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A waste management model for optimal recycling–landfilling policies under macroeconomic conditions

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ABSTRACT

This research provides a waste management model in the presence of macroeconomic conditions. An optimal control problem which integrates the recycling–landfilling decision with industry supply–demand dynamics is designed to achieve the value-maximizing objective. The model simultaneously considers idiosyncratic technical and aggregate demand shocks, while the stoppage time for landfill use is assumed to follow a Cox process with the intensity function of a firm's total waste collection. The closed-form solution of the optimal recycling ratio is also derived. The results suggest that when macroeconomic effects are neglected, optimal recycling ratios tend to be underestimated.

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1. Introduction

Optimal waste management policies require relentless and immediate attention due to increasing recognition of global environmental protection and the mainstream environmental economics movement (Highfill and McAsey, 1997; Huhtala, 1997; Costi et al., 2004; Minciardi et al., 2008; Xu et al., 2010). Intuitively, all wastes are sourced from consumption, and as there is substantial evidence of macroeconomic effects on asset returns in capital markets, an interesting problem that arises here is: how do macroeconomic conditions affect optimal waste management policies?[1] However, there is a dearth of literature focusing directly on the effects of macroeconomic shocks on waste management issues. To fill this theoretical gap, this study aims to develop a waste management model that allows for examining optimal recycling–landfilling ratios in the presence of variable macroeconomic conditions.

An ideal recycling–landfilling plan for solid waste management is important for all sectors and agents in the economy. Inefficiencies in waste management inevitably contribute to the deterioration of living environments as well as entail potential risks to public health (Rathi, 2007; Macawile and Sia Su, 2009). According to a survey by the U.S. Environmental Protection Agency (EPA) in 2008, Americans totally generate approximately 250 million tons of trash per year while 83 million tons are recycled, equivalent to a 33.2% recycling rate.[2] These recycling activities save 1.3 quadrillion Btu of energy, the equivalent of more than 10.2 billion gallons of gasoline.[3]

In view of the enormous benefits and demand for effective waste processing, many governments and international organizations actively put into practice specific waste management and recycling policies. For example, step-by-step recycling targets approved by the European Commission require their member states to achieve minimum ratios of not less than 50% by weight for the re-use and recycling of waste materials by 2020.[4] The importance of optimal recycling–landfilling strategies for solid waste management has also received considerable attention from the academic literature, as with Chang et al. (1997), Highfill and McAsey (1997), Huhtala (1997), André and Cerdá (2001), Costi et al. (2004), Rathi (2007), Alshammari

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[1] How macroeconomic factors affect financial asset return has already received considerable attention in finance and economics, e.g., Flannery and Protopapadakis (2002), Korajczyk and Levy (2003), Hackbarth et al. (2006), Liu and Zhang (2008), and Chen (2010).

[2] On average, Americans recycled and composted 1.5 of 4.5 lb of waste generated per person per day in 2008, with total waste increasing from 3.66 lb per person per day in 1980. The recycling rate has also increased—from less than 10% in 1980 to over 33% in 2008.

[3] Every ton of mixed paper recycled can save the energy equivalent of 185 gal of gasoline.

[4] The recycling targets are established under Article 11(2) of the Council Directive (EC). See Nash (2009) for more details.

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et al. (2008), Minciardi et al. (2008), and Xu et al. (2010). Related areas of exploration have broadly included the tradeoffs between recycling and landfilling, empirical estimations of optimal recycling ratios, and the effects of landfill space constraints. For example, Huhtala (1997) developed a post-consumer waste management model to examine the optimal recycling and landfilling levels for municipal solid waste (MSW) services. Using waste disposal data from the Helsinki region in Finland, that study suggested that mandates to achieve 50% recycling ratios are not far-fetched while being both economically and environmentally justified. Xu et al. (2010) applied an interval-parameter stochastic robust model to investigate optimal MSW management. Considering the various economic and environmental costs associated with MSW management, Rathi (2007) developed a linear programming model that integrated the different options and stakeholders involved in the decision problem.

It is notable that, among the literature, little attention has been directly paid to the effect of shocks or risks to individual wealth on waste generation. One such typical manifestation of these effects is the so-called macroeconomic effects. There has been a growing body of seminal work devoted to understanding optimal decision making under varying macroeconomic conditions (Miao, 2005; Hackbarth et al., 2006; Huang et al., 2008; Chen, 2010). Since economic intuition suggests that all waste generation is rooted in human consumption (see page 3 in Highfill and McAsey, 1997) and that consumption plans are further financed by individual wealth, it is reasonable to assume that macroeconomic conditions do play a significant role in determining waste management policies.

Departing from existing models, this study introduces industry supply–demand dynamics into the recycling–landfilling choice problem. Aggregate demand and idiosyncratic technical shocks are integrated in extending the works of Miao (2005), Hackbarth et al. (2006), and Huang et al. (2008). The base setting is assumed to be static, to support the considered circumstance where a reference firm tends to open a new landfill. The managerial objective is to choose an optimal level of recycling and landfilling that maximizes the total firm profit under the interference of macroeconomic conditions. Applying the model put forward here, the impact of aggregate demand shocks and stochastic firm-level recycling productivity on optimal recycling ratios can be investigated.

This paper details some contributions to making ideal waste management. Firstly, our optimal solution has a number of the testable implications involved with macroeconomic effects. The numerical results convey the significance of macroeconomic conditions in making optimal waste management policies. Neglecting the macroeconomic effects will lead to the underestimation of the optimal recycling ratios. This implies that levels of recycling predicted by prior models cannot accurately meet an efficient waste management. We further show that the optimal recycling ratios increase with levels of the waste generation, landfilling costs, and sensitivities of the landfilling damage to waste, but decrease with recycling costs.

The remainder of this paper is organized as follows. Section 2 builds a waste management model in the presence of macroeconomic conditions. Based on the profit-maximizing preference assumption, optimal recycling ratios are resolved. Section 3 provides a numerical analysis that examines the properties of the optimal recycling policy. Summary and discussion are given in Section 4.

2. The model

Consider an industry with competitive equilibrium consisting of firms involved in recycled waste manufacturing and waste management activities. Also consider a reference firm with sufficient funds in this industry, which intends to open a new landfill at cost F. Since capital structure endogeneity is not considered, the total value of this reference firm is equivalent to its unlevered value; in other words, the firm is totally equity financed. Further assume that the information is perfect, that all economic agents are risk-neutral, and that future cash flows are discounted at a constant riskless interest rate r. This supposition of risk neutrality does not result in any loss of generality. If agents are risk-averse, the analysis may be conducted under martingale measures (Harrison and Kreps, 1979).

Time is continuous and varies over $[0,\infty)$. Uncertainty is governed by a filtered probability space $(\Omega, F, (F_t)_{t\geq 0}, \mathrm{P})$ over which all stochastic processes are defined. The objective is to examine optimal waste management and recycling policies in the presence of macroeconomic conditions.

2.1. Industry demand, individual production, and the profit function

Extending Miao (2005) and Huang et al. (2008), industry demand is given by a decreasing function. For the sake of brevity, take the following iso-elastic functional form:

$$P(t) = \tilde{Y}^{-\frac{1}{\varepsilon}} h(t) \tag{1}$$

In addition, the individual production function of the reference firm is assumed to follow a standard Cobb–Douglas form, shown as

$$Y(t) = [\theta G(t)]^{\beta} L^{\alpha} A(t) \tag{2}$$

Notations for Eqs. (1) and (2) are as follows: $P(t)$ is the output price; $Y(t)$ is individual production; $\tilde{Y}$ is industrial demand; $\varepsilon>0$ is demand elasticity; θ is the ratio of recycling to the firm's total waste collection $G(t)$; $\alpha<1$ and $\beta<1$ are the output elasticities of labor L and capital (i.e., recycled waste), respectively. Aggregate demand shocks $h(t)$, the firm's total waste collection $G(t)$, and firm-level recycling productivity $A(t)$ all evolve according to geometric Brownian motion w^{P} on $(\Omega, G, (G_t)_{t\geq 0}, \mathrm{P})$ satisfying $G \subseteq F$:

$$dh(t) = h(t)\hat{\sigma}_h \cdot dw^{P}(t) \tag{3}$$

$$dG(t) = G(t)\left[(\mu_G - \delta_G)dt + \hat{\sigma}_G \cdot dw^{\mathrm{P}}(t)\right] \tag{4}$$

$$dA(t) = A(t)\left[\mu_A\, dt + \hat{\sigma}_A \cdot dw^{\mathrm{P}}(t)\right] \tag{5}$$

The drift terms $\mu_G, \delta_G, \mu_A > 0$ are constant parameters; the diffusion terms $\hat{\sigma}_G, \hat{\sigma}_h, \hat{\sigma}_A$ and the standard Brownian motion are 3 by 1 vectors:

$$\hat{\sigma}_G = \sigma_G \cdot \begin{bmatrix} 1 \\ 0 \\ 0 \end{bmatrix};\ \hat{\sigma}_h = \sigma_h \cdot \begin{bmatrix} \rho_{Gh} \\ \sqrt{1-\rho_{Gh}^2} \\ 0 \end{bmatrix};$$

$$\hat{\sigma}_A = \sigma_A \cdot \begin{bmatrix} \rho_{GA} \\ (\rho_{hA} - \rho_{GA}\rho_{Gh}) / \sqrt{1-\rho_{Gh}^2} \\ \sqrt{1-\rho_{GA}^2 - \left[(\rho_{hA} - \rho_{GA}\rho_{Gh})^2 / (1-\rho_{Gh}^2)\right]} \end{bmatrix};$$

$$w^{\mathrm{P}}(t) = \begin{bmatrix} w_G^{\mathrm{P}}(t) \\ w_h^{\mathrm{P}}(t) \\ w_A^{\mathrm{P}}(t) \end{bmatrix};$$

where $\rho_{GA}, \rho_{Gh}, \rho_{hA}$ symbolizes the correlation between w_G^P and w_A^P, w_G^P and w_h^P, and w_h^P and w_A^P respectively. Observations of aggregate demand shock, total waste collection, and firm recycling productivity are continuous and can be collected by joint σ-algebra: $G_t = G_t^G \vee G_t^A \vee G_t^h$ where $G_t^x = \sigma(x(u), 0 \leq u \leq t)$ for $x = A, G, h$ and $t \in R_+$.

In deriving the profit from waste management activities, a portion θ of labor hired by the firm is assigned to waste recycling while the remainder is in charge of waste landfilling and collection. Denoted by $W \equiv \theta C_R + (1-\theta)C_L$, the average wage earned by a unit of labor, the firm's total promised wage payment WL thus equals the sum of total recycling costs $C_R L\theta$ and total landfilling costs $C_L L(1-\theta)$. Combining the product of Eqs. (1) and (2) (i.e., sales revenue) with waste management costs yields the firm's instantaneous operating profit (EBIT) function:

$$f(t) = P(t)Y(t) - [C_R\theta L + C_L(1-\theta)L] \tag{6}$$

Since labor choice and wages are non-stochastic and predetermined, $f(t)$ and $P(t)Y(t)$ have the same dynamic. Applying the Ito formula with SDEs (3)–(5), we have the following dynamics:

$$dP(t) = \tilde{Y}^{-\frac{1}{\varepsilon}} h(t)[dh(t)/h(t)] = P(t)\left[\hat{\sigma}_h \cdot dw^{\mathrm{P}}(t)\right] \tag{7}$$

$$\begin{aligned} dY(t) &= \theta^{\beta} L^{\alpha} G(t)^{\beta} A(t)[dA(t)/A(t)] + \beta\theta^{\beta} L^{\alpha} G(t)^{\beta} A(t)[dG(t)/G(t)] \\ &\quad + \frac{1}{2}\beta(\beta-1)\theta^{\beta} L^{\alpha} G(t)^{\beta} A(t)[dG(t)/G(t)]^2 \\ &\quad + \beta\theta^{\beta} L^{\alpha} G(t)^{\beta} A(t)[dG(t)/G(t)][dA(t)/A(t)] \\ &= Y(t)\left[\left(\mu_A + \beta\mu_G - \beta\delta_G + \frac{1}{2}\beta^2\|\hat{\sigma}_G\|^2 - \frac{1}{2}\beta\|\hat{\sigma}_G\|^2 + \beta\hat{\sigma}_A\hat{\sigma}_G\right)dt \right. \\ &\quad \left. + (\hat{\sigma}_A + \beta\hat{\sigma}_G)\cdot dw^{\mathrm{P}}(t)\right]; \end{aligned} \tag{8}$$

Define $\mu_Y \equiv \left(\mu_A + \beta\mu_G - \beta\delta_G + \frac{1}{2}\beta^2\|\hat{\sigma}_G\|^2 - \frac{1}{2}\beta\|\hat{\sigma}_G\|^2 + \beta\hat{\sigma}_A\hat{\sigma}_G\right)$, $\tilde{f}(t) \equiv P(t)Y(t)$ and $\hat{\sigma}_Y \equiv (\hat{\sigma}_A + \beta\hat{\sigma}_G)$. Again, using the Ito formula gives the SDE for instantaneous profit:

$$d\tilde{f}(t) = \tilde{f}(t)\left[(u_Y + \hat{\sigma}_h \cdot \hat{\sigma}_Y)dt + (\hat{\sigma}_h + \hat{\sigma}_Y)\cdot dw^{\mathrm{P}}(t)\right] \tag{9}$$

2.2. Landfill use stoppage time

The available space in a landfill is always limited. To model landfill use stoppage time, define $\tau := \inf\left(t : \int_0^t \lambda[\ln G(u)]du \geq E\right)$, with the convention $\inf\phi = +\infty$ as a random default time following the properties of a first jump time of the Cox process with a non-negative hazard function:

$$\Lambda(t) \equiv \int_0^t \lambda[\ln G(u)]du \equiv \int_0^t [\lambda_0 + \lambda_1 \ln G(u)]du$$

where the parameters $\lambda_0 > 0$ and $\lambda_1 > 0$ respectively denote the spontaneous default intensity and sensitivity of environmental damage due to waste collection. Current information on observations of the occurrence of this stoppage time is collected by $H_t = \sigma(1_{(\tau \leq u)}, 0 \leq u \leq t)$, which implies $(H_t)_{t \geq 0} = H \subseteq F$ (i.e.$H \vee G = F$). Notably, at the moment of τ's occurrence, the firm is not only required to abandon the use of the current landfill immediately, but also carries environmental damage costs D (i.e., costs of tree planting or area landscaping; see Korajczyk and Levy (2003) for more details).

Now introduce the probability law of τ. According to Lando (1998), an inhomogeneous Poisson process N with non-negative intensity function $\tilde{\lambda}(\cdot)$ satisfies: if $t > s \geq 0$

$$\mathrm{P}(N_t - N_s = k) = \frac{\left(\int_s^t \tilde{\lambda}(u)du\right)^k}{k!}\exp\left(-\int_s^t \tilde{\lambda}(u)du\right), k = 0, 1 \ldots \infty$$

In particular, assuming $N_0 = 0$, we have:

$$\mathrm{P}(N_t = 0) = \exp\left(-\int_0^t \tilde{\lambda}(u)du\right)$$

Thus the definition for the first jump time of N is the following:

$$\tilde{\tau} := \inf\left(t : \int_0^t \tilde{\lambda}(u)du \geq \mathrm{E}_1\right)$$

where E_1 is a unit exponential random variable.

A Cox process is a generalization of the Poisson process in which the intensity is allowed to be random, e.g., $\lambda(u) = \lambda[\ln G(u)]$. Since G is an R^3-valued stochastic process, the default time τ is defined from R^3 to $[0, \infty)$. From this definition, the key relationships are shown below:

$$\mathrm{P}(\tau > t \,|\, (G(s))_{0 \leq s \leq t}) = \exp\left(-\int_0^t \lambda[\ln G(s)]ds\right)$$

$$\mathrm{P}(\tau > t) = \mathrm{E}_{\mathrm{p}}\left[\exp\left(-\int_0^t \lambda[\ln G(s)]ds\right)\right]$$

Hence, by using stochastic exponential solutions, changes of measure, and Fubini's theorem (see Musiela and Rutkowski (1997) and Klebaner (2004) for more detailed proofs), the total probabilities of survival until time-t under the measure P on $H_0 \vee G_0 = F_0$ are:

$$\begin{aligned} \mathrm{P}(\tau > t \,|\, F_0) = \exp\Bigg\{ &-\lambda_0 t - \lambda_1\left[\ln G(0)t + \left(\mu_G - \delta_G - \frac{1}{2}\|\hat{\sigma}_G\|^2\right)\frac{t^2}{2}\right] \\ &+ \frac{1}{6}\lambda_1^2 t^3 \|\hat{\sigma}_G\|^2\Bigg\} \end{aligned}$$

Differentiating $\mathrm{P}(\tau > t \,|\, F_0)$ with respect to t yields the density function of $\tau = t$ on $H_0 \vee G_0 = F_0$ under P, for any $t > 0$,

$$\begin{aligned} f_{\tau,\mathrm{P}}(t \,|\, F_0) = &\left\{\lambda_0 + \lambda_1\left[\ln G(0) + \left(\mu_G - \delta_G - \frac{1}{2}\|\hat{\sigma}_G\|^2\right)t\right] - \frac{1}{2}\lambda_1^2 t^2 \|\hat{\sigma}_G\|^2\right\} \\ &\times \exp\Bigg\{-\lambda_0 t - \lambda_1\left[\ln G(0)t + \left(\mu_G - \delta_G - \frac{1}{2}\|\hat{\sigma}_G\|^2\right)\frac{t^2}{2}\right] \\ &+ \frac{1}{6}\lambda_1^2 t^3 \|\hat{\sigma}_G\|^2\Bigg\}. \end{aligned}$$

Formulas $\mathrm{P}(\tau > t | F_0)$ and $f_{\tau,\mathrm{P}}(t | F_0)$ jointly describe the probability law of the stoppage time for landfill use. These two formulas will be used repeatedly below in deriving optimal waste management policies.

2.3. Objective function and optimal ratio of recycling to total waste collection

The total value of the reference firm is the sum of the entire contingent claim on cash flows that would be taken as the present value of all future profits, and is therefore affected by aggregate demand and firm-level recycling productivity shocks, and by their correlations. This can be calculated as the conditional expected value of all future after-tax cash flows with a corporate tax rate $\gamma \in [0, 1]$ discounted at r,

$$\mathrm{E}_{\mathrm{p}}\left(\int_0^{\infty} 1_{(\tau > t)} f(t)(1-\gamma)\mathrm{e}^{-rt}dt \,|\, F_0\right). \tag{10}$$

Given the introduction to the relevant notations, integrating (Eq. (10)) with the costs of opening a new landfill and environmental damage results in the objective function:

$$\underset{\theta}{\text{Sup}}\ \mathrm{E_p}\left[\int_0^\infty 1_{(\tau>t)} f(t)(1-\gamma)\mathrm{e}^{-rt}dt - D\mathrm{e}^{-r\tau} - F\,|\,F_0\right]. \tag{11}$$

Based on the profit-maximizing preference, the objective of decisions making agents is to choose an optimal recycling ratio that maximizes their own wealth and firm total value; more exactly,

$$\theta^* = \underset{\theta\in[0,1]}{\text{argmax}}\,\mathrm{E_p}\left[\int_0^\infty 1_{(\tau>t)} f(t)(1-\gamma)\mathrm{e}^{-rt}dt - D\mathrm{e}^{-r\tau} - F\,|\,F_0\right].$$

By deriving the explicit solution for θ^* via the use of Fubini's and Girsanov's theorems and martingale properties, Eq. (11) can be derived as:

$$\begin{aligned}
&\text{Sup}_\theta \int_0^\infty \exp\Big\{-(\lambda_o + r)t - \lambda_1\Big[\ln G(0)t + \left(\mu_G - \delta_G - 0.5\|\hat{\sigma}_G\|^2\right)0.5t^2\Big] \\
&\quad + \lambda_1^2 t^3\|\hat{\sigma}_G\|^2/6\Big\} \times \Big\{(1-\gamma)\,\tilde{Y}^{-1/\varepsilon}h(0)[\theta G(0)]^\beta L^\alpha A(0) \\
&\quad \times \exp\Big[(\mu_Y + \hat{\sigma}_h\cdot\hat{\sigma}_Y)t - 0.5\lambda_1 t^2\hat{\sigma}_G(\hat{\sigma}_h + \hat{\sigma}_Y)\Big] - (1-\gamma)L[\theta C_R + (1-\theta)C_L] \\
&\quad - D\Big[\lambda_o + \lambda_1\Big(\ln G(0) + \left(\mu_G - \delta_G - 0.5\|\hat{\sigma}_G\|^2\right)t\Big) - 0.5\lambda_1^2 t^2\|\hat{\sigma}_G\|^2\Big]\Big\}dt - F
\end{aligned}$$

or

$$\begin{aligned}
&\text{Sup}_\theta \int_0^\infty \mathrm{P}(\tau > t\,|\,F_0)\mathrm{e}^{-rt}\Big\{(1-\gamma)P(0)Y(0)\exp\Big[(\mu_Y + \hat{\sigma}_h\cdot\hat{\sigma}_Y)t \\
&\quad - 0.5\lambda_1 t^2\hat{\sigma}_G(\hat{\sigma}_h + \hat{\sigma}_Y)\Big] - (1-\gamma)L[\theta C_R + (1-\theta)C_L] \\
&\quad - D\Big[\lambda_o + \lambda_1\Big(\ln G(0) + \left(\mu_G - \delta_G - 0.5\|\hat{\sigma}_G\|^2\right)t\Big) - 0.5\lambda_1^2 t^2\|\hat{\sigma}_G\|^2\Big]\Big\}dt \\
&\quad - F
\end{aligned} \tag{12}$$

By Leibnitz's rule, differentiating Eq. (12) with respect to θ has the following first-order condition (FOC):

$$\begin{aligned}
&\int_0^\infty \Big\{(1-\gamma)\tilde{Y}^{-1/\varepsilon}h(0)\beta\theta^{\beta-1}G(0)^\beta L^\alpha A(0)\exp\Big[(\mu_Y + \hat{\sigma}_h\cdot\hat{\sigma}_Y)t \\
&\quad - 0.5\lambda_1 t^2\hat{\sigma}_G(\hat{\sigma}_h + \hat{\sigma}_Y)\Big] - (1-\gamma)L(C_R - C_L)\Big\}\mathrm{P}(\tau > t\,|\,F_0)\mathrm{e}^{-rt}dt = 0.
\end{aligned}$$

Through this condition, the close-form solution of the optimal recycling ratio is:

$$\theta^* = \left(\frac{\int_0^\infty L(C_R - C_L)\mathrm{P}(\tau > t\,|\,F_0)\mathrm{e}^{-rt}dt}{\int_0^\infty P(0)\beta G(0)^\beta L^\alpha A(0)\exp\left[(\mu_Y + \hat{\sigma}_h\cdot\hat{\sigma}_Y - r)t - \lambda_1 t^2\hat{\sigma}_G(\hat{\sigma}_h + \hat{\sigma}_Y)/2\right]\mathrm{P}(\tau > t\,|\,F_0)dt}\right)^{\frac{1}{\beta-1}}. \tag{13}$$

By the same token, twice differentiating Eq. (12) with respect to θ has the corresponding second-order condition (SOC):

$$\begin{aligned}
&\int_0^\infty (1-\gamma)\beta(\beta-1)\theta^{-2}\tilde{f}(0)\exp\Big[(\mu_Y + \hat{\sigma}_h\cdot\hat{\sigma}_Y - r)t - \lambda_1 t^2\hat{\sigma}_G(\hat{\sigma}_h + \hat{\sigma}_Y)/2\Big] \\
&\quad \times \mathrm{P}(\tau > t\,|\,F_0)dt < 0.
\end{aligned}$$

Since it is known that $\beta,\gamma\in[0,1]$ and $\tilde{f}(0)\geq 0$, SOC ensures the validity of the prior optimal solution.

In view of the formula expressed by Eq. (13), observe that θ^* has a number of testable implications, for example, the impacts of aggregate and idiosyncratic shocks on optimal recycling policies. To investigate this issue, a numerical analysis is given in the following section.

Table 1
Base parameter values.

$G(0)=0.1$	The current level of the firm's total waste collection
$\mu_G=0.014$	The growth rate of waste
$\delta_G=0.008$	The decay rate of waste production
$\sigma_G=0.0005$	Volatility of the waste process
$A(0)=21.21$	Initial firm-level recycling productivity
$u_A=0.0839$	Technical improvement rate
$\sigma_A=1.1$	Volatility of technical shock
$h(0)=1$	Initial aggregate demand shock
$\sigma_h=0.0123$	Volatility of the aggregate shock
$\rho_{Gh}=0.5$	The correlated coefficients
$\rho_{GA}=0.5$	The correlated coefficients
$\rho_{hA}=0.0264$	The correlated coefficients
$\varepsilon=1.381$	The demand elasticity
$P(0)=0.05$	The output price
$L=10$	Labor
$\alpha=0.7323$	Output elasticity of labor
$\beta=0.2872$	Output elasticity of capital
$\lambda_0=0.1$	Spontaneous default intensity
$\lambda_1=0.001$	Sensitivity of landfilling damage to waste
$C_R=0.306$	Unit recycling cost
$C_L=0.102$	Unit landfilling cost
$\gamma=0.25$	Effective tax rate
$r=0.05$	Riskless interest rate

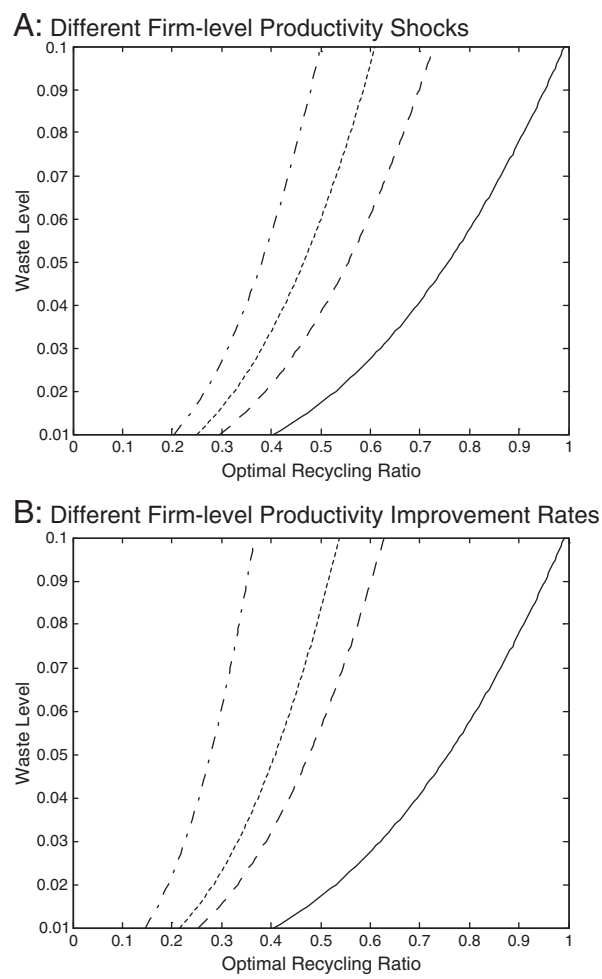

Fig. 1. Optimal recycling ratios as a function of waste levels with different firm-level productivity shocks and improvement rates. This figure plots optimal recycling ratios as a function of the waste levels $G(0)$, ranging from 0.01 to 0.1, with varying choices of firm-level productivity shock and improvement rates in Panels A and B respectively (dash–dot line in Panel A: $A(0)=13$, dotted line in Panel A: $A(0)=15$, dashed line in Panel A: $A(0)=17$, solid line in Panel A: $A(0)=21.21$, dash–dot line in Panel B: $u_A=0.02$, dotted line in Panel B: $u_A=0.05$, dashed line in Panel B: $u_A=0.06$, and solid line in Panel B: $u_A=0.0839$). The combination of parameter choices is based on the base case.

3. Numerical analysis

This section numerically examines the optimal recycling ratio with idiosyncratic technical and aggregate demand shocks. For the sake of brevity, let the initial time be $t=0$; the current level of the firm's total waste collection $G(0)=0.1$; the growth rate of waste $\mu_G=0.014$; the decay rate of waste production $\delta_G=0.008$; volatility of the waste process $\sigma_G=0.0005$; initial firm-level recycling productivity $A(0)=21.21$; technical improvement rate $u_A=0.0839$; volatility of technical shocks $\sigma_A=1.1$; initial aggregate demand shock $h(0)=1$; volatility of the aggregate shock $\sigma_h=0.0123$; the correlated coefficients $\rho_{Gh}=0.5$, $\rho_{GA}=0.5$, and $\rho_{hA}=0.0264$; the demand elasticity $\varepsilon=1.381$; the output price $P(0)=0.05$; labor $L=10$; output elasticity of labor $\alpha=0.7323$; output elasticity of capital $\beta=0.2872$; spontaneous default intensity $\lambda_0=0.1$; sensitivity of landfilling damage to the waste $\lambda_1=0.001$; unit recycling cost $C_R=0.306$; unit landfilling cost $C_L=0.102$; effective tax rate $\gamma=0.25$; and riskless interest rate $r=0.05$. Values for most of these parameters are borrowed from the model calibration by Liao and Huang (2006) and Huang et al. (2008). In addition, since all consumption becomes waste, values for δ_G and μ_G are chosen based on changes in human consumption, directly correlated with the rate of population growth and death. The preceding parameters are summarized in Table 1.

3.1. Optimal recycling policy properties

Given the combination of the reasonable range of model parameters, Figs. 1 and 2 exhibit optimal recycling ratios as a function of current waste levels $G(0)$, ranging from 0.01 to 0.1. From the pattern of curves plotted in Fig. 1, observe that at each level of waste collection, the optimal recycling ratio increases with the firm's recycling productivity (Panel A) and technical improvement rate (Panel B). Fig. 2 shows that as volatilities in aggregate demand shocks σ_h and firm-level recycling productivity σ_A increase, high levels of recycling are employed regardless of waste collection levels. Thus, if more waste is generated, the optimal recycling ratio climbs to a higher level, which in turn lessens the need for landfilling, alleviating immediate environmental damage. The result is economically intuitive and consistent with Huhtala (1997) and Costi et al. (2004).

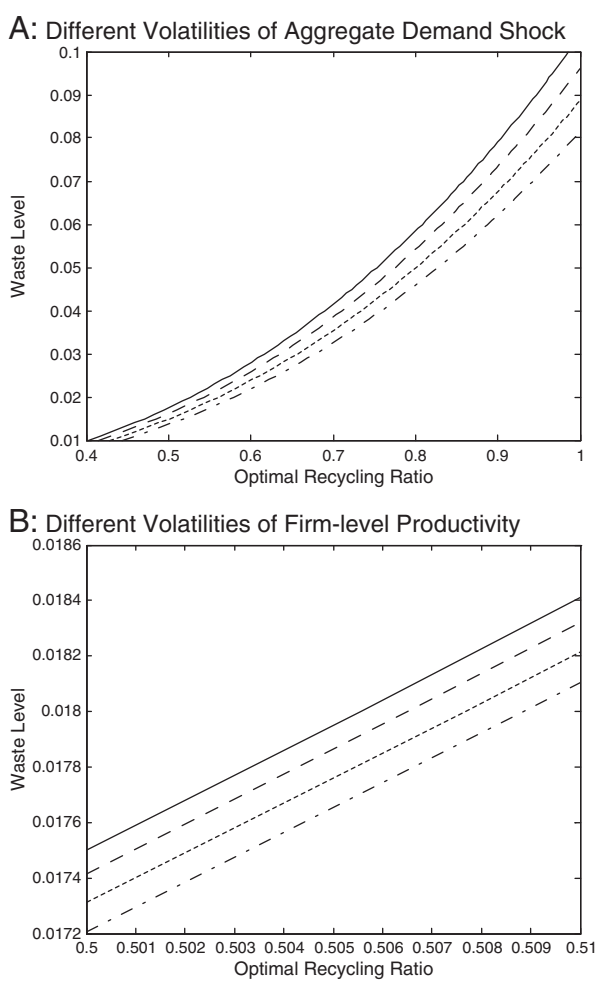

Fig. 2. Optimal recycling ratios as a function of waste levels with different volatilities of aggregate demand shocks and firm-level productivity. This figure plots optimal recycling ratios as a function of the waste levels $G(0)$, ranging from 0.01 to 0.1, with varying volatilities of aggregate demand shock and firm-level productivity in Panels A and B respectively (dash–dot line in Panel A: $\sigma_H=0.6$, dotted line in Panel A: $\sigma_H=0.4$, dashed line in Panel A: $\sigma_H=0.2$, solid line in Panel A: $\sigma_H=0.0123$, dash–dot line in Panel B: $\sigma_A=1.1$, dotted line in Panel B: $\sigma_A=0.8$, dashed line in Panel B: $\sigma_A=0.5$, and solid line in Panel B: $\sigma_A=0.2574$). The combination of parameter choices is based on the base case.

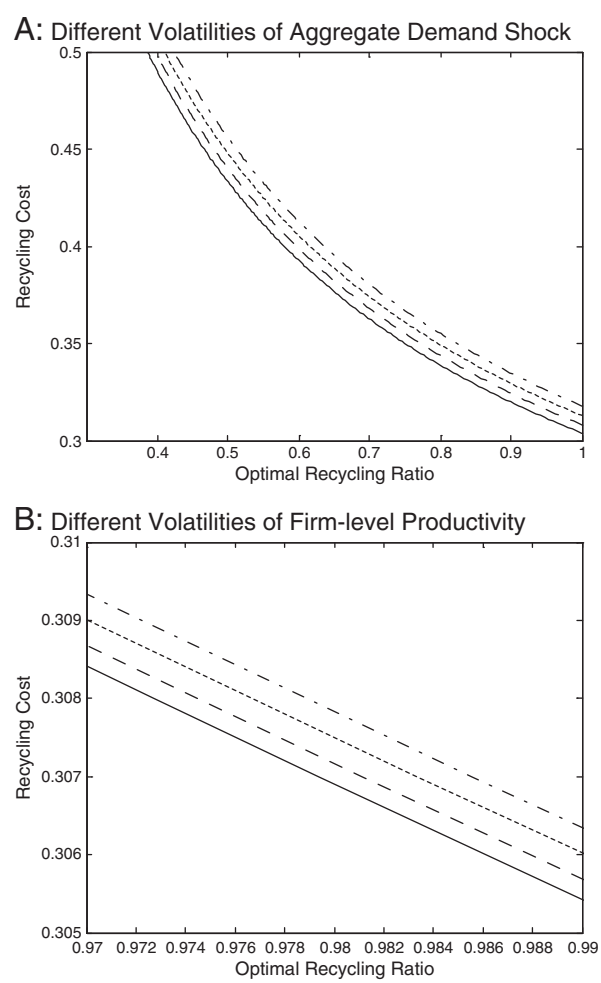

Fig. 3. Optimal recycling ratios as a function of recycling costs with different volatilities of aggregate demand shocks and firm-level productivity. This figure plots optimal recycling ratios as a function of recycling costs C_R, ranging from 0.3 to 0.5, with varying volatilities of aggregate demand shock and firm-level productivity in Panels A and B respectively (dash–dot line in Panel A: $\sigma_H=0.6$, dotted line in Panel A: $\sigma_H=0.4$, dashed line in Panel A: $\sigma_H=0.2$, solid line in Panel A: $\sigma_H=0.0123$, dash–dot line in Panel B: $\sigma_A=1.1$, dotted line in Panel B: $\sigma_A=0.8$, dashed line in Panel B: $\sigma_A=0.5$, and solid line in Panel B: $\sigma_A=0.2574$). The combination of parameter choices is based on the base case.

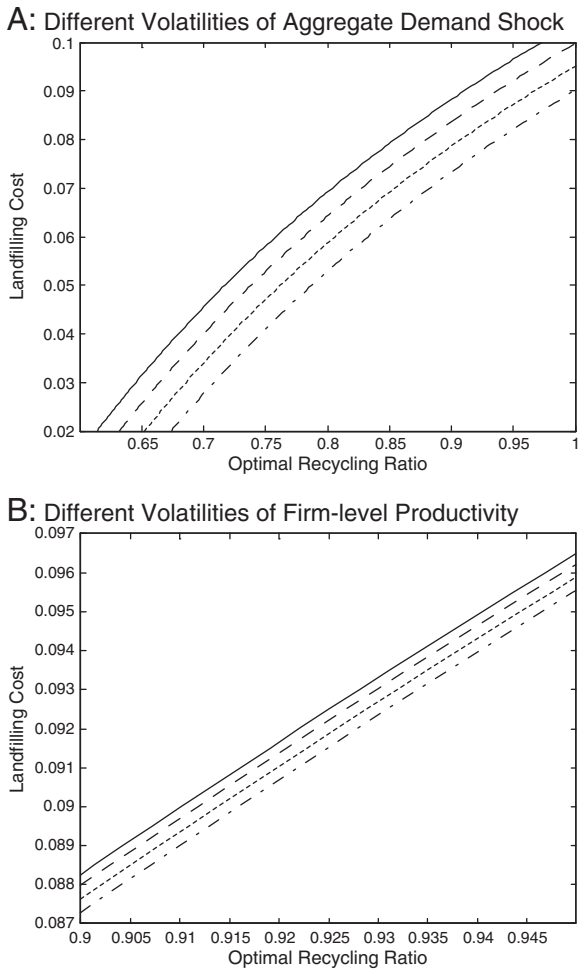

Fig. 4. Optimal recycling ratios as a function of landfilling costs with different volatilities of aggregate demand shocks and firm-level productivity. This figure plots optimal recycling ratios as a function of landfilling costs C_L, ranging from 0.02 to 0.1, with varying volatilities of aggregate demand shock and firm-level productivity in Panels A and B respectively (dash–dot line in Panel A: $\sigma_H = 0.6$, dotted line in Panel A: $\sigma_H = 0.4$, dashed line in Panel A: $\sigma_H = 0.2$, solid line in Panel A: $\sigma_H = 0.0123$, dash–dot line in Panel B: $\sigma_A = 1.1$, dotted line in Panel B: $\sigma_A = 0.8$, dashed line in Panel B: $\sigma_A = 0.5$, and solid line in Panel B: $\sigma_A = 0.2574$). The combination of parameter choices is based on the base case.

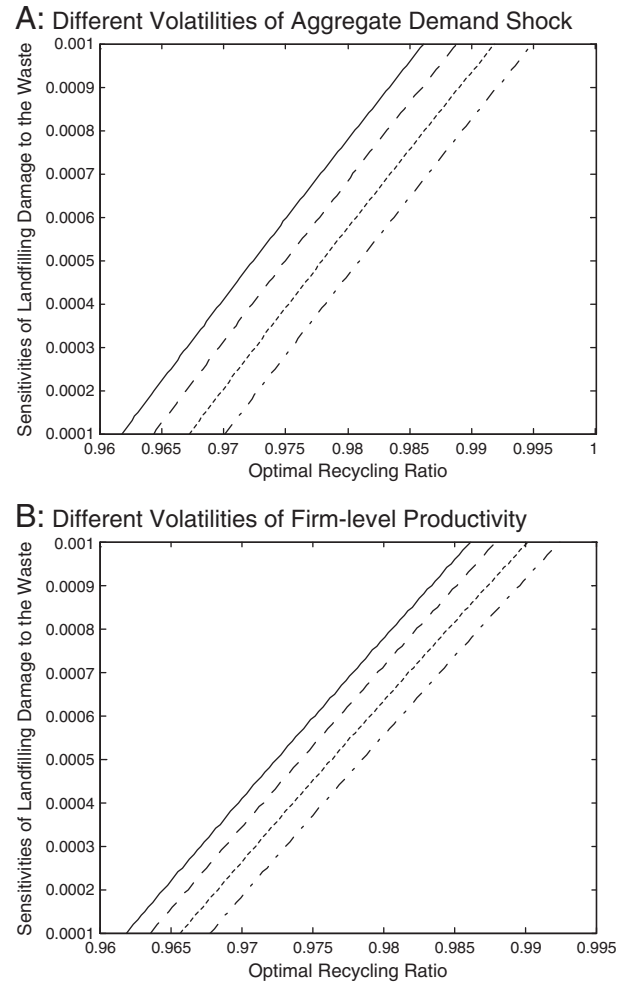

Fig. 5. Optimal recycling ratios as a function of sensitivities to landfilling damage with different volatilities of aggregate demand shocks and firm-level productivity. This figure plots optimal recycling ratios as a function of sensitivities to landfilling damage λ_1, ranging from 0.0001 to 0.001, with varying volatilities of aggregate demand shock and firm-level productivity in Panels A and B respectively (dash–dot line in Panel A: $\sigma_H = 0.07$, dotted line in Panel A: $\sigma_H = 0.05$, dashed line in Panel A: $\sigma_H = 0.03$, solid line in Panel A: $\sigma_H = 0.0123$, dash–dot line in Panel B: $\sigma_A = 1.1$, dotted line in Panel B: $\sigma_A = 0.8$, dashed line in Panel B: $\sigma_A = 0.5$, and solid line in Panel B: $\sigma_A = 0.2574$). The combination of parameter choices is based on the base case.

An efficient waste management policy ensures that an appropriate ratio between the use of recycling and landfilling is achieved such that costs can be minimized while maintaining efficiency. Figs. 3 and 4 exhibit optimal recycling ratios as functions of recycling and landfilling cost respectively. In light of Fig. 3, along with the recycling cost, as volatilities σ_h and σ_A go up, the waste management policy shifts the recycling level to a higher ratio, thus ensuring optimality. In addition, with smaller recycling costs, more waste recycling will be used to fulfill the profit-maximizing objective. Fig. 4 depicts the relationship between landfilling costs and recycling levels. Obviously, more recycling is preferred if landfilling costs increase. Further, volatilities σ_h and σ_A induce risks into waste management; as they rise, recycling, which is a more profitable method than landfilling, must increase to compensate for these associated risks such that profit is maximized.

Lastly, we investigate the optimal recycling ratio as a function of sensitivities to landfilling damage as in Fig. 5. It appears that complementary risks induced by σ_h and σ_A cause recycling levels to increase. In accordance, higher sensitivities to landfilling λ_1 lead to higher risks of environmental damage. Therefore, it is intuitive for the level of recycling to increase with λ_1, such that environmental damage can be minimized, ensuring profitability maximization of the waste management policy, in both the economical and environmental senses.

3.2. The implication of macroeconomic effects

Based on these figures, the effect of macroeconomic conditions on the optimal recycling ratio is clear and significant. Recycling levels increase in the presence of higher aggregate demand shock volatilities and firm-level recycling productivity. This implies that waste management policies for determining optimal recycling levels, absent of macroeconomic conditions as predicted by earlier studies, may have been underestimated. In brief, our results suggest that recycling more waste is both necessary and beneficial while neglecting macroeconomic effects leads to an underestimation of optimal recycling ratios.

4. Conclusion

This research examined optimal waste management policies for determining recycling and landfilling levels in the presence of macroeconomic conditions. The model proposed extends the frameworks

of earlier studies (Highfill and McAsey, 1997; Huhtala, 1997; Costi et al., 2004) by incorporating industrial demand–supply dynamics (Miao, 2005; Hackbarth et al., 2006) into the recycling–landfilling decision problem. The modeling of macroeconomic states captured aggregate and idiosyncratic shocks simultaneously, assuming they follow geometric Brownian motion. The decision variable of analysis was the ratio of recycling to total waste, and optimization was achieved by fulfilling the value-maximizing objective. The paper employed Girsanov's theorem and Leibnitz's rule via the martingale method in the mathematical derivation to solve the optimal recycling ratio. The explicit solution of the optimal ratio has rich testable implications.

Numerical results amply reveal the positive significance of macroeconomic conditions in deriving optimal waste management policies. We show that, if macroeconomic effects are neglected, optimal recycling ratios are normally underestimated. In other words, the recycling levels predicted by existing models appear insufficient for reflecting the real demand behind efficient solid waste management. Such a finding is consistent with current trends in mainstream global environment protection policy, relentlessly stressing that more recycling is always beneficial and less landfiling is definitely required. The comparative static analysis presented here reveals that the optimal recycling ratio increase with waste collection, landfilling costs, and sensitivities to landfiling damage, but decreases with recycling costs. This makes intuitive sense, with implications that are expected to be helpful in attaining effective recycling targets.

This research can be applied in several dimensions. Empirical analysis of optimal recycling policies based on macroeconomic data can be studied. More difficult extensions would include dynamic waste management policies under stochastic environments or optimal consumption–waste–investment policies. It is hoped that future studies and applications will be devoted to this subject.

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