An Economic Analysis of Household Waste Management*  

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This paper provides a comprehensive model of household waste management policy incorporating the possibility of waste reduction effort by the firm and the household and of illegal waste disposal by the household. When household waste reduction effort is insignificant, the first-best optimum can be achieved using various combinations of environmental tax on the firm and waste collection charge on the household. However, when household waste reduction effort is significant, the first-best optimum is not achievable and explicit monitoring of illegal waste disposal is needed, rendering a simple Pigouvian tax sub-optimal. This paper solves for the second-best optimal policy and provides some comparative statics of the optimal policy.  

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I. INTRODUCTION

How a society should deal with household waste has become an important policy problem. Legislation and policy range from schemes targeted specifically at households to those focusing on an economy-wide effort to minimize waste. For example, in the United States and Canada, individual localities have introduced various initiatives such as curbside collection charges for household waste as an attempt to reduce the amount of household waste. In Australia, the Commonwealth government has declared a target of halving the amount of domestic waste going to landfill by the year 2000.1

While it is recognized that a comprehensive waste management policy should target the four sequential goals of reduction, reuse, recycling, and disposal, most

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1 For more details of the various household waste reduction schemes, see Choe and Fraser (1998).
existing studies fail to provide a comprehensive framework within which to provide policy recommendations. For example, Wertz (1976), Dobbs (1991), Dinan (1993), Morris and Holthausen (1994), and Jackus et al. (1996) are among many that focus on waste management at the consumption and disposal stages, while Copeland (1991), Palmer et al. (1997), and Conrad (1997) pay attention to the production stage alone. Waste management policy aimed only at source reduction in the production stage ignores subsequent household behavior such as waste reduction effort, including reuse and recycling, as well as household disposal decisions. Policy directed at waste diversion in the consumption and disposal stages such as a waste collection charge on the household can lead the household to demand products with less waste content, thereby affecting production decisions as well (Fullerton and Wu, 1998). While such a waste collection charge can give the household incentives to reduce waste, it may also lead the household to consider the option of illegal dumping to avoid the charge. In short, a satisfactory analysis of household waste management policy warrants a comprehensive framework that includes policy instruments directed at production, consumption, and disposal stages.

This paper provides a theoretical framework for analyzing comprehensive waste management policy incorporating the waste reduction effort by the household as well as the possibility of illegal dumping. In the production process, the firm can undertake costly waste reduction efforts that affect the intrinsic waste content of a consumption good produced. The household can also make costly waste reduction efforts that affect the amount of waste to be disposed of after consumption. Reuse or composting are examples of household waste reduction effort. The final environmental impact of waste depends not only on the amount of waste after consumption but also on how the household disposes of waste. As pointed out by Fullerton and Kinnaman (1995), the legal collection and disposal of waste will generally result in less environmental damage than illegal burning or dumping of waste.

Without explicit incentives, neither the firm nor the household will necessarily undertake costly actions to reduce the amount of waste, but explicit incentives such as waste charges might induce households to choose the option of illegal disposal. The environmental regulator provides incentives to the firm and household and monitors both waste generation and disposal. Assuming that waste reduction effort by the firm is easier to monitor than that by the household, we assume that the regulator can control the waste reduction effort of the firm through an environmental tax levied on the waste content of a product. Instead of directly monitoring household waste reduction effort, the regulator (randomly) monitors illegal dumping by the household and imposes a fine accordingly. The final policy instrument is the collection charge on household waste legally disposed of.

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2See Jenkins (1993) for reviews of related earlier studies.
3The Economist (1993), for example, suggests that the social costs incurred as a result of illegal dumping are greater than the costs of effectively operating a managed landfill.
5An example is the Litter Act (1987, amended 1991) in Victoria, Australia. On the spot fines for littering are A$600, court-imposed fines can be up to A$4,000, and some 3,000 littering notices (fines) are issued each year. In addition there is also community education and the use of moral suasion. Although not considered here, education can be included in a way that raises the cost of enforcement activity as well as household (perceived) private costs of illegal dumping.
Not surprisingly, optimal waste management policies depend crucially on the presence of household waste reduction effort and the possibility of illegal dumping. When household waste reduction effort is not significant, the first-best optimum can be achieved using various combinations of an environmental tax on the firm and a waste collection charge. However, the presence of household waste reduction effort makes the first-best optimum unachievable and necessitates explicit monitoring of illegal waste disposal. The main reason for this difference is the dual role played by the household waste collection charge: the higher the waste collection charge, the more incentives the household has for waste reduction as well as for illegal waste disposal. This renders a simple Pigouvian tax sub-optimal (Fullerton and Kinnaman, 1995) and calls for the simultaneous determination of various policy instruments. The resulting second-best policy requires a strictly positive waste collection charge on the household, explicit monitoring of illegal waste disposal, and a strictly positive environmental tax on the firm. In short, a meaningful second-best policy problem arises when both household waste reduction effort and the possibility of illegal dumping are present, which is what we address in this paper.

The rest of this paper is organized as follows. In Section 2 we describe the model, briefly summarizing the results from earlier studies within the context of our model. Section 3 characterizes the second-best optimal waste management policy in the presence of household waste reduction effort and illegal waste disposal. Section 4 provides a summary of our results and discusses the directions of future research.

II. THE MODEL

A representative competitive firm produces a consumption good with the cost function \( C(q, k) = (c + k)q \), where \( q \) is the quantity of the consumption good produced, \( c > 0 \) is the constant marginal cost of production, and \( k \geq 0 \) is the marginal cost incurred in reducing the amount of waste intrinsic in the goods produced, e.g., packaging, containers, environmentally toxic substance. The amount of waste intrinsic in the good at the end of the production stage is \( \alpha(k) \), \( 0 \leq \alpha(k) \leq 1 \), \( k \geq 0 \), \( \alpha' < 0 \), and \( \alpha'' > 0 \), where a prime indicates a derivative. That is, \( \alpha \) is the fraction of a consumption good that would have to be disposed of if the firm did not make the effort to reduce waste. It is also assumed that the firm is competitive, allowing us to ignore policies directed at improving allocative efficiency and to focus solely on environmental issues.

A representative household has the utility function \( U(q, e, y) = u(q) - v(e) - y \) where \( e \) is the amount of effort made to reduce waste, \( e \in [0, \bar{e}] \), and \( y \) is the monetary cost of waste disposal. It is assumed that \( u' > 0 \), \( u'' < 0 \), \( v' > 0 \), \( v'' > 0 \), and \( v(0) = 0 \). Household waste reduction effort is the effort devoted to physical reduction and disposal of waste such as the purchase of compost bins for food

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6This was the main conclusion of Fullerton and Wu (1998).

7Fullerton and Kinnaman (1995), Bovenberg and Goulder (1996), Palmer and Walls (1997), and Fullerton and Wu (1998) studied models similar to ours, but they did not consider household waste reduction effort.

8For example, a larger \( k \) could correspond to higher recyclability and/or lower packaging content of a product. For detailed modeling of this, see Fullerton and Wu (1998).

9Oates and Strassmann (1984) and Parry (1995) suggest that allowing for imperfect competition is unlikely to have much empirical effect on environmental policy analysis.
waste and the time and effort spent on recycling and/or composting waste. The amount of household waste after consumption is represented by the waste function $w'(k)q;e$, with $w_1 > 0$, $w_2 < 0$, and $w[a(k)q, 0] = a(k)q$, where subscripts denote partial derivatives. Without household waste reduction effort, the amount of waste after consumption is equal to the intrinsic amount from production. The amount of household waste is increasing in the amount of waste generated from production and decreasing in the amount of effort made by the household to reduce waste. The household can dispose of waste either legally or by illegal methods which may include illicit burning or dumping. The fraction of household waste illegally disposed of is denoted by $f$. Thus, the final environmental impact of household waste is dependent on three elements, cost to reduce the amount of waste intrinsic in a good $k$, household effort to reduce waste $e$, and the amount of household waste illegally disposed of $f$.

If the household illegally disposes of waste, then the cost per unit of waste to the household is $\text{cost}_f$ and the per unit environmental cost is $\gamma$, so that per unit total social cost of illegal waste is $\delta + \gamma$. If the household legally disposes of waste, then the regulator bears the cost per unit of waste equal to $\gamma$ (e.g., collecting and sorting wastes, incineration, operating landfills, and the social and environmental cost of legal disposal). Unless the household is directly charged for legal waste disposal, it is assumed to be a costless activity to undertake. It is assumed that the cost to the regulator of legal waste disposal is higher than the private cost of illegal waste disposal but lower than the social cost of illegal waste disposal, $\delta < \gamma < \delta + \gamma$. This assumption seems not only reasonable but also makes the whole issue of regulated waste management nontrivial.

The regulator can monitor the firm’s waste reduction effort in the production process, and we assume that $a(k)q$ is costlessly observable and verifiable by the regulator. Thus the regulator can set a price on $a(k)q$ without directly monitoring the amount $k$ spent. Such a price can be interpreted as an environmental tax on the firm based on the waste content of a product. Similarly, we assume that the regulator can monitor illegal waste disposal by the household (at some cost) but not waste reduction effort. The regulator can set a charge on the amount of legal disposal by the household, $(1 - f)w[a(k)q, e]$, while monitoring and fining the amount of illegal disposal. Let $\pi$ be the probability of catching illegal waste disposal and let $m\pi$ be the associated monitoring cost, for given $m > 0$. Thus, the regulator’s monitoring is identified by the choice of $\pi$.

The model described above is in the nature of a second-best problem insofar as household illegal waste disposal has to be monitored at additional cost. However, we can exclude the need for monitoring when there is no scope for the household to reduce waste after consumption. This case has been analyzed extensively in the

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10Alternatively, one could work, at the cost of additional complexity, with a more general formulation of $w(q, e, k)$, where $w_1 > 0$, $w_2 < 0$, and $w_3 < 0$.
11We do not consider such costs as time and effort spent on sorting, recycling, or driving to tipping sites, although such costs can easily be included without changing the qualitative results of the paper.
12This assumption does not seem that stringent. Many firms disclose environmentally relevant information on their products. Environmental accounting or mandated product labeling are also ways of eliciting such information. Arora and Cason (1996) and Khanna and Damon (1999) find that increasing public recognition is central to the firm’s voluntary compliance with environmental regulation.
13One could imagine that the probability depends on the amount of illegal disposal. To make things tractable, we abstract away from this possibility.
literature. For future reference, we briefly summarize the results from the earlier studies in the context of the present model.

If there were no household waste reduction effort, then the first-best optimum is guaranteed by the equality between the marginal utility and marginal social cost of consumption \( u'(q) = c + k + \gamma a(k) \), the equality between the marginal cost and marginal social benefits of the firm's waste reduction effort \( k = -\alpha'(k)q \), and the legal waste disposal \( f = 0 \). Consider now an equilibrium allocation in the decentralized market mechanism where the regulator uses the combination of a per-unit environmental tax \( t \) levied on the firm's \( \alpha(k)q \) and a per-unit waste collection charge \( \tau \) levied on the legal waste disposal by the household. Following Fullerton and Wu (1998), it can be shown that the first-best optimum can be achieved in the decentralized market through various combinations of \( t \) and \( \tau \) such that \( t + \tau = \gamma \) and \( \tau \leq \delta \). There is a continuum of first-best policies in this case ranging from \((t = \gamma, \tau = 0)\) to \((t = \gamma - \delta, \tau = \delta)\). However, the presence of household waste reduction effort leads to two modifications of this result. First, it reduces the flexibility of policy choice, as the waste collection charge provides counterveiling incentives to the household, as discussed. Second and more importantly, it makes the first-best optimum no longer achievable. We turn to this problem in the next section.

III. THE SECOND-BEST OPTIMAL POLICIES

We start this section by showing that the first-best optimum cannot be achieved through a decentralized market mechanism. Because of the assumption \( \gamma < \delta + \epsilon \), the first-best optimum involves legal disposal of all household waste, i.e., \( f = 0 \). Thus the social planner's maximization of total surplus \( u(q) - v(e) - (c + k)q - \gamma w[\alpha(k)q, e] \) with respect to \((q, e, k)\) leads to the first-order conditions
\[
\begin{align*}
    u'(q) &= c + k + \gamma a(k)w_2[\alpha(k)q, e], \\
    v'(e) &= -\gamma w_2[\alpha(k)q, e], \\
    \gamma \alpha'(k)w_2[\alpha(k)q, e] &= -1,
\end{align*}
\]
where the prime indicates a derivative and subscripts denote partial derivatives.

Consider next a decentralized market mechanism where the regulator uses the combination of per-unit environmental tax \( t \) on the firm and per-unit waste collection charge \( \tau \) on the household. Denoting the price of the consumption good by \( p \), the firm maximizes profit given by \( pq - (c + k)q - \tau \alpha(k)q \) with respect to \((q, k)\), yielding the first-order conditions
\[
\begin{align*}
    p &= c + k + \tau \alpha(k), \\
    \frac{\partial p}{\partial k} q - q - \tau \alpha'(k)q &= 0.
\end{align*}
\]
In Eq. (5), the term \( \frac{\partial p}{\partial k} \) reflects the fact that firms in the aggregate face a “demand” schedule for \( k \) reflected in the price \( p \) that consumers are willing to pay.\(^{15}\)

\(^{14}\)The inequality \( \tau \leq \delta \) is necessary to preclude illegal waste disposal.

\(^{15}\)See Fullerton and Wu (1998).
Consider now the household optimization problem assuming legal waste disposal, which will be the case if \( t \leq \delta \). The household maximizes utility \( u(q) - v(e) - pq - \tau w[\alpha(k)q, e] \) with respect to \((q, e, k)\), leading to the first-order conditions

\[
u'(q) = p + \tau \alpha(k)w_1[\alpha(k)q, e],
\]
\[
u'(e) = -\tau w_2[\alpha(k)q, e],
\]
\[
-\frac{\partial p}{\partial k} q - \tau \alpha'(k)qw_1[\alpha(k)q, e] = 0,
\]
where the term \( \frac{\partial p}{\partial k} \) in Eq. (8) reflects the fact that households in the aggregate face a “supply” schedule for \( k \) that is reflected in the price \( p \) at which firms are willing to sell.

Substituting Eqs. (4) and (5) into Eqs. (6) to (8), and comparing them with Eqs. (1) to (3), it is evident that the first-best optimum can be achieved through the decentralized market mechanism if and only if \( t = 0 \) and \( \tau = \gamma \), where \( \gamma \) is the full social cost of legal waste disposal. However, \( \tau = \gamma \) violates the assumption \( \tau \leq \delta \) since \( \gamma > \delta \). That is, the waste collection charge necessary to induce the first-best level of household waste reduction effort is too high to induce legal waste disposal at the same time.

We now turn to the second-best problem, where the regulator has the additional policy instruments of monitoring and fining illegal waste disposal by the household. Recall that monitoring was identified with choosing the probability \( \pi \) of catching illegal waste disposal. As the household is assumed to be neutral to income risks, and the size of the penalty for illegal waste disposal and monitoring costs can be traded off against each other, any optimal policy will set the penalty at its allowed maximum.\(^{16}\) Such a maximum per-unit penalty will be denoted by \( \phi \), which is assumed to be exogenously given. It will be also assumed that \( \phi \geq e \). That is, the penalty for illegal waste disposal is higher than the marginal environmental cost of illegal waste disposal. Whether the regulator should implement legal or illegal waste disposal depends on the costs of inducing legal disposal relative to its benefits. In the present case of identical households, it is not difficult to show that legal waste disposal is always second-best optimal and we can restrict attention to policies such that \( \delta + \pi \phi = \tau \).\(^{17}\)

To simplify the analysis further, we assume throughout this section that the waste function is given by \( w[\alpha(k)q, e] = \max\{0, \alpha(k)q - pe\} \) for \( \rho > 0 \), where \( \rho \) is the

\[\footnote{See, for example, Becker (1968), Polinsky and Shavell (1979), or Kaplow and Shavell (1994).} \]

\[\footnote{Suppose the regulator implements legal waste disposal by choosing \((\tau, \pi)\) such that \( \delta + \pi \phi > \tau \). This is not optimal since the regulator can reduce \( \pi \) for the same \( \tau \) until \( \delta + \pi \phi \) is equal to \( \tau \), where the household is indifferent between legal waste disposal and illegal waste disposal. As is common in the literature on regulation, assume that the household, in case of indifference, chooses the disposal behavior desired by the regulator. This reduction in \( \pi \) does not change the household choice of \((q, e)\) but leads to lower monitoring cost. Thus, at any optimal policy implementing legal waste disposal, the monitoring probability and the waste collection charge will be chosen so that \( \delta + \pi \phi = \tau \). To implement illegal waste disposal, it is optimal to set \( \pi = 0 \) and \( \tau = \delta \) so that monitoring cost is zero. This is a boundary case of problem (9) below. Because \( \delta + e \geq \gamma \), and because the solution to the household problem is the same for either disposal method (given \( \pi = 0 \) and \( \tau = \delta \)), the boundary solution of legal waste disposal results in higher surplus than the boundary solution of illegal waste disposal. Consequently, the solution to the problem (9) of implementing legal waste disposal results in higher surplus than any policy implementing illegal waste disposal. (However, this may no longer be the case if households have different private costs of illegal waste disposal.)} \]
constant marginal waste reduction from household effort. With suitable restrictions on \( \alpha(k) \), \( \rho \), and the disutility of waste reduction effort \( v(e) \), we can focus only on the continuous part of the waste function. In that range, household waste reduction effort has a constant marginal waste reduction of \( \rho \) units, regardless of the total amount of waste at the end of production.\(^{18}\) With this assumption, partial derivatives in Eqs. (1) to (8) above are simplified to \( w_1 = 1 \) and \( w_2 = -\rho \).

We first note how the firm's waste reduction effort and the price of the consumption good change at the equilibrium in response to a policy. As the demand for and supply of \( k \) have to match at the equilibrium, we have \( (t + \tau)\alpha'(k) + 1 = 0 \) from Eqs. (5) and (8) above. Totally differentiating this yields \( \partial k / \partial t = \partial k / \partial \tau = (\alpha'(k))^2 / \alpha''(k) > 0 \). That is, a higher environmental tax on the firm and a higher waste collection charge on the household both lead to the same increase in the firm's waste reduction effort. In this sense, these two policy instruments can be regarded as substitutes insofar as the firm's waste reduction effort is concerned. The reason for this is the existence of feedback from consumption to production decisions in demanding products with specific waste content.

Next, differentiating the equilibrium price given in Eq. (4) and using \( \partial k / \partial t \), we obtain \( \partial p / \partial t \). Thus, either a higher environmental tax on the firm or a higher household waste collection charge leads to an increase in the equilibrium price of the consumption good. However, the increase in price is larger for the environmental tax on the firm. The reason is that the environmental tax affects the price of a consumption good through two channels: the first term in \( \partial p / \partial t \) can be regarded as the indirect effect on price through changes in \( k \) while the second term captures the direct effect.

**Lemma 1.** At the equilibrium of the decentralized market with policy instruments \( (t, \tau) \), we have \( \partial k / \partial t = \partial k / \partial \tau = (\alpha'(k))^2 / \alpha''(k) > 0 \), \( \partial p / \partial t = (\partial k / \partial t)(\tau / t + \tau) + \alpha(k) > 0 \), and \( \partial p / \partial \tau = (\partial k / \partial t)(\tau / t + \tau) > 0 \).

The equilibrium condition for \( k \) given by \( (t + \tau)\alpha'(k) + 1 = 0 \) and the price in Eq. (4) completely summarize the firm's response to a policy. For the analysis of second-best optimal policy, it remains to describe the household response. As argued before, the restriction \( \delta + \pi \phi = \tau \) leads the household to choose legal waste disposal. Moreover, since \( \pi \) only affects the household disposal decision and is set such that \( \delta + \pi \phi = \tau \), we may denote the solution to the household optimization problem by \( q(t, \tau) \) and \( e(t, \tau) \). The following comparative statics results are derived in the Appendix.

**Lemma 2.** Suppose the policies are such that the household chooses \( f = 0 \). Then \( \partial q(t, \tau) / \partial t = \partial q(t, \tau) / \partial \tau = \alpha(k) / u'(q) < 0 \), \( \partial e(t, \tau) / \partial t = 0 \), and \( \partial e(t, \tau) / \partial \tau = \rho / u'(e) > 0 \).

Lemma 2 can be explained as follows. An increase in the environmental tax on the firm increases the price of the consumption good, leading to a decrease in consumption, hence \( \partial q(t, \tau) / \partial t < 0 \). As a decrease in consumption resulting from an increase in the environmental tax does not change the marginal benefit of waste reduction effort, waste reduction effort is not affected, hence \( \partial e(t, \tau) / \partial t = 0 \).

\(^{18}\)For all the analyses to follow, it is sufficient to assume that the cross partial derivative of the waste function is zero; i.e., \( w_{12} = 0 \). Whether this assumption is reasonable is, of course, an empirical question.
increase in the waste collection charge increases the marginal cost of consumption, as an additional unit of waste from consumption has to be disposed of at higher cost,\textsuperscript{19} hence $\partial q(t, \tau)/\partial \tau < 0$. Finally, an increase in the waste collection charge increases the waste reduction effort, as it increases the marginal benefit of such effort; hence $\partial e(t, \tau)/\partial \tau > 0$.

The second-best optimal problem can now be stated. Denoting the equilibrium $k$ by $k(t, \tau)$, and using $\delta + \pi\phi = \tau$ to replace $\pi$ with $(\tau - \delta)/\phi$, the second-best optimal policy is the solution to maximizing surplus $S(t, \tau)$ in

Maximize\(_{(t,\tau)} S(t, \tau) \equiv u[q(t, \tau)] - v[e(t, \tau)] - [c + k(t, \tau)]q(t, \tau) \]

\[-\gamma\{a[k(t, \tau)]q(t, \tau) - pe(t, \tau)\} \]

\[-m\left(\frac{\tau - \delta}{\phi}\right)\]

subject to $\delta \leq \tau \leq \delta + \phi$ and $(t + \tau)\alpha[k(t, \tau)] + 1 = 0$. \hspace{1cm} (9)

In the above problem, $\delta \leq \tau \leq \delta + \phi$ is necessary to ensure $0 \leq \pi \leq 1$, and the second constraint is the equilibrium condition for $k(t, \tau)$. The following proposition is our main result and is proved in the Appendix.

**Proposition 1.** The second-best optimal policy implementing legal waste disposal by the household takes either of the following two forms: (i) if $\gamma - (mv''(e)/\rho^2 \phi) > \delta$, then $\tau = \gamma - (mv''(e)/\rho^2 \phi)$, $t = mv''(e)/\rho^2 \phi$, and $\pi = \tau - \delta/\phi$; (ii) if $\gamma - (mv''(e)/\rho^2 \phi) \leq \delta$, then $\tau = \delta$, $t = \gamma - \delta$, and $\pi = 0$.

A number of points can be made about Proposition 1. First, the household collection charge $\tau$ is larger than the private cost of illegal disposal $\delta$ but strictly smaller than the cost (to the regulator) of legal waste disposal ($\delta < \tau < \gamma$). Second, the environmental tax on the firm is strictly positive and is equal to the difference between the cost of legal waste disposal and the household collection charge ($0 < t = \gamma - \tau$). Thus, the entire cost of legal waste disposal is broken up into $\tau$ and $t$, as was the case without household waste reduction effort. However, there is now the additional cost of monitoring illegal waste disposal. Third, the choice of policy instruments is no longer as flexible as was the case without household waste reduction effort. It was argued in Section 2 that, without household waste reduction effort, the first-best optimum can be achieved by combinations of $t$ and $\tau$ such that $t + \tau = \gamma$ and $\tau \leq \delta$. Thus, the policymaker has flexibility in choosing a desired combination of these instruments as circumstances dictate. Such flexibility no longer exists in the presence of household waste reduction effort. Fourth, and related to the third point, the choice between the interior optimum (case (i)) and the boundary optimum (case (ii)) depends on various exogenous parameters of the model. For example, if the cost of monitoring illegal waste ($m$) is too high, or the penalty for illegal dumping ($\phi$) cannot be set high enough, or if the waste reduction benefit from household effort ($\rho$) is relatively small, then an optimal policy is likely to be the one with minimal waste collection charge as in the boundary solution of case (ii).

The above proposition can be contrasted with Fullerton and Wu (1998). When the amount of waste is independent of household waste reduction effort, a zero waste

\textsuperscript{19}Note that the full cost to the consumer is the same. In one case the cost is all reflected in price (which covers the cost of waste reduction and tax paid by the firm). In the other case, the price reflects only the cost of waste reduction by the firm, but the household pays the waste disposal charge in addition to paying the higher price.
collection charge is one of many policy combinations that achieve the first-best optimum, as the policy only needed to focus on the firm's waste reduction effort while ensuring the legal waste disposal by the household. If the amount of waste can be reduced by household effort, then the optimal policy does include a positive waste collection charge on the household in order to provide proper incentives for waste reduction effort. Such a collection charge can induce illegal dumping, however, and may need to be accompanied by monitoring of illegal dumping. Lowering the waste collection charge can lower monitoring cost, but can also reduce household incentives for waste reduction effort. As the monitoring cost can be reduced to zero by setting $\tau = \delta$ while still inducing legal waste disposal by the household, $\tau = \delta$ is the lower bound on the household collection charge. A further decrease in the waste collection charge, however, induces too much waste without lowering monitoring cost any further. On the other hand, imposing the full cost of legal waste disposal ($\gamma$) on the household may require too much monitoring cost. Instead, the regulator can indirectly tax household waste through the environmental tax on the firm. However, this tax is not directly focused on household waste, which limits its effectiveness relative to the direct waste collection charge. In sum, an optimal waste management policy is characterized by a positive environmental tax on the firm, a waste collection charge on the household (set between the private cost of illegal waste disposal and the social cost of legal waste disposal), and the monitoring probability necessary to support these two instruments to induce household compliance with legal waste disposal.

As is clear from the household optimization problem, the optimal choice of $e$ is independent of $\gamma$, $m$, and $\phi$ as long as the household complies with legal waste disposal. The following proposition then follows immediately from Proposition 1.

**Proposition 2.** For the second-best optimal policy implementing legal waste disposal by the household, an optimal environmental tax on the firm is nondecreasing in the cost of legal waste disposal ($\partial t/\partial \gamma \geq 0$), nonincreasing in the size of penalty for illegal waste disposal ($\partial t/\partial \phi \leq 0$), and nondecreasing in monitoring cost ($\partial t/\partial m \geq 0$). An optimal waste collection charge on the household is nondecreasing in the cost of legal waste disposal ($\partial \tau/\partial \gamma \geq 0$), nondecreasing in the size of penalty for illegal waste disposal ($\partial \tau/\partial \phi \geq 0$), and nonincreasing in monitoring cost ($\partial \tau/\partial m \leq 0$). An optimal probability of monitoring illegal waste disposal is nondecreasing in the cost of legal waste disposal ($\partial \pi/\partial \gamma \geq 0$), nonincreasing in the size of penalty for illegal waste disposal ($\partial \pi/\partial \phi \leq 0$), and nonincreasing in monitoring cost ($\partial \pi/\partial m \leq 0$).

Obvious as it may be, Proposition 2 has important policy implications. A higher monitoring cost makes it more costly to induce legal waste disposal, which has to be compensated for through a lower waste collection charge. To make up for the reduced waste collection charge necessary for legal waste disposal, a higher environmental tax on the firm is needed. The size of the penalty for illegal waste disposal plays a role exactly opposite to that of the monitoring cost. If the penalty for illegal waste disposal is high enough, then the waste collection charge need not be set too low so as to avoid illegal waste disposal. A clear message emerges: an optimal environmental tax on the firm's sale of household goods should take into account the effect of such a tax on subsequent household waste disposal decisions, a point that models of Pigouvian environmental tax focusing on the production side alone may not successfully address.
IV. SUMMARY AND DISCUSSION

This paper analyzes a comprehensive model of household waste management policy incorporating the possibility of waste reduction effort by the firm and the household, and illegal waste disposal by the household. The regulator chooses an environmental tax on the firm, a household waste collection charge, monitoring of illegal waste disposal by the household, and a penalty for illegal disposal. For waste where household waste reduction effort is not significant, the first-best optimum can be achieved using various combinations of environmental tax and waste collection charge, without the need to monitor illegal waste disposal. However, the significant possibility of household waste reduction effort makes the first-best optimum unachievable and necessitates explicit monitoring of illegal waste disposal. The reason for this is the dual role played by the household waste collection charge: the higher the waste collection charge, the more incentives the household has for waste reduction as well as for illegal waste disposal. The resulting second-best optimal policy is a combination of a strictly positive waste collection charge on the household, explicit monitoring of illegal waste disposal, and a strictly positive environmental tax on the firm. A general lesson from this study is that any comprehensive waste management policy has to take into account the interdependent nature of waste generation and disposal, or its policy recommendations could be misleading.

Since the basic model of this paper has a single representative household, an optimal policy always implements legal waste disposal. This may not be very realistic, especially in view of the second-best nature of the problem where explicit monitoring of illegal waste disposal is necessary. Given that the penalty for illegal waste disposal is exogenously fixed, whether it is optimal to eliminate any illegal waste disposal entirely depends on the monitoring costs necessary to induce such extreme compliance. An extension of the current model could describe this more plausible scenario. For example, suppose a continuum of households have different private costs of illegal disposal, but are identical in all other respects. For a given set of nondiscriminatory policy instruments, one can identify a threshold household that is indifferent between legal and illegal waste disposal. Those households whose private costs of illegal disposal are lower than that of the threshold household will all dispose of waste illegally, while the rest will comply with legal waste disposal. At an optimal policy, the threshold household is determined endogenously, and so is the amount of waste illegally disposed of. Needless to say, the position of the optimally determined threshold household depends on monitoring costs.

A question remains, though, as to how such monitoring and enforcement could take place. One can first note an obvious role for the general community. Mookherjee and Png (1992) and Heyes (1997) have studied the role of individual economic agents in the enforcement of environmental regulation. In Victoria, Australia, for example, individuals are encouraged to phone and report littering offences. Furthermore, Harrington (1988) emphasizes the role of targeting. In the case of household waste management, this would take the form of targeting locations that are known to be major sources of illegal dumping. Finally, Gren and Kaitala (1997) discuss the role for the environmental regulator to signal (or not to signal) violation detection skills and enforcement.

A general message of this paper is the importance of clearly recognizing the interdependent nature of policy instruments at different levels of implementation. Such interdependence calls for careful coordination of policies among different regula-
tory bodies. It is often the case that environmental taxes are determined nationally and waste disposal programs are worked out by each municipality, while monitoring and penalizing illegal waste disposal are implemented by the environmental protection authorities or other law enforcement bodies. For various reasons (including informational asymmetry, political constraints, and the agency cost of delegation), the coordination of policies at different levels of implementation may not be a practical possibility. In line with the emerging literature on environmental federalism, this paper can be extended to address the cost of coordination failure. For instance, one can study the municipal government’s problem of choosing an optimal waste disposal program given that the environmental tax rate is fixed exogenously by national government. While the objective functions of the two governments would have to be modeled explicitly, it is not hard to imagine that the optimality of the policies so designed would be a mere coincidence. We hope to address this issue in future research.

APPENDIX

Proof of Lemma 2. The household optimization problem leads to the first-order conditions $u'(q) - p - \tau \alpha(k) = 0$, $-v'(e) + \tau p = 0$. The assumptions $u'' < 0$ and $v' > 0$ ensure that the conditions for the implicit function theorem are satisfied, so these first-order conditions become identities in the neighborhood of the solution to the optimization problem. Total differential of the second identity leads to \( \frac{\partial e}{\partial t} = 0 \) and \( \frac{\partial e}{\partial \tau} = \rho / v'(e) > 0 \). Totally differentiating the first identity and arranging terms, we have \( u''(q) dq - [(\partial p/\partial t) + \tau \alpha'(k) (\partial k/\partial t)] dt - [(\partial p/\partial \tau) + \tau \alpha'(k) (\partial k/\partial \tau)] d\tau = 0 \). Thus \( \frac{\partial q}{\partial t} = \frac{1}{u'(q)} \left[ (\partial p/\partial t) + \tau \alpha'(k) (\partial k/\partial t) \right] \). Using Lemma 1 to replace \( \frac{\partial p}{\partial t} \) with \( (\partial k/\partial t)(\tau + \gamma) + \alpha(k) = (\partial k/\partial t)[1 + \alpha'(k)] + \alpha(k) \), and using \( (t + \gamma) \alpha'(k) + 1 = 0 \), we have \( \frac{\partial q}{\partial t} = \alpha(k)/u'(q) < 0 \). That \( \frac{\partial q}{\partial \tau} = \alpha(k)/u'(q) < 0 \) follows from a similar algebra. \( \blacksquare \)

Proof of Proposition 1. We will first solve for the interior optimum to problem (9) ignoring constraints, and then check if the solution indeed satisfies constraints. In fact, we need only check the boundary case for \( \tau \) since \( t \) is not constrained by an inequality. The first-order conditions for the interior solution to problem (9) can be written as

\[
\frac{\partial S(t, \tau)}{\partial t} = \frac{\partial q}{\partial t} [u'(q) - (c + k) - \gamma \alpha(k)] - \frac{\partial k}{\partial t} [1 + \gamma \alpha'(k)] q = 0, \tag{A1}
\]

\[
\frac{\partial S(t, \tau)}{\partial \tau} = \frac{\partial q}{\partial \tau} [u'(q) - (c + k) - \gamma \alpha(k)] - \frac{\partial k}{\partial t} [1 + \gamma \alpha'(k)] q - \frac{\partial e}{\partial \tau} [v'(e) - \gamma p] - \frac{m}{\phi} = 0, \tag{A2}
\]
where the second equalities in Eqs. (A1) and (A2) are derived using the envelope theorem for the household optimization problem.

Note first that \( t + \gamma = \gamma \) is necessary and sufficient for Eq. (A1). Sufficiency is straightforward since \( t + \gamma = \gamma + 1 + \gamma \alpha'(k) = 0 \) if \( t + \gamma = \gamma \). For necessity, suppose first \( t + \gamma > \gamma \). Then \( \partial e/\partial t(t + \gamma - \gamma)\alpha(k) < 0 \) since \( \partial q/\partial t < 0 \) by Lemma 2, and \( (\partial k/\partial t)[1 + \gamma \alpha'(k)]q > 0 \) since \( \partial k/\partial t > 0 \) by Lemma 1 and \( 1 + \gamma \alpha'(k) > 1 + (\gamma + t)\alpha'(k) = 0 \). This leads to \( \partial S(t, \tau)/\partial \tau < 0 \), contrary to Eq. (A1). Using a similar argument, it can be shown that \( t + \gamma < \gamma \) leads to \( \partial S(t, \tau)/\partial \tau > 0 \), again contrary to Eq. (A1). As \( t \) is not constrained, Eq. (A1) always holds with equality, implying that any optimal policy should satisfy \( t + \gamma = \gamma \).

Given \( t + \gamma = \gamma \), Eq. (A2) becomes \(-\partial e/\partial \tau)(\gamma - \gamma)\rho - (m/\phi) = 0 \). Since \( \partial e/\partial \tau = \rho / \nu''(e) \) from Lemma 2, we can solve Eq. (A2) for \( \tau \): \( \tau = \gamma - (m/\phi) \). From this follows \( t = m/\phi \). Obviously, \( t > 0 \). Note also that \( \tau = \gamma - (m/\phi) < \delta + \phi \) since \( \gamma < \delta + \phi \) and \( \Delta \leq \phi \). If \( \gamma - (m/\phi) > \delta \), we thus have an interior solution \( t = m/\phi \), \( \tau = \gamma - (m/\phi) \) and a strictly positive probability of monitoring illegal waste disposal given by \( \pi = \tau - \delta + \phi \). If \( \gamma - (m/\phi) \leq \delta \), then an optimal policy is \( \tau = \delta \), \( \pi = 0 \), and \( t = \gamma - \delta \).

**REFERENCES**