Collective Sanctions as a Remedy to the Household Waste Problem

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ABSTRACT

In an attempt to provide a solution to excessive solid waste generation by households, this paper steps outside the standard representative agent framework in the household waste management literature, considers an economy consisting of strategically-interacting individuals, and proposes a novel economic mechanism to implement a first-best outcome. The proposed mechanism amends consensus-based collective sanctions to the standard price-per-unit policy, and is potentially applicable especially in small communities.

Keywords: Waste reduction; dumping; environmental policy.

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1 Introduction

The disposal of excessive solid waste by households is costly, mainly due to declining landfill capacity, and represents a case of market failure that needs to be remedied. This paper steps outside the standard representative agent framework in the household waste management literature, considers an economy consisting of strategically-interacting individuals, and proposes a novel economic mechanism to implement a first-best outcome. The proposed mechanism amends consensus-based collective sanctions to the standard price-per-unit policy, and is potentially applicable especially in small communities.

The economics discipline has been paying increasing attention to the question of household waste management in the last two decades, providing theoretical, experimental and policy inputs (for two surveys covering early contributions, see Choe and Fraser, 1998; Kinnaman and Fullerton, 2000). Broadly speaking, the literature on household waste management can be divided into two strands. The first one aims to provide incentives to switch to environmentally-sustainable designs and to increase the use of recycled inputs within a general equilibrium setup by employing upstream and downstream taxation mechanisms (for a selection of papers along that line, see, e.g., Fullerton and Wu, 1999; Calcott and Walls, 2000; Fullerton and Wolverton, 2000; Walls and Palmer, 2001; Shinkuma, 2007). Although these mechanisms are shown to adhere to the socially-optimal waste policy, they come with high administrative and transaction costs, such as determining deposit fees for each and every recyclable commodity, not to mention the technical difficulties in using recyclable materials in the production processes.

Conversely, the second strand is concerned explicitly with households, regarding how they allocate their time among market labor, waste reduction/reuse/recycle efforts, and leisure (à la Becker). The Pigovian solution to put a price on waste equal to marginal cost of its disposal was proven to be naive long ago (Fullerton and Kinnaman, 1996), since rational households, faced with such a scheme, would rather illegally dump or burn their waste to evade tax. To combat illegal dumping and burning of waste, a properly-designed monitoring system may certainly be put in place to secure a first-best solution, but this would also suffer from heavy administrative and transaction costs, such as determining the appropriate level of fines for different households, based on individual characteristics like wealth and risk attitude (see, e.g., Choe and Fraser, 1999).

In addition to their implementation-related structural problems–heavy administrative and transaction costs–these mechanisms are derived from models that are based on agents' price-taker behavior and fail to consider strategic interactions among them. Given these shortcomings, it is hardly surprising that empirical studies mostly indicate that various waste management schemes along the lines of models described above have so far had only limited success (Allers and Hoeben, 2010).

As waste reduction/reuse/recycling exhibits a public good character, and hence the optimal provision of which is shadowed by the well-known collective action problem, we deploy in our paper a framework that does explicitly acknowledge this very possibility of strategic interaction. Hereby we revisit the household waste management problem, and our model consists of (identical) households that consume two types of commodities, a packaged good and a homemade one. While the packaged good is ready for consumption but produces waste that needs to be collected and disposed of, the homemade one is to be prepared at home, by using household labor and the unpackaged good purchased from the market, and produces no waste (or compostable waste). Households may either deposit the waste as garbage or dispose of it through illicit means. The average amount of uncollected dumped waste has a negative effect on household satisfaction, which results from the consumption of goods (packaged and homemade) that are taken as perfect substitutes.

After setting up the socially-optimal waste management solution, the paper proceeds to analyse two waste management policies: the standard price-per-unit policy and the novel, so-called cost-sharing, policy that is based on collecting all waste (legally or illicitly disposed) and imposing a per household waste collection and disposal fee on all households. By using a pure-strategy Nash equilibrium concept, the paper highlights the inefficiencies associated with both these policies, and offers a hybrid one that employs the two and involves a consensus-based collective sanctions as a means to implement the socially-optimal solution.

2 The model

Assume there are I identical households in the community. Households either consume packaged (ready-to-eat) goods or combine unpackaged goods and time to produce household commodities. Let x_i denote household i's consumption of packaged good, which is assumed to be the numeraire.[2] Let z_i denote household i's consumption of home-produced good, which uses y_i, the unpackaged good, and h_i, the amount of labor spent in home production as inputs. Let p denote the price of an unpackaged good. All households have a fixed endowment of time, normalized to 1, which may be used either to supply l_i units to the labor market in return for an hourly wage rate of w, or spent at home as an input for home production, h_i.[3] Households are endowed with identical home production technology, which is described by the production function $f(h_i, y_i)$, where $f : \mathbb{R}^2_+ \to \mathbb{R}$. We impose the following assumption on the production technology.

Assumption 1 (A1): $f(h_i, y_i)$ is strictly increasing and strictly concave function, and $f(h, 0) = 0$ for all $h \in \mathbb{R}$ and $f(0, y) = 0$ for all $y \in \mathbb{R}$.[4]

The consumption of packaged goods produces waste as a by-product, whereas the consumption of unpackaged goods does not. As a typical exam-

[2]Throughout the model we follow the following convention in notation; lower case letters denote individual amounts, capital letters denote aggregate amounts, and bold characters denote the vector of variables.

[3]For the sake simplicity, leisure and housework were aggregated into one entity.

[4]The assumptions of concavity and the possibility of inaction imply that the production technology exhibits non-increasing returns to scale.

ple, consider that x_i represents a store-bought, ready-to-eat spinach salad, the package of which goes to waste, and y_i stands for market-bought spinach that is used to produce z_i, the spinach salad, when combined with labor h_i.[5] Every unit of x_i purchased by household i produces solid waste denoted by s_i, given by the relationship

$$s_i = \theta x_i, \tag{1}$$

where θ is a waste production technology parameter such that $\theta \in (0, 1)$. Let $S = \Sigma_{i=1}^{I} s_i$ be the total amount of solid waste produced.

Households can either deposit the waste as garbage, g_i, which will be collected by the municipality or illicitly dump the waste, d_i, which may or may not be collected, according to the waste management program adopted. Therefore, $s_i = d_i + g_i$. Let $\mathbf{g} = (g_1, ..., g_I) \in \mathbb{R}^I$ be the vector of garbage generated, $\mathbf{d} = (d_1, ..., d_I) \in \mathbb{R}^I$ the vector of waste dumped by community, $G = \Sigma_{i=1}^{I} g_i$ the total amount of garbage disposed, and $D = \Sigma_{i=1}^{I} d_i$ the total amount of dumped waste. While there are no transportation costs to dumping waste within the community, costs of dumping outside the community are prohibitively high.[6]

[5]The model may also be interpreted in the sense that labor is used to reduce the environmental impact of human activities (as in the example of cycling instead of driving a private car).

[6]The discontinuity assumption on the cost of transporting waste to dumpsites within and outside the neighborhood may be based on the following: There may be dumpsites within walking distance in a given district, such as deserted dwellings or parking lots, in contrast to dumpsites outside the community that are accessed by transportation and thus

Households derive enjoyment from consuming both x_i and z_i, and consider them perfect substitutes. Moreover, the average amount of dumped waste, $\bar{d}\left(= \frac{1}{I}\Sigma_{i=1}^{I} d_i\right)$, if not collected, would adversely affect their enjoyment.[7] Again assume that households have identical preferences and the utility function of household i is given by $U(x_i + z_i, \eta\bar{d}) : \mathbb{R}_+^2 \to \mathbb{R}$, where η takes the value of 0 or 1, indicating whether the dumped waste is collected or not, respectively, depending on the waste management program adopted. We impose the following assumption on the utility function.

Assumption 2 (A2): $U(x_i+z_i, \eta\bar{d})$ is a continuous and strictly concave function with the properties: $U_1 > 0$, $U_2 < 0$ and $U_{12} \leq 0$.

The household's problem is to choose (x_i, z_i, d_i, g_i) to maximize its utility subject to technological and budget constraints. The problem is solved in two stages. First, the cost of producing z_i for a given price vector (p, w) is characterized. Then, based on the cost of production at home, the consumption decision of a household is analyzed.

Household i's cost minimization problem[8] is given as follows:

$$\min_{h_i, y_i \geq 0} \quad wh_i + py_i \tag{2}$$

$$\text{s.t.} \quad f(h_i, y_i) = z_i \tag{3}$$

may involve a fixed cost.

[7]The rationale of this assumption is to normalize the total amount of dumped waste with respect to the population size. In this stylized model, other types of pollution, such as littering, industrial pollution and noise pollution, are not considered.

[8]Since production function is assumed to be strictly increasing, the constraint of the maximization problem is written with equality.

Given the assumptions imposed on the production function, (A1), a unique solution to the above problem exists. Let $c(z_i)$ denote the value function of the above problem. Here, $c(z_i)$ measures the cost of consuming z_i units of a home-produced good. Given the assumptions made regarding the production function, it follows that $c'(\cdot) > 0$ and $c''(\cdot) > 0$. Thus, the price of home-produced good increases as more of it is produced.

The total cost of depositing solid waste for each household is denoted by $K(\mathbf{g}, \mathbf{d})$, which depends on the waste management policy adopted. Based on the program, household costs may depend on the amount of solid waste produced by others. For the waste management programs to be analyzed here, $K(\mathbf{g}, \mathbf{d})$ is considered to be linear.

A given household's utility maximization problem can now be stated as follows:

$$\max_{x_i, z_i, d_i, g_i \geq 0} \quad U(x_i + z_i, \eta \bar{d}_i) \tag{4}$$

$$\text{s.t.} \quad x_i + c(z_i) + K(\mathbf{g}, \mathbf{d}) \leq w \tag{5}$$

Since $U(\cdot)$ is strictly concave, $c(\cdot)$ is strictly convex and $K(\cdot)$ is linear, the above problem is well-defined.

Finally, society bears the disposal costs of garbage and, if collected, dumped waste. The unit cost of cleaning up garbage, g_i, is α and that of dumped waste, d_i, is β, where $\alpha < \beta$.[9] We further assume that

Assumption 3 (A3): $c'(0) < 1$ and $1 + \alpha\theta < c'(z^m)$, where z^m is defined

[9] This assumption may be justified on the grounds that locating dumped waste requires an additional effort compared to curbside collection.

by $c(z^m) = w$.

Here, z^m is the maximum amount of home-produced good a household can produce given its potential income. (A3) implies that the price of the packaged good is higher than the marginal cost of producing the very first unit of home-produced good and the effective price of it is lower than that of producing the maximum amount.

2.1 The Social Planner's Problem

Consider a utilitarian social planner who announces that all garbage deposits will be collected, and naively believes that no one will dump any waste. While our model considers one-period lived households and is therefore static, the social planner takes the welfare of next generations into account as well, and is thus motivated to collect any and all deposited waste.

We therefore characterize the constrained-Pareto efficient allocation as a solution to the social planner's problem, in which all waste will be disposed of as garbage and all garbage will be collected. The Pareto efficient allocation maximizes the sum of the utilities of households subject to society's budget constraint and $\eta = 0$:

$$\max_{\{x_i, z_i\}_{i=1,..,I}} \quad \Sigma_{i=1}^{I} U(x_i + z_i, 0) \tag{6}$$

$$\text{s.t.} \quad \Sigma_{i=1}^{I} [(1 + \alpha\theta)x_i + c(z_i)] \leq Iw \tag{7}$$

The unique equilibrium is symmetric, where $x_i^* = x^*$, $z_i^* = z^*$ (and $d_i^* = 0$)

for all i. Thus, we have[10]

Proposition 1. *The unique (interior) Pareto efficient equilibrium* (x^*, z^*) *is characterized by*

$$c'(z^*) = 1 + \alpha\theta \tag{8}$$

$$x^* = \frac{w - c(z^*)}{1 + \alpha\theta} \tag{9}$$

Every unit of x_i costs a dollar in the market plus the cost of cleaning up the waste it creates, $1 + \alpha\theta$. In equilibrium, the marginal cost of z_i is equal to the unit cost of x_i, replicating the well-known Pigovian solution.[11] The optimal level of home production, z^*, increases in both α and θ. Once optimal home production is calculated from equation (8), the optimal amount of packaged good, x^*, is recovered by using the budget constraint in equation (7). Then, the optimal amount of total waste generated will be $S^* = I\theta x^*$.

[10] All proofs are provided in the Appendix.

[11] In passing, let us note that the same solution could have been reached if households were given the choice to dump their waste in addition to disposing of it as garbage, and the social planner was able to observe households that dumped their waste and charge them β for it. Since $\beta > \alpha$, no one would prefer to dump their waste.

2.2 Non-cooperative Equilibrium under Price-per-unit Policy

Still believing that none of the households would dump their waste, the social planner selects the obvious policy of putting a price on per unit of garbage equal to the cost of collecting it, α, to achieve the socially-optimal outcome. Households, however, are not naive and realize that dumping waste is an option. They also realize that dumped waste will become a source of disutility, since it remains uncollected. A waste management program is denoted by (t, τ, η), where t is the tax (fee) on garbage, τ is the tax (fee) on dumped waste, and η indicates whether the dumped waste is collected or not. Under the price-per-unit policy[12], $(\alpha, 0, 0)$, households would have to pay for each unit of garbage and bear the negative impact of uncollected dumped waste. Then, the waste disposal costs of household i depend only on the garbage it produces, $K(\mathbf{g}, \mathbf{d}) = K(g_i) = \alpha g_i$, where $g_i = s_i - d_i$.

Under the price-per-unit policy, households benefit from dumping their waste, since this allows them to avoid the tax imposed on the solid waste disposal. All households consider the amount of waste dumped by everyone else as given and maximize their utility subject to their budget constraint.

[12]In practice, most applications are volume-based, i.e., bag or cart. We acknowledge that, while taking volume as the measurement unit is easy to implement, in many cases this has proven subject to manipulation with people compacting garbage into fewer bags, known as the "Seattle stomp". Although difficult to implement, weight-based applications have been introduced recently. Our model does not impose any unit of measurement in the *a priori* sense.

Let $D_{-i} = D - d_i$ be the total amount of dumped waste, excluding that of household i. Household i's problem, given the levels of waste dumping of others taken as fixed at $\hat{D}_{-i}$, is

$$\max_{x_i, z_i, d_i \geq 0} \quad U(x_i + z_i, \tfrac{d_i + \hat{D}_{-i}}{I}) \tag{10}$$

$$\text{s.t.} \quad x_i + c(z_i) + \alpha(\theta x_i - d_i) \leq w \tag{11}$$

The unique equilibrium is symmetric, where $x_i^p = x^p$, $z_i^p = z^p$ and $d_i^p = d^p$ for all i.[13]

Proposition 2. *Under the price-per-unit policy,* $(\alpha, 0, 0)$*, the unique (interior) Nash equilibrium* (x^p, z^p, d^p) *is characterized by*

$$c'(z^p) = 1 + \alpha\theta \tag{12}$$

$$\frac{\alpha}{1+\alpha\theta} U_1(x^p + z^p, d^p) + \frac{1}{I} U_2(x^p + z^p, d^p) = 0 \tag{13}$$

$$x^p = \frac{w - c(z^p) + \alpha d^p}{1 + \alpha\theta} \tag{14}$$

Equation (12) clearly shows that all households choose $z^p = z^*$. The first

[13] Depending on the parameter space, there may also be two types of equilibrium involving a corner solution with respect to waste dumping. In the first one, the disutility from the very first waste dumped is so high that each household refrains from dumping. In the second one, the disutility from dumping, even from the very last unit dumped, is so low that households dump all their garbage. These two equilibria are characterized in the proof of the Proposition 2 in the Appendix.

order condition (13) solves for the response function of household i, after imposing that the solution will be a symmetric one, i.e., $\bar{d} = d^p$.

The adjusted price of the packaged good then becomes $1 + \alpha\theta$. The optimal level of home production increases in both α and θ. In the interior equilibrium, recalling that the average amount of dumped waste causes disutility for households, the waste dumped by each household in equilibrium is proportional to the number of households in the community, bringing about a collective action problem.

Comparing equilibrium under the price-per-unit policy with Pareto efficient equilibrium, the following is observed:

Corollary 1. *Under the price-per-unit policy* $(\alpha, 0, 0)$, $z^p = z^*$, $d^p > d^*$, $x^p > x^*$, *and* $S^p > S^*$.

Acting naively and thinking that no one would dump their waste, the planner set the tax rate equal to the cost of cleaning garbage, which resulted in an inefficient outcome (replicating the well-established finding of the price-per-unit literature).[14] When $t = \alpha$, although home production is efficient because waste is correctly priced, inefficiency arises from the incentive to dump it. Evading taxes by dumping waste, leads to the excessive consumption of packaged goods, which in turn increases the total waste pro-

[14]Note that $t = \alpha$ is not the optimal tax rate that maximizes the indirect utility of the representative household. In fact, the optimal tax rate would be greater than α, resulting in excess tax revenue, which is also inefficient.

duced. As society grows larger, the price-per-unit policy will become more inefficient due to the free rider problem–an expected outcome that results from strategic interactions within the model.

2.3 Non-cooperative Equilibrium under the Cost-sharing Policy

At this point, the social planner would realize that under the price-per-unit policy households would dump their waste illegally to evade taxes. Unsatisfied, the social planner would begin to consider a new policy, cost-sharing, where all waste would be cleaned up and its cost would be divided equally among households. Since waste is dumped within the community in the model, the total waste produced within the community would be equal to the sum of waste produced by each household, either garbage or dumped waste. Consequently, household i's problem is,

$$\max_{x_i, z_i, d_i \geq 0} \quad U(x_i + z_i, 0) \tag{15}$$

$$s.t. \quad x_i + c(z_i) + \frac{\alpha}{I}\Sigma_{i=1}^{I}(\theta x_i - d_i) + \frac{\beta}{I}\Sigma_{i=1}^{I} d_i \leq w \tag{16}$$

The unique equilibrium is symmetric, where $x_i^c = x^c$, $z_i^c = z^c$ for all i, and $D^c = D^* = 0$. Thus, we have the following result:

Proposition 3. *Under the cost sharing policy,* $(\frac{\alpha}{I}, \frac{\beta}{I}, 0)$*, the unique (interior)*

Nash equilibrium (x^c, z^c, d^c) *is characterized by*

$$c'(z^c) = 1 + \frac{\alpha}{I}\theta \tag{17}$$

$$x^c = \frac{w - c(z^c)}{1 + \frac{\alpha}{I}\theta} \tag{18}$$

$$d^c = 0 \tag{19}$$

Since each household bears an I^{th} of the overall cost of waste disposal, the adjusted price of the packaged good is $1 + \frac{\alpha}{I}\theta$. Comparing the equilibrium under the cost-sharing policy with the Pareto efficient equilibrium, we observe the following:

Corollary 2. *Under the cost-sharing policy,* $(\frac{\alpha}{I}, \frac{\beta}{I}, 0)$, $z^c < z^*$, $d^c = d^* = 0$, $x^c > x^*$, *and* $S^c > S^*$.

In cost-sharing, waste dumping is kept at an optimal level. However, home production is distorted: Since each household bears an I^{th} of the cost of waste disposal, the effective price of a packaged good is lesser and the real price of a home-produced good is greater, leading to the under-consumption of home-produced goods. To compensate for this, the consumption of packaged goods increases, so does waste as its by product. The social planner is dissatisfied once again.

2.4 The Hybrid Policy

Both the price-per-unit and the cost-sharing policies display certain deficiencies. Under the price-per-unit policy, the amount of home production is efficient. However, households dump waste to avoid paying taxes, which results in the over-production of waste. In cost-sharing, the amount of waste dumping is optimal (zero) but home-produced goods are under-produced and packaged goods are consumed excessively, hence there is an over-production of waste. Both mechanisms are infected by collective action problems. The collective action problem with regard to the price-per-unit policy is due to multilateral externality created by uncollected dumped waste; under the cost-sharing policy, on the other hand, the problem arises from households not bearing the full cost of their actions.

The social planner finally proposes a policy that targets both types of collective action problems to achieve an efficient level of home production with no waste dumping in the economy. Named the "hybrid policy," it amends the price-per-unit policy by introducing a collective sanction fee as means to impose the cost of dumping waste onto the entire community. In the hybrid policy $(\alpha, \beta, 0)$, the garbage is taxed at a rate of $t = \alpha$, as in the price-per-unit policy. In addition, all dumped waste is cleaned up (i.e., $\eta = 0$), and each and every household is charged a fee of of $\tau = \beta$ per unit of the total dumped waste to discourage dumping. Naturally, total taxes collected from dumped waste, if there is any, will exceed the total cost of cleaning up, the difference of which will need to be burned down as otherwise redistributing it to households as in-kind or cash payment would distort their incentive structures.

The problem is solved for each household i under the hybrid policy as shown below:

$$\max_{x_i, z_i, d_i \geq 0} \quad U(x_i + z_i, 0) \tag{20}$$

$$s.t. \quad x_i + c(z_i) + \alpha(\theta x_i - d_i) + \beta \Sigma_i^I d_i \leq w \tag{21}$$

Under this policy, since $\alpha < \beta$, the dominant strategy for all households is to throw away the waste as garbage rather than dumping it for any given level of (x_i, z_i). Setting $d_i = 0$ for all i to iteratively eliminate the dominated strategies, the problem of each household is reduced to:

$$\max_{x_i, z_i \geq 0} \quad U(x_i + z_i, 0) \tag{22}$$

$$s.t. \quad x_i + c(z_i) + \alpha\theta x_i \leq w \tag{23}$$

The unique equilibrium is symmetric, where $x_i^h = x^h$, $z_i^h = z^h$, and $d_i^h = d^h$ for all i. Noting that the first order conditions to household problems under the hybrid policy are the same as that of the social planner's problem, we have the following result:

Proposition 4. *Under the hybrid mechanism* $(\alpha, \beta, 0)$*, the unique Nash equilibrium* (x^h, z^h, d^h) *is Pareto efficient.*

3 Discussion and Concluding Remarks

This paper revisited the household waste management problem by explicitly considering strategic interactions among agents. First, two waste management policies–the standard price-per-unit and the cost-sharing policies–were analyzed, and inefficiencies associated with both were illustrated. These results formed the backbone of the hybrid policy that was introduced in the paper, which consists of offering households the choice of paying a unit individual fee for their garbage, or a unit communal fee along with all households in the neighbourhood for the collection and disposal of dumped waste. The unique Nash equilibrium illustrates that households will choose not to dump their waste, and the waste generated will be at the socially-optimal level.

The forte of the policy introduced here is that the social planner will require only two observable parameters–the cost of collecting garbage and that of dumped waste–and therefore the policy tools are independent of household characteristics such as wealth, disutility from uncollected dumped waste, and productivity at home. This property lends itself to immediate extensions of the model by allowing heterogeneity among the population along these dimensions, which will not disturb the policy's efficiency. One way of extending the model is by allowing households to have differing earning capabilities, thus making wages household-specific. In this case, the level of home production will be the same across all households, but richer families (those earning higher wages) will purchase more packaged goods and produce more waste. This result is derived from the assumption that packaged good x and home-produced good z are perfect substitutes in household preferences, which generates no wealth effect on the consumption of home-produced goods. Thus, the entire increase in income will be channelled into the consumption of packaged good x. The model can also be extended by introducing heterogeneity into the home production technologies of the household. This will be reflected in the budget constraint of each household via differing cost functions for the home-produced good. Households that are technologically challenged will produce less home-produced goods and purchase more packaged ones, hence produce more waste. At any rate, our new policy implements the Pareto efficient outcome not only for these extensions but for any variations of household characteristics.

Recall that in the case where waste is dumped, each and every household in that community will pay in full the total collection and disposal costs. This in fact resembles the "ambient tax" scheme proposed in solution to the nonpoint source pollution problem, in which regulators are not able to observe individual emission levels but can gauge the ambient pollution level of a given geography. The proposed ambient tax scheme requires each and every polluter within this area to pay a tax based on the aggregate level of emissions (see, e.g., Xepapadeas, 1999). Yet, this scheme is known to suffer from multiplicity of equilibria, which leads to coordination failure, and comes with an unfair distribution of costs and benefits, making it almost impossible to implement. Achieving a socially-optimal solution is possible only when, as Xepapadeas (1995) and more recently Kritikos (2004) suggested, individual polluters are randomly monitored in addition to the ambient-based scheme.

Although their solution and our hybrid policy are based on the same common spirit, there exist two differences that arise from the nature of the problem at hand that renders ours easier to implement. First, individual penalties in our policy, i.e. garbage tax, are not based on outcomes of random monitoring but on perfectly observable actions (i.e. units of garbage disposed); and consequently, second, their scheme will have to shoulder the transaction cost of monitoring, while ours does not involve such a dead-weight loss.

Although our mechanism ensures that there will be no dumped waste in the equilibrium, hence no excess revenues at hand, we should nevertheless consider off-the-equilibrium path. Obviously, this would have drastic effects if the community size were large. In other words, to ensure none of the households would be bound by the limited liability constraint, and the amount of surplus money has only a symbolic meaning, the size of the settlement should rather be small.[15] Restricting population size will have an additional benefit, since a collective sanction that is not self-imposed but applied instead in a top-down manner would likely lead to revolt (see, e.g., Heckathorn, 1988). It is thus necessary to build consensus on the implementation of a collective

[15] Consider the following example: Under the plausible assumptions that waste disposal costs for 1 ton of waste is €200 and a typical household generates 15 kg of waste per week (see, e.g., Dijgraaf and Gradus, 2008), if one household from a neighbourhood of 100 families deviates from the established norm and dumps its weekly waste, all households will have to pay a fine of €3 according to our policy, and the total money burned will be €297. Households can easily afford this fine, and the money burned down will have a symbolic meaning. However, with growing population size, the picture would become increasingly dismal.

sanction, and the smaller the size of the community, the easier this will be (Olson, 1965). If consensus is reached, then the community may also be expected to follow the rules not only because of economic incentives but also, equally importantly, because of moral duties (see, e.g., Levinson, 2003). In short, our proposal will face difficulties when applied in large cities, but could easily be applied in small communities.

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4 Appendix: Omitted Proofs

Proof of Proposition 1

The Pareto efficient allocation maximizes the sum of the utilities of households subject to society's budget constraint and $d_i = 0$ for all i

$$\max_{\{x_i,z_i\}_{i=1,..,I}} \quad \Sigma_{i=1}^{I} U(x_i + z_i, 0) \tag{24}$$

$$\text{s.t.} \quad \Sigma_{i=1}^{I}[(1+\alpha\theta)x_i + c(z_i)] \leq Iw \tag{25}$$

$$x_i \geq 0 \text{ for all } i \tag{26}$$

$$z_i \geq 0 \text{ for all } i \tag{27}$$

Letting (λ, μ_i, η_i) be the Lagrange multipliers for the constraints (25-27), the first order conditions to the problem for all $i = 1, ..., I$ are:

$$\frac{\partial \mathcal{L}}{\partial x_i} = U_1(x_i + z_i, 0) - \lambda(1+\alpha\theta) + \mu_i = 0 \quad (28)$$

$$\frac{\partial \mathcal{L}}{\partial z_i} = U_1(x_i + z_i, 0) - \lambda c'(z_i) + \eta_i = 0 \quad (29)$$

$$\frac{\partial \mathcal{L}}{\partial \lambda} = Iw - \Sigma_{i=1}^{I}[(1+\alpha\theta)x_i + c(z_i)] \geq 0, \text{ with equality if } \lambda > 0 \quad (30)$$

$$\frac{\partial \mathcal{L}}{\partial \mu_i} = x_i \geq 0, \text{ with equality if } \mu_i > 0 \quad (31)$$

$$\frac{\partial \mathcal{L}}{\partial \eta_i} = z_i \geq 0, \text{ with equality if } \eta_i > 0 \quad (32)$$

First, note that from first order condition (28) we obtain that $\lambda > 0$, as we assumed that $U_1 > 0$ in (A1). Hence, the budget constraint is binding. Next, we characterize all possible solutions.

Case i: $\mu_i > 0$ and $\eta_i > 0$.

If $\mu_i > 0$ and $\eta_i > 0$, then $x_i^* = 0$ and $z_i^* = 0$ for all i. This implies that budget constraint is not binding, which contradicts with $\lambda > 0$. Thus, this case cannot arise in equilibrium.

Case ii: $\mu_i = 0$ and $\eta_i > 0$.

In this case, the equilibrium, if exists, involves a corner solution, where households only consume packaged good. The first order conditions are:

$$\frac{\partial \mathcal{L}}{\partial x_i} = U_1(x_i, 0) - \lambda(1+\alpha\theta) = 0 \quad (33)$$

$$\frac{\partial \mathcal{L}}{\partial z_i} = U_1(x_i, 0) - \lambda c'(0) + \eta = 0 \quad (34)$$

$$\frac{\partial \mathcal{L}}{\partial \lambda} = Iw - (1+\alpha\theta)\Sigma_{i=1}^{I} x_i = 0 \quad (35)$$

$$\frac{\partial \mathcal{L}}{\partial \eta} = z_i = 0 \quad (36)$$

From the first order condition (33), we find that $\lambda = U_1(x_i, 0)/(1+\alpha\theta)$, which holds for all i. Thus, $x_i^* = x^*$ for all households. From the budget constraint we solve for $x^* = w/(1+\alpha\theta)$. From the first order conditions (33-34) we find $\eta > 0$ only if $c'(0) > (1+\alpha\theta)$, which contradicts assumption (A3). Therefore, such a case will not arise.

Case iii: $\mu_i > 0$ and $\nu_i = 0$.

In this case the equilibrium, if exists, involves a corner solution, where households only consume home-produced good. The first order conditions are:

$$\frac{\partial \mathcal{L}}{\partial x_i} = U_1(z_i, 0) - \lambda(1 + \alpha\theta) + \mu = 0 \tag{37}$$

$$\frac{\partial \mathcal{L}}{\partial z_i} = U_1(z_i, 0) - \lambda c'(z_i) = 0 \tag{38}$$

$$\frac{\partial \mathcal{L}}{\partial \lambda} = Iw - \Sigma_{i=1}^{I} c(z_i) = 0 \tag{39}$$

$$\frac{\partial \mathcal{L}}{\partial \mu_i} = x_i = 0 \tag{40}$$

From the first order condition (38), we find that $\lambda = U_1(z_i, 0)/c'(z_i)$, which holds for all i. Thus, $z_i^* = z^*$ for all households. From the budget constraint we find $c(z^*) = w$; hence, the optimal amount of home-produced good is equal to z^m. A necessary condition for this case to arise in equilibrium is $1 + \alpha\theta > c'(z^m)$, which contradicts the assumption (A3). Therefore, such a case will not arise.

Case iv: $\mu_i = \eta_i = 0$.

In this case we have an interior solution and the first order conditions are:

$$\frac{\partial \mathcal{L}}{\partial x_i} = U_1(x_i, z_i, 0) - \lambda(1+\alpha\theta) = 0 \tag{41}$$

$$\frac{\partial \mathcal{L}}{\partial z_i} = U_1(x_i, z_i, 0) - \lambda c'(z_i) = 0 \tag{42}$$

$$\frac{\partial \mathcal{L}}{\partial \lambda} = Iw - \Sigma_{i=1}^{I}[(1+\alpha\theta)x_i + c(z_i)] = 0 \tag{43}$$

From (41-42), for each household the optimal level of home production is identical and satisfies $c'(z^*) = (1+\alpha\theta)$. In equilibrium households' consumption of packaged good will also be identical, thus $x_i^* = x^*$. Substituting z^* into the budget constraint and solving for x_i we find x^*.

Proof of Proposition 2

The household i's problem, given the total amount of wasted dumped by others $\hat{D}_{-i}$, is

$$\max_{x_i, z_i, d_i} \quad U(x_i + z_i, \tfrac{d_i + \hat{D}_{-i}}{I}) \tag{44}$$

$$\text{s.t.} \quad x_i + c(z_i) + \alpha(\theta x_i - d_i) \leq w \tag{45}$$

$$x_i \geq 0 \tag{46}$$

$$z_i \geq 0 \tag{47}$$

$$d_i \geq 0 \tag{48}$$

$$d_i \leq \theta x_i \tag{49}$$

Letting $(\lambda, \mu, \eta, \nu, \xi)$ be the Lagrange multipliers for the constraints (45-49), the first order conditions to the problem are:

$$\frac{\partial \mathcal{L}}{\partial x_i} = U_1(x_i + z_i, \frac{d_i + \hat{D}_{-i}}{I}) - \lambda(1 + \alpha\theta) + \mu + \xi\theta = 0 \quad (50)$$

$$\frac{\partial \mathcal{L}}{\partial z_i} = U_1(x_i + z_i, \frac{d_i + \hat{D}_{-i}}{I}) - \lambda c'(z_i) + \eta = 0 \quad (51)$$

$$\frac{\partial \mathcal{L}}{\partial d_i} = \frac{1}{I} U_2(x_i + z_i, \frac{d_i + \hat{D}_{-i}}{I}) + \lambda\alpha + \nu - \xi = 0 \quad (52)$$

$$\frac{\partial \mathcal{L}}{\partial \lambda} = Iw - \Sigma_{i=1}^{I}[(1 + \alpha\theta)x_i + c(z_i) - \alpha d_i] \geq 0, \text{ with eq. if } \lambda > 0 \quad (53)$$

$$\frac{\partial \mathcal{L}}{\partial \mu} = x_i \geq 0, \text{ with eq. if } \mu > 0 \quad (54)$$

$$\frac{\partial \mathcal{L}}{\partial \eta} = z_i \geq 0, \text{ with eq. if } \eta > 0 \quad (55)$$

$$\frac{\partial \mathcal{L}}{\partial \nu} = d_i \geq 0, \text{ with eq. if } \nu > 0 \quad (56)$$

$$\frac{\partial \mathcal{L}}{\partial \xi} = d_i \leq \theta x_i, \text{ with eq. if } \xi > 0 \quad (57)$$

First note that from the first order condition (50) it follows that $\lambda > 0$ by the assumption (A1); hence, the budget constraint is always binding. There are numerous cases to consider. We will analyze each in turn.

Case i: $\mu > 0$, $\eta > 0$, $\nu \geq 0$ and $\xi \geq 0$.

In this case $x_i^p = z_i^p = 0$ for all households. Thus, household's budget constraint is not binding, which contradicts with $\lambda > 0$. Therefore, in equilibrium this case will never arise.

Case ii: $\mu > 0$, $\eta = 0$, $\nu \geq 0$ and $\xi \geq 0$.

Since we assume that $c'(z^m) > 1 + \alpha\theta$ in (A3), the equilibrium will involve a non-zero consumption of packaged good. Therefore, in equilibrium this case will never arise.

Case iii: $\mu = 0$, $\eta > 0$, $\nu \geq 0$ and $\xi \geq 0$.

Since we assume that $c'(0) < 1$ in (A3), the equilibrium will involve a non-zero consumption of home-produced good. Therefore, in equilibrium this case will never arise.

Case iv: $\mu = 0$, $\eta = 0$, $\nu \geq 0$ and $\xi \geq 0$.

Case iv.a: $\nu > 0$.

In this case $d_i^p = 0$ for all households; thus, $\xi = 0$. The first order conditions that characterizes the equilibrium are:

$$\begin{aligned}
\frac{\partial \mathcal{L}}{\partial x_i} &= U_1(x_i + z_i, 0) - \lambda(1 + \alpha\theta) = 0 && (58)\\
\frac{\partial \mathcal{L}}{\partial z_i} &= U_1(x_i + z_i, 0) - \lambda c'(z_i) = 0 && (59)\\
\frac{\partial \mathcal{L}}{\partial d_i} &= \frac{1}{I} U_2(x_i + z_i, 0) + \lambda\alpha + \nu = 0 && (60)\\
\frac{\partial \mathcal{L}}{\partial \lambda} &= Iw - \Sigma_{i=1}^{I}[(1 + \alpha\theta)x_i + c(z_i)] = 0 && (61)\\
\frac{\partial \mathcal{L}}{\partial \nu} &= d_i = 0 && (62)
\end{aligned}$$

First note that from (58-59) it can easily be seen that all households choose $z^p = z^*$. From (60), we find that $x_i = x$ for all households. Substituting z^* into the budget constraint we solve for $x = x^*$. From (59-60) for such an equilibrium to exist, it must be the case that $-U_2(x^* + z^*, 0)/I > \alpha U_1(x^* + z^*, 0)/c'(z^*)$, which indicates that the marginal disutility from the very first unit of dumped waste should be greater than its marginal utility in terms of extra consumption. Therefore, households will dump no waste. Note that the solution in this case is the same as that of the socially-optimal one.

Case iv.b: $\nu = 0$ and $\xi > 0$.

In this case $d_i = \theta x_i$. The first order conditions that characterize the equilibrium are:

$$\frac{\partial \mathcal{L}}{\partial x_i} = U_1(x_i + z_i, \theta x_i) - \lambda(1 + \alpha\theta) + \xi\theta = 0 \quad (63)$$

$$\frac{\partial \mathcal{L}}{\partial z_i} = U_1(x_i + z_i, \theta x_i) - \lambda c'(z_i) = 0 \quad (64)$$

$$\frac{\partial \mathcal{L}}{\partial d_i} = \frac{1}{I}U_2(x_i + z_i, \theta x_i) + \lambda\alpha - \xi = 0 \quad (65)$$

$$\frac{\partial \mathcal{L}}{\partial \lambda} = Iw - \Sigma_{i=1}^{I}[x_i + c(z_i)] = 0 \quad (66)$$

$$\frac{\partial \mathcal{L}}{\partial \nu} = d_i = \theta x_i \quad (67)$$

Let (x^{p1}, z^{p1}) be the solution to this problem. First note that from (63-65) it can easily be seen that all households choose z^{p1} such that $c'(z^{p1}) = 1$, i.e., the marginal cost of home production is set equal to 1, the price of packaged good. Note that $z^{p1} < z^*$, given that $c(\cdot)$ is strictly convex. Then, from (64), we observe that every household's consumption of the packaged good is identical. Substituting z^{p1} into the budget constraint we solve for $x = x^{p1}$. For such an equilibrium to exists, it must be that $-\frac{1}{I}U_2(x^{p1} + z^{p1}, \theta x^{p1}) < \frac{\alpha}{c'(z^{p1})}U_1(x^{p1} + z^{p1}, \theta x^{p1})$. That is the disutility from dumping the last unit of waste generated is less than the utility the extra tax-savings would bring about.

Case iv.c: $\nu = 0$ and $\xi = 0$.

This is the interior solution. In this case $0 < d_i < \theta x_i$. The first order conditions that characterize the equilibrium are:

$$\frac{\partial \mathcal{L}}{\partial x_i} = U_1(x_i + z_i, \frac{d_i + \hat{D}_{-i}}{I}) - \lambda(1+\alpha\theta) = 0 \quad (68)$$

$$\frac{\partial \mathcal{L}}{\partial z_i} = U_1(x_i + z_i, \frac{d_i + \hat{D}_{-i}}{I}) - \lambda c'(z_i) = 0 \quad (69)$$

$$\frac{\partial \mathcal{L}}{\partial d_i} = \frac{1}{I} U_2(x_i + z_i, \frac{d_i + \hat{D}_{-i}}{I}) + \lambda\alpha = 0 \quad (70)$$

$$\frac{\partial \mathcal{L}}{\partial \lambda} = Iw - \Sigma_{i=1}^{I}[(1+\alpha\theta)x_i + c(z_i) - \theta d_i] = 0 \quad (71)$$

First note that from (68-69), it can easily be seen that all households choose $z_i = z^p$. Substituting $z_i = z^p$ into (70-71) and solving simultaneously yield $d_i(D_{-i})$, the response function of household i. Solving the response functions of all households simultaneously we find their optimal level of dumping, $d_i^p = d^p$. The existence of Nash equilibrium is guaranteed by the assumption (A2) and the fact that the strategy spaces of players are nonempty, convex and compact.[16] Inserting d^p and z^p into the household's budget constraint we find the optimal amount of packaged good, x^p, consumed. Further note that $z^p = z^*$.

Proof of Proposition 3

[16]The household's problem can be written as $U(\frac{w - c(z_i) + \alpha d_i}{1+\alpha\theta} + z_i, \frac{d_i + \hat{D}_{-i}}{I})$. This function is concave in d_i, given the assumption (A2), and the strategy space of household i is $[0, \theta w/(1+\alpha\theta)]$, which is nonempty, convex and compact. Thus, a Nash equilibrium exists.

The household i's problem is:

$$\max_{x_i, z_i, d_i} \quad U(x_i + z_i, 0) \tag{72}$$

$$\text{s.t.} \quad x_i + c(z_i) + \tfrac{\alpha}{I}\Sigma_{i=1}^{I}(\theta x_i - d_i) + \tfrac{\beta}{I}\Sigma_{i=1}^{I} d_i \leq w \tag{73}$$

$$x_i \geq 0 \tag{74}$$

$$z_i \geq 0 \tag{75}$$

$$d_i \geq 0 \tag{76}$$

$$d_i \leq \theta x_i \tag{77}$$

First note that, as $\alpha < \beta$, dumping is a dominated strategy for each household. Therefore, we set $d_i = 0$ and the constraints (76-77) are nulled. Letting (λ, μ, η) be the Lagrange multipliers for the constraints (73-75), the first order conditions to the problem are:

$$\frac{\partial \mathcal{L}}{\partial x_i} = U_1(x_i + z_i, 0) - \lambda(1 + \frac{\alpha}{I}\theta) + \mu = 0 \tag{78}$$

$$\frac{\partial \mathcal{L}}{\partial z_i} = U_1(x_i + z_i, 0) - \lambda c'(z_i) + \eta = 0 \tag{79}$$

$$\frac{\partial \mathcal{L}}{\partial \lambda} = w - x_i - \frac{\alpha\theta}{I}\Sigma_{i=1}^{I} x_i - c(z_i) \geq 0, \text{ with equality if } \lambda > 0 \tag{80}$$

First note that the first order condition (78) and the assumption (A1) imply $\lambda > 0$; hence, the budget constraint is always binding.

Case i: $\mu > 0$, $\eta > 0$.

In this case $x_i^c = z_i^c = 0$ for all households. Thus, household's budget constraint is not binding, which contradicts with $\lambda > 0$. Therefore, in equilibrium this case will never arise.

Case ii: $\mu > 0$, $\eta = 0$.

Since we have assume that $c'(z^m) > 1+\alpha\theta$ in (A3), it follows that $c'(z^m) > 1+\frac{\alpha}{I}\theta$. Thus, the equilibrium will involve a non-zero consumption of packaged good and in equilibrium this case will never arise.

Case iii: $\mu = 0$, $\eta > 0$.

Since we assume that $c'(0) < 1$ in (A3), for any I, it is true that $c'(0) < 1 + \frac{\alpha}{I}\theta$. Thus, the equilibrium will involve a non-zero consumption of home-produced good and in equilibrium this case will never arise.

Case iv: $\mu = 0$, $\eta = 0$.

This is the interior solution. The first order conditions that characterize the equilibrium are:

$$\frac{\partial \mathcal{L}}{\partial x_i} = U_1(x_i + z_i, 0) - \lambda(1 + \frac{\alpha}{I}\theta) = 0 \quad (81)$$

$$\frac{\partial \mathcal{L}}{\partial z_i} = U_1(x_i + z_i, 0) - \lambda c'(z_i) = 0 \quad (82)$$

$$\frac{\partial \mathcal{L}}{\partial \lambda} = w - x_i - \frac{\alpha\theta}{I}\Sigma_{i=1}^{I} x_i - c(z_i) = 0 \quad (83)$$

First note that from (81-82) it can easily be seen that all households choose $z_i = z^c$, where $c'(z^c) = 1 + \frac{\alpha}{I}\theta$. Given the consumption of home-produced good is identical across households, it follows from (81) and (82) that the consumption of packaged good is also identical and can be derived from the budget constraint, $x^c = [w - c(z^c)]/(1 + \frac{\alpha}{I}\theta)$.