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Economic Efficiency of Compost Production: The Case of Israel

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by

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Abstract

This paper presents a comprehensive economic analysis of recycling organic wastes through composting. A mathematical programming model is developed to examine the optimal level of compost production from sources of organic municipal solid waste, livestock manure and wastewater-treatment sludge. The model incorporates the spatial nature of the problem by referring to the locations of the sources for raw organic matter, of the composting plants and agricultural regions. Agricultural demand for compost is derived using estimated production functions for 42 crops, price elasticity of the vegetative agricultural outputs, and farmers' stated willingness to utilize compost. The model accounts for the costs of waste collection, compost production, transportation and landfilling; all include both direct costs and externalities. The optimal allocation of raw materials and outputs is achieved when the financial contribution of the composting system is maximized relative to the alternative of disposing of these organic wastes in landfills.

We apply the model to the case of Israel. Today, despite the relatively high levels of organic material in municipal solid waste, the scarcity of landfill sites, and the low level of organic content in agricultural soils, only 37% of Israel's composting potential is realized. Subject to compliance with new environmental regulations, our analysis points to the possibility of an 89% composting rate, in which all livestock manure and sludge are composted, but only 75% of the organic municipal solid waste is utilized in this manner. This finding supports the strict enforcement of these environmental regulations, and indicates the need for a composting encouraging policy. However, regulations aimed at increasing the rate of municipal solid waste recycling should leave enough freedom for municipalities to select their waste disposal strategies. It is also concluded that, given the high costs of separating municipal waste at the source, the government can increase composting rates by initializing and stimulating the formation of regional cooperation to ensure steady long run consumption of raw organic materials. Moreover, the government can increase agricultural demand for compost by both setting clear standards for high quality compost, and spreading the scientific information on the advantages of composting via the governmental agricultural instruction system.

The presented methodology is applicable to other cases, as is the scientific-based data, which include the external costs and the compost production functions. This information is relevant for regions facing the same challenges, particularly where the soil's organic content is less than 2%; e.g., Portugal, Spain, Italy and Greece.

Key words

Compost, Economics, Livestock-Manure, Mathematical-Programming, Municipal-Solid-Waste, Waste-Water-Treatment-Sludge.

Economic Efficiency of Compost Production: The Case of Israel

I. Introduction

Most of the national strategies for the reduction of biodegradable municipal waste going to landfills, set up according to Article 5(2) of the EU Directives (EU website), stress the importance of composting organic municipal solid waste (OMSW), and of using source separation to obtain high quality compost. Yet, the extent to which the composting of OMSW is economically justifiable depends on various factors influencing the compost supply and demand curves. On the demand side there is the compost's contribution to agricultural production, as well as the savings realized by avoiding landfilling. The supply depends on the production and transportation costs associated with the compost produced, not only from OMSW, but also from alternative sources for organic matter, such as livestock manure (LM) and wastewater treatment sludge (WTS). In addition, from a social point of view, one should take into account a variety of environmental effects (Ayalon et al., 2000, 2001), as well as the impact of internalizing externalities by regulations.

There is a vast scientific information on various aspects of organic waste treatment and its agricultural use; e.g., logistic processes (Chakrabarti and Sarkhel, 2003), air pollution (He et al., 2001), compost productivity (Avnimelech, 1997), and socio-economic aspects (Hayashi et al., 2004, Janzen et al., 1999). Each of these studies considers some of the elements associated with the question raised in this study: to what extent is it economically worthwhile to use composting as a solution for organic waste disposal? In effect, to the best of our knowledge there is, as yet, no comprehensive economic analysis of organic waste recycling through composting that (1) encompasses the main types of competing sources for organic raw materials, (2) explicitly incorporates the agricultural demand for compost, (3) considers costs associated with alternative disposal methods, (4) includes the external costs caused by each of the relevant components, and

(5) takes into account the spatial nature of the problem. This paper presents an economic analysis that encompasses all these elements, and applies it to the case of Israel.

Composting seems a promising disposal solution in Israel: first, OMSW comprises 40% of the total municipal solid waste (MSW) produced; second, landfill volume is expected to be exhausted by the year 2014 (Hoshva, 2005); and third, in this semi-arid region compost productivity is high due to the low soil-organic content. The purpose of our analysis is to examine the economical feasibility of recycling organic materials from sources of MSW, LM and WTS. To this end, we develop a mathematical programming model, in which the viability of recycling is examined relative to the alternative of disposing of these organic wastes in sanitary landfills - the cheapest disposal alternative.

II. Organic Waste Management in Israel

The Israeli system of organic materials management is in a transition period, where new strict environmental regulations are taking place. Our analysis assumes that these regulations are fully enforced.

The local authorities are required to recycle MSW by regulation (MoE, 1998). Consequently, the amount of recycled OMSW has been increased from approximately 48,000 tons in 1998 to almost 200,000 tons in 2004. This is about 14% of the total OMSW, which amounts to 1.47 million tons per year. However, in all sites organic waste is separated by a revolving drum screen, so that small inorganic items slip through, and reduce the quality of the product, which is therefore sold at a price of only $15 per ton. Home production does not constitute a significant source for compost (Afik and Lavee, 2000).

At present about 370,000 tons of compost are produced annually from LM in official sites. Gate prices for compost range between $38 and $45 per ton. In addition, production by farmers is estimated at 50,000 tons a year, mainly from cow manure mixed with 10% chicken manure

(Afik and Lavee, 2000). In 1999, a reform was instituted in the milk industry, according to which all the manure (1.40 million tons/year) will reach organized facilities (Zadikov, 2005).

The Israeli new regulations for disposal of WTS (December 2003) require treating the entire amount of WTS so it reaches the level of sludge Class A according to the EPA directive (EPA 2006), which implies no limitations on agricultural application. Today, about 16,000 tons of sludge are treated to the Class A level, and sold for nearly $11 per ton (Zadikov, 2005). In our analysis we assume that all the sludge will be thickened and squeezed to 20% solids (altogether nearly 111,000 ton/year) before it is directed to either landfills or composting plants.

According to the aforementioned numbers and transformation coefficients the total potential production of compost throughout the country amounts to 1.7 million tons/year, while the current aggregated annual compost production is around 570,000 tons. Excluding gardening consumption, the amount currently used by the agricultural sector is about half a million tons per year.

III. The Programming Model

The model takes into account the spatial distribution of the sources of organic wastes, of the composting plants and of the agricultural regions in which compost may be applied; all of them are presented in Figure 1. Fourteen groups of urban and rural settlements are the sources of OMSW and WTS, respectively. Each settlements group (SG) is characterized by the quantity of OMSW and WTS produced there, and a geographic location represented by the center of the group's largest city. We consider 13 agricultural regions of demand for compost based on data reported by the Central Bureau of Statistics (CBS, 2004). Each region is characterized by a point located at its geographic center, and by the different crops grown there; all together we consider 42 crops. The agricultural regions also constitute sources for LM. Compost is assumed to be produced at eight plants, where some of them are existing plants. Since the process of collecting the OMSW is based on separation at the source, the model does not incorporate sorting plants.

The objective of the model is to optimize the allocation of the organic wastes to the compost plants, the compost produced in the plants to the agricultural regions, and the distribution of the compost to the various crops grown there. Altogether there are 978 variables. The optimal allocation is achieved when the financial contribution of the composting system is maximized relative to the alternative of disposing of these organic wastes in landfills.

For the purpose of brevity, we base the formal presentation of the model on Table 1, which summarizes all the definitions and symbols of the model's elements. The table also indicates the main parameter values and includes references to the relevant tables. Data are for 2003, and all monetary values are in terms of July 2004 US dollars.

The objective function, Π (\$/year), is:

$$
\begin{aligned}
\Pi = & \sum_{k=1}^{K}\sum_{m=1}^{M} g_{km}\, p_m(Y_m, \hat{p}_m)\cdot y_{km}\cdot\left[v_{1km}(a_{km}-\bar{a}_{km}) + v_{2km}\left(a_{km}^2-\bar{a}_{km}^2\right)\right] \\
& + \sum_{i=1}^{I}\beta_i^w \sum_{j=1}^{J} w_{ij} + \sum_{k=1}^{K}\beta_k^l \sum_{j=1}^{J} l_{kj} + \sum_{i=1}^{I}\beta_i^s \sum_{j=1}^{J} s_{ij} \\
& - \phi^w \sum_{i=1}^{I}\sum_{j=1}^{J} w_{ij} - \phi^l \sum_{k=1}^{K}\sum_{j=1}^{J} l_{kj} + \phi^s \sum_{i=1}^{I}\sum_{j=1}^{J} s_{ij} - \alpha_1^w \sum_{i=1}^{I}\sum_{j=1}^{J} w_{ij} - \alpha_2^w \sum_{i=1}^{I}\sum_{j=1}^{J} d_{ij} w_{ij} \\
& - \alpha_1^{lc} \sum_{k=1}^{K}\sum_{j=1}^{J} l_{kj} - \alpha_2^{lc} \sum_{k=1}^{K}\sum_{j=1}^{J} d_{jk} l_{kj} - \alpha_1^s \sum_{i=1}^{I}\sum_{j=1}^{J} s_{ij} - \alpha_2^s \sum_{i=1}^{I}\sum_{j=1}^{J} d_{ij} s_{ij} - \alpha_1^c \sum_{j=1}^{J}\sum_{k=1}^{K} c_{jk} - \alpha_2^c \sum_{j=1}^{J}\sum_{k=1}^{K} d_{kj} c_{jk} \\
& - \eta_1 \sum_{j=1}^{J}\delta_j - (\eta_2+\eta_3)\sum_{j=1}^{J}\sum_{k=1}^{K} c_{jk}
\end{aligned} \quad . \qquad (1)
$$

In (1), $p_m(Y_m, \hat{p}_m)$ represents the output price. To account for price elasticity we let $p_m(Y_m, \hat{p}_m) = \mu_m^1 + \mu_m^2 Y_m + \mu_m^2 \hat{p}_m$ be the demand function of crop *m*, where $Y_m = \sum_{k=1}^{K} g_{km} y_{km}\left[v_{1km}(a_{km}-\bar{a}_{km}) + v_{2km}\left(a_{km}^2-\bar{a}_{km}^2\right)\right]$ is the nationwide production of crop *m*, and

$$\hat{p}_m = \frac{\sum_{k=1}^{K}\sum_{n=1}^{M} \rho_n^m g_{kn} p_n(Y_n, \hat{p}_n) y_{kn}\left[v_{1kn}(a_{kn} - \bar{a}_{kn}) + v_{2kn}\left(a_{kn}^{\ 2} - \bar{a}_{kn}^{\ 2}\right)\right]}{\sum_{k=1}^{K}\sum_{n=1}^{M} \rho_n^m g_{kn} y_{kn}\left[v_{1kn}(a_{kn} - \bar{a}_{kn}) + v_{2kn}\left(a_{kn}^{\ 2} - \bar{a}_{kn}^{\ 2}\right)\right]}$$

, $n \neq m$, is the average price of crop-m's substitute products; ρ_n^m is an indication factor, which is equal to one for substituting crops, and zero otherwise; the demand function intercept, μ_m^1, is net of yield-quantity-dependent costs.

The term in the square brackets in (1) represents the annual rate of yield increase achieved as a result of the application of compost in an annual amount of a_{km} tons per 1000 m^2, relative to the actual observed yield, y_{km}, which is associated with the observed compost application, $\bar{a}_{km}$. This quadratic production function was chosen because 1) it fits well the results of field experiments conducted on several crops, and 2) this formulation enables using these experimental findings to estimate responses of other crops, for which such experiments were not performed.

The objective function is to be maximized subject to the $k \times m$ agricultural application constraints $a_{km} \leq A_{km}$; k compost supply constraints $\sum_{m=1}^{M} g_{km} a_{km} \leq \sum_{j=1}^{J} c_{jk}$; j organic wastes supply constraints $\sum_{k=1}^{K} c_{jk} \leq \gamma^{wl}\left[\sum_{i=1}^{I} w_{ij} + \sum_{k=1}^{K} l_{kj}\right] + \gamma^{wl}\sum_{i=1}^{I} s_{ij}$; $3 \times j$ plant capacity constraints $\sum_{i=1}^{I} w_{ij} \leq C_j^w$, $\sum_{k=1}^{K} l_{kj} \leq C_j^l$, and $\sum_{i=1}^{I} s_{ij} \leq C_j^s$; $2i+k$ organic materials availability constraints $\sum_{j=1}^{J} w_{ij} \leq W_i$, $\sum_{k=1}^{K} l_{kj} \leq L_k$ and $\sum_{j=1}^{J} s_{ij} \leq S_i$; and non-negativity constraints with respect to all the variables; altogether there are 1,610 constraints. Note that internal solution to this problem depends on the values associated with the compost contribution to agricultural income, which is the single non-linear element in the model.

IV. Production Functions

A key element in our model is the response of yields to compost application, which creates the incentive for the composting disposal alternative. As aforementioned, with the appropriate assumptions, the quadratic function in (1) can be adjusted for a large number of crops based on experimental results associated with only a few crops. The following is a description of the procedure used for this purpose. For tractability purposes, we have omitted the region index.

The procedure is based on two assumptions: (I) all the crops belonging to a predefined group of crops are characterized by an identical rate of change in yield with a change in the amount of compost applied, relative to the situation in which no compost is applied at all; (II) the level of annual yield per 1000m^2, y_m, reported by the CBS for each crop, is based on conditions under which a known amount of compost is applied, $\overline{a}_m$.

Assuming that we have field experiment findings for a given crop, *m*, it is possible to estimate the following quadratic function:

$$f^m(a_m) = \theta_0^m + \theta_1^m a_m + \theta_2^m {a_m}^2, \qquad (2)$$

where $f^m(a_m)$ is the level of yield and θ_0^m, θ_1^m and θ_2^m are crop specific parameters. The CBS reports an average yield, y_m, where $y_m = f^m(\overline{a}_m) = \theta_0^m + \theta_1^m \overline{a}_m + \theta_2^m {\overline{a}_m}^2$. From this expression we isolate θ_0^m, substitute into (2), and rearrange to get the rate of yield change resulting from applying the amount of a_m of compost relative to the situation in which $\overline{a}_m$ is applied:

$$\frac{f^m(a_m) - y_m}{y_m} = \frac{\theta_1^m}{y_m}(a_m - \overline{a}_m) + \frac{\theta_2^m}{y_m}\left({a_m}^2 - {\overline{a}_m}^2\right). \qquad (3)$$

We define $\frac{\theta_1^m}{y_m} = v_1^m$ and $\frac{\theta_2^m}{y_m} = v_2$. Assume now that we have the value y_n, which represents the average annual yield per 1000m^2 achieved in some crop, *n*, $n \neq m$, given that the amount $\overline{a}_n$

is applied. If crops m and n belong to the same group of crops for which, according to (I), there is $v_1^m = v_1^n$ and $v_2^m = v_2^n$, then, the yield increase of crop n as a result of applying compost in quantity a_n relative to the yield obtained when the amount $\overline{a}_n$ is applied, $f^n(a_n) - y_n$, can be calculated according to:

$$f^n(a_n) - y_n = y_n\left[v_1^m(a_n - \overline{a}_n) + v_2^m\left(a_n{}^2 - \overline{a}_n{}^2\right)\right] . \qquad (4)$$

According to (II), the CBS data provide us with a value of y_m obtained for a known level of $\overline{a}_m$. Thus, we reach the response function in equation (1).

In order to perform this procedure, the crops must be grouped according to (I), so that there is at least one crop in each group for which field experiments have been conducted. In order to neutralize the effect of variance related to climate and soil factors, we chose to base the estimation on the findings of field experiments conducted in areas with climate conditions as similar as possible to that of Israel. Sources that report on yield response to application of compost were found for corn (Avnimelech et al., 1990; Mor et al., 1990), wheat and clover (Agassi et al., 2004), potatoes (Fine et al., 2003; Avnimelech et al., 1996), broccoli (Jackson et al., 2004; Perez-Murcia et al., 2006), strawberries (Arancon et al., 2004), olives, oranges and grapevines (Aguilar et al., 1997) and for sunflowers and watermelons (Izencot and Zilberman, 2004). Table 2 summarizes the estimated parameters v_1 and v_2 for these representative crops. When available, allocation into groups was based on botanical families, where all other crops were divided according to a classification of 'trees' and 'non-trees.'

Nationwide estimations for observed compost applications, $\overline{a}_m$, and maximum applications, A_m, are based on findings of a survey conducted by Afik and Lavee (2000), who studied actual compost practices in Israel and farmers' willingness to utilize compost. According to their $\bar{a}_m$ values, current agricultural compost application, $\sum_{k=1}^{K}\sum_{m=1}^{M} g_{km}\bar{a}_{km}$, amounts to 475,000 tons/year, which is practically equal to the aforementioned 0.5 million tons/year total agricultural consumption, estimated based on recycling data.

V. Economic Data

The model itself and additional data not reported herein are available as an electronic supplementary material to this article. Here we outline the procedures used for estimating the economic parameters.

Demand function coefficients were calculated based on elasticity factors estimated by Hadas (2001) for the internal Israeli consumption of vegetative agricultural products, and by Kachel (2004) for the major Israeli exported crops. Let, $\bar{p}_m^L$ and $\bar{p}_m^E$ be, respectively, the observed prices of local and exported productions of crop *m*. Define the demand functions $p_m^L(Y_m, \hat{p}_m) = \mu_m^{1L} + \mu_m^{2L} r_m Y_m + \mu_m^{3L}\hat{p}_m$ and $p_m^E(Y_m) = \mu_m^{1E} + \mu_m^{2E}(1 - r_m)Y_m$, where r_m is the observed fraction of crop-*m*'s local consumption. With information on the demand elasticity with respect to the local crop-*m*'s consumption, η_m^{2L}, to the local prices of crop-*m*'s substitutes, η_m^{3L}, and to the exported quantity, η_m^{2E}, we get $\mu_m^{2L} = \frac{\bar{p}_m^L}{r_m Y_m \eta_m^{2L}}$, $\mu_m^{3L} = -\frac{\eta_m^{3L} r_m Y_m \mu_m^{2L}}{\bar{p}_m^L}$ and $\mu_m^{2E} = \frac{\bar{p}_m^E}{r_m Y_m \eta_m^{2E}}$. Given these, and the costs dependent upon yield levels, ψ_m, the coefficients μ_m^1, μ_m^2 and μ_m^3 can be calculated by substituting into the expression $p_m(Y_m, \hat{p}_m) = r_m p_m^L(Y_m, \hat{p}_m) + (1 - r_m)p_m^E(Y_m) - \psi_m$.

A survey among waste transport contractors provided data for estimating transportation costs parameters of MSW. Transportation costs of compost, LM and WTS were estimated based on Pluda (2002). In all cases we add external costs of \$0.008/ton-km (EMC, 1996) to the distance dependent parameter. The unit cost of landfilling raw materials, β_i^w, β_k^l and β_i^s, were calculated for each source as the sum of the cost of transporting to, and of dumping at the landfill which currently associated with the source. Costs at the landfills include gate price and external costs of $1.77/ton, as estimated by EMC (1996).

A significant element in the analysis is the additional cost of collecting and separating the organic component of the municipal domestic waste - ϕ^w. Our estimation relies upon two sources: 1) Kahat et al. (1999) have estimated the average collection costs in Israel, without separation at the source, to be $41/ton; 2) Eunomia (2005) have surveyed costs of collecting waste in five cities in Italy, where separation at the source takes place. A multivariate regression indicates that the cost of collecting a ton of separated waste is 102 Euro/ton (P value = 0.03), while the cost of collecting non-separated waste is 53 Euro/ton (P value = 0.06). Hence, separation increases costs by 91%; utilizing Kahat's datum we get $\phi^w =$ $37.1/ton. Pretreatments of LM and WTS were assumed negligible; i.e., $\phi^l = \phi^s = 0$.

Calculations of η_1 and η_2, the compost production costs, are based on Pluda's work (2002). The variable cost, η_2, includes external cost associated with N_2O emissions, which is equal to the emission of 11 grams per ton (Avnimelech et al., 2005), multiplied by the damage of $11.2 per kg of N_2O (Eshet et al., 2005); this amounts to $0.12 per ton of compost. The cost involved in applying the compost in the field, η_3, is estimated at $4.5/ton.

The quantities of SG's OMSW, W_i, were calculated according to CBS (2004) data on the MSW production by cities. LM productions, L_k, were estimated based on the annual production of milk, eggs, chickens, turkeys, heads of sheep for milk, and heads of calves for meat (CBS, 2004); all of these were converted to amounts of manure according to conversion coefficients (Afik and Lavee, 2000; Pluda, 2002). Amounts of WTS, S_i, are from Zadikov (2005).

VI. Results

The mathematical programming model was formulated on an Excel spreadsheet, and run by means of the Premium Solver Platform V6.5 manufactured by Frontline Systems, Co., using the Large-Scale Generalized Reduced Gradient engine.

The analysis indicates that it is economically feasible to recycle all of the LM (about 1,440,000 tons/year), all the WTS (111,000 tons/year), but only 75% of the OMSW; i.e., 1,108,000 tons/year of the total amount produced in the country, 1,470,000 tons/year. Table 3 presents the model's compost productions in comparison to the potential and the current production levels. The explanation for this finding is simple: LM and WTS constitute cheaper raw materials, because the cost of supplying them does not necessitate separation costs.

The optimal allocations of raw organic materials to the compost plants, and of the compost produced there to the agricultural regions, are presented by three-dimenssional diagrams in Figure 2. Sources and destinations are ordered from north to south, such that along the diagonal distances are the shortest. The figure shows that, as expected, factories get organic materials from sources nearby, and allocate the compost to the agricultural regions in their surroundings. It was found that the maximal return is achieved when we refrained from using a compost plant in Tuvlan. In addition, it is not worthwhile to send OMSW to the Duda'im plant in the south and to Shazarim in the north; they should receive only LM and WTS as their raw materials. The plant in Kalansuwa should receive OMSW and WTS, but not LM. As to the sources of OMSW, it is not economically worthwhile to recycle the OMSW from the northern SGs of Kiryat-Shemona, Zefat, and Tiberius, from Jerusalem in the center of Israel, and from Ashkelon and Be'er Sheva in the south; these settlements would do better by shipping their OMSW to landfills.

The total amount of compost produced is 1,530,000 tons/year (89% of the potential quantity) and the value of the objective function is $88,576,000/year. This value expresses the financial return to the Israeli economy from the composting array relative to sending the organic wastes to landfills. Table 4 presents the benefits and costs comprising this return. On the benefits side, the contribution of compost to agricultural production constitutes about two thirds of the total, while the rest is attributed to the savings on landfill costs. The most prominent element among the cost components is the added cost due to separation at the source, which comprises one third of the total costs.

Our analysis points to an internal solution with respect to the utilization of OMSW for compost production. Considering the market for compost, this implies that the nationwide compost demand and supply curves intersect at the optimal compost production level, 1,530,000 tons/year. To illustrate this we calculate the compost's value of marginal production (VMP) and the Marginal Costs (MC) curves by rerunning the model, while in each run the compost production amount is imposed; Figure 3a shows the resultant curves. The VMP curve is an estimation of the agricultural sector demand curve, and it represents the marginal increase in agricultural revenue minus the compost marginal application costs. All the other model's elements are incorporated into the MC curve; that is, savings on landfill costs are considered negative costs. The VMP* (bold dashed) curve in Figure 3a is calculated for fixed agricultural output prices; i.e., $p_m = r_m \overline{p}_m^L + (1 - r_m)\overline{p}_m^E - \psi_m$. The fact that the VMP* curve lays below the VMP curve calculated based on the demand functions $p_m(Y_m, \hat{p}_m)$, indicates that, in the latter, the effect of the prices of substituting crops, $\hat{p}_m$, exceeds the impact of the self output quantity, Y_m. Based on the VMP* curve the optimal compost production is lower, and amounts to only 1,260,000 tons/year.

In Figure 3b, 3c and 3d we break the MC curve into its components, and separate the production according to the three raw materials, OMSW, LM and WTS, respectively. It can be clearly seen that first LM is utilized as a raw material, then WTS, and finally OMSW, where each one enters into production only when the former is exhausted. Marginal transportation costs fluctuate and actually play a relatively minor role in determining the spatial order of raw materials utilization. Landfill costs, however, constitute an important factor, particularly with respect to LM and OMSW, where sources with high landfilling costs are used first.

Potato is the crop with the lowest VMP to which compost is applied, \$22.1/ton. Under equilibrium, this is the price expected for compost in the regions where potato is grown and do receive compost: Golan, Western Galil, Haifa and the Jordan Valley (Regional VMP values are calculated based on the VMP* function, assuming that farmers take prices as given). The second lowest VMP crop is marrow in the Galil with \$43.5/ton; then, watermelon sets an equilibrium price of \$44.0/ton in the regions Yizre'el Valley, Lower Galil, Hasharon, Center, Ashkelon and Yehuda. In Arad there is onion with \$49.2/ton, and finally almond in the Negev-Arava region, \$54.5/ton. Table 3 shows that these prices are quite similar to current actual prices of high quality compost produced from LM. Based on these prices we calculate the total annual expenditures for farmers to purchase the compost at \$61.7 million. Using Table 4, the annual consumers' surplus amounts to about \$34.5 million, which on average is \$22.5 per ton of compost. This increase in farmers' profits constitutes about 20% of the total vegetative agricultural net income in Israel.

The settlements bear all the costs associated with supplying the separated OMSW, and therefore expect to be paid for the materials at the composting plant gate; otherwise, they might prefer the landfill alternative. This payment should cover the cost involved in separating the waste at the source plus the cost of transporting it to the plants, minus the saved landfill costs: a national total of $17.1 million/year. In other words, on average, the price of separated OMSW waste at the composting plant gate should be at least $15.5/ton. With respect to LM and WTS, their alternative disposal costs are $ 21.5 million and $1.8 million per year, respectively; it is therefore expected that suppliers will pay up to these sums to compost producers. Accordingly, average gate prices are $14.9/ton and $16.3/ton for LM and WTS, respectively. Given these numbers, and the expenses detailed in Table 4, the profit of the composting plants operators is $54.0 million per year, which is on average $35.2 per ton of compost.

VII. Conclusions

Our analysis has a few implications in terms of organic waste management and policies. First, we demonstrate that the regulations recently set by the Israeli authorities with respect to the management of LM and WTS, originated primarily for environmental protection considerations, actually create an opportunity for additional benefits if these materials are to be reused within the agricultural production; this potential supports the strict enforcement of these regulations, and also encourages disposal by compostation.

Second, although the relative advantage of LM and WTS as raw materials, it is economically justifiable to reuse most of the OMSW. However, the composting is not worthwhile in all settlements. Therefore, regulations aimed at increasing the rate of MSW recycling should leave enough freedom for municipalities to select their waste disposal strategies. In this regard, a major cost element is the separation of OMSW at the source; this is a prerequisite to the production of high quality compost valuable to the agricultural sector. It is expected that municipalities will adopt this method provided that agreements ensure a steady consumption of the separated materials for the long-run. Since such agreements frequently require the involvement of a few neighboring agricultural enterprises and local authorities, the central government may initiate and stimulate the formation of regional cooperation by creating appropriate economic incentives. For example, our model shows that setting a tax of $25/ton on OMSW landfilling increases the recycling rate of OMSW from 75% to 100%.

Finally, the realization of the aforementioned scenario depends on the agricultural demand for compost, which depends on the recognition by farmers of the benefits of compost application. In our analysis we take into account both the scientific data on compost productivity and the real-world farmers' conceptions about compost application. However, the latter is based on a survey of farmers' stated willingness to utilize compost rather than on observed actual consumption. It appears that this willingness is highly dependent on the quality of the compost and on recommendations by the authorities (Afik and Lavie, 2000). Therefore, the government can play a major role in increasing the demand for compost by both setting and enforcing clear standards for high quality compost, and by spreading the scientific information on compost advantages through the governmental agricultural instruction system.

How applicable is this analysis to other cases throughout the world? At the heart of the programming model is the compost production function, which is based on data collected from the scientific literature. This information can be used in similar analyses with respect to regions facing the same challenges, particularly areas where the percentage of organic matter in the soil is less than 2%; e.g., Portugal, Spain, Southern France, Italy and Greece (Zdruli et al., 2004). Our estimation of the compost's VMP is based on elasticities of demands for agricultural products, as well as on farmers' stated willingness to utilize compost; both are specific to the case of Israel. Most of the external costs are transferable, whereas other economic data are mainly from official reports by governmental agencies, and therefore are case specific.

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Table 1: Symbols of Indices, Parameters and Variables in the Model

Symbol	Description	Units	Value/Reference
Sets			
i	Settlements groups (i = 1,…,I)		I = 13
j	Compost plants (j = 1,…,J)		J = 8
k	Agricultural regions (k = 1,…,K)		K = 14
m	Crops (m = 1,…,M)		M = 42
Parameters			
g_{km}	Area of land allocated to crop m in region k	$1000m^2$	Appendix 1[a]
y_{km}	Average yield per $1000m^2$ as reported by the CBS, for application of $\bar{a}_{km}$ tons of compost.	ton/$1000m^2$–year	Appendix 3[a]
μ_m^1	Intercept coefficient of crop-m's demand function net of yield-quantity-dependent costs	\$/ton_{yield}	Appendix 4[a]
μ_m^2	Quantity coefficient of crop-m's demand function	\$/$(ton_{yield})^2$-year	Appendix 4[a]
μ_m^3	Substitute's price coefficient of crop-m's demand function	-	Appendix 4[a]
v_{1km}	Linear coefficient of rate of yield increase achieved by applying the amount of compost a_{km} relative to yield obtained under application of the amount $\bar{a}_{km}$ of compost	ton_{yield}/ ($ton_{compost}$ × $ton_{yield\text{-}without\text{-}compost}$)	Table 2
v_{2km}	Quadratic coefficient of rate of yield increase achieved by applying the amount of compost a_{km} relative to yield obtained under application of the amount $\bar{a}_{km}$ of compost	ton_{yield} / (($ton_{compost})^2$ × $ton_{yield\text{-}without\text{-}compost}$)	Table 2
β_i^w	Cost of landfilling domestic waste in SG i	\$/ton	Appendix 2[a]
β_k^l	Cost of disposing of LM in region k	\$/ton	Appendix 1[a]
β_i^s	Cost of disposing of WTS in SG i	\$/ton	Appendix 2[a]
ϕ^w	Added cost due to separation of domestic waste at the source	\$/ton	37.5
ϕ^l	Added cost for pre composting preparation of LM	\$/ton	0
ϕ^s	Added cost for pre composting preparation of WTS	\$/ton	0
α_1^w	Fixed cost of transporting OMSW	\$/ton	0.79
α_2^w	Distance variable cost of transporting OMSW	\$/ton–km	0.062
α_1^{cl}	Fixed cost of transporting compost or LM	\$/ton	1.57

α_2^{cl}	Distance variable cost of transporting compost or LM	\$/ton–km	0.066
α_1^{s}	Fixed cost of transporting WTS	\$/ton	7.86
α_2^{s}	Distance variable cost of transporting WTS	\$/ton–km	0.32
d_{ij}	Distance between settlement group *i* and plant *j*	Km	Based on data in Appendix 2[a]
d_{jk}	Distance between region *k* and plant *j*	Km	Based on data in Appendices 1&2[a]
η_1	Fixed cost at plant for production of compost	\$/year	79,420
η_2	Variable cost of producing compost from organic materials	\$/ton $_{compost}$	5.2
η_3	Compost application costs in the field	\$/ton $_{compost}$	4.44[b]
$\overline{a}_{km}$	Compost application constraint	ton/1000m^2-year	Appendix 4[a]
A_{km}	Compost application constraint	ton/1000m^2-year	Appendix 4[a]
C_j^{w}	Plant's capacity constraint for organic waste	ton/year	∞
C_j^{l}	Plants' capacity constraint for LM	ton/year	∞
C_j^{s}	Plants' capacity constraint for WTS	ton/year	∞
W_i	Total amount of OMSW produced in SG *i*	ton/year	Appendix 2[a]
L_k	Total amount of LM produced in region *k*	ton/year	Appendix 1[a]
S_i	Total amount of WTS produced in SG *i*	ton/year	Appendix 2[a]
γ^{wl}	Production ratio, by weight – compost/OMSW and compost/LM	-	0.52 (Pluda 2002)
γ^{s}	Production ratio, by weight – compost/WTS	-	1.8[c]
Variables			
w_{ij}	OMSW transported from SG *i* to plant *j*	ton/year	
l_{kj}	LM transported from region *k* to plant *j*	ton/year	
s_{kj}	WTS transported from SG *i* to plant *j*	ton/year	
c_{jk}	Compost transported from plant *j* to region *k*	ton/year	
a_{km}	Compost applied in region *k* to yield *m*	ton/1000 m^2-year	
δ_j	Plant operation logical coefficient	δ_j = 1 if the plant operates; otherwise, δ_j = 0	

a. Appendices are presented in the electronic supplementary material to this article.

b. Bruner, M., Israel Ministry of Agricultural and Rural Development, personal communication, November 2004.

c. Zadikov, I., Israel MoE, Personal communication, June 2005.

Table 2: Estimated Production Function Parameters for Crop Groups

Botanical Family	Representative Crops	Location of experiment	Crops in the Group	Obs.	v_1×100%	v_2×100%
Vitaceae	Grape	Spain	Grape	15	19.11**	-2.30**
Compositae	Sun flower	Israel	Sun-flower, Lettuce, Artichoke	3	8.33 na	-0.86 na
Citrus	Orange	Spain	Orange, Lemon, Grapefruit, Other Citrus	3	14.83na	-2.52na
Cruciferae	Broccoli	California & Mexico	Cauliflower, Cabbage, Radish	5	9.78***	-0.12***
Solanaceae	Potato	Israel	Potato, Pepper, Tomato, Eggplant	4	3.17***	na
Oleaceae	Olive	Spain	Olive	9	15.23***	na
Papilionaceae	Clover	Israel	Alfalfa, Ground nut, Bean, Chick Pea, Pea	3	6.17na	-0.19 na
Gramineae	Wheat	Israel	Wheat, Barley	3	11.47na	-0.42 na
Gramineae	Corn	Israel	Corn	5	3.03**	-0.18*
Cucurbitaceae	Watermelon	Israel	Watermelon, Melon, Marrow, Cucumber	2	2.44na	na
Trees	Orange	-	Plum, Avocado, Almond, Apple, Pear, Peach, Banana	3	14.83na	-2.52na
Non-trees	Sun-flower, Broccoli, Potato, Clover, Wheat, Corn, Watermelon	-	Celery, Carrot, Cotton, Onion, Garlic, Strawberry	19	5.60**	-0.04***

* = significant at 10%, ** = significant at 5%, *** = significant at 1%, na = not available

Table 3: Compost production and prices.

	Compost production (ton/year)			Compost prices ($/ton)	
Source	***Potential***	***Current***	***Model***	***Current***	***Model***
OMSW	770,000	200,000	580,000	15	
LM	750,000	420,000	750,000	38 - 45	
WTS	200,000	30,000	200,000	11	
All	1,720,000	570,000	1,530,000		22 - 54

Table 4: Benefits and costs under optimal management

Benefits	**$/year**
Revenue increase in agriculture	103,121,000
Savings on OMSW landfilling	27,211,000
Savings on LM landfilling	25,857,000
Savings on WTS landfilling	3,673,000
Total benefits	159,862,000
Costs	
OMSW separation at the source and collection	41,556,000
LM preparation	0
WTS preparation	0
OMSW transportation	2,785,000
LM transportation	4,335,000
Sludge transportation	1,862,000
Compost variable production costs	7,966,000
Compost fixed production costs	556,000
Compost transportation	5,405,000
Compost application in the field	6,821,000
Total costs	71,286,000
Net benefits	**88,576,000**

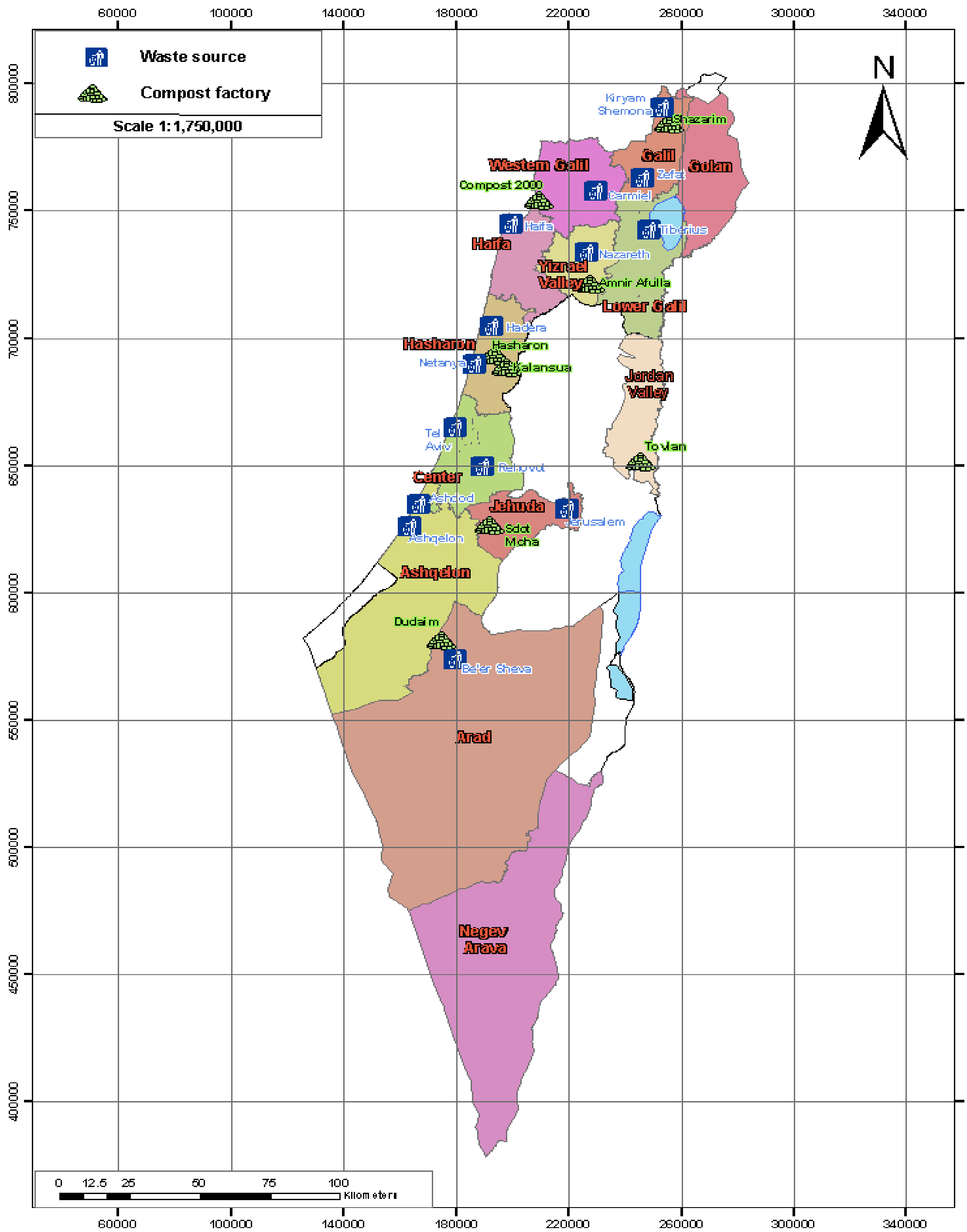

Figure 1: Groups of Settlements, Compost Factories and Agricultural Regions

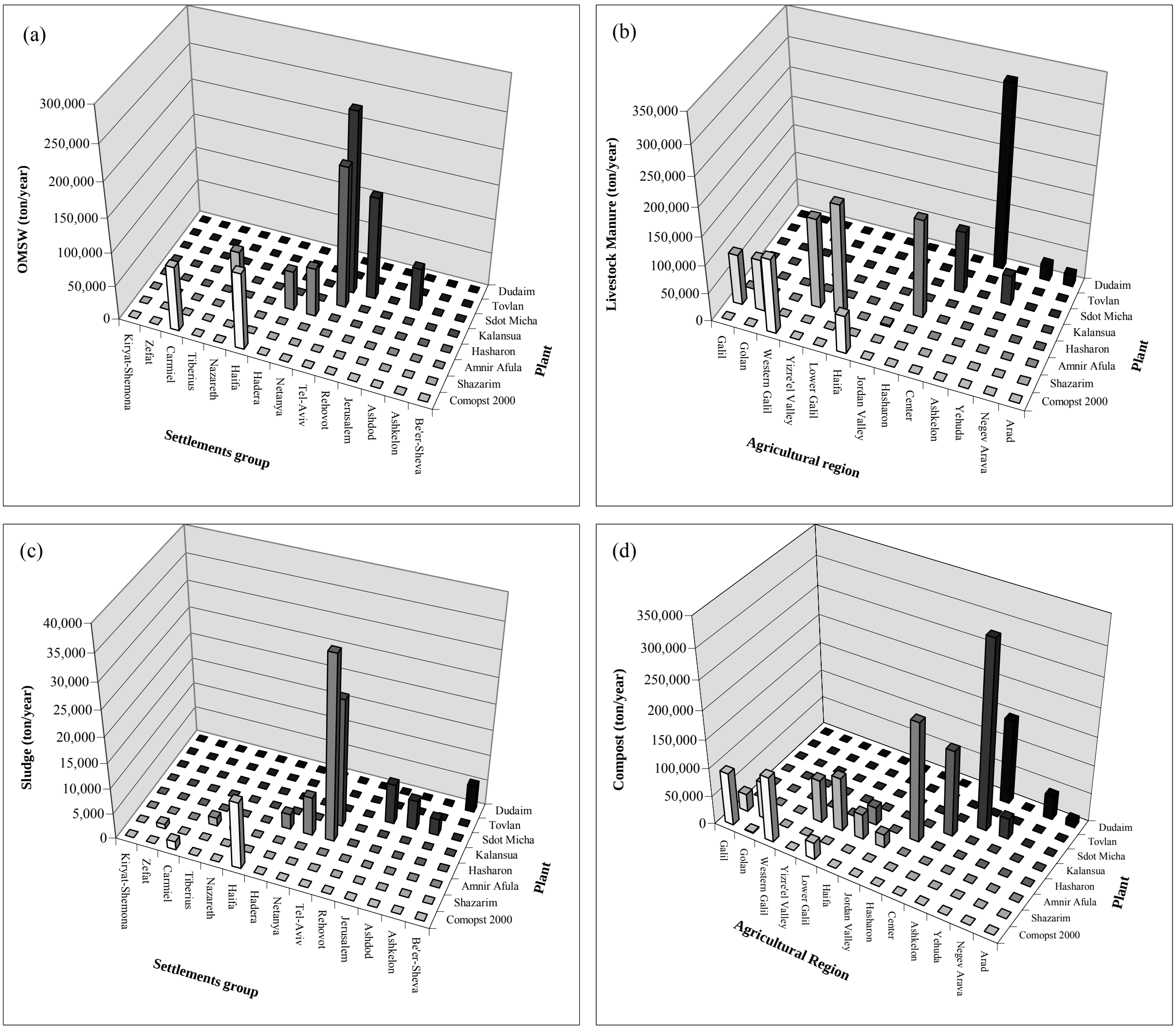

Figure 2: Optimal allocation of (a) OMSW, (b) LM, and (c) WTS to compost plants, and (d) optimal allocation of compost to agricultural regions

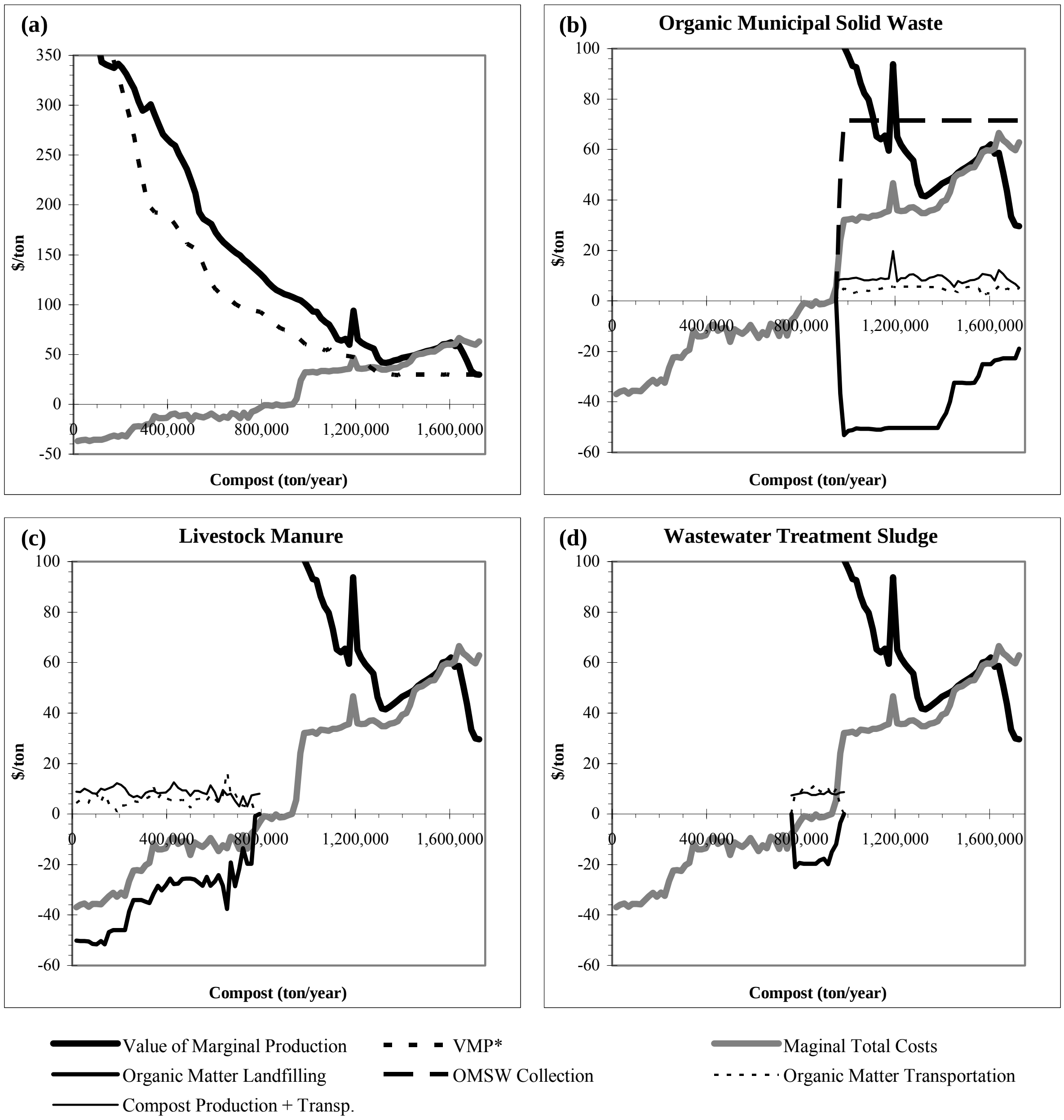

Figure 3: (a) Value of marginal production under varying and fixed prices, and marginal total costs; marginal organic matter landfilling costs, marginal OMSW collection costs, marginal organic matter transportation costs, and marginal compost production + transportation costs for (b) OMSW, (c) LM and (d) WTS.

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