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Spatially and intertemporally efficient waste management: The costs of interstate flow control

by

Eduardo Ley[*]
Molly K. Macauley[**]
Stephen W. Salant[***]

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[*] FEDEA.

[**] Resources for the Future, Washington DC, USA.

[***] University of Michigan, Ann Arbor MI, USA.

JORGE JUAN, 46; 28001 MADRID. ADMON Y DOCUMENTACION: TEL. 4359020. INVESTIGACION: TEL. 4350401. FAX. 5779575

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Eduardo Ley
F.E.D.E.A., Madrid, Spain

Molly K. Macauley
Resources for the Future, Washington DC, USA

Stephen W. Salant
University of Michigan, Ann Arbor MI, USA

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Address. Eduardo Ley, FEDEA, Jorge Juan 46, ES-28001 Madrid. Phone: (+34-1) 435 0401. Fax: (+34-1) 577 9575. Email: `edley@bigfoot.com`.

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Eduardo Ley
F.E.D.E.A., Madrid, Spain

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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 seveal recent Congressional proposals to exempt waste generation from the jurisdiction of that clause. To date, however, very little is known 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).[1] 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?

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[1] 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.

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 a central planning model of interstate waste trade developed recently by Gaudet, Moreaux and Salant (1997). Their model characterizes the efficient allocation over time of spatially differentiated resources in finite supply such as the nation's waste disposal facitilities. We add policy constraints to their theoretical model and then implement it on the computer. Because of data limitations, we take no account of psychic benefits communities may feel if imports of waste from other locales are reduced. Nor do we account for other possible benefits such as reducing trasportation congestion and noise. We apply our computerized 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 (S. 534) 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. We then impose various restrictions on the model to investigate the effects of several recently proposed constraints on interstate waste flows. Specifically, we analyze four policies: (1) restrictions on the volume of waste exports, (2) an outright prohibition of interstate shipments, (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 5 and 6. In Section 7, we offer some conclusions about restrictions on interstate waste flow.

1. Background – Municipal solid waste and interstate waste trade

1.1. Municipal Solid Waste

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 306,866,000 tons of MSW were generated in the United States during 1994 (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 (see figure 1).[2] This "interstate waste market" has handled an estimated 14,000,000 tons of MSW annually in recent years (about 5% of the total MSW generated). Although this volume may seem small, the transport costs associated with it amount to about $500 million annually.[3]

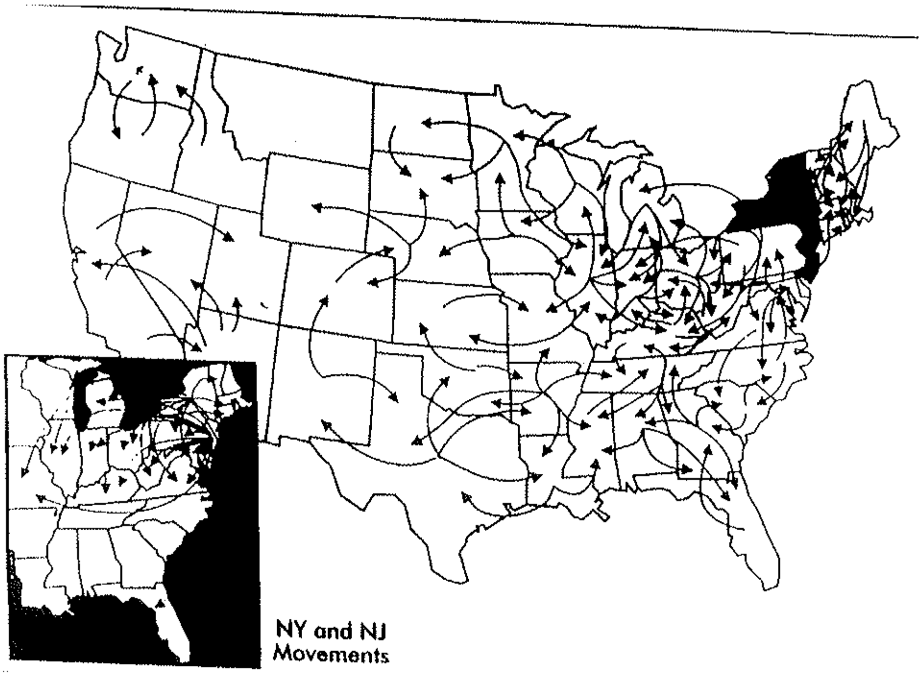

Fig. 1. Interstate flows of Municipal Solid Waste.

Source: National Solid Waste Management Association (now Environmental Industry Association) (1992): "Interstate Movement of Municipal Solid Waste", Washington DC: National Solid Waste Management Association, February, p. 3.

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.[4] For instance, landfill tipping fees average $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

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[2] The map is for 1989–1990 but based on McCarthy (1995) these flow patterns appear to have continued to the present.

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

[4] Much of this discussion is based on Macauley, Salant, Walls, and Edelstein, 1993.

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 to $30 per ton. Thus, even with transportation costs, it can remain cheaper in many cases for northeastern states to export refuse to landfills in the Midwest. For example, assuming transportation costs of ten to fifteen cents per ton mile, the per-ton cost of shipping waste from New York to Ohio is just $75 to $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 6–3 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)*.[5] 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 local controls on waste flows. The Congress has proposed numerous bills to allow controls since the mid 1990s,[6] and in fall, 1995, the Senate passed a bill amending the Solid Waste Disposal Act to permit some types of restrictions on the export and import of waste (S. 534, 'The Interstate Transportation of Municipal Solid Waste Act of 1995').

1.2. A Brief Review of the Debate.[7]

Actions taken by the New Jersey legislature in 1973 were among the first movements to restrict waste trade. The legislature effectively banned the importation of most MSW, but operators of private landfills in New Jersey and city governments in neighboring states challenged the action charging that it violated the Commerce Clause of the U.S.

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

[6] For example, draft bills on flow control/interstate transport have included a bill sponsored by Robert Smith (R, N.H.) and John Chafee (R, R.I.) in the Senate, a bill sponsored by Michael Oxley (R, OH) and Christopher Smith (R, N.J.) in the House of Representatives, and a bill sponsored by Fred Upton (R., MI) in the House (see Woods, 1995).

[7] Additional discussion is in Macauley, Salant, Walls and Edelstein, 1993.

Constitution. The Supreme Court eventually ruled the action impermissible *(Philadelphia v. New Jersey)*.

During the following two decades, over 40 states sought to restrict interstate waste flows and in most cases, court proceedings overturned these actions. Most recently, and impelled largely by the costs of new landfill capacity constructed in the wake of a perceived shortage during the 1980s, states and localities have sought new forms of flow controls. As we noted earlier, whereas previously, "flow control" had primarily referred to controls on interstate movements of waste, now such control also includes other restrictions on waste, including intra-state restrictions that indirectly affect interstate shipments. For example, among the most widely practiced flow control schemes are requirements that MSW generated within local borders be managed at a designated waste processing facility. The practice is generally undertaken as a means of guaranteeing a waste stream for publicly financed disposal facilities. It is estimated that new facilities built in the last 15 years or so have been financed with as much as $20 billion worth of revenue bonds.[8] In *Carbone*, the Supreme Court suggested that the town could ensure the long-term financial viability of the facility through fiscal measures rather than flow control. Proponents of controls have also argued that controls are a means of protecting the environment and achieving state and local recycling goals. In the case of *Carbone*, the Court said that such goals could be addressed through other, non-discriminatory safety, health, and environmental regulation.

Since the *Carbone* decision, other flow control measures have also been invalidated by the courts. In February, 1995, the U.S. Court of Appeals for the Third Circuit found that New Jersey's flow controls requiring disposal of non-recyclable waste at designated facilities may discriminate against interstate commerce and remanded the case back to the U.S. District Court for the District of New Jersey.[9] Also in February, 1995, the U.S. Court of Appeals for the Eighth Circuit invalidated a referendum blocking a large MSW dump in South Dakota because the Court said that by excluding out-of-state waste from being disposed of at the site, it discriminated against interstate commerce.[10]

Since 1989, Congress has drafted numerous proposals to permit flow control, including attempts to do so by amending the Resources Conservation and Recovery Act or the Solid Waste Disposal Act. Following the 1994 *Carbone* decision, Congress moved quickly to advance various legislative proposals. Supporters argued, among other reasons, that waste flow control is properly the prerogative of local government, not federal authorities. Opponents claimed that such control is "anti-business" and imposes an "unfunded mandate" in the form of the higher disposal and waste processing costs that will be forced on municipal budgets.

In the fall, 1995, the Senate passed S. 534, "The Interstate Transportation of Municipal Solid Waste Act of 1995" amending the Solid Waste Disposal Act. Titles I and

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[8] For discussion, see, for example, Woods, 1995.

[9] See "New Jersey's Flow Control Regulations Unduly Discriminate, Federal Court Rules," *Environment Reporter*, 24 February 1995, p. 2032.

[10] See "Referendum on 'Mega-Garbage Dump' Thrown Out for Discriminating Against Interstate Commerce," *Environment Reporter*, 10 February 1995, p. 1907.

II of the bill 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 II 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, flow controls may continue only until the end of the remaining life of contracts between the political subdivision and its contractors.

2. Overview of the Model

We turn now to the model we use to assess empirically the consequences of these proposed restrictions. 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 can serve as a benchmark to assess the performance of the landfill market. Such a benchmark can suggest the magnitude of surplus losses attributable to the imposition of regulations or the exercise of market power.[11] Moreover, the allocation which achieves the maximum surplus often provides a useful guide to the kinds of reallocations which would improve the functioning of the private market. The computerized model we have developed is intended to provide quantitative estimates of the aggregate social surplus which potentially can be generated by the solid-waste industry. The model determines how the capacities of landfills located in different states in the U.S. should be drawn down or expanded over time, and which populations 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 flow controls permitted by the Congress. In addition, we can quantify the distribution of these changes in surplus across states or other geographical regions.

2.1. Nonspatial Extensions of Hotelling's Model of Depletable Resources

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[11] Nordhaus (1973), for example, used such a model to assess the distortions in the world energy market attributable to OPEC's exercise of market power.

The lineage of our work can be traced to Hotelling's (1931) model of depletable resources.[12] Several authors have noted the similarity between solid waste disposal problems and the depletable resource problem first studied by Hotelling, including Dunbar and Berkman (1991); Chang and Schuler (1990); and Ready and Ready (1995).

Dunbar and Berkman discuss tipping fees, focusing in part on why they may be too low if they fail to incorporate the cost of depleting the landfill over time. Chang and Schuler develop a conceptual model of landfill use over time, also focusing on optimal tipping fees. Ready and Ready model landfills as depletable resources and focus on the optimal tipping fee and its relationship to the timing of investment in other waste reduction technologies.

2.2. Spatial Aspects of the Landfill Problem

An important aspect of the solid waste industry in the U.S. is that landfills in some parts of the country are being called upon to serve the needs of "consumers" in other parts of the country. Moreover, regulations are being introduced to limit waste shipments. Similar regulations are being introduced within other countries and between different countries.

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 (1984), Kolstad (1994), and Gaudet, Moreaux, and Salant (1997). Although only the last of these applies its results to landfills, we will interpret each in terms of this application.

Laffont and Moreaux (1984) study resource extraction in a competitive model with one city at the end of a line segment and multiple landfills along the line segment. Without its complications, Laffont-Moreaux's analysis is just like Herfindahl's problem of extraction at least discounted cost where there exist mines with different constant marginal costs of extraction.[13] Herfindahl showed it is always optimal to exhaust a lower cost pool before beginning to extract from the next higher cost pool. If the transport cost of shipping one unit is higher for more distant resource pools, Herfindahl's nonspatial result can be given the following spatial reinterpretation: it is socially optimal to draw down the closest pool first and then the next closest ... It should be noted that this reinterpretation of Herfindahl is equally valid if the resource pools were not located on a line segment but anywhere around the one city.[14]

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[12] For an extensive bibliography and an up-to-date, nontechnical introduction to the Hotelling literature see Salant, 1995.

[13] In fact, Laffont-Moreaux applied their model to the extraction of gravel from a continuum of sites outside of Bordeaux and its shipment to Bordeaux where it is used to make concrete. Complications arise because of the continuum assumption and the fact that the land can be used as vineyards before the gravel is extracted but not afterward.

[14] Weitzman (1976) has extended Herfindahl's analysis to cases where the marginal cost of extraction at any landfill depends in an arbitrary specified way on the amount of space extracted there so far. This permits the solution of social planning problems where spatially located landfills serving a single city have substantial opening and closing costs. Roberts and Weitzman (1980) show that this earlier analysis is a special case of what is now known in the statistics and operations research literatures as a "Gittins index" solution to a multi-arm bandit problem. Such problems can always be formulated

Kolstad (1994) considered the case of multiple cities on a line segment which use space extracted from two landfills, one located at each end of the segment. Since there are two landfills, there are two initial title prices—one for title to a unit of unused space in the left-hand landfill and one for title to a unit of unused space in the right-hand landfill. For familiar reasons, each title price starts at a different level but rises at the rate of interest. As usual, the initial levels of these two title prices are set so that the usage of space in each fill adds up over time to their respective capacities.

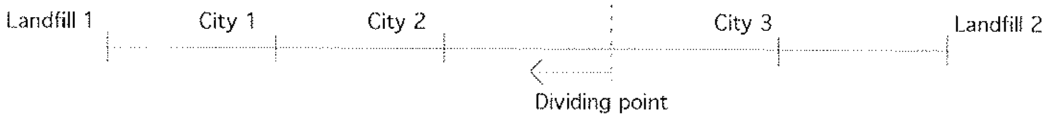

Fig. 2. Kolstad's spatial configuration: two landfills.

Kolstad notes that at any date t, there is some location between the two landfills with the property that the supply price of the left-hand fill (the cost of purchasing at time t title to a unit of the left-hand resource plus the cost of shipping it to the location in question) equals the supply price of the right-hand fill. Call this location the "dividing point." All cities to the left of the dividing point find purchase from the left-hand fill to be preferable while all cities to its right purchase from the right-hand fill. Over time, the dividing line changes position. Figure 2 depicts a situation in which two landfills serve 3 cities. In the period depicted, City 1 and City 2 patronize Landfill 1 while City 3 patronizes Landfill 2. As time passes however, the "dividing point" moves to the left and City 2 (and later City 1) will switch to patronizing Landfill 2.

Gaudet, Moreaux, and Salant (1997) 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 (herafter GMS) then determine the solution to the planning problem (or, equivalently, the solution to the competitive equilibrium). In their model, title to one unit of resource in pool i has price λ_i. For such a title to be held, its price must rise by the rate of interest. Consider city j. That city could be served by any of the I landfills and, therefore, faces I *supply prices*. The supply price from landfill i is equal to the full marginal cost of shipping another unit of "landfill space" to city j: the sum of the price of title to the space and the cost of shipping from landfill i to city j (if there is more than one way of shipping, the cheapest of the ways). City j buys 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

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instead as straightforward dynamic programming problems. But the crucial advantage of the Gittins-index approach is that it permits solution of problems which would easily run aground on the "curse of dimensionality" if analyzed via dynamic programming. A Gittins-index approach cannot be used to solve our problem, however. For the Gittins approach to yield the optimal solution, only one landfill can be used at a time or, alternatively, it must be optimal to dedicate a distinct set of landfills to each city. Such an approach may be useful, however, in approximating the optimal program or, at least, in bounding its value when setup costs must be incurred to open a landfill.

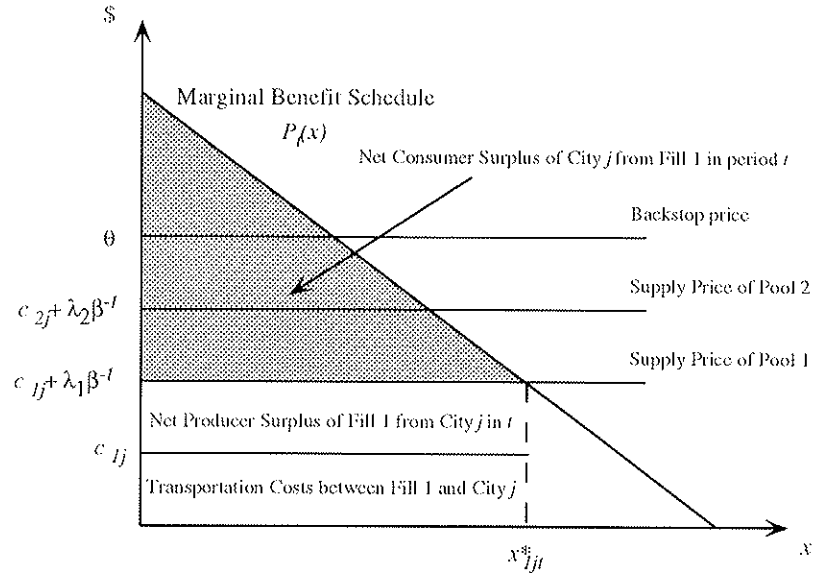

Fig. 3. GMS Model in t with 2 Landfills and 1 Incinerator available to City j

every landfill equals its initial capacity.

Figure 3 depicts the three best choices facing city j at time t : 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. 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." Since there are *no flow constraints* on waste deposited by city j in fill 1, its tip fee is simply $\lambda_1\beta^{-t}$. All cities of origin not subject to flow controls 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).

We have appended to the GMS model source-specific flow constraints. If a *flow control* restricted what city j could ship to fill 1, it might be induced to ship to fill 2 at the same time. Figure 4 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 and fill 2. This would be true as long as permits allowing city j to ship a unit of waste to fill 1 are tradeable. 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 flow controls, 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* to ship a unit of waste from city j to fill 1.

Two related points deserve emphasis. First, if fill 1 also accepts waste in the same period from a city which is not subject to flow controls then that city will pay a smaller effective tipping fee. This follows since that city purchases title to the space it depletes

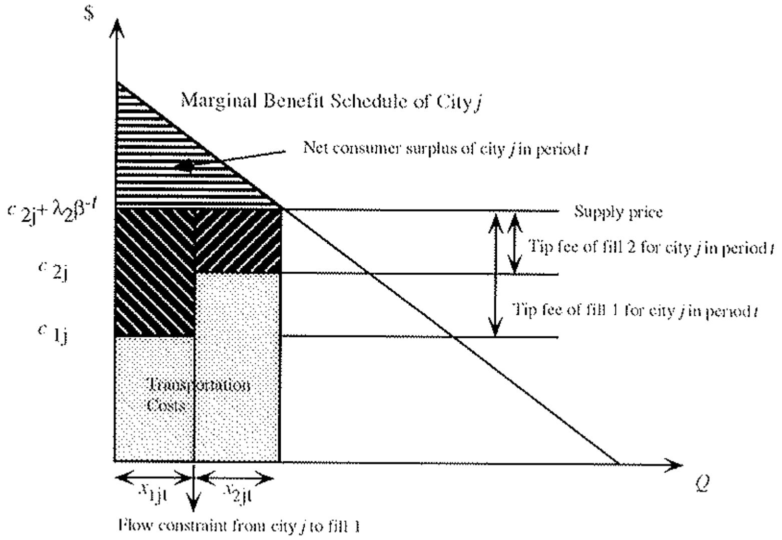
$
Marginal Benefit Schedule of City *j*
Net consumer surplus of city *j* in period *t*
$c_{2j}+\lambda_2\beta^{-t}$
c_{2j}
c_{1j}
Supply price
Tip fee of fill 2 for city *j* in period *t*
Tip fee of fill 1 for city *j* in period *t*
Transportation Costs
x_{1jt}
x_{2jt}
Flow constraint from city *j* to fill 1
Q

Fig. 4. GMS: City j at t with 2 fills and flow controls.

at the same price as city j but does not have to purchase a permit to use the fill. This difference in the tip fees charged at fill 1 does not reflect price discrimination against city i but merely the presence of binding source-specific flow controls in a competitive setting. Different cities shipping to the same fill and each subject to a separate source-specific flow control would each pay a different permit price and hence 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 and would therefore pay the same tip fee—once again higher than what an unconstrained city would have to pay. Second, until a flow control binds, the tip fee grows at the rate of interest. When the control 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 flow controls can grow slower or faster than the rate of interest.

Figure 4 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 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 flow control and must purchase a permit to use fill 1.

2.3. *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. Our notation is summarized in the following table:

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.
γ	Rate of increase of marginal cost in handling another unit of waste at any landfill.[15]
θ	Unit cost of the backstop technology.
$U_{jt}(Q)$	City j's utility function for disposing of Q units of waste at t.
$P_{jt}(Q)$	City j's inverse demand for waste disposal, Q; $P_{jt}(Q) \equiv U'_{jt}(Q)$ at time t.
$D_{jt}(P)$	City j's demand for waste disposal at time t at price P; $D_{jt}(P) \equiv P_{jt}^{-1}(Q)$.
$\bar{x}_{ijt}$	Maximum amount of waste that could be shipped from city j to landfill i at time t.
$\bar{f}_{it}$	Maximum amount of waste that could be shipped to landfill i from all cities at time t.
$\bar{x}_{ijt}$	An upper bound to waste shipped from city j to landfill i at time t (x_{ijt} defined below) if there are flow constraints.

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.

Endogenous Outputs

x_{ijt}	Amount of waste shipped from city j to landfill i at time t.
$x_{\bullet jt}$	Total amount of waste shipped by city j to all landfills at time t; $x_{\bullet jt} \equiv \sum_i x_{ijt}$.
$x_{i \bullet t}$	Total amount of waste shipped to landfill i from all cities at time t; $x_{i \bullet t} \equiv \sum_j x_{ijt}$.
$x_{i \bullet \bullet}$	Total cumulative amount of waste shipped to landfill i from all cities; $x_{i \bullet \bullet} \equiv \sum_t \sum_j x_{ijt}$.

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[15] This is a negligible constant introduced to eliminate indeterminacies which were tripping up the algorithm.

e_{ijt}	Exports of waste at time t from the state where city j belongs to the state where landfill i is located; $x_{ijt} = \sum_{j \in S_j} \sum_{i \in S_i} x_{ijt}$.
m_{it}	Imports of waste at time t into the state where landfill i is located; $m_{it} = \sum_{j \notin S_i} x_{ijt}$.
b_{jt}	Amount of waste of city j handled by the backstop technology at time t.
η_{it}	Shadow price associated with $\bar{f}_{it}$.
μ_{ijt}	Shadow price associated with $\bar{x}_{ijt}$.
λ_i	Shadow price associated with $\bar{s}_i$.

The planner's problem is given by:

$$\max_{x_{ijt}, b_{jt}} \quad \sum_j \sum_t \beta^t \left\{ U_{jt}(x_{\bullet jt} + b_{jt}) - \theta b_{jt} - \sum_i (c_{ij} x_{ijt} + \frac{\gamma}{2} x_{ijt}^2) \right\} \tag{1}$$

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

$$x_{i \bullet t} \leq \bar{f}_{it} \tag{3}$$

$$x_{i \bullet \bullet} \leq \bar{s}_i \tag{4}$$

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

The GMS model would consist of the objective function (1), the reserve costraints (4), and the nonnegativity constraints (5). To these we add the following political constraints in various simulations. City-landfill political flow constraints are captured by (2). They limit the amount that city j can ship to landfill i at each t. Since physical access to the landfill or agreements with the surrounding community frequently limit the number of trucks which can come and go from a landfill in the same day, the maximization is constrained by limits on the daily operating capacity of the disposal facilities — (3) captures these physical landfill flow constraints.

The Lagrangean of the constrained problem is given by:

$$\begin{aligned} \mathcal{L} = & \sum_j \sum_t \beta^t \left\{ U_{jt}(x_{\bullet jt} + b_{jt}) - \theta b_{jt} - \sum_i (c_{ij} x_{ijt} + \frac{\gamma}{2} x_{ijt}^2) \right\} \\ & + \sum_i \sum_j \sum_t \mu_{ijt} (\bar{x}_{ijt} - x_{ijt}) \\ & + \sum_i \sum_t \eta_{it} (\bar{f}_{it} - x_{i \bullet t}) \\ & + \sum_i \lambda_i (\bar{s}_i - x_{i \bullet \bullet}). \end{aligned}$$

The first-order conditions are:

$$\frac{\partial \mathcal{L}}{\partial x_{ijt}} \leq 0 \Rightarrow \quad P_{jt}(b_{jt}^* + x_{\bullet jt}^*) \leq c_{ij} + \gamma x_{ijt}^* + (\lambda_i^* + \mu_{ijt}^* + \eta_{it}^*) \beta^{-t} \tag{6}$$

$$\frac{\partial \mathcal{L}}{\partial x_{ijt}} x_{ijt}^* = 0 \Rightarrow \quad \{(P_{jt}(b_{jt}^* + x_{\bullet jt}^*) - c_{ij} - \gamma x_{ijt}^* - (\lambda_i^* + \mu_{ijt}^* + \eta_{it}^*) \beta^{-t}\} x_{ijt}^* = 0 \tag{7}$$

$$\frac{\partial \mathcal{L}}{\partial b_{jt}} \leq 0 \Rightarrow \quad P_{jt}(b^*_{jt} + x^*_{\bullet jt}) \leq \theta \tag{8}$$

$$\frac{\partial \mathcal{L}}{\partial b_{jt}} b^*_{jt} = 0 \Rightarrow \quad \{P_{jt}(b^*_{jt} + x^*_{\bullet jt}) - \theta\} b^*_{jt} = 0 \tag{9}$$

$$\frac{\partial \mathcal{L}}{\partial \mu_{ijt}} \geq 0 \Rightarrow \quad \bar{x}_{ijt} \geq x^*_{ijt} \tag{10}$$

$$\frac{\partial \mathcal{L}}{\partial \mu_{ijt}} \mu^*_{ijt} = 0 \Rightarrow \quad \{\bar{x}_{ijt} - x^*_{ijt}\} \mu^*_{ijt} = 0 \tag{11}$$

$$\frac{\partial \mathcal{L}}{\partial \eta_{it}} \geq 0 \Rightarrow \quad \bar{f}_{it} \geq x^*_{i \bullet t} \tag{12}$$

$$\frac{\partial \mathcal{L}}{\partial \eta_{it}} \eta^*_{it} = 0 \Rightarrow \quad \{\bar{f}_{it} - x^*_{i \bullet t}\} \eta^*_{it} = 0 \tag{13}$$

$$\frac{\partial \mathcal{L}}{\partial \lambda_i} \geq 0 \Rightarrow \quad \bar{s}_i \geq x^*_{i \bullet \bullet} \tag{14}$$

$$\frac{\partial \mathcal{L}}{\partial \lambda_i} \lambda^*_i = 0 \Rightarrow \quad \{\bar{s}_i - x^*_{i \bullet \bullet}\} \lambda^*_i = 0 \tag{15}$$

with $x_{ijt} \geq 0$, $b_{j,t} \geq 0$, $\lambda_i \geq 0$, $\eta_{it} \geq 0$ and $\mu_{ijt} \geq 0$.

We can now elaborate on our previous discussion of the "tip fee" charged city j by landfill i in the presence of flow constraints. 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. From (6), the formula for the tip fee is: $P_{jt} - c_{it} = \gamma x_{ijt} + (\lambda^*_i + \mu^*_{ijt} + \eta^*_{it})\beta^{-t}$. Since γ is virtually zero and is introduced in the code only to facilitate computation, we ignore it henceforth. In the absence of flow controls, $\mu^*_{ijt} = \eta^*_{it} = 0$ and the tip fee is simply the price of title to the space in landfill i which will be depleted. However, if city j is constrained by political flow controls, it must purchase permits to ship to landfill i and the tip fee includes the multipliers reflecting the prices of these permits. In a market setting, the distribution of these tradeable permits would not affect the competitive equilibrium allocation or the aggregate surplus. It would, however, affect the *distribution* of the surplus generated. In the simulations we report, we assume that: (1) η^*_{it} is collected by landfill i; and (2) the multiplier associated with the regulatory constraint, μ^*_{ijt}, is treated as a tariff imposed on city j by the state where landfill i is located, and it is calculated separately.

As discussed previously, we can accomodate either the creation of space in a completely new landfill or the marginal expansion of space in an existing landfill provided that in neither case are there setup costs or other nonconvexities. 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 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 sufficienty large, it would never be developed (implying $\lambda_i = 0$). If there are potential landfills in many different locations, the planner would decide which ones it 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. We defer further discussion of how one might proceed in the presence of nonconvexities until the "extensions" section at the end of the paper.[16]

The computational problem is to find the $I \times J \times T$ x^*_{ijt}'s; $J \times T$ b^*_{jt}'s; $I \times J \times T$ μ^*_{ijt}'s, $I \times T$ η^*_{it}'s, and I λ^*_i's which satisfy conditions (6)–(15). Given our curvature assumptions, there will be a unique solution to (6)–(15) corresponding to the global optimum to (1).[17]

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 fourteen states in the Northeast and Midwest; although this market represents only about 36% of the total volume of waste generated nationwide, it represents 75% to 84% of the total volume of waste shipped interstate (the range reflects differences between estimated imports and exports; see below). Table 1 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

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[16] Problems arise if the creation of *any* new landfill space involves a large setup cost. Nonconvexities cause familiar problems. In the market context, competitive equilibrium may not exist (Fischer, 1995). The planning problem still has a global optimum but since some non-optimal programs also solve the first-order conditions, more cases must be examined to locate the global optimum. GMS have considered planning problems with setup costs when there are three landfills and have identified characteristics of the solution which have no counterparts in the cases previously studied in the literature. For example with as few as two cities, they find it is sometimes optimal to draw down a landfill part way, abandon it in favor of a newly developed landfill, and then return to it after the new one is exhausted. In the concave problems analyzed by Herfindahl (1967), such behavior is never optimal. Indeed, it is never optimal in the one-city problem with setup costs analyzed by Weitzman (1976).

[17] The Fortran code used is available available upon request from edley@bigfoot.com. We have also posed the problem as a mixed complementary problem in GAMS.

Table 1. Waste Generated, Exported and Imported, and Trading Partners, 1993

	Millions of tons per year			Shipments[c]	
	Waste Generated[a]	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[b]	109.5	9.8	12.2		
Total as % of US	36%	75%	84%		
US Totals	306.9	13	14.5		

Sources: Waste generated: *BioCycle*, 1994; Waste exported and imported: McCarthy, 1995 (see also notes therein); Shipment destination/origination: McCarthy and state data available from authors.

[a] 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 1/3 of imports go to waste-to-energy facilities (see McCarthy for discussion)).

[b] 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 McCarthy for discussion).

[c] 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).

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 2 lists the locations we have 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 the baseline simulation and its results.[18]

Our third simplification concerns the inverse demand curves. Each inverse demand curve is assumed to pivot out around its vertical intercept at 5% per year to reflect population (and income) growth. To calibrate our model we use as the initial horizontal intercept of each inverse demand curve the quantity of waste which is actually shipped

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[18] 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 2. Locations and abbreviations used in the model

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

by that particular city to landfills. 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).

A fourth simplification concerns recycling and incineration. We assume that a fixed proportion of a city's growing waste stream would be recycled, independent of time or the price of recycling or disposing of waste in alternative ways. Hence, the inverse demand curve of a city reflects a city's need to landfill or incinerate that portion of its wastes which are not recycled. In the simulations reported here, we assume away the need to dispose of ash and other residuals which in fact result when waste is incinerated. These simplifications create biases that are to some extent offsetting. If recycling rates were to increase by more than 5% per year, we would overestimate landfilling since we have assumed that recycling grows at the same rate as the overall waste stream. On the other hand, our treatment of incineration underestimates landfilling since, contrary to our assumptions, incinerator ash is typically landfilled. Among our sample of states, the percentage of waste landfilled ranges from 25% (Massachusetts) to 88% (West Virginia); eleven of the states in our sample landfill 60% or more.[19] (The national average is 71%.)

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[19] An extension of the model could take into account the residuals which arise when waste is incinerated. The planner would consider the full cost of incinerating a ton of waste at each incinerator: the sum of the cost of shipping it to that facility, the cost of using that facility, and the cost of shipping a constant fraction representing the residual from the incinerator to the cheapest landfill or "ultimate backstop" for final disposal. If the residuals from incineration are landfilled, the cost of title to the space would be taken into account. If processed by the "ultimate backstop" the cost of doing so must be specified. It would be necessary to postulate an "ultimate backstop" since the landfills would ultimately fill up and, in the current version of the model, the siting of new landfills is not possible.

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 data are from publicly available surveys reported in the trade literature or state agencies. Also, most of our data are for 1993–1994, the most recent years for which information is available.[20]

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 1, 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. 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. The subscripts j and t refer respectively to the city and the time period. The price elasticity is then:

$$\varepsilon_{jt} = -B\frac{P_{jt}}{Q_{jt}} = -\frac{A_j - Q_{jt}}{Q_{jt}} \tag{16}$$

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, 1994).[21]

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[20] 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. We compare our 1993 state data with 1994 state data from the April 1994 and 1995 issues of *BioCycle* and find only small differences among states in our model. More recent data, when they are available, may shed further light on the effects of Subtitle D and other changes in the disposal market.

[21] 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 our parameter g is a mix of income and population growth. Econometric estimates of income elasticities are generally small (around .05) although some estimates are as large as .2 or .4 (see discussion and references in Fullerton and Kinnaman).

We parameterize equation (16) 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, 1993; Jenkins, 1991; Wertz, 1976; Morris and Byrd, 1990, and Skumatz and Breckinridge, 1990). These estimates generally suggest highly price-inelastic demand, on the order of −.26 to −.075. The price elasticities in our baseline model vary across geographic states and over time; the average across states for 1993 is −.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.[22]

Operating capacity and backstop costs. The operating capacity of landfills (tons per day) are state-wide averages reported for 1993 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. 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. We vary this estimate between 5 cents and 11 cents in sensitivity tests.[23] We calculate travel distances between states using Rand McNally and American Automobile Association maps.

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

MSW generation, percentage of waste landfilled, landfill capacity. Data on the annual number of tons of MSW generated by state, the percentage landfilled, and state-wide 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

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[22] 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, and Sigman for discussion of elasticity differences).

[23] 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, 1997)), we use estimates of trucking costs.

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 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, 1995) and, where available, additional data we obtained from state agencies that identify waste flows among all trading partners (these data were available from Pennsylvania, Illinois, and Indiana). 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.)

4. Results of the 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 3 lists the parameters we use for the baseline model.

Table 4 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 to 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. However, the model yields fewer trading partners, 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 co-located 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. The model underestimates interstate shipments:

- among states that are large or whose city/landfill sites are in the interior of the state

Table 3. Baseline parameters

Demand slope parameter: (implies demand elasticity: −.15)	−.0002
Transportation costs:	11 cents/ ton /mile
Discount rate:	5% /year
Rate of demand growth:	5% / year

City/Fill	Total Waste Generated (mil/tons/year)	Fill Life (yrs)	Fill Capacity (mill/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

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;
- and among states where landfill capacity is not near the large population centers from which waste generation is assumed to originate.

Our model also estimates the discounted present value of economic surplus, reported in table 5. Of total surplus of $1,658 billion, consumer surplus represents $1,629 billion or 98%. Total discounted surplus is about $7,988 per person for the state populations represented in the model. The per capita amounts vary widely among states, however, ranging from $34 in CT to $20,088 in OHCl. They are large among some waste importing sites (such as OHCl, IL, NYB, and MO).

Figure 5 illustrates the time path of real tip fees from 1993 to 2013 (by 2013, all but two 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,

Table 4. Baseline: Simulated Results and Actual Values for 1993

	Tip Fee ($/ton)		Interstate Shipments		Shipments
	Actual	Simulated	Actual[b]	Simulated[b]	To (From)[d]
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	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	.8 (3.9)		(NYB, OHCl) **WV, NJ**
PAPh	55.00	51.05			(NYC)
RI	48.48	44.54	0.5		(CT), **MA**
OHCl[c]	33.29	41.33	.3 (1.7)	2.2	PAPi (INI) **MI, KY, WV, NY, NJ**
OHCi	24.00	30.34			
VA	33.75	25.49	(1.5)		(NJ), **NC**
WVA	29.94	17.49	.1 (.5)		**KY, MD, OH, PA**
CT	65.26	50.03		0.1	**MA**
MA	55.97	42.38	.4 (.7)		**NH, RI, NY**
NH	41.36	36.61	0.03		**MA, ME**
INI[c]	22.81	42.26	.08 (.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	

Source: Actual tip fee for landfills: *Solid Waste Digest*, various issues.

[a] Average may be larger; *BioCycle*(1994) reports $25.

[b] In millions of tons per year; numbers in parentheses are imports; estimated are either.

[c] States divided in model; see text.

[d] Boldfaces are trading partners reported in McCarthy (1995) but not predicted by the simulation.

—Insert figure around here—

Fig. 5. Baseline: Time Path of Tip Fees (unweighted average).

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.

—Insert figure around here—

Fig. 6. Baseline: Total Volume and Number of Trades.

Figure 6 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 percent of waste generated increases from 15% in 1993 to 33% in 1998 as states exhaust in-state landfill capacity. By 1998, these interstate flows occur among 11 different pairs of trading partners (*e.g.*, NY – PA, NJ – VA). After 1998, 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 public perception. Large numbers of small shipments may generate roadway wear and tear or congestion, say, and large shipments "use up"communities' landfill space.

Table 5. Baseline Model: Discounted Producer and Consumer Surplus

	Billions of 1993 dollars			Dollars
State/ Landfill	Producer Surplus	Consumer Surplus	Total Surplus	Total Surplus per capita
NYC	0.649	180.364	181.013	7,453
NYB	3.087	214.825	217.912	14,099
NJ	1.025	22.861	23.886	1,352
IL	3.812	503.999	507.811	19,165
MO	1.930	139.428	141.358	12,804
PAPi	4.672	4.612	9.284	1,051
PAPh	1.796	91.060	92.856	5.257
RI	0.511	1.956	2.467	1,117
OHCL	1.832	264.298	266.130	20,088
OHCI	1.403	76.399	77.802	7,047
VA	3.700	71.157	74.857	5,650
WV	0.934	6.699	7.633	1,728
CT	0.221	0.115	0.336	51
MA	0.899	7.603	8.502	642
NH	0.161	0.989	1.150	521
INI	0.773	19.844	20.617	3,112
ING	0.266	1.373	1.639	247
KS	1.226	21.459	22.685	3,425
Totals	28.897	1,629.041	1,657.938	5,823

—Insert figure around here—

Fig. 7. Landfill Expansion at $5/Ton.

Landfill expansion. Expanding a landfill is usually quite political 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 order of a few percent of capacity. Accordingly, we permitted our baseline model to expand landfill capacity endogenously, at 2% a year for four years, under three scenarios: expansion at $5, $10, and $15 per ton. We find that the volume of waste traded and the number of pairs of states that trade waste is virtually unchanged. Not all landfills expand; expansion largely takes place in the Midwest. Figure 7 illustrates the results for expansion at \$5 per ton.

5. Sensitivity of the Baseline Simulation

In this section, we discuss the sensitivity of the baseline model to changes in several exogenous parameters: price elasticity of demand, the discount rate, transportation costs, and the cost of the backstop technology. When price elasticity changes, what are the effects on the volume traded and the pattern of trade? When transportation costs decline, does trade with, say, the Midwest increase? If so, among which trading partners? When the cost of the backstop technology increases, do states use more of their own landfill capacity or do they increase exports? If they increase exports, with whom do they trade?

Table 6. Results of Sensitivity Tests

Direction of change compared with baseline.

Reducing demand elasticity to −.01 (average across states)					
	Average Tip Fee	Volume Traded (% Total)	Discounted Present Value of Surplus, 1993–2013		
			Producers	Consumers	Total
1993	$\uparrow$	$\Uparrow\Uparrow$	$\uparrow$	$\Uparrow\Uparrow$	$\Uparrow\Uparrow$
2013	$\uparrow$	$\uparrow^a$			
Increasing the discount rate to 10%					
	Average Tip Fee	Volume Traded (% Total)	Discounted Present Value of Surplus, 1993–2013		
			Producers	Consumers	Total
1993	$\Downarrow$	$\Uparrow$	$\Downarrow\Downarrow$	$\Downarrow\Downarrow$	$\Downarrow\Downarrow$
2013	$\Uparrow\Uparrow$	$\sim$			
Reducing Transportation Costs to 5¢/ton/mile					
	Average Tip Fee	Volume Traded (% Total)	Discounted Present Value of Surplus, 1993–2013		
			Producers	Consumers	Total
1993	$\sim^b$	$\uparrow^d$	$\Uparrow$ ($\downarrow$ NE, $\uparrow$ MW)	$\uparrow$	$\uparrow$
2013	$\sim^c$	$\sim$			
Increasing the cost of the backstop technology to \$100/ton					
	Average Tip Fee	Volume Traded (% Total)	Discounted Present Value of Surplus, 1993–2013		
			Producers	Consumers	Total
1993	$\Uparrow\Uparrow^e$	$\Uparrow$	$\Uparrow\Uparrow$ (wide variation)	$\Downarrow$	$\downarrow$
2013	$\Uparrow\Uparrow$	$\sim$			

Notation: $\uparrow$ ($\downarrow$): small increase (decrease) of less than 5%, $\Uparrow$ ($\Downarrow$): increase (decrease) of 5 - 10%; $\Uparrow\Uparrow$ ($\Downarrow\Downarrow$): substantial increase (decrease) of more than 10%; $\sim$: negligible.

[a] Most states now use backstop technology.

[b] Fees decrease in the Northeast and increase in the Midwest.

[c] Fees increase relatively less in the Northeast than in the Midwest compared with the baseline.

[d] Largely within state.

[e] Fees increase in all states; double in the Midwest.

Moreover, the model enables us to study these effects over time. For example, if transportation costs decline or the cost of the backstop technology increases, do states export more waste in the short run and save their own in-state disposal capacity for the future? Table 6 summarizes the results of the sensitivity tests for 1993–2013, at which time backstop technologies are used at all disposal sites.

5.1. Reducing price elasticity of demand [24]

More inelastic demand (averaging $-.01$ across states) results in a small increase in the average tip fee compared with the baseline. Total waste flows in 1993 increase about 4% over the baseline and the volume of waste traded increases about 15%. The backstop technology is now used in some states (the backstop was not used in 1993 in the baseline results). The pattern of trade is not affected—the increase in traded waste occurs between states that already trade in the baseline model. The largest effect of reducing the price elasticity is on surplus measures. As expected when demand becomes more inelastic, all else equal, total surplus increases. In our model, almost all of the increase accrues to consumers. The increase in the total surplus and in consumer surplus is on the order of tenfold in all states. Producer surplus increases about 4%.

5.2. Increasing the discount rate

Increasing the discount rate (that is, reducing the discount factor) causes the initial shadow value of future resources to decline. When the discount rate increases from 5% to 10%, average tip fees fall substantially, about 30%, in the first year of the model's operation. Fees decline in all states. The total volume of waste in interstate flows increases 10% and the number of trading partners increases by one. This increase in the discount rate reduces total surplus over the lifetime of the model by 25%. Producer surplus falls about 30%, due to the reduction in tip fees, and consumer surplus falls about 20%.

5.3. Reducing transportation costs

A 50% reduction in transportation costs, from 11 cents to 5 cents per ton per mile, results in only a negligible change in the unweighted average tip fee but wide differences in the tipping fees across states. In 1993, the fee decreases as much as 20% in the Northeast and increases on the order of 30% in the Midwest. Thus, tipping fees are bid up in states which increase their imports of waste due to the reduction in transportation costs, and the fees decline in exporting states. Although such differences would be expected as a result of a decline in transportation costs, the size of the changes among states may be due in part to our assumptions about the locations of landfills and waste generation. We also might expect trading volumes to change, but they increase only slightly (again, probably due to our assumptions about landfill/waste generation locations). The number of trading partners increases by one.

The reduction in transportation costs generates very little change in overall surplus—it increases less than 1%. Consumer surplus increases about 1% in most states. The small change in surplus is explained by the fact that total transportation costs are small compared with the size of surplus in the model. As might be expected given the changes in tip fees, changes in producer surplus vary markedly across regions. There is a decline of 20 to 40% in the Northeast and an increase of 10% in some Midwest states; total producer surplus increases about 5%.

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[24] We reduce demand price elasticity by decreasing the B parameter in (2), thus rotating the initial inverse demand curve at its horizontal intercept so that it becomes steeper.

5.4. Increasing the cost of the backstop technology (to a uniform cost of $100 across states)

Our baseline model is quite flexible in allowing us to specify different backstop technologies, each with its own marginal operating cost and transportation cost to various cities. In sensitivity tests we find that the results are sensitive to changes in the cost of the backstop technology. Here, we increase the backstop cost to $100 for all states.[25] We also assume that the same producers own the backstop facilities as well as the landfills. The increase causes the average tip fee to increase; in 1993, this increase is above 60%. It increases in all states and doubles in the Midwest, as we would expect in response to the now-more-expensive substitute disposal option represented by the backstop. Although the total waste flow falls about 3% in response to the price effect, trading volume increases 17% and a new trading partner is added. The backstop is not used in any state.

Over time, in this simulation, there is very little change in the percent of interstate shipments as a percent of total waste generation. However, there are substantial differences in the handling of waste. For example, Northeast states reduce interstate shipments and use their own landfills for more of their waste, and there are many trades among Midwest states (MO ships to KS, OHCi ships to WV, OHCl ships to PA, and INI ships to OHCi). The change in backstop costs reduces total surplus about 3%. Consumer surplus falls about 6%. Producer surplus increases about 65%, however, with state variation from 10% to 100%.

5.5. Summary of sensitivity results

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 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 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.

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[25] Arguably, one form of backstop would be a disposal option avaialble to all states at some large cost (such as disposal of waste in outer space, perhaps). If so, then equalizing the cost of the backstop across states is appropriate.

6. 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 one-dollar 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 one-dollar 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 restricting waste shipments (see discussion in section II). Specifically, this bill proposes that importing states be permitted to levy a one-dollar surcharge per ton of imports. It also proposes to require 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).[26] 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.

—Insert figure around here—
Fig. 8. Trade under Policy Simulations.

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 figure 8 and table 7. 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.

6.1. 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

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[26] 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.

Table 7. Policy Simulations: Surplus Effects

% Change Compared with Baseline

	Producers	Consumers	Total
Surcharge	1% (↓ OHCi, WV, IN)	−.01%	−.0001%
Export Restrictions: Cap	−4% (↓ PA, VA)	−.01%	−.08%
Export Restrictions: Cap and Floor	−6% (↓ PA, IN, VA)	−.01%	−1%
Surcharge, Cap and Floor	−5% (↓ PA, VA, IN WV)	−.02%	−1%
No Trade	−8.5% (↓ PA, OHCi, VA, WV, IN)	−.08%	−2%

titles to landfill capacity in states which formerly imported waste. When we impose a one-dollar 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 figure 9 , 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 one-dollar per ton surcharge yields the smallest reduction in total surplus. The reduction is about $2 million, about .0001% of the baseline surplus. There are larger losses in total surplus in some importing states than 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 1%; 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.

6.2. 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 takes takes effect in 1996.

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 figure 9, the annual volume of waste traded and the number of trading partners increase throughout much of the entire time period. The increases begin immediately in 1993, in anticipation of the date at which the restrictions take 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 about \$1.3 billion. The largest loss is in producer surplus; aggregate loss in producer surplus is about 4% (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 \$162 million. As in the case of the surcharge, the largest consumer surplus losses accrue in the Northeast. Consumers in some waste importing states gain.

6.3. 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 1% or \$16.6 billion. Aggregate producer and consumer surpluses both fall, about 6% and .01%, 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.

6.4. Surcharges and volume restrictions

The Senate bill permits several of its provisions to be combined. In this simulation we impose a one-dollar 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 falls 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 1%; the reduction in producer surplus is smaller than in the preceding simulation because we allow producers to keep the surplus revenues. Consumer surplus declines about .02%. 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.

6.5. 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 —about 8.5%, .08%, and 2%, respectively. Per capita losses in total surplus range from $370 in PAPh and $93 in NYC to 17 cents in IL. The total surplus loss is about $33 billion, roughly twice the size of the loss generated by the volume-based restrictions in the two preceding simulations.

6.6. 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 one-dollar 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 cents 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 one-dollar-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.

7. 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 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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Figure 5.
Baseline: Time Path of Tip Fees (unweighted average)

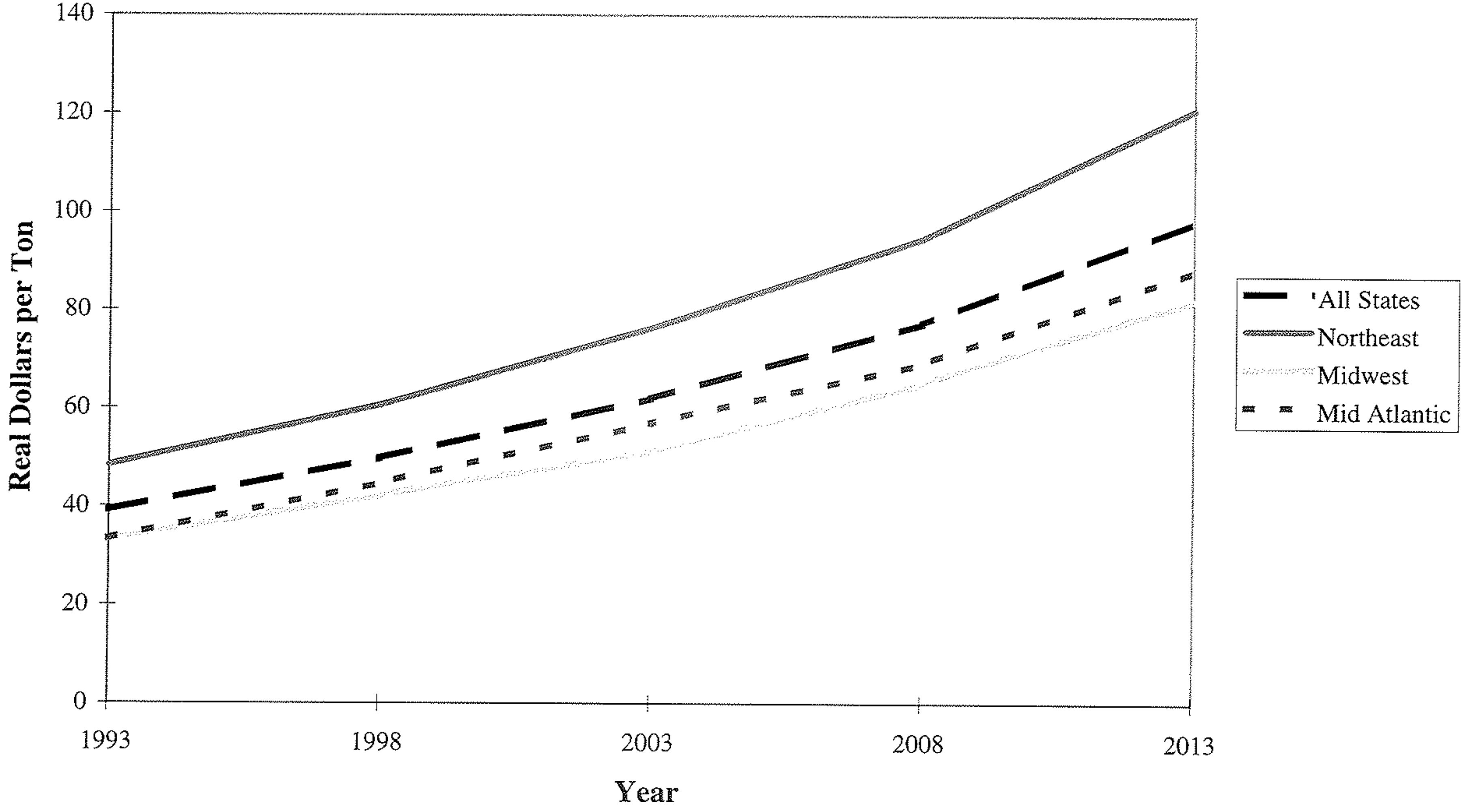


Figure 6.
Baseline: Total Volume and Number of Trades

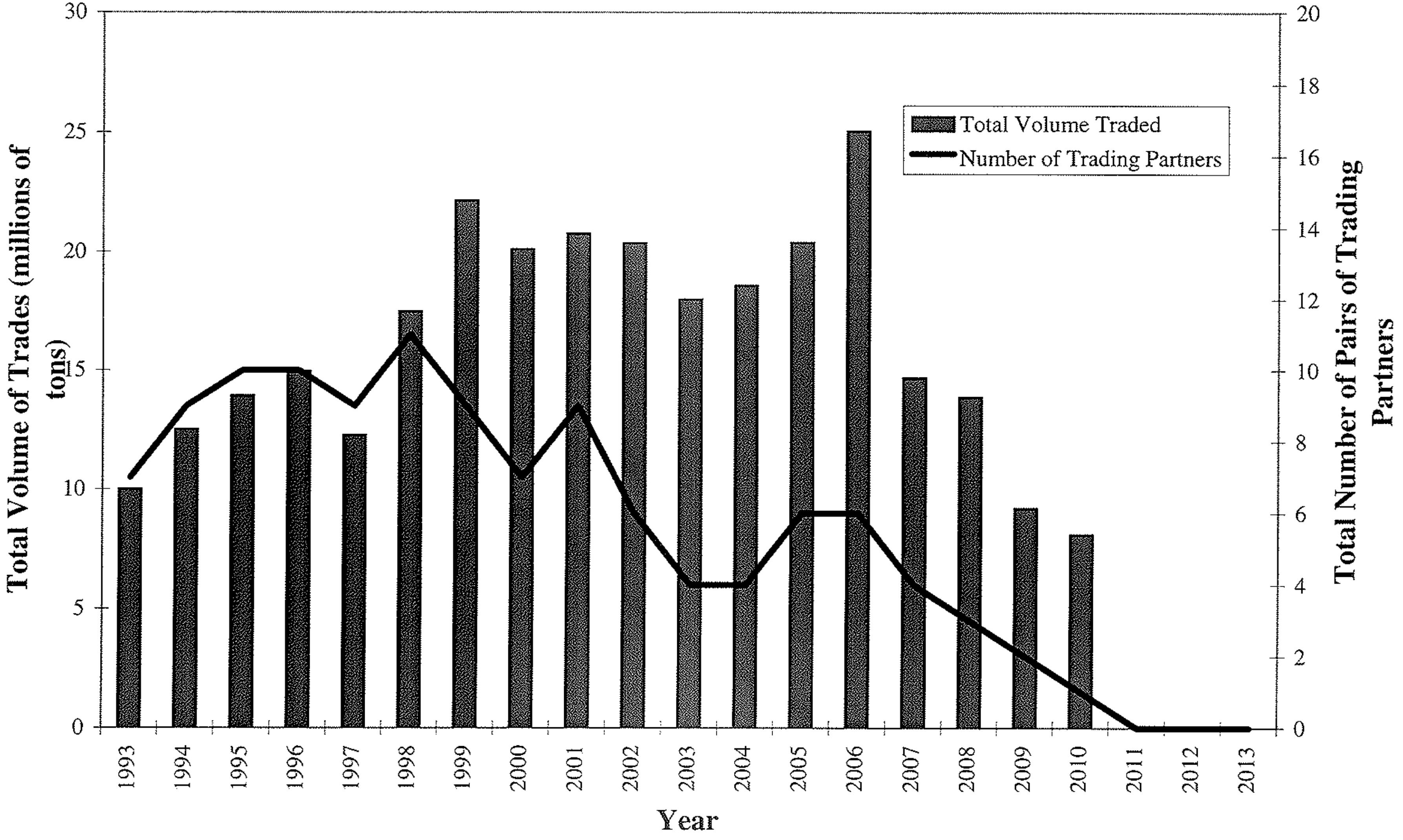


Figure 7.
Landfill Expansion at $5 Per Ton

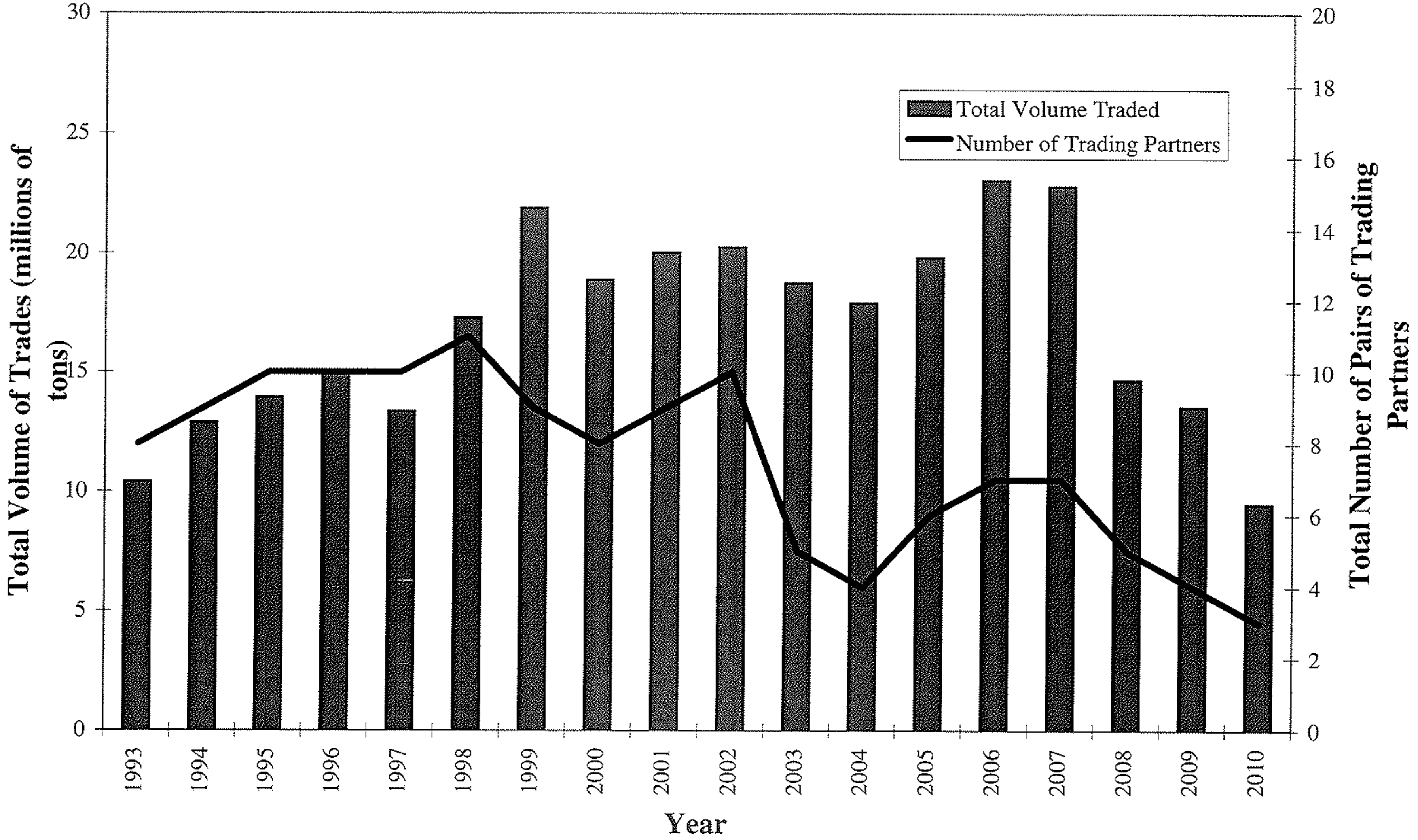
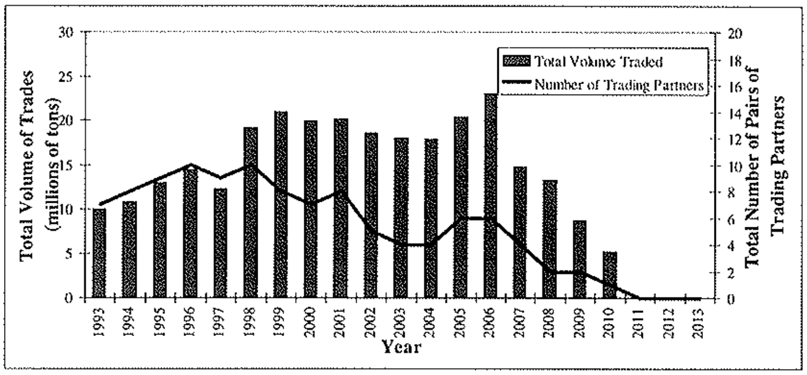
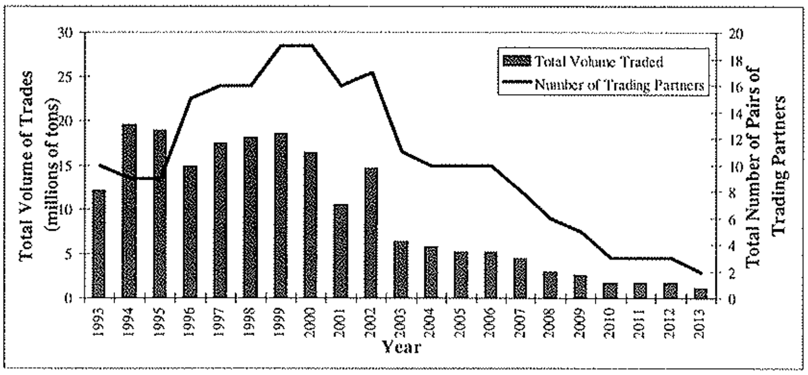


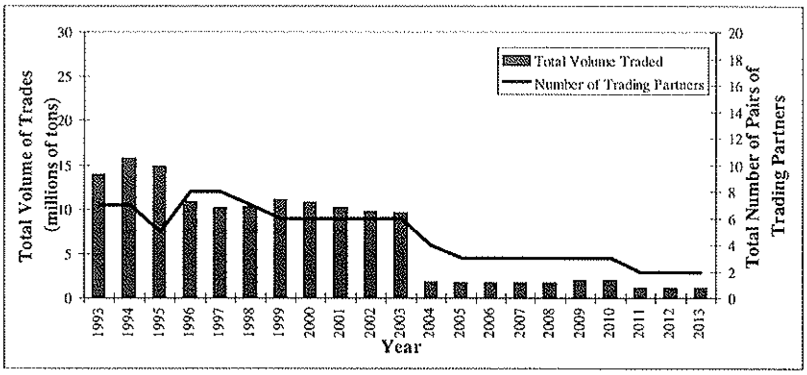
Figure 8.
Trade Under Policy Simulations



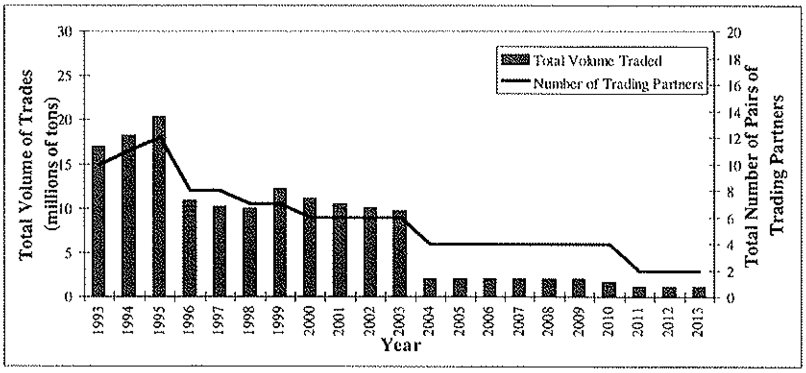
(a) Surcharge



(b) Export Restrictions, Cap Only



(c) Export Restrictions, Cap & Floor



(d) Surcharge & Export Restrictions

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