplus accruing to other landfill owners can increase substantially. Short of prohibiting trade entirely, the largest loss in discounted social surplus occurs under a policy that restricts the maximum flow volume between states and does not permit states to trade at all unless they had been trading prior to implementation of the policy. In addition, and perhaps most important, some policies to restrict exports may actually substantially increase the number of interstate waste shipments as states export smaller volumes to more destinations in order to meet limits on the size of shipments to any one state. If these policies are established to take effect at a future date, states respond by increasing interstate flows in anticipation of that date.

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