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Surviving from garbage: the role of informal waste-pickers in a dynamic model of solid-waste management in developing countries

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ABSTRACT. In developing countries, informal waste-pickers (known as scavengers) play an important role in solid waste management systems, acting in a parallel way to formal waste collection and disposal agents. Scavengers collect, from the streets, dumpsites, or landfills, re-usable and recyclable material that can be reincorporated into the economy's production process. Despite the benefits that they generate to society, waste-pickers are ignored when waste management policies are formulated. The purpose of this paper is to integrate the role of scavengers in a dynamic model of production, consumption, and recovery, and to show that, in an economy producing solid waste, efficiency can be reached using a set of specific and complementary policies: a tax on virgin materials use, a tax on consumption and disposal, and a subsidy to the recovery of material. A numerical simulation is performed to evaluate the impact of these policies on landfill lifetime and natural resource stocks. A discussion on the implementation of these instruments is also included.

Introduction

In both developed and developing countries, population growth, as well as production and consumption patterns, has increased rates of solid waste production, creating constraints on the improvement of human environmental and health conditions. These constraints are aggravated in the developing world by lack of environmental controls on industrial processes, and inadequate or insufficient facilities for waste management and treatment (Ojeda-Benítez *et al*., 2002).

In several developing countries, a significant proportion of the urban poor are involved in waste collection and recycling as a source of income.

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They are known as scavengers or waste-pickers. This activity benefits society as production costs in some sectors are reduced and landfills' lifetime is lengthened. In addition, virgin materials are less intensively used, increasing the availability of natural resources.

The purpose of this paper is to show that scavengers in developing countries generate a positive externality to society (lengthening of empty landfill space and natural resources availability) and, therefore, their activity should be encouraged through economic incentives that lead them to increase the amount of solid waste recovery up to economically efficient levels.

The role of waste-pickers is incorporated in an integrated dynamic model of production, consumption, disposal, and recycling of waste. The first part of the model involves the inter-temporal maximization of a social welfare function, which depends on consumption and an environmental quality index, constrained by evolution functions for the stock of empty landfill space and natural resources used in the production of commodities. In the second part, a dynamic competitive equilibrium scenario is constructed for each of three groups of agents, producers, consumers, and waste-pickers, and optimality conditions are derived for each group.

The conditions for social optimality are then compared with the competitive equilibrium conditions, in order to derive the set of economic instruments needed to reach efficiency in resource allocation, including empty landfill space, in a market economy.

The results of this paper show that efficiency in this economy of production, consumption, waste disposal, and recycling requires the implementation of a set of optimally targeted policies working simultaneously rather than a single policy. A policy aimed at recognizing the activity of waste-pickers in developing countries is part of the necessary set of instruments required for efficiency. Numerical analysis is then developed to illustrate the implications of the model. A discussion on the implementation of these policies is also included.

Background

The physical characteristics of cities in developing countries, their rapid expansion, and the lack of resources to provide for necessary infrastructure and urban services translates into an insufficient collection of waste generated, as well as its improper disposal on the streets, vacant lots and, at best, in municipal open dumps. Despite spending 30 to 50 per cent of their operational budgets on waste management, authorities in developing countries only collect between 50 and 80 per cent of the refuse generated, leaving, in some cases, a significant portion of the population without access to waste collection services. Systems for transfer, recycling and/or disposal of solid waste are unsatisfactory from an environmental, economic, and financial point of view (Bernstein, 1993; Schubeler, 1996).

Urban solid waste management in developing countries comprises both formal and informal sectors. The formal sector consists of municipal agencies or private firms that are responsible for waste collection, transport, and disposal. The informal sector comprises unregistered, unregulated activities carried out by individuals, families, groups, or small enterprises.

It includes several actors such as waste-pickers, itinerant buyers, small scrap dealers, and wholesalers. Householders also contribute informally to recycling by engaging in source separation in a limited way (Sudhir *et al.*, 1996).

An important characteristic of informal waste recovery and recycling in developing countries is the participation of waste-pickers. These self-employed workers are also called scavengers, recyclers, or rag pickers, although they receive other names depending on the local language, the place they work, and the materials they collect (Medina, 1997). Since such waste recovery is labor intensive, it provides a livelihood for many new immigrants and marginalized people in metropolises whose basic motivation is income generation (Ojeda-Benítez *et al.*, 2002). Scavenging is associated with high unemployment, widespread poverty, and the lack of a safety net for the poor. As stated by Medina (2001), in times of war or severe economic crises, scavenging increases with particular intensity.

In some cases, informal waste workers belong to religious, caste, or ethnic minorities, and social discrimination is a factor that obliges them to work under completely unhygienic conditions as waste collectors or sweepers. Their association with an activity, which the public perceives to be filth-related, tends, at the same time, to perpetuate discrimination against them. Informal waste workers usually live and work under extremely precarious conditions; scavenging, in particular, requires very long working hours and is often associated with homelessness. Besides social marginalization, waste workers and their families are subject to economic insecurity, health risks, lack of access to normal social services such as health care and schooling for children, and the absence of any form of social security (Schubeler, 1996).

Waste-pickers can be classified into two groups, according to the place where they collect recyclables: dump waste-pickers and itinerant waste-pickers. Dump scavengers live either on or beside landfills in order to await the arrival of waste filled trucks. Itinerant scavengers collect recyclables on the streets, near the source, before waste is transported to the dump or landfill. Commonly, waste-pickers do not have access to adequate equipment and storage places, sorting the garbage with their bare hands, sticks, or simple hooks, and thus they are exposed to public and environmental health hazards (Kaseva and Gupta, 1996; Medina, 2000; Ojeda-Benítez *et al*., 2002).

The existence of scavenging is based on the presence of markets for recovered materials; waste in sufficient quantity and quality to meet industrial demand; and people willing or compelled to do work that is poorly paid, hazardous, and of a low status (Hogland and Marques, 2000).

The contribution of waste-pickers in developing countries is difficult to quantify due to the informal nature of this sector. Nonetheless, there are well-recognized environmental, economic, and social benefits associated with scavenging activity:

- Recycling of solid waste reduces air and water pollution, saves energy, reduces waste from industrial processes compared with the use of virgin materials, and in many cases reduces imports of raw materials (Johnson *et al.*, 1984; Medina 1997; Medina, 2000).

- Informal waste picking reduces the cost of a city's solid waste management (SWM) program by reducing the amount of waste that needs to be collected, transported, and disposed of, which translates into savings to local governments and extends the life of dumps/landfills (Ali *et al.*, 1993; Baud and Schenk, 1994; Lardinois and Klundert, 1994; DiGregorio, 1995; Assaad, 1996; Taylor, 1999; Medina, 2000; D'Souza, 2001).
- Scavenging represents an income-generating activity for the poorest in the developing world. Medina (2000) estimates that, in Asian and Latin American cities, up to 2 per cent of the population survives by scavenging. Hogland and Marques (2000) report that 1–2 per cent of the population in large cities in developing countries is supported by the refuse generated by the upper 10–20 per cent of the population.
- Unlike standard recycling, waste-pickers recover material from garbage that has already been disposed of and put into the municipal solid waste stream. Without contribution of scavenging, this valuable material would be lost in landfills and dumpsites.

Although SWM policies in both developed and developing countries seek to achieve the same environmental goals, in practice their implementation in the latter has been limited due to lack of resources, particular socioeconomic conditions, and severe difficulties associated with enforceability and monitoring. Surprisingly, activities such as recycling have shown high rates in developing countries compared with more developed economies. Recycling in developing countries, however, is not strictly the result of an environmentally oriented policy. Informal waste-pickers in developing economies collect up to 40 per cent of the recyclable material from the waste stream as a result of an income-generating strategy. This activity reflects both an effective demand for recyclables by industry and low opportunity cost of labor from low-income and marginalized groups that are able and willing to engage in the activity of recovering recyclable material from garbage.

Despite its significant contribution to the recovery and recycling process, the role of informal waste-pickers in municipal waste management is still not acknowledged (Ojeda-Benítez *et al.*, 2002). Authorities in many developing countries do not fully realize the benefits of the recycling carried out by scavengers, and their activity is either banned or ignored when designing SWM policies and programs (Medina, 2000).

Economic approaches for solid waste management

SWM economic models are characterized by the recognition of externalities generated in the production and disposal of garbage, as well as the identification of economic instruments to correct them. In the case of solid waste, the Pigouvian prescription establishes that a per-unit tax on the polluting activity, a waste-end tax that is equal to the marginal damage should be enough to internalize efficiently the externality generated from waste disposal. However, a waste-end tax is difficult to implement because waste is hard to monitor and taxes are difficult to enforce (Fullerton and Wolverton, 1999).

In order to deal with these measurement and enforcement difficulties, several authors have sought alternative economic instruments to deal efficiently with SWM. Some of the policies that have been proposed and evaluated include fees per unit of garbage (Callan and Thomas, 1999; Kinnaman and Fullerton, 2002); advance disposal fees, recycling subsidies, and recycling rate standards (Palmer *et al*., 1995; Walls and Palmer, 1997), among others. Other approaches include taxes on virgin material use or on production processes as a means of reducing the generation of solid wastes or increasing recycling (Miedema, 1983; Conrad, 1999).

Two-part instruments have also been proposed to address incentive compatibility and adverse selection problems associated with SWM. This kind of instrument, usually the combination of a tax and a subsidy, has been studied for the case of waste disposal using different approaches, the most widely discussed being the deposit-refund system, e.g. Macauley and Walls (2000). Holterman (1976) demonstrates that a tax on output and a subsidy on inputs can result in an efficient solution when it is not possible to directly tax an externality. Confirming Holterman's (1976) results, but opposing Conrad's (1999) and Miedema's (1983) findings, Dinan (1993) shows that instead of a virgin material tax, a combined disposal tax and reuse subsidy is an efficient method of reducing waste. The disposal tax provides an efficient signal for source reduction and the reuse subsidy provides an incentive to use an efficient amount of recycled materials.

A similar approach has been suggested by Fullerton and Wolverton (1999), who generalize the deposit–refund system proposing a combination of a presumptive tax and an environmental subsidy, which do not need to be either explicitly linked or equal to one another. They show that a two-part instrument accomplishes the same efficiency effect of a waste-end tax. The presumptive tax, a tax on the output, is imposed upon the assumption either that all production uses a dirty technology or that all consumption goods become waste. This tax makes the good more expensive, reducing production and therefore consumption of the good, which is analogous to the output effect of the waste-end tax. The environmental subsidy is provided only if the production uses clean technology or if consumption goods are recycled. This subsidy makes waste more expensive relative to other inputs of production and reduces waste per unit of output, which is analogous to the second effect of the waste-end tax, the substitution effect.

Another consideration included in SWM models is the effect of waste generation on landfill depletion. Ready and Ready (1995), by treating landfill as a depletable, replaceable asset, find that an optimal fee, which increases as empty space reduces, might be needed and, at low levels of depletion, is enough as a program for solid waste management.

Our paper draws on the earlier work of Moreno-Sánchez (1997), where she proposed a dynamic model of disposal and recycling for two recyclable goods in Bogotá, Colombia. We develop a dynamic model of production, consumption, disposal, and recycling, where the role of scavengers is explicitly introduced. Empty landfill space is treated as a depletable resource and other natural resource stocks depletion is also included to account for the impact of using virgin material compared with recycled material.

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In several aspects, this model could be seen as an extension of the previous models proposed by Fullerton and Wolverton (1999) and Dinan (1993), where two-part instruments are used to deal with solid waste disposal externalities. Our paper analyses SWM problems using a more comprehensive approach that integrates previous work and adjusts it to particular conditions of solid waste systems in developing countries. First, the model includes the inter-temporal effects of landfill depletion; second, the externality associated with the extraction of virgin material is included as a failure different from the externality generated by the disposal of the goods made from this material, and it is shown that those externalities should be addressed using different and complementary instruments. Finally, the most important contribution of this paper is the incorporation of waste-pickers into the SWM systems in developing countries. The inclusion of waste-pickers in our model is grounded on findings by Baumol and Oates (1988), who show that, in the presence of shiftable externalities (positive externalities from recycling), it is efficient to target the economic instrument (subsidy) to those agents who perceive the least marginal damage (the most marginal benefit) from the externality; in this case, waste-pickers.

The model

Several models have been proposed to analyze the behavior of economic agents facing the decision of waste generation and recycling. Suppose that from the many goods produced and consumed in a society, there are n goods whose production is based on natural resource extraction and these goods can be recycled. These goods, denoted by $q_i^p (i = 1, \ldots, n)$, are produced using either extracted/harvested resources (X_i) or domestic recycled materials[1] (R_i). As in the standard case, labor (L_i) and capital (K_i) are included in the production function. The production function can be written as:

$$q_i^p = f_i(L_i, K_i, I_i) \text{ where } I_i = I(X_i, R_i) = X_i + \theta_i R_i \quad i = 1, \ldots, n. \tag{1}$$

Here I_i is a function that reflects how different raw inputs (extracted resources, recycled material) can be combined to produce good i. This restriction is assumed linear which implies that inputs are perfect substitutes. Including this relation, the production function becomes

$$q_i^p = f_i\,(L_i, K_i, X_i, R_i) \quad i = 1, \ldots, n, \tag{2}$$

which is assumed to exhibit decreasing marginal product for all the inputs.

The linear relationship among inputs can be manipulated to express X_i in terms of domestic recycled material

$$X_i = X(I_i, R_i) = I_i - \theta_i R_i \quad i = 1, \ldots, n. \tag{3}$$

Including this new relation, the production function becomes

$$q_i^p = f\,(L_i, K_i, X(I_i, R_i), R_i) = f^*(L_i, K_i, R_i) \quad i = 1, \ldots, n. \tag{4}$$

[1] In this paper, the terms recovered material and recycled material are intended to have the same meaning. They refer to the material collected by scavengers that is offered to the firms that produce final goods.

This relation can be written in terms of a transformation function

$$g_i\left(q_i^p, L_i, K_i, R_i\right) \leq 0 \quad i = 1, \ldots, n. \tag{5}$$

Households consume the n goods, denoted by $q_i^c (i = 1, \ldots, n)$, obtaining utility. If we think of q_i^c as packaging materials, they are converted into waste when consumption occurs. It implies that consumption of q_i^c generates utility but, at the same time, generates disutility to society because of the garbage generated. This approach to incorporating the double effect of consumption has been previously suggested by Meyer (1971).

Recycled material comes from the waste produced domestically. Consumed and discarded goods can be either disposed of in the landfill (d_i) or recycled in the production process (R_i), so that $q_i^c = d_i + R_i$. Waste not recovered goes to the landfill. As depletion of empty landfill space is a dynamic process, we include time considerations to analyze it. The evolution equation for empty landfill space (B) is written as follows

$$\dot{B} = -\sum_i d_i(t) = -\sum_i \left(q_i^c(t) - R_i(t)\right). \tag{6}$$

Recycling these materials by waste-pickers requires labor (L_R) and capital (K_R) (waste picking is considered a labor-intensive activity). Waste-pickers do not discriminate among collected material, so we have a multi-output transformation function

$$g_R(R_1, \ldots, R_n, L_R, K_R) \leq 0, \tag{7}$$

where R_i ($i = 1, \ldots, n$) refers to the different types of materials collected by waste-pickers.

The other source of material for production is extraction (X_i). Natural resources, renewable or non-renewable, used in the production process are depleted over time. If renewable, there exists an intrinsic growth function h_i, which may depend on the available stock S_i, and on environmental conditions (E_i). If the growth function is denoted as $h_i = h_i(S_i, E_i), i = 1, \ldots, n$, the evolution equation for the resource can be expressed as

$$\frac{dS_i}{dt} = \dot{S}_i(t) = -X_i(t) + h_i(S_i(t), E_i(t)). \tag{8}$$

For non-renewable resources $h_i(\cdot) = 0$.

Suppose environmental quality matters to society. This model considers two environmental concerns. One is the depletion of empty space in the landfill. Currently, land space available for landfills is becoming increasingly scarce, mainly in areas close to big cities, where they are most needed. As a result, social welfare is affected by the depletion of empty space for waste disposal. The second concern is the extraction and depletion of natural resources, which impact social welfare.[2] The distinction between these two types of externalities is important in order to clarify which policy

[2] There is a concern directly related to the activity of waste-pickers itself, the negative externalities associated with use of public space, road congestion, and the visual impacts they may cause to society. These externalities emerge only in the case of street waste-pickers. The net effect of these negative and positive externalities is an empirical question, and should be considered on a case-by-case basis.

is best to solve each of the problems, a confusion that has emerged in some studies. These external effects are aggregated in a variable called environmental quality (A), which is a function of extraction and empty landfill space availability

$$A = A(X_1, \ldots, X_n, B) = A(\boldsymbol{X}, B), \tag{9}$$

where $\boldsymbol{X}$ is the vector of extracted resources $\{X_1, \ldots, X_n\}$ and the function has the properties $A_{X_i} \leq 0$ (for $i = 1, \ldots, n$) and $A_B \geq 0$.

Assume that a social welfare function (W) exists. This function depends on the amount of goods consumed (q_i^c), and on the environmental quality of the economy (A), $W = W(q_1^c, \ldots, q_n^c, A(X, B))$, and exhibits the usual convexity conditions.[3]

Using this framework, the methodology we follow consists of finding, first, the maximization conditions of the social welfare function for this economy and, then, the competitive equilibrium conditions for each group of agents. Comparison of these two sets of conditions allows us to identify market failures and to find optimal policies to solve them.

Social optimality conditions

The social optimality conditions are found by solving the following problem

$$\underset{q_i^c, R_i, q_i^p}{Max} \int_0^T \left(W\left(q_1^c, \ldots, q_n^c, A(X, B)\right)\right) e^{-\rho t} dt + F_B(B(T)) e^{-\rho T} + \sum_{i=1}^{n} F_i(S_i(T)) e^{-\rho T}$$

subject to the transformation functions (equations (5) and (7)), the evolution equations ((6) and (8)), market clearing conditions, initial and terminal conditions for state variables, and non-negativity conditions for control variables. Here, ρ refers to the discount rate and $F_B(B(T))$ and $F_i(S_i(T))$ are final value functions for stocks at terminal time T. The objective function and evolution equations can be integrated into a present value Hamiltonian. Following the maximum principle (Chiang, 1992), a Lagrangian to include other restrictions is formulated and a current value Lagrangian is used to obtain the first-order conditions.[4]

The first-order conditions with respect to control variables (q_i^c, q_i^p), assuming interior solutions, are

$$\frac{dW}{dq_i^c} - \gamma - \mu_i = 0 \tag{10}$$

$$-\alpha_i \frac{dg_i}{dq_i^p} + \mu_i = 0, \tag{11}$$

which imply that the marginal utility of consumption of a unit of good i must equal the marginal cost of producing it, plus the intertemporal marginal

[3] $W_{q_i^c} \geq 0$, $W_{q_i^c q_i^c} \leq 0$, $W_{x_i} \leq 0$, $W_{x_i x_i} \leq 0$, $W_B \geq 0$, $W_{BB} \leq 0$.
[4] Details are available from the authors upon request.

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cost of disposing of this unit in a landfill, i.e., the marginal cost of reducing empty space in the landfill.

The first-order conditions with respect to variable R_i imply that

$$-\theta_i \frac{\partial W}{\partial A}\frac{\partial A}{\partial X_i} + \gamma + \lambda_i\theta_i + \alpha_i\left(\theta_i \frac{\partial g_i}{\partial X_i} - \frac{\partial g_i}{\partial R_i}\right) - \beta \frac{\partial g_R}{\partial R_i} = 0 \quad i = 1, \ldots, n, \qquad (12)$$

where $-\theta_i \frac{\partial W}{\partial A}\frac{\partial A}{\partial X_i}$ is the marginal environmental benefit to society of recycling one unit of input and using it in the production of good i, thus reducing the marginal damage caused by extraction; γ is the marginal benefit to society of recycling one unit of input and avoiding disposal in a landfill; $\lambda_i\theta_i$ is the marginal inter-temporal benefit to society of recycling one unit of input instead of using one unit of virgin material, thus avoiding reduction of the stock of natural resources used in the production process; $\alpha_i(\theta_i \frac{\partial g_i}{\partial X_i} - \frac{\partial g_i}{\partial R_i})$ refers to the difference between the marginal cost of producing good i using virgin material in terms of recycled material and the marginal cost of producing good i using recycled material. The sign of this expression is ambiguous: if positive, it reflects the marginal benefit of using recycled material instead of virgin material in the production process; if negative, it represents the marginal cost of using recycled material instead of virgin material in the production process. The final term in equation (12), $-\beta \frac{\partial g_R}{\partial R_i}$, is the marginal cost of recovering material by waste-pickers.

The condition with respect to state variable B requires that the rate of change in the landfill space shadow price should equal the sum of the marginal social utility of one unit of empty space and the profitability of keeping available a unit of empty space for next period: $\dot{\gamma} = \frac{dW}{dA}\frac{dA}{dB} + \rho\gamma$. Also, the condition with respect to state variable S_i shows that there should be equality between the percentage rate of change in the shadow price of every resource and the difference between the discount rate and the marginal growth of stock (which is zero for non-renewable resources): $\frac{\dot{\lambda}_i}{\lambda_i} = \rho - \frac{dh}{dS_i}$ for $i = 1, \ldots, n$.

Other conditions from the maximum principle are those that recover the evolution of stocks, the transformation functions, the market clearing conditions, and the transversality conditions.

Competitive equilibrium conditions

In this economy, there are three groups of private agents: consumers, producers, and waste-pickers, each of them making decisions independently. Their market optimization conditions emerge from the following problems:

Consumers: Assuming a representative consumer, or one of H identical consumers with identical weight in the social welfare function, such an individual will seek to maximize her utility derived from consuming goods ($q_i, i = 1, \ldots, n$) and environmental quality (A), subject to a budget constraint. This individual faces prices of goods p_i and an exogenous income m^h. Deriving the maximum principle conditions related to control variables ($q^c_{ih}, i = 1, \ldots, n$), the usual result is obtained that the marginal utility of the

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last dollar spent on good i should equal the marginal utility of income for consumer h, and, therefore, be equal across all of the goods consumed by individual h

$$\frac{MU^h_{q_i^c}}{p_i} = \phi^h \quad i = 1, \ldots, n. \tag{13}$$

Producers: Assuming a representative producer of good i, the problem for this firm is to find the amount of inputs (recycled and virgin material, labor and capital) and of output (final product) that maximize its present value of benefits, subject to the technology and the evolution equation for extraction of virgin material. That is, the producer takes into account the intertemporal allocation of the natural resource being used for production of good i. Following the maximum principle and the same procedure as followed in the social optimality conditions derivation, the first-order conditions are obtained. For the control variables (q_i^p, R_i), these conditions are

$$\frac{\partial Lc}{\partial q_i^p} = p_i - \beta_i \frac{\partial g_i}{\partial q_i^p} = 0 \quad i = 1, \ldots, n. \tag{14}$$

This equation reflects the typical marginal cost-pricing rule for producers acting competitively.

$$\frac{\partial Lc}{\partial R_i} = \theta_i w_i^x - w_i^R + \theta_i \lambda_i + \theta_i \beta_i \frac{\partial g_i}{\partial X_i} - \beta_i \frac{\partial g_i}{\partial R_i} = 0 \quad i = 1, \ldots, n, \tag{15}$$

where $\theta_i w_i^x$ is the marginal avoided cost (benefit) of using one unit of domestic recycled material instead of virgin material in terms of recycled material and w_i^R is the marginal cost of using domestic recycled material. These two terms have meaning when interpreted jointly. Writing $-(w_i^R - \theta_i w_i^x)$, this reflects the weighted (in terms of recycled input) marginal incremental cost (benefit) of using recycled material instead of virgin material. $\theta_i \lambda_i$ is the inter-temporal marginal benefit of using one unit of recycled material, delaying the depletion of the natural resource used for production of good i. $\theta_i \beta_i \frac{\partial g_i}{\partial X_i} - \beta_i \frac{\partial g_i}{\partial R_i}$, reflects the incremental value of the marginal product (benefit if greater than zero, or cost if less than zero) of using recycled material instead of extracted material in the production process of good i.

Waste-pickers: Scavengers maximize profits from collecting and selling recycled material subject to a transformation function. They face competitive prices in both output and factor markets, so they have to maximize their benefits subject to a labor-intensive technology. Optimality conditions for the control variable R_i imply the marginal cost-pricing rule for any producer under perfect competition

$$p_i^R - \beta^R \frac{dg_R}{dR_i} = 0 \quad i = 1, \ldots, n. \tag{16}$$

Comparing the results

In table 1, we can observe the similarities and differences between the first-order conditions from social optimality and those from competitive

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Table 1. *Comparison of first-order conditions between social optimality and competitive equilibrium*

Variable	*Social optimality*		*Competitive equilibrium*	
q_i^c $i = 1, \ldots, n$	$\frac{dW}{dq_i^c} - \gamma - \mu_i = 0$	(10)	$\frac{dU^h}{dq_i^c} - \phi^h p_i = 0$	(13)
q_i^p $i = 1, \ldots, n$	$-\alpha_i \frac{dg_i}{dq_i^p} + \mu_i = 0$	(11)	$p_i - \beta_i \frac{\partial g_i}{\partial q_i^p} = 0$	(14)
R_i	$-\theta_i \frac{\partial W}{\partial A} \frac{\partial A}{\partial X_i} + \gamma + \lambda_i \theta_i$		$\theta_i w_i^x - w_i^R + \theta_i \lambda_i$	
$i = 1, \ldots, n$	$+\alpha_i \left(\theta_i \frac{\partial g_i}{\partial X_i} - \frac{\partial g_i}{\partial R_i}\right) - \beta \frac{\partial g_R}{\partial R_i} = 0$	(12)	$+\beta_i \left(\theta_i \frac{\partial g_i}{\partial X_i} - \frac{\partial g_i}{\partial R_i}\right) = 0$	(15)
			$p_i^R - \beta^R \frac{dg_R}{dR_i} = 0$	(16)

equilibrium. Comparing these two sets of conditions, the following facts emerge.

Consumption of good *i* (q_i^c): Assuming the social welfare function can be written as a function of all the individuals' utilities, $W^* = W(U_1, \ldots U_h, \ldots, U_m)$, where $U_h = u^h(q_{ih}^c; A)$, and comparing conditions (10) and (13) we obtain

$$\frac{\partial W^*}{\partial U^h} = \frac{1}{\phi^h}, \tag{17}$$

$$p_i = \mu_i + \gamma. \tag{18}$$

Equation (17) suggests that the weight for individual h in the social welfare function should be the inverse of the marginal utility of income for that individual. Equation (18) implies that in addition to the shadow price of the good, the consumer price must include the intertemporal cost of using up empty space that this unit of consumption will create on the landfill's lifespan (γ).

Production of good *i* (q_i^p): From equations (11) and (14) we have

$$p_i = \mu_i. \tag{19}$$

Equation (19) says that the price that producers receive should equal the shadow price of the good.

Production of domestic recycled material (*R_i*): Adding equations (15) and (16) and comparing with equation (12), we observe that in order for the market conditions to be an optimum, the following must be true

$$\alpha_i = \beta_i, \tag{20}$$

$$\beta = \beta_R, \tag{21}$$

$$p_i^R = w_i^R + \gamma, \tag{22}$$

$$w_i^x = -\frac{\partial W}{\partial A} \frac{\partial A}{\partial X_i}. \tag{23}$$

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The expressions in equations (20) and (21) reflect the correspondence between the shadow prices from the social optimality and competitive equilibrium analyses. Equation (22) implies that the price that waste-pickers receive for domestic recycled material should be the sum of the marginal production cost and the marginal benefit to society of saving an extra unit of empty space in the landfill through recycling. Equation (23) says that the price of virgin material, w_i^x, must include not only the extraction costs (which in this analysis are assumed to be zero) but also the cost of the negative externality caused to society as a result of this extraction.

Policy implications

For markets to be efficient, current conditions would require that $\gamma = 0$ and $\frac{\partial W}{\partial A}\frac{\partial A}{\partial X_i} = 0$. These terms are not zero, as externalities exist in this economy, therefore generating market failures. In order for markets to reach a social optimum, the following set of policies should be introduced.

***Proposition* 1:** *Consumers should pay a per-unit tax on consumption equal to the marginal effect generated by the disposal of the consumed unit in the landfill.*

Proof: Equations (18) and (19) show that the price producers receive should be different from the price consumers pay. The difference is given by the marginal damage generated by using up empty space in the landfill. Therefore, consumers should pay not only the producer price but also a per-unit tax equivalent to this marginal damage. After a consumption tax, t_i, consumers face a budget constraint with a final price on good i equal to $(p_i + t)$, as shown by Davis and Whinston (1962). Incorporating this new constraint in the utility maximization problem alters the first-order conditions. Now, these conditions require

$$\frac{\partial U^h}{\partial q_{ih}^c} - \phi^h(p_i + t_i) = 0. \tag{24}$$

Confronting this condition with the social optimality condition (10), equation (18) becomes $p_i + t_i = \mu_i + \gamma$, and given (19), then $t_i = \gamma$.

***Proposition* 2:** *Waste-pickers should receive a per-unit subsidy on recovered material given by the marginal benefit generated to society for avoiding the use of empty space in the landfill.*

Proof: Equations (18) and (19) imply that under competitive equilibrium, society perceives γ to be zero. This undervaluation of the impact generated to society due to the depletion of empty space in the landfill leads waste-pickers to recover a sub-optimal amount of discarded material. A subsidy (s_i) equal to the landfill empty space intertemporal shadow price (γ) will encourage waste-pickers to increase the domestic recycled material up to the optimal level. Given this subsidy (s_i), waste-pickers now face an output price given by $(p_i^R + s_i)$ and then equation (16) becomes

$$\left(p_i^R + s_i\right) - \beta_R \frac{\partial g_R}{\partial R_i} = 0 \quad i = 1, \ldots, n. \tag{25}$$

Adding (25) and (15) and comparing with (12) yields $p_i^R + s_i = w_i^R + \gamma$, and, given $p_i^R = w_i^R$, then $s_i = \gamma$.

Corollary: *The per-unit consumption tax is exactly equal to the per-unit recycling subsidy, and equal to the intertemporal marginal cost of reducing empty space in the landfill.*

***Proposition* 3:** *Producers of final goods that use natural resources as inputs should be charged a per-unit extraction tax equal to the marginal disutility generated to society.*

Proof: From equation (23) it is observed that, in order to reach optimality, producers using virgin material should assume not only the extraction costs but also the cost of the negative externality generated to society from this extraction. It is worth noticing that this externality does not refer to the intertemporal allocation of the resource being exploited. The intertemporal effect is already accounted for through the shadow price (λ_i). Producers paying a per-unit extraction tax (z_i) now face a price on extracted resources equal to ($w_i^x + z_i$), and thus condition (15) becomes

$$\left(w_i^x + z_i\right)\theta_i - w_i^R + \theta_i\lambda_i + \beta_i\left(\theta_i\frac{\partial g_i}{\partial X_i} - \frac{\partial g_i}{\partial R_i}\right) = 0. \qquad (26)$$

Adding conditions (26) and (16) and comparing with condition (12) implies that equation (23) becomes $w_i^x + z_i = -\frac{\partial W}{\partial A}\frac{\partial A}{d X_i}$. If w_i^x accounts for the extraction and processing cost, then $z_i = -\frac{\partial W}{\partial A}\frac{\partial A}{d X_i}$.

Discussion

The model proposed here includes two market failures associated with solid waste systems. One of them refers to the lack of internalization of the inter-temporal costs associated with the depletion of the empty space in the landfill. The other one concerns the environmental costs associated with extraction of virgin material for the production of goods that, in the end, need to be disposed of. This discrimination is important because, in some studies, the environmental cost associated with *extraction* of virgin material is ignored and, instead, a tax on virgin material is proposed in order to encourage efficient disposal of solid waste. For instance, Miedema (1983) advocates the use of virgin material fees as a means of motivating efficient waste disposal practices, i.e. encouraging recycling and reducing the disposal of solid waste. Although virgin material fees can, in fact, increase the demand for recycled materials and hence reduce disposal requirements, Dinan (1993) shows that there are important drawbacks in terms of efficiency associated with using virgin material fees to reduce disposal requirements. He demonstrates that a virgin material tax cannot result in an optimal resource allocation but that a combined disposal tax and reuse subsidy policy can.

In our model, we show that a tax on virgin material extraction is needed, not to deal with the externality associated with waste disposal but to internalize the externality associated with environmental damage from extraction of virgin material. Differentiating these effects leads one to recognize the need for different policies aimed at correcting each of these failures. The externality associated with waste disposal, as Fullerton and Wolverton (1999) demonstrate, should be addressed through a two-part instrument: a presumptive tax and an environmental subsidy. Thus, our model proposes three simultaneous policies. A tax on virgin-material extraction, not aimed at the final purpose of reducing disposal of solid waste, but instead targeted at the externality associated with raw material extraction. The other two policies act as a two-part instrument, which in our case corresponds to a disposal tax and a reuse/recycling subsidy.

Compared with a Pigouvian tax, e.g. unit-based pricing or waste-end tax, the combination of a tax on consumers and subsidy to recycling has the same practical advantages as the two-part instrument proposed by Fullerton and Wolverton (1999). Particularly, the two-part instrument is easier to enforce and discourages illegal disposal. On the other hand, under unit-based pricing, households would be charged the same for each unit of trash, regardless of the contents. Not all types of trash impose the same disposal costs, however. As Dinan (1993) states, a tax-reuse subsidy policy may be better suited to deal with potentially recyclable waste items that have higher than average disposal costs.

Administratively, Fullerton and Wolverton (1999) argue that a two-part instrument will often have lower costs than a waste-end tax. However, Dinan (1993) argues that administration of this instrument can be very expensive if all the items from the waste stream are included. This policy would be best targeted at selected items in the waste stream: for instance, those items that have a higher share in the composition of waste or those that have higher environmental impact. In our model, the externality generated on empty landfill space depletion can be measured in terms of the volume that the item occupies in the landfill. So, those items with higher volume and higher share in the waste stream are best candidates for the implementation of this policy.

In addition, the two-part instrument has the advantage that it is self-financing. The subsidy can be taken directly from the tax collected on consumers. Although Fullerton and Wolverton (1999) demonstrate that, under some conditions, the tax and the subsidy can differ, in our model they coincide since both of them are directly related to the marginal intertemporal value of empty space in the landfill (γ). The marginal damage that generates one unit of garbage disposed of by a consumer is exactly the same marginal benefit that generates this unit collected and recycled by waste-pickers.

Finally, with respect to the pricing of the instruments, similar to the case of a Pigouvian tax, the rate of the disposal tax and the recycling subsidy will need to be adjusted by trial and error because authorities cannot know *a priori* the exact amounts to induce optimal behavior of involved agents.

We argue that, for developing countries, the environmental subsidy should be aimed at favoring scavengers' activity. As Fullerton and Wolverton (1999) state, if markets work, the subsidy can be passed on to suppliers of recycled goods. Specifically, these authors assert that one of the attributes of the deposit–refund system is that the deposit does not need to be claimed by the original purchaser, in our case, the consumer who pays the tax. The incentive to collect and return the item is effectively transferred to the agents with the lowest opportunity cost of time. This is in accordance with Baumol and Oates' (1988) findings, which show the efficiency of transferring the externality to the group with the least marginal damage (the most marginal benefit). For instance, householders with high time value might not find it worthwhile to separate and recycle beverage bottles, since the marginal benefit associated with this activity is too low compared with its marginal cost. Conversely, waste-pickers can recover the material and capture its value, obtaining a high marginal benefit due to their need for income and the low opportunity cost of their time. In turn, the subsidy will benefit more waste-pickers who have a higher marginal utility of income than householders. So, this policy not only would lead to an efficient outcome, i.e. maximizing social welfare, but also would imply important distributional effects.

The subsidy proposed here to scavengers might become administratively expensive because of the large number of people devoted to this activity and its highly informal nature. A way of reducing these administrative costs is to target the subsidy to organized scavengers groups. Thus, a first step requires organizational and technical support to scavenging activity through the formation of cooperative societies or micro-enterprises. In some Latin American countries such as Brazil, Colombia, Mexico, Peru, and some Asian countries such as Indonesia and Malaysia, scavengers have achieved different levels of organization, which has allowed them to be included as an important actor in formal SWM systems. Funds from the received subsidy might be oriented to: (i) improving working conditions and facilities, (ii) achieving more favorable marketing arrangements for services and scavenged materials, and (iii) introducing health protection and social security measures.

Numerical simulation

Given the informality associated with the collection and recycling of solid waste by waste-pickers, reliable data are extremely scarce and when available they are limited to case studies with aggregated information. Therefore, econometric analysis cannot be performed in order to obtain either production functions for scavenging activity or marginal benefit (damage) functions from generation and disposal of solid waste. Thus, optimal values for economic instruments cannot be derived from actual information. In order to get a sense of the implications of the proposed set of policies on the most relevant variables analyzed in the theoretical model, we perform a numerical simulation.[5]

For simplicity, a unique good is assumed to be produced, consumed, and able to be recycled. The simulation is focused on the variables of interest, i.e. empty landfill space, resource stock and extraction, waste recovery, and environmental quality.

The first step is to assume functional forms for the social welfare function and production functions to be incorporated into the theoretical model. The social welfare function is assumed to be Cobb–Douglas. The production function for the good is also assumed to be Cobb–Douglas with decreasing returns to scale and perfect substitutability between extracted and recycled input. Producers are in charge of extraction, so they face an extraction

[5] Full details about used data, calibration and simulation are available from the authors upon request.

Table 2. *Specification of the equations and the parameter values assumed in the numerical simulation*

Parameter	*Value*	*Interpretation*
Utility function: $W = W(q, A(X, B)) = Dq^{\gamma} A^{1-\gamma}$, $A(X, B) = \ln(B) - \ln(X+1)$		
γ	0.6	Parameter for consumption in Cobb Douglas utility function
D	10	Utility function parameter
Production function: $q = q(X, R) = M(X+R)^{\beta}$ Extraction cost function: $C = C(X, S) = c\,X^2/2S$		
β	0.306	Parameter for inputs in Cobb Douglas production function
M	2,673	Production function technical parameter
c	11,333	Parameter in extraction cost function
Waste-pickers production function: $R = R(L, K) = \theta L^{\alpha_1} K^{\alpha_2}$		
α_1	0.49	Parameter for labor in Cobb Douglas recovery function
α_2	0.26	Parameter for capital in Cobb Douglas recovery function
θ	21.82	Recovery function technical parameter

Initial values for stock variables

Variable	*Initial value*	*Units*
Empty landfill space (B)	3×10^7	Tons
Natural resource (S)	1×10^7	Tons

Market Prices

Variable	*Value*	*Units*
Commodity	80	US $/ton
Recovered material	34	US $/ton
Scavengers labor	25	US $/man/month
Scavengers capital	20	US $/equipment unit/month

cost function with the standard assumption of increasing costs as the stock reduces. The production function for waste-pickers is assumed to have a Cobb–Douglas functional form, be labor intensive, and have decreasing returns to scale. Using these functions, the model is solved analytically and expressions for the optimal policy instruments (consumption tax, recycling subsidy, and extraction tax) obtained.

The numerical simulation is based on data from Bogotá (Colombia). Unknown parameters were obtained through numerical approximation from known data. Specification of the equations and the parameter values assumed in the simulations are presented in table 2.

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Table 3. *Results from the numerical simulation. Percentage changes in main variables during the 20-year period of analysis compared to the baseline under three scenarios: optimal-level instruments, low-level instruments and high-level instruments*

Variable	*Optimal-level instruments*		*Low-level instruments*		*High-level instruments*	
	First Year	*Last year*	*First year*	*Last year*	*First year*	*Last year*
Empty space availability	0	40	0	18	0	62
Resource stock availability	0	18	0	8	0	27
Resource extraction	−23	−9	−12	−4	−33	−15
Recycling	95	42	42	20	146	70
Environmental quality	4	6	2	3	6	9.5
Consumption of the good	−8	−7	−4	−3	−12	−9
Utility	−3.5	−1.4	−2	−0.8	−5	−2

The model is first calibrated for the baseline case, and then simulated under the optimal policies to observe the impact on the variables of interest over a 20-year period. The main results are presented in table 3 (column 2). From the simulation it is observed that the set of optimal policies increases the availability of empty space of the landfill by about 40 per cent at the end of the 20-year period. This is the result of both a reduction in consumption of the good (output effect) and an increase in the amount of recycled material (substitution effect). The natural resource stock is extracted at a lower pace as a result of the set of policies. After 20 years, there are savings corresponding to 18 per cent of the original stock. Consequently, extraction is reduced during all the periods of analysis.

Recovery and recycling of solid waste (R) is encouraged when optimal policies are implemented, and it increases by nearly 95 per cent at the beginning and reduces to 42 per cent by the end of the 20-year period, showing that recovery and recycling performed by waste pickers turns out to be the most elastic variable to changes in prices as a result of the set of policies. The combination of reduced prices of recycled material for final good producers and greater prices of extracted material pushes the use of recovered material up.

Environmental quality exhibits an interesting path: with no policy in place, the environmental quality function reaches a maximum after 13 years, and then decreases rapidly as a consequence of the reduction in empty space. When the optimal policies are included, environmental quality takes greater values for every period, and even after 20 years the maximum is still not reached. This is a result of both the reduction in the extraction of natural resource, i.e. the externalities associated with it, and an increase in the available empty space in the landfill. On average, environmental quality increases by 5 per cent as a result of the policy during the 20-year period.

The results from the numerical simulation confirm the results obtained from the theoretical model. These results, however, are specific to the assumptions and data adopted and further applications should be analyzed for particular cases. To give some flexibility to the results, a sensitivity analysis is also performed. Two additional scenarios are proposed for comparison: a low-level tax policy and a high-level tax policy (see table 3, columns 3 and 4). In the low-level tax scenario, the two taxes and the subsidy are reduced to a half of the calculated optimal values for each year in the simulation period. In the high-level tax scenario, the value of each of the instruments is increased by 50 per cent compared with every-year calculated optimal value.

The high-level tax policy increases the savings in empty space up to 62 per cent after the 20 years of analysis, while increasing the savings in natural resource stock up to more than 25 per cent. This implies a reduction in the use of the extracted resource of more than 30 per cent during the first years. Recycling, being the most sensitive activity to the policy, is increased up to a maximum of nearly 150 per cent compared with the baseline. As a result of these changes, environmental quality increases are in the range of 6 to 9 per cent as a result of the high-level tax policy. Even though consumption is reduced in the first years up to 12 per cent, utility is only reduced up to a maximum of 5 per cent. This is explained by the fact that reduction in consumption is offset by the increase in environmental quality. For the case of the low-level tax, policy changes are smoother compared to the optimal case. The most significant change is recycling, which increases more than 40 per cent during the first years, compared with the baseline.

Given the highly non-linear nature of the equations, and of the system as a whole, the stability of the results from the sensitivity analysis around the optimal policies demonstrates that there is some range of values where policies can be put in place and expected results can be obtained. This implies that policymakers do not need to have perfect knowledge of the exact optimum values to start implementing a policy and that some trial and error in application is possible in practice.

Conclusions

Scavenging is a growing phenomenon in large cities of the developing world. This activity is not only a source of income for many people facing precarious economic conditions, but it also generates a positive environmental externality on natural resource use and on landfill lifespan. Informal waste-picking activities should be encouraged and successful experiences should be replicated. With the increasing trend towards privatization of services and the drive for increased efficiency, legislative frameworks and contracts should be flexible enough to allow the participation of small-scale service providers, e.g. groups of organized waste-pickers.

The Pigouvian prescription implies that such a positive externality should be encouraged with a subsidy equal to the marginal benefit to society. This model shows that in a dynamic framework the prescription is still valid, though corrections over time should be included. The model generates a policy prescription that is dynamic in nature. Although optimal, changing the values of the tax every period would imply prohibitive policies due to

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high transaction and administrative costs and they would be impractical. Instead, what the model suggests is the definition of a set of taxes that consider intertemporal relationships but that can be set at a certain level and be revised periodically depending on the evolution of conditions in the economy.

The optimal set of policies from this model comprises a combination of policies similar to the two-part instrument proposed by Fullerton and Wolverton (1999): a tax on households per unit of good consumed equal to the shadow price of the empty landfill space, and a subsidy to waste-pickers per unit of material recovered and saved from being disposed in the landfill, equal to the shadow price of empty landfill space. In addition to these two instruments, a tax on firms extracting virgin resources equal to the marginal damage generated by extraction of the resource is also needed to reach efficiency in this economy.

The optimal subsidy to waste-pickers under perfect competition must equal the tax on consumers, which implies a transfer from consumers to waste-pickers. The optimal tax and subsidy should be determined based on the equivalent space that each commodity would use in the landfill.

Given that consumption of packaging goods is directly related to income, the tax would not be regressive, if equity considerations are to be included. Besides, directing the subsidy towards waste-pickers not only leads to the efficiency of the policy but also accounts for distributional effects that help the least favored groups in developing country economies.

Industries that consume recyclables in developing countries encourage and support the existence of waste dealers between them and waste-pickers in order to assure an adequate volume and quality of the materials. As a result, opportunities arise for exercising market power. Several authors suggest that the low prices that waste-pickers receive are due to the presence of imperfect competition in the market for recovered material (Kaseva and Gupta, 1996; Medina, 2000; Ojeda-Benítez *et al.*, 2002). An extension to this model would be the incorporation of imperfect competition in waste collection.

Impacts from trade might also be considered. Some developed countries are able to produce recycled material of a higher quality compared with recycled material in developing countries. Given environmental regulation in developed countries, firms may be interested in diverting recycling surpluses to developing countries. Although these imports may reduce production costs in developing countries, they generate two negative impacts. First, domestic recycling by waste-pickers in developing countries might be discouraged, with the social implications of unemployment and indigence for these people on the social fringe. Second, domestic landfills would be exposed to higher pressure because they would have to receive domestic waste not recovered, in addition to the garbage coming from the imported material. This would be a case of losses from trade that should be carefully considered to avoid additional distortions that can be costly economically and socially. Further research in this area is encouraged.

The implications of this paper do not mean that misery conditions of waste-pickers in developing countries should be encouraged. Rather, they suggest that waste-pickers could reach a better standard of living if local authorities recognize their role in the solid waste management system and the positive externalities they generate are compensated adequately. Due to waste-pickers current lack of basic services, social security programs, including industrial safety, access to health services, access to education for their children and for themselves, and some retirement benefits for elderly people, would assure recognition of their activity.

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