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A REVIEW OF RECENT EXTENSIONS OF LINEAR ECONOMIC MODELS TO REGIONAL ENVIRONMENTAL QUALITY ANALYSIS

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ABSTRACT

Regional economic planning can no longer be primarily concerned with the regional economy and its development, but it also must take cognizance of the effect of economic development on the natural environment. This expansion of regional planning necessitates the development of new tools and methodologies for evaluating alternatives. This paper selectively reviews recent extensions of input-output and linear programming models to include a regional environmental quality component.

Introduction

Until very recently in the economic literature, externalities associated with residuals from production and consumption have been viewed as curiosa, and not as central problems in decision making. An important new task for regional economists is to consider the environmental externalities associated with regional development and their significance for regional economic planning. In most highly industrialized regions the assimilative capacity of the environment is being tried. Projections of environmental residuals must be included in regional planning to permit a rational choice between curtailing or controlling the production of residuals or tolerating the effects thereof.

Researchers are in a very early stage with respect to models in this area. One of the alleged problems in the field of regional

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economic planning is that it is already so broad. The models reviewed here will not make the regional scientist's life any simpler, but they add one more step towards that elusive goal of comprehensive regional planning.

Critical environmental relationships have in the past typically received inadequate attention in regional economic development models. The idea of integrating aspects of natural resource requirements with those of the economy for a given region began in the late 1950's. Most of the first generation models of this sort focused on the incorporation into the traditional form of input-output models data on water inputs [1]. But none of these models focused on the other type of linkage, namely that in which the social system provides a basic input into the ecologic system. This paper is concerned with these second generation models.

The purpose of this paper is to broadly review recent extensions of linear economic regional models which include a regional environmental quality component. Some of the models reviewed here are presently non-operational and others have just recently been applied. It is not the function of this paper to review linear economic models in general (primarily linear programming (L.P.) and input-output (I-O) models), as this has had ample coverage in the literature [2]. Rather, it is the purpose of this paper to review recent extensions of these well-known linear model techniques to regional environmental quality analysis. This review is highly selective, and does not pretend to include all recent extensions in this area, but it does try to review the major developments. This review also avoids detailed criticisms of each model, and instead tries to point out the models' basic assumptions and limitations. Such a group review will not only give the reader some idea of the current state of the art, but will also enable him to more adequately judge the possibilities and limitations of these model extensions.

A General Equilibrium Approach to Environmental Quality Analysis

Kneese and Ayres (K and A) believe that residual problems must be seen in a broad regional context rather than as isolated problems of disposal of solid, liquid, and gaseous wastes [3]. The term *regional* refers here to spatial dimensions other than global. A regional approach is stressed here rather than one based on political jurisdictions such as states, counties, or cities because pollution generally follows meterological and hydrological systems rather than political boundaries. From the First Law of Thermodynamics (man can neither create nor destroy matter) follows their materials balance approach. The amount of residuals inserted into the natural environment must be approximately equal to the weight of basic fuels, food, and raw materials entering the processing and production system.

Most undesirable substances can in principle be removed from water and air streams, but what is left must be disposed of in solid form, transformed, or reused. This interdependence among the residual streams casts doubt upon the traditional classifications of air, water, and land pollution as individual categories for regional planning.

In light of the above, K and A extend the Walras-Cassel general equilibrium model of resource allocation to trace residuals flows in the economy. A summary of their basic model follows:

$r_1, \ldots, r_m$ resources and services; $r_1 \ldots r_L$ raw materials; $r_{L+1} \ldots r_m$ services
$x_1, \ldots, x_n$ products
$v_1, \ldots, v_m$ resource and service prices; $v_1 \ldots v_L$ raw material prices; $v_{L+1} \ldots v_m$ service prices
$p_1, \ldots, p_n$ commodity prices
$y_1, \ldots, y_n$ final demands

$$r_j = \sum_{k=1}^{n} a_{jk} X_k \qquad j = 1, \ldots m \qquad \text{(Resource Allocation Equation)} \qquad (1)$$

or

$$[r_j]\ m, 1 = [a_{jk}]\ m, n\ [X_k]\ n, 1$$

$$x_j = \sum_{k=1}^{n} A_{jk} Y_k \qquad j = 1 \ldots n \qquad \text{(Commodity Production Final Demand Equation)} \qquad (2)$$

or

$$[x_j]\ n, 1 = [A_{jk}]\ n, n\ [Y_k]\ n, 1$$

where

$$[A_{jk}] = [I\text{-}C]$$

and I is the identity matrix, and the elements C_{ij} are the input-output coefficients.

$$(1) \text{ and } (2) \rightarrow r_j = \sum_{k=1}^{n} a_{jk} \sum_{L=1}^{n} A_{kL} Y_L = \sum_{k,L=1}^{n} a_{jk} A_{kL} Y_L \qquad (3)$$

or

$$[r_j]\ m,1 = [a_{jk}]\ m,n\ [A_{k,L}]\ n,n\ [Y_L]\ n,1$$

$$p_k = \sum_{j=1}^{n} b_{j,k} v_j \qquad k = 1 \ldots n \qquad \text{(Imputed Price Equation)} \tag{4}$$

or

$$[p_k]\ 1,n = [V_j]\ 1,m\ [b_{jk}]\ m,n$$

To the above fairly typical general equilibrium model is added an environmental sector, whose physical output is X_o, and a final consumption sector, X_f. The residual system is balanced by including flows both to and from these sectors. C_{ij} now comprises all material exchanges including residuals. Equation (4) can now be written:

$$p_k = \underbrace{\sum_{j=1}^{L} b_{jk}^{m}\ v_j^{m}}_{\text{prices imputed to cost of raw materials}} + \underbrace{\sum_{j=1}^{p} b_{jk}^{s} v_j^{\ s}}_{\text{prices imputed to cost of services}} \qquad (k = 1, \ldots n) \tag{4a}$$

where

$$\begin{bmatrix} r_1 \\ \cdot \\ \cdot \\ \cdot \\ r_L \end{bmatrix} = \begin{bmatrix} r_1^m \\ \cdot \\ \cdot \\ \cdot \\ r_L^m \end{bmatrix}, \quad \begin{bmatrix} r_{L+1} \\ \cdot \\ \cdot \\ \cdot \\ r_m \end{bmatrix} = \begin{bmatrix} r_1^s \\ \cdot \\ \cdot \\ \cdot \\ r_p^s \end{bmatrix},$$

$$\begin{bmatrix} v_1 \\ \cdot \\ \cdot \\ \cdot \\ v_L \end{bmatrix} = \begin{bmatrix} v_1^m \\ \cdot \\ \cdot \\ \cdot \\ v_L^m \end{bmatrix}, \quad \begin{bmatrix} v_{L+1} \\ \cdot \\ \cdot \\ \cdot \\ v_m \end{bmatrix} = \begin{bmatrix} v_1^s \\ \cdot \\ \cdot \\ \cdot \\ v_p^s \end{bmatrix},$$

$$\begin{bmatrix} b_{1j} \\ \cdot \\ \cdot \\ \cdot \\ b_{Lj} \end{bmatrix} = \begin{bmatrix} b_{1j}^m \\ \cdot \\ \cdot \\ \cdot \\ b_{Lj}^m \end{bmatrix}, \quad \begin{bmatrix} b_{L+1,j} \\ \cdot \\ \cdot \\ \cdot \\ b_{m,j} \end{bmatrix} = \begin{bmatrix} b_{1j}^s \\ \cdot \\ \cdot \\ \cdot \\ b_{pj}^s \end{bmatrix},$$

$$Y_k = F_k \quad (p_1, \ldots p_n) \qquad \text{(Demand)} \qquad (5)$$

$$r_k = G_k \quad (v_1 \ldots v_m) \qquad \text{(Supply)} \qquad (6)$$

$$\sum_{k=1}^{n} C_{ok} X_k = \sum_{j=1}^{L} r_j^m = \sum_{j=1}^{L} \sum_{k=1}^{n} a_{jk}^m X_k \qquad \text{(Materials flow from environment to all other sectors)} \qquad (7)$$

$$= \sum_{j=1}^{L} \sum_{k=1}^{n} b_{jk}^m Y_k$$

(This assumes that no materials flows from the environment directly to the final consumption sector.)

$$\underbrace{\sum_{k=1}^{n} C_{ok} X_k}_{\text{sum of all raw materials flows}} = \underbrace{\sum_{k=1}^{n} C_{ko} X_o + C_{fo} X_o}_{\text{sum of all return flows}} \qquad \text{(Materials balance for gross output)} \qquad (8)$$

$$\underbrace{\sum_{k=1}^{n} C_{kf} X_f}_{\text{sum of all final goods}} = \underbrace{\sum_{k=1}^{n} C_{fk} X_k}_{\text{sum of all materials recycled}} + \underbrace{C_{fo} X_o}_{\text{waste residuals}} \qquad \text{(Materials balance for final demand)} \qquad (9)$$

(Here accumulation in the final sector is treated as a return flow to the environment.)

The physical flow of materials between production sectors and the final consumption sector are accompanied by a reverse flow of dollars. But the physical flow of material from and back to the environment is only partly reflected by land rents and payments for raw materials. There is no counterpart economic transaction for the flow of materials from the consumption sector to the environment. A and K claim this model can theoretically be generalized to handle these externalities (a divergence between marginal private and marginal social costs and benefits, assuming environmental assimilative capacity is scarce relative to demand) by introducing a set of common property raw materials as another subset of r_j, $(r_1^{cp}, \ldots r_R^{cp})$ with corresponding prices v_j^{cp} which would constitute an income from the environment.

But K and A seem to contradict their above generalization and go on to point out that the total value of those services cannot be calculated. In the remainder of their discussion, K and A omit these common property variables and as a simplification for externalities they introduce a new set of S environmental disservices imposed on consumers of material resources by forcing them to accept unwanted inputs $r_1^u \ldots r_s^u$, whose magnitudes are proportional to the levels of consumption of basic raw materials. It is interesting to note that in K and A's later version of this part of the model [4], they never finish presenting this model after dwelling on the enormous problems the presence of pervasive externalities impose on an optimum social product [5].

To complete our summary of the K and A model we add the remaining equations:

$$r_k^u = G_k^u \quad (Y_1 \ldots Y_n) \tag{10}$$

$$r_k^u = \sum_{j=1}^{n} b_{kj} \ Y_j \quad (k = 1 \ldots s) \tag{11}$$

$$\text{Equation (4a)} \rightarrow P_k = \sum_{j=1}^{L} b_{jk}^m v_j^m + \sum_{j=1}^{p} b_{jk}^s v_j^s + \underbrace{\sum_{j=1}^{s} b_{jk}^u v_j^u}_{\substack{\text{cost (compen-}\\ \text{sation) for}\\ \text{providing environ-}\\ \text{mental disservices}}} \tag{12}$$

K and A claim that if solutions exist for the normal Walras-Cassel system of equations, the arguments presumably continue to hold for their [2 n + 2 m−1] variables (r_i, y_i, p_i, v_i) and [2n+2m−1] independent equations model. Thus, the above model theoretically should be able to calculate the prices associated with the undesirable inputs. But Noll and Trijonis show that the above model will not generate negative prices for the undesired inputs because nowhere in the model does pollution generate costs, either as disutility to consumers or as additional resource requirements to producers [6]. Noll and Trijonis suggest alterations which greatly complicate K and A's model but, needless to say, make it more realistic and applicable.

As with most linear models, the assumption of unique coefficients introduces difficulties because this is not consistent with factor substitution. As K and A are well aware, the supply of the Kth unwanted residual will be produced in strict relationship to the composition of the final goods. Hence, the shadow prices for the unwanted residuals might be higher than the real economic optimum since the latter could only be achieved by introducing factor and process charges.

In spite of the comprehensiveness of the K and A model, it is still a static and deterministic model that has no time dimension and is non-stochastic. This may be a serious limitation when dealing with physical residuals, which by their very nature are temporal and probability oriented. For example, treating accumulations in the final sector as a return flow to the environment is simplistic. In truth, many structures actually become part of the environment and are only returned to the environment after a long period of time. Also, future extensions of this model must make a finer distinction between residuals and pollutants. For example, some residuals are harmless and are assimilated by the environment, while two harmless residuals may interact over time to form a pollutant.

The K and A model takes materials from the environment and returns others of equal mass but of different chemical composition. K and A do not consider what happens to these materials once returned to the environment except when they point out that the assimilative capacity of the environment is limited.

A theoretical limitation of the K and A model is that it is constrained by the Second Law of Thermodynamics, which it completely ignores [7]. The Second Law states that matter tends toward disorder in a closed system. Therefore, we must not only account for matter, we must also account for energy. In recycling, we use up more low entropy energy than the decrease in entropy of what is recycled. So there are really leaks in the materials balance approach after all. In a similar vein, Dr. Converse notes that pollution treatment, while changing the composition of waste residuals, does increase the total amount of them [8]. Hence, he says, any analysis that considers only the total amount will be unable to properly evaluate pollution control measures.

As K and A are ready to admit, their model is severely limited in its practical application. An enormous quantity of data would be required to fit such a model. However, this theoretical, non-operational, highly abstract general equilibrium model does have value for regional planning. The K and A model reminds us that partial equilibrium approaches, while trackable, may lead to serious errors. The model underscores the need for a regional or "problem shed" accounting of residuals for at least the most important residuals generating activities of an area and since regional economies are open to some degree, the most significant material imports and exports also have to be accounted for. Finally, the K and A model would seem to indicate that in projecting waste residuals for a regional economy, the inter-industry materials flow input-output relations model is a superior approach to the normal aggregative extrapolations of solids, liquids, and gaseous wastes treated separately.

Extension of I-O Models to Regional Environmental Quality Analysis

THE LEONTIEF MODEL

Leontief has extended his basic national I-O model so as to permit forecasting of residual emissions. The following exposition is based on his 1970 article [9].

Leontief's static-open physical input-output model with residuals included in the system is shown by the following matrix of equations:

$$
\begin{array}{c|cc|c|c|c|c|c}
 & \text{ORDINARY OUTPUT} & \text{RESIDUALS REDUCTION ACTIVITIES} & & & & & \\
\hline
\text{ORDINARY INPUTS} & I-A_{11} & -A_{12} & \text{ORDINARY OUTPUTS} & X_1 & & Y_1 & \text{ORDINARY GOOD FINAL DEMAND} \\
 & & & & & = & & \\
\text{RESIDUALS ODUCED} & A_{21} & -I+A_{22} & \text{RESIDUALS REDUCTION OUTPUTS} & X_2 & & Y_2 & \text{RESIDUALS REMAINING FOR FINAL DEMAND}
\end{array}
$$

or $A^* X = Y$

There are $1, \ldots m$ ordinary goods, and $m + 1 \ldots n$ residuals.

To better understand the above generalized model which was taken from Leontief's mathematical appendix, assume three ordinary commodities (1, 2, 3) and two residual reduction activities (4, 5).

Thus:

$$
[I] = \begin{array}{c} \\ 1 \\ 2 \\ 3 \end{array}
\begin{array}{c} \begin{array}{ccc} 1 & 2 & 3 \end{array} \\ \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \end{array}
\qquad
[A_{11}] = \begin{array}{c} \\ 1 \\ 2 \\ 3 \end{array}
\begin{array}{c} \begin{array}{ccc} 1 & 2 & 3 \end{array} \\ \begin{bmatrix} 0 & a_{12} & a_{13} \\ a_{21} & 0 & a_{23} \\ a_{31} & a_{32} & 0 \end{bmatrix} \end{array}
$$

$$[A_{12}] = \begin{array}{c|cc} & 4 & 5 \\ \hline 1 & a_{14} & a_{15} \\ 2 & a_{24} & a_{25} \\ 3 & a_{34} & a_{35} \end{array} \qquad [A_{22}] = \begin{array}{c|cc} & 4 & 5 \\ \hline 4 & 0 & a_{45} \\ 5 & a_{54} & 0 \end{array}$$

$$[X_1] = \begin{bmatrix} x_1 \\ x_2 \\ x_3 \end{bmatrix} \quad [Y_1] = \begin{bmatrix} y_1 \\ y_2 \\ y_3 \end{bmatrix} \quad [X_2] = \begin{bmatrix} x_4 \\ x_5 \end{bmatrix} \quad [Y_2] = \begin{bmatrix} y_4 \\ y_5 \end{bmatrix}$$

Therefore,

$$\underbrace{\begin{array}{c|ccccc} & 1 & 2 & 3 & 4 & 5 \\ \hline 1 & 1 & -a_{12} & -a_{13} & -a_{14} & -a_{15} \\ 2 & -a_{21} & 1 & -a_{23} & -a_{24} & -a_{25} \\ 3 & -a_{31} & -a_{32} & 1 & -a_{34} & -a_{35} \\ 4 & a_{41} & a_{42} & a_{43} & -1 & a_{45} \\ 5 & a_{51} & a_{52} & a_{53} & a_{54} & -1 \end{array}}_{A^*} \quad \underbrace{\begin{bmatrix} x_1 \\ x_2 \\ x_3 \\ x_4 \\ x_5 \end{bmatrix}}_{X} = \underbrace{\begin{bmatrix} y_1 \\ y_2 \\ y_3 \\ y_4 \\ y_5 \end{bmatrix}}_{Y}$$

$a_{12}, a_{13}, a_{21}, a_{23}, a_{31}, a_{32}$, or a_{ij} = the amount of the ith ordinary input required per unit of jth ordinary output. Note that $a_{ii} = 0$, so that industry output is always net of its own output that it uses. $a_{14}, a_{15}, a_{24}, a_{25}, a_{34}, a_{35}$, or a_{jk} = the amount of the ith ordinary input required to produce a unit of the kth pollutant reduction output. $a_{41}, a_{42}, a_{43}, a_{51}, a_{52}, a_{53}$, or a_{ki} = the amount of the kth residual resulting from producing a unit of the ith ordinary output. a_{45}, a_{54}, or a_{k1} = the amount of the kth residual produced as a result of a unit reduction in the 1th pollutant. Note also that $a_{kk} = 0$ for the same reason as $a_{ii} = 0$.

x_i ($i = 1 \ldots 3$) = total output of ordinary good i
x_k ($k = 4, 5$) = total amount of pollutant k eliminated
y_i ($i = 1 \ldots 3$) = final household demand of good i
y_k ($k = 4, 5$) = final delivery of pollutant k to households
p_i ($i = 1 \ldots 3$) = price of good i
p_k ($k = 4, 5$) = price of eliminating one unit of pollutant k
v_i ($i = 1 \ldots 3$) = value added in industry i per unit of good i produced by it
v_k ($k = 4, 5$) = value added in antipollution sector k per unit of pollutant k eliminated by it.

The system of equations $A^*X = y$ can be solved for the vector X similar to ordinary I-O, given the final demand Y. The general input-output balance between prices and values added is given by the following matrix:

$$
\begin{array}{cc}
 & \begin{array}{cc}\text{m GOODS} & \text{n-m RESIDUALS}\end{array} \\
\begin{array}{c}\text{m ORDINARY GOODS}\\[2em] \text{n-m RESIDUALS}\end{array} & \left[\begin{array}{c:c} I-A'_{11} & -Q'_{21} \\ \hdashline -A'_{12} & I-Q'_{22}\end{array}\right]
\end{array}
\begin{array}{c}\text{PRICES OF ORDINARY GOODS}\\[2em] \text{PRICES FOR RESIDUALS REDUCTION}\end{array}
\left[\begin{array}{c}P_1\\ \hline P_2\end{array}\right] = \left[\begin{array}{c}V_1\\ \hline V_2\end{array}\right]
\begin{array}{c}\text{VALUE ADDED FOR m ORDINARY GOODS}\\[2em] \text{VALUE ADDED FOR n-m RESIDUALS}\end{array}
$$

OR $Q^* P = V$

The coefficients involving residuals generation have now been modified. They are reduced by a factor which reflects the proportion of residual generated by an industry, the elimination of which is paid for it. Thus, if industry i generates a_{ki} residual per unit of output and pays for the elimination of 100 r_{ki} per cent of it, we replace a_{ki} by $q_{ki} = r_{ki}a_{ki}$. A similar modification is made for residuals produced by the residual control industries. For our particular example we derive:

$$[A_{21}] \rightarrow [Q_{21}]$$

$$[A_{22}] \rightarrow [Q_{22}]$$

$$
\underset{Q^*}{\begin{bmatrix}
1 & -a_{21} & -a_{31} & -q_{41} & -q_{51} \\
-a_{12} & 1 & -a_{32} & -q_{42} & -q_{52} \\
-a_{13} & -a_{23} & 1 & -q_{43} & -q_{53} \\
-a_{14} & -a_{24} & -a_{34} & 1 & -q_{54} \\
-a_{15} & -a_{25} & -a_{35} & -q_{45} & 1
\end{bmatrix}}
\qquad
\underset{P}{\begin{bmatrix} p_1 \\ p_2 \\ p_3 \\ p_4 \\ p_5 \end{bmatrix}}
\underset{=}{=}
\underset{V}{\begin{bmatrix} v_1 \\ v_2 \\ v_3 \\ v_4 \\ v_5 \end{bmatrix}}
$$

If the value added in the production of a unit of commodity is known, we can calculate the prices of the commodities. The above model can calculate the changes in residuals resulting from a change in final demand or the net increase in production needed to achieve a specific reduction in residuals. This model allows for the possibility of some residuals being controlled by the manufacturing industries themselves rather than only by the residual control sector. The above model does not consider any pollution produced directly by final users, but Leontief does provide in his mathematical appendix a theoretical description of the way in which pollution generated by the final demand sectors may be introduced.

Shortcomings of the above model, some of which are discussed in a book by Kneese and Herfindahl, include the fixity of coefficients and the absence of residuals accounting once they enter into the environment [10]. Fixed coefficient production functions do not permit pollutants to alter resource requirements in the production of other goods. Process changes resulting in residual control are important control alternatives. These changes in technology can only be incorporated in the above model by changing the I-O coefficients.

This model focuses on residuals generation and discharge and does not incorporate the more comprehensive materials balance approach of K and A. Leontief ignores the flow of material through the economy since he concerns himself only with flows from the economy to the environment and not in the reverse direction. Having introduced pollution coefficients, Leontief simply adds an antipollution industry, which, for given quantities of inputs from other industries in the economy, can eliminate a technologically determined amount of pollution. Leontief is vague in the definition of his terms and it is not absolutely clear what he means by a reduction in the discharge of wastes. The antipollution industry could either recycle waste products or treat waste prior to discharge. It would seem that Leontief is referring to waste treatment, thus ignoring the materials balance principle.

Leontief's model was presented from a national viewpoint, but national boundaries seldom describe a satisfactory area for analysis of pollution problems. Pollution "problem sheds" tend to be on a regional scale, and sometimes the region is quite small. On the positive side, this model is operational, given production functions for direct pollution abatement, and in principle, can be extended to a set of interregional models for the nation by adding imports and exports of both residuals and products to and from the various regions. Also, the model could be easily adopted to just a regional table, simply connecting the region to the rest of the nation. But much work still needs to be done on adapting current I-O tables for residuals. A big problem is lack of data, especially at the regional and interregional level.

THE CHARLESTON METROPOLITAN REGION STUDY

The Laurent and Hite (L and H) study provides a good example of an application, at the regional level, of a simplified version of the above Leontief model [11]. The L and H study extended a 28-sector economic inter-industry I-O table, constructed for the Charleston, South Carolina SMSA on the basis of field survey data by adding a selected 16-sector environmental matrix showing the inflow from the environment and outflow to the environment associated with one dollar of gross sales arising from various sectors of the economy. This involved post multiplying the environmental linkages matrix by the inverse matrix of the I-O model:

$$(E)\ (I\text{-}A)^{-1} = R$$

where E is a matrix of inflows to and outflows from the economy to the environment (inflows from the environment are given a positive sign and residual outflows are given negative signs), $(I\text{-}A)^{-1}$ is the inverse matrix of an area I-O model, and R is a matrix of the direct and indirect environmental impact of each economic sector.

In this particular model, households are closed into the I-O model and following export base theory, external sales are designated as the final demand sector and considered autonomous factors in the area's economy. The model allows a comparison of the direct and indirect ecologic linkages that result from the economic interdependence between sectors in the local economy.

A unique aspect of this emperical study was the way in which the authors minimized problems arising from the assumption of linearity. For example, coefficients related to private automobile emissions were charged to gasoline service stations on the premise that exhaust emissions are much more likely to be linearly associated with gasoline sales than household income. In general, the convention was to charge a linkage to the sector where linearity was most likely to be realistic, rather than to the sector directly responsible for a specific emission. It should be noted though that this approach does not consider the important locational aspect of non-point sources of pollution in consumption.

An important finding of this study was that *all* economic sectors in the Charleston study area, either directly or indirectly, had ecologic linkages and were responsible for some level of natural environmental degredation. A given sector may have little or no direct effect on the environment; however, it must purchase inputs from other sectors which do draw directly upon environmental resources. Economic-ecologic linkages are far more complex and far-reaching than direct and easily identifiable linkages would indicate. A beauty of the I-O approach is that we can identify these complex linkages.

THE VICTOR MODEL

Peter A. Victor has made comprehensive estimates of material flows by extending input-output analysis in order to quantify links between the economy and the environment of a country [12]. Victor estimates the use of water and the output of waste products attributable to Canadian economic activity. His study shows how the activity of each of seventeen industry groups and the final demand for three commodities used water and produced water-borne, airborne, and landborne wastes.

Unlike Leontief's model, Victor makes explicit use of the materials balance principle. Victor's approach is very complex and comprehensive. In order to avoid confusion, I will omit the more detailed equation presentations of the earlier models and briefly describe his approach and leave it to the reader to refer to Victor's dissertation for added detail.[1]

Victor uses two different I-O models and adapts ecologic commodities into each of the models. Both of the models are commodity-by-industry models. Until recently, input-output analysis and interindustry analysis (used in the Charleston Metropolitan Region Study) have been synonyms for each other. Interindustry studies aggregate the various commodity outputs of each industry into one average product. With commodity-by-industry input-output analysis both enter explicitly. Full recognition is given to the fact that each industry uses and produces many commodities, and that some are produced by more than one industry.

The two basic I-O models that Victor uses are respectively attributed to the Development Staff of the Dominion Bureau of Statistics, Canada (D.B.S. model) and Professor G. Rosenbluth of the University of British Columbia (Rosenbluth model). Both of

[1] Most of Victor's book is based on his dissertation, "Input-Output Analysis and the Study of Economic and Environmental Interactions," University of British Columbia, 1971. For a more detailed explanation, see Victor's book [12, Supra n. 12, pp. 84-86].

these models assume that one unit of an industry's output always requires the same quantities of commodity inputs. Where the two models differ is in the assumed commodity composition of one unit of an industry's output. The Rosenbluth model assumes that one unit of an industry's output is always composed of the same quantities of commodity outputs. The D.B.S. model assumes that the total output of each commodity is produced by different industries in fixed proportion, whatever the amount of commodity that is produced. In the Rosenbluth model, the commodity composition is fixed irrespective of the pattern of final demand.

After Victor sets up the two basic models to include all relevant economic data, he adapts them for relations between the Canadian national economic system and the environment. Victor is more precise in his definitions than Leontief. Victor sees all economic activity as requiring inputs of raw materials. These inputs may come from privately owned parts of the environment such as coal from the land or from publicly owned parts such as oxygen from the air. Victor defines these material inputs on their first introduction into the economy as ecologic commodities. Once the material is being processed for final use or is satisfying the demand of a final consumer, it is then referred to as an economic commodity. When it is discarded by an economic agent, a producer or consumer, and so leaves the economy, it becomes once again an ecologic commodity.

Ecologic commodities are introduced into the D.B.S. model by assuming that the ecologic commodity inputs and outputs of an industry are proportional to the industry's marketed output valued at base period prices. (This is the same procedure used for primary inputs.) Ecologic commodities are classified according to the source from which they came or the sink to which they go: land, air and water.

Victor goes into great detail in his extension of this D.B.S. model. For example, ecologic commodity inputs and outputs may be used and produced directly by final demand as well as indirectly via the activities of industry. A final demand for motor gasoline implies ecologic commodity inputs and outputs when the gasoline is used, over and above the ecologic commodity inputs and outputs required in the manufacture of gasoline. Victor, unlike Leontief who relinquishes pollution in consumption to a footnote, incorporates exports of consumption goods into his model, which are relevant from the domestic point of view since no domestic ecologic commodities are associated with their consumption. Conversely, Victor includes imports, which require no domestic ecologic commodity inputs and outputs in their manufacture, but do imply ecologic commodity inputs and outputs when they are consumed.

The D.B.S. model assumes that the input requirements of an industry are affected only by the size of its output and not by the composition of its output. Such an assumption implies that the interactions between an industry and the environment depend only on the amount of the industry's output and not on its commodity composition. In the Rosenbluth model, the commodity composition of an industry's output is assumed to be fixed. Given these assumptions, Victor claims it makes sense to consider an industry's output of marketable commodities and waste products as joint products. Victor goes on to claim that it is more meaningful to relate industrial wastes to industry outputs within the Rosenbluth model than within the D.B.S. model. But Victor later points out that, ultimately, if a choice is to be made between the D.B.S. and the Rosenbluth models, the criterion of predictive power must be employed.

In spite of the comprehensiveness of Victor's model, it is still very distinct from Isard's model (which will be reviewed next) in that no subsystem of the environment is included [13]. Victor rationalizes that the data requirements of the ecologic subsystems are so great that it is expedient to include only flows between the economic-ecologic systems and not flows within the ecologic system itself. However, Victor does realize that it is important for the model to allow for the relations between the ecologic outputs of industry and the subsequent ecologic inputs from the environment. Thus, Victor notes a theoretical means to adapt the D.B.S. model so that the relations are recognized without introducing the entire ecologic system. He does this by introducing treatment classes for each of the three environmental sectors. A treatment class describes the environmental sector's capacity to assimilate a particular type of waste. The effectiveness of each treatment class is written in terms of treatment coefficients which express the concentration of an ecologic commodity some time after it has been introduced into a sink of a certain size class. (An example of a treatment coefficient: C_{jk} = concentration of one unit of the kth ecologic commodity remaining after dispersal by one unit of a sink of the jth treatment class during a unit of time.) As in any I-O model these coefficients are assumed stable over time. These complex treatment coefficients that Victor suggests are in all likelihood not stable over time. There is a relation between the waste introduced into the environment in one time period and the environment's assimilative capacity in subsequent periods.

The brief summary of the extension of the D.B.S. I-O model to include ecologic commodities is now complete. Victor extends the Rosenbluth model in a similar way.

Victor has been able to estimate from his model ecologic impact tables that show the effect on the ecologic inputs and outputs of industry, of supplying one dollar's worth of each economic commodity at producers' prices, to final demand. Because of lack of ecologic data, Victor was able to do no more than examine the grossest relations between the Canadian economy and environment. Only when significantly improved data become available will it be possible to really use this model to its fullest extent.

By applying a set of shadow prices indicating the social evaluation of the ecologic commodities, Victor was able to estimate the relative ecologic cost of producing and consuming one dollar's worth of each commodity. The set of weights Victor used was for illustrative purposes only. Victor recognizes the serious difficulties in formulating a unique vector of weights which indicate the "social evaluation" of each ecologic commodity according to whether it is used as an input or output and also according to the source or sink of the ecologic commodity.

Though the Victor approach is for the Canadian national economy, the model could be significantly improved upon by a regional disaggregation of industries and final demand. In this way, the direct and indirect input and output of ecologic commodities attributable to different patterns of final demand could be estimated for each region.

THE ISARD MODEL

Walter Isard and his colleagues within the Regional Science group at Harvard have provided one of the most comprehensive economic-ecological models to date and have gone some way towards deriving the enormous quantity of data which such a complex model requires [14].

Table 1 illustrates the author's use of an input-output coefficient table to depict interrelations among ecologic variables. The table is interregional in scope with regions designated as land, marine, and air. The three regions are further subdivided into zones, each having a high degree of identity in terms of geographical location and ecological processes. Sectors are divided between ecologic and economic designations. The economic sector is further subdivided by the Standard Industrial Classification (S.I.C.) system. Isard suggests a tentative classification system used to code ecological

Table 1. Summary Organization of Interregional Economic-Ecologic Activity Analysis

				Land																						Marine		
				Zone A											Zone U											Zone A		
				Economic				Ecologic							Economic				Ecologic									
				Agriculture	Manufacturing	Services	Government	Climate	Geology	Physiography	Hydrology	Soils	Plants	Animals	Agriculture	Manufacturing	Services	Government	Climate	Geology	Physiography	Hydrology	Soils	Plants	Animals	Agriculture	Manufacturing	Services
Land	Zone A	Economic	Agriculture																									
			Manufacturing																									
			Services																									
			Government																									
		Ecologic	Climate																									
			Geology																									
			Physiography																									
			Hydrology																									
			Soils																									
			Plants																									
			Animals																									
	Zone U	Economic	Agriculture																									
			Manufacturing																									
			Services																									
			Government																									
		Ecologic	Climate																									
			Geology																									
			Physiography																									
			Hydrology																									
			Soils																									
			Plants																									
			Animals																									
Marine	Zone A	Economic	Agriculture																									
			Manufacturing																									
			Services																									
			Government																									
		Ecologic	Climate																									
			Geology																									
			Physiography																									
			Hydrology																									
			Soils																									
			Plants																									
			Animals																									
Air																												

Source: Walter Isard, *Ecologic-Economic Analysis for Regional Development,* Table 3.5d, p. 60.

processes in much the same manner as the S.I.C. code disaggregates conventional economic processes.

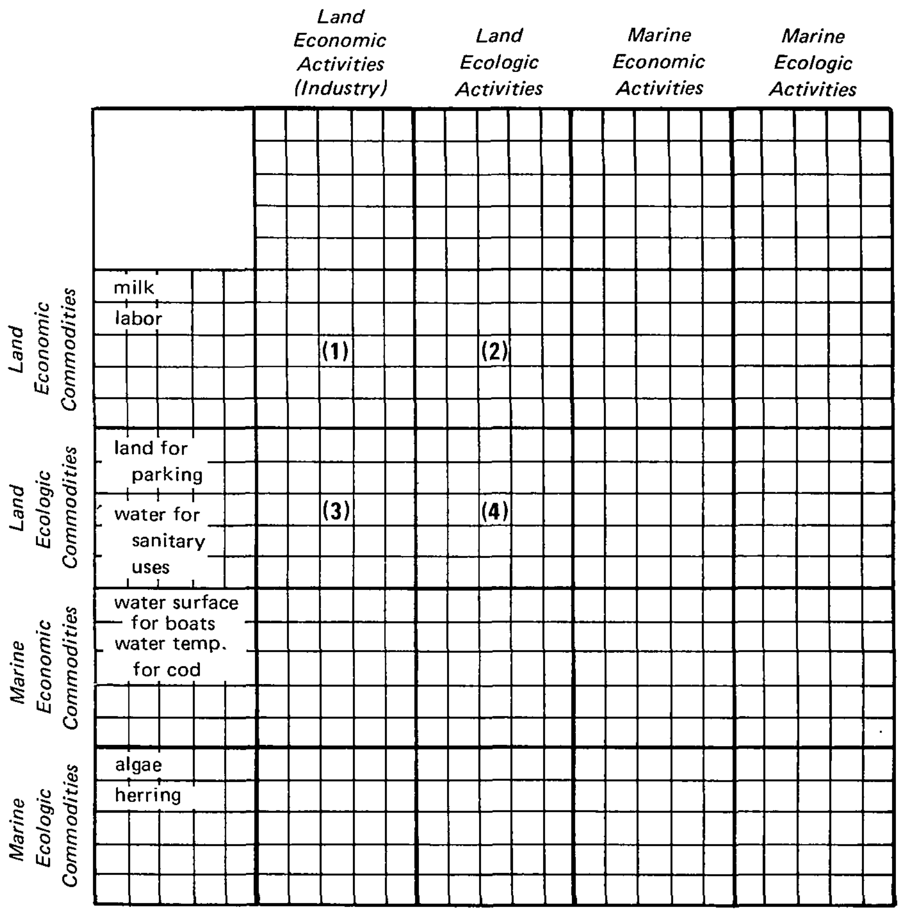
In chapter 4 of his book, Isard links the economic and ecologic sectors in what he terms "The General Interrelations Table." To place the discussion in context, Table 2 is an outline of this twelve-page table taken from the Isard book [15]. Only two of the authors' proposed three regions are considered. What is stated for quadrants (1-4) below for the land region also similarily applies for the other two regions.

Quadrant (1) is the traditional coefficient table, with columns representing sectors and rows representing commodities associated with these sectors, as outputs and resources. Within a column of the table, inputs are represented by a minus sign, and outputs by coefficients bearing a positive sign. Quadrant (3) displays input and output of land ecologic commodities to land economic activities in coefficient format. Similarily, quadrant (2) shows the inputs and outputs of the land economy that enter into the land ecologic processes. Quadrant (4) represents the land ecologic system. The ecologic commodities of the rows enter the ecologic activities of the columns as inputs and/or outputs.

Like Victor's model, Isard seems to be using the commodity-by-industry approach where each industry may have many economic outputs. There are at least two outputs from each industry: an economic commodity and an associated waste product. The model actually goes much beyond one waste product in that each industry is assumed to produce several types of wastes or ecologic commodities.

With economic commodities, outputs of industry are aggregated in terms of their money value. There is no such common denominator for ecologic commodities. No explicit market values exist for waste products, though it may be possible to impute market values by estimating the various associated damage costs. Nevertheless, in general, it is not possible to aggregate ecologic commodities in a manner that corresponds to the aggregation involved in traditional I-O models. Though Isard is not explicit about this, the quadrants do not necessarily have to be (and would not normally expected to be) square, hence the table really constitutes a programming matrix and not a traditional Leontief-type I-O table. However, this does not prevent the construction of an I-O model of an ecologic system. The lack of an ecologic counterpart to an industry's aggregate output (except when an ecologic process has only one output or its outputs are produced in fixed proportions) means that the ecologic system must be viewed in a commodity-by activity (industry)

Table 2. A Summary Organization of "The General Interrelations Table"



context. The assumption that each activity produces its different commodity outputs in fixed proportions is necessary for a surrogate measure of activity output. The level of operation of an industry may be measured by the value of output at base period prices, by the quantity of some major commodity produced, or by the quantity of a major input. The last two of these three options remain open for I-O models of the ecologic system, and so integration of economic and ecologic system may proceed at least at the theoretical level.

Isard has applied a simplified version of his ecologic-economic matrix in a cost-benefit analysis using public costs and benefits of three alternative marine recreational complex sites near Plymouth, Massachusetts. His group estimated I-O matrices for winter flounder growth, cod growth, and the phosphorous flow cycle upon which mussel growth depends. These privately valued species live on the Continental Shelf where they can be harmed by pollution diffusing (measured by a gravity model) from whichever river is next to the complex. Isard points out that in principle, shadow (theoretical) prices could be calculated for any of the input species to the economically significant species' value, measured in whatever unit, among its inputs by their respective proportions. This methodology raises many intriguing possibilities, going much beyond any of our previous models to account for a more meaningful definition of costs in regional development decisions.

Site selection problems are common in regional planning, but Isard's analysis includes estimates of the ecological costs of the alternative developments. For example, Isard measures costs as the damages to tidal grasses and clam, mussel, and sea worm populations caused by disposal of the dredgings of marina construction. Comparative cost analysis then proceeds to select the minimum cost site under this expanded definition of costs.

The Isard model requires a matrix that completely describes all of the interrelated processes that take place within the eco-system under consideration. This necessitates extreme disaggregation of environmental resources. For example, Isard quantifies the various components of the food chain for winter flounder in the Plymouth case study in order to develop inputs for the commercial fisheries sector. The broad nature of his model makes extreme disaggregation difficult to avoid. Though the disaggregation of environmental resources may be conceptually desirable, the Isard model requires enormous amounts of quantitative environmental data, much of which is not available given the present state of ecologic science.

The models discussed up to now have not included flows within the ecologic system itself (for example quadrant (4)). Isard's model is unique in this respect. However, inclusion of this system presents the above-mentioned severe data problems. It is not simply a question of data quantity since there is also the question of data quality, required for such an analysis. Finally it is not know how adequate solutions are when derived using such models for purposes of decision making. But this does not mean that I-O principles should be abandoned until the ecologic system has been quantified. Quadrants (2) and (3) link the land economic and land ecologic systems and can provide useful decision-making information as shown by Victor's model, even if it is not yet clear how inputs into the land ecologic system, quadrant (2), effect outputs from the land ecologic system, quadrant (3).

Isard suggests that future directions for research would be to link the local study area to the region, nation, and world as a whole. Isard's book is concerned primarily with local interdependent environmental systems, but a dynamic land-water use plan must be systematically redefined in terms of larger contexts and the variables that are pertinent in each.

An L.P. Politico-Pollution Model

The Russell and Spofford (R and S) approach to regional pollution problems is a set of general optimization models [16]. Their approach can be divided into three submodels. First, residual discharges from production and consumption activities are determined. Then, mathematical approximations of natural world processes (diffusion models) are used to transform discharges into ambient environmental conditions.[2] Finally, these ambient conditions are compared to exogenously imposed standards. The general model deals with air, water, and solid waste problems simultaneously, reflecting the materials balance approach.

The general model, instead of assuming that the generation of residuals is fixed per unit of physical output, includes options for decreasing generation through input substitution, process change, and by recovery. The R and S general theoretical framework is, in principle, capable of dealing with various types of regional environmental models from the simplest linear transformation functions to simulation models of environmental systems. This flexibility was built into their model by designing a solution algorithm for a nonlinear programming problem. The algorithm involves iteration through the three submodels. This general theoretical multistage mathematical programming model is much more sophisticated and complex in the handling of residuals and the environment than our above linear models.

But most of the R and S actual hypothetical empirical work has been done with a simplified version of this general framework in which the above environmental submodels are collapsed to constants relating discharges to ambient concentrations. Their applied model involves a hypothetical region with only a few point

[2] Environmental diffusion models are used to compute the effect, i.e. concentration, at any location due to a specified discharge from any source. The building of diffusion simulation models is a complex art that requires a multidisciplined team of hydrologists, meteorologists, sanitary engineers, and operation researchers [10, Supra n. 10, p. 373].

sources of air and water pollution. The hypothetical regional economy consists of a river, a beet-sugar refinery, a petroleum refinery, an electric power plant, a water treatment plant, and a municipal incinerator.[3] The model keeps track of B.O.D. (biochemical oxygen demand) and heat residuals in water, SO_2 and suspended particles in air, and ash and sludge in the ground. Also, the model subdivides the region into 25 grids to track distributional impacts of the costs of adjustment to fulfill the ambient standards. Extensions of this model by the Resources for the Future group simulate different vote-trading mechanisms between grids whereby policy is determined.[4]

Simply stated, R and S's applied didactic model is designed to solve the following linear programming problem:

Minimize $C'X$ subject to

$$\begin{bmatrix} A_1 \\ A_2 \\ A_3 \end{bmatrix} X \begin{matrix} \geqslant \\ \leqslant \\ \leqslant \end{matrix} \begin{bmatrix} b_1 \\ b_2 \\ b_3 \end{bmatrix}$$

where:

- A_1 represents the technology matrix
- b_1 the vector of minimum required final demands
- A_2 the flow of pollution from the economy to the environment
- b_2 the vector of maximum ambient levels of pollutants allowed in the environment by government policy
- A_3 the distribution among the region's subgroups of the costs of achieving the ambient standards
- b_3 the vector of maximum acceptable costs for each subgroup

The C's are cost parameters and X is the vector of activity levels of the various production alternatives, treatment and recirculation possibilities, and discharges.

In essence, this working hypothetical L.P. model tells us the aggregate cost of simultaneously meeting certain production and environmental quality requirements. This L.P. model is nothing more

[3] For a very detailed and interesting L.P. model that optimizes control technologies for specified output mixes and discharges for the U.S. petroleum refining industry [17].

[4] Geographical distribution across local political entities is made possible by the fact that the model is location specific in the sense that activities are assigned addresses in a grid. Accordingly, changes in environmental quality parameters can be associated with particular locations. Consequently the stage is set for a social choice process to come into play. For a description of the political extension of the Russell-Spofford model [18].

than a fairly straight-foreward application of interindustry analysis with the exclusion of residuals from consumption activities. A version of the above model is now in the process of actually being applied on the Delaware Estuary region of New Jersey, Pennsylvania, and Delaware.

It may be reasonable to assume linearity of A_1, but it is much more questionable to assume linearity of A_2. For example, there may be a proportional relation between the rate of discharge of air pollutants and ambient air quality only under very special situations, and in general we would not expect it. As for the linearity of A_3, it is much less clear exactly what is involved in this assumption.

Also, the above model structure may be too complex to apply to a large region with many discharge sources and overlapping political jurisdictions. Though this politico-pollution model has problems, this attempt to integrate economics, pollution, and politics into a single optimizing model certainly is unique.

Summary

In general, the above models stress the need for synthesis. Regional development and regional planning can no longer be treated in their traditionally narrow context of economics. Emphasis must also be placed on physical environment and design, social, political and other cultural factors.

Unfortunately, all of the above models do not provide any objective basis for defining the optimum balance between pecuniary economic growth and environmental quality. The optimum level will depend on the value system of people and their willingness to sacrifice pecuniary income in order to preserve environmental quality. But the above models can help regional planners identify paths of economic growth which will do minimum physical damage to the environment. These models can identify the minimum cost means of achieving preassigned standards.

A second major problem of all the above models is their absence of, or difficulty of incorporation of, residuals from consumption or nonpoint sources of pollution. For example, the automobile is the largest single source of air pollution in the U.S. In principle, future research may have to work with a more disaggregated description of a region's demand patterns by goods and consumption locations, for then the differences in costs associated with different types and quantities of consumption residuals generated at different locations in the region could be fully reflected in the model solution.

Finally, a third major criticism of all the above linear models is indeed their assumption of linearity. Unfortunately, ecologic relations are not necessarily linear. For example, the speed of a chemical reaction may increase exponentially with temperature, a fact which is relevant to thermal pollution.

A strong argument could be made that another major research effort should explore mathematical simulations of the natural system, especially the meterological, hydrological, and ecological subsystems such that the time and spatial patterns of residuals concentrations could be estimated in probability terms, as well as secondary effects of residuals discharges (for example, photochemical reactions in the atmosphere). The point made here is that simulation models may have the edge over I-O and L.P. models for really complicated models.

After reviewing the above models, many a reader could easily dream of an I-O model that explains everything, which links ecology to politics to economics to weather to history, etc. One may wonder if the conceptual appeal of I-O for constructing multidisciplinary models has gone too far. Robert Dorfman points out that models striving for ever-increasing inclusiveness and literal realism, with the ultimate goal of being able to prescribe detailed plans for environmental management are aiming in the wrong direction, as this is a hopeless cause [19]. The above models are much better at detecting inefficiency than at measuring its extent. For example, the above models draw attention to the fact that the assimilative capacity of the environment has become a scarce economic good and a pertinent consideration in industrial location decisions. Although we cannot take numerical estimates from the above models literally, the methods reviewed in this paper can be used to revise the rankings of industrial costs in light of differential impacts on the environment. A most important consideration in the above model building is how far it is possible to simplify the representation of the chosen region without destroying the validity of the intended demonstration of reality.

In defense of linear I-O models, it should be noted that the environmental effects of economic activity are pervasive and these linkages are uniquely captured by economic-ecologic I-O type models. In spite of all the deficiencies of I-O models, if economists are to grapple with environmental problems, they must look beyond the partial equilibrium approach.

Isard's research explicitly proceeds on the premise that the use of linear systems analysis, with side computations for nonlinearities, makes a useful linkage of the economic and ecologic systems possible, at least conceptually. A description of processes in linear form, as of a given point in time, is useful in terms of the data it makes available, as well as the consistent classification system it imposes. A projection based on linear analysis, good judgment, and perhaps a few side computations for several key non-linear relations is, in many critical situations, certainly as useful as a projection based on good judgment alone [20].

While the methods and concepts employed in most of the above models are beyond the full reach of present data systems, their value cannot be overstated. At present, our data do no more than examine the grossest relations between the economy and the environment. The present models serve as guides to the type of data that need to be collected if these models are to become truly operational. The relationships and insights brought to light by the above-reviewed models, though not of immediate short-run use, lay the foundations for future work which will, hopefully, be even more vigorous, and in addition capable of successful application to the complex problems they seek to describe.

REFERENCES

1. E. Lofting and P. McGauhey, Economic Evaluation of Water, Part III, *An Interindustry Analysis of the California Economy*, University of California, Berkeley, Water Resources Center, Contribution No. 67, 1963.
2. C. Tiebout, Regional and Interregional Input-Output Models: An Appraisal, *Southern Economic Journal, 24*, pp. 140-147, 1957.
3. R. Ayres and A. Kneese, Production, Consumption, and Externalities, *American Economic Review, 59:*3, June, 1969.
4. A. Kneese, R. Ayres and R. D'Arge, Residuals and General Equilibrium, Chapter 3, *Economics and the Environment*, John Hopkins Press, 1970.
5. O. Davis and A. Whinston, Welfare Economics and the Theory of Second Best, *Review of Economic Studies, 32*, January, 1965.
6. R. Noll and J. Trijonis, Mass Balance, General Equilibrium and Environmental Externalities, *American Economic Review, 61*, pp. 730-735, September, 1971.
7. G. Roegen, Economics and Entropy, *The Ecologist, 2:*7, July, 1972.
8. A. Converse, On the Extension of Input-Output Analysis to Account for Environmental Externalities, *American Economic Review, 61*, pp. 197-198, March, 1971.
9. W. Leontief, Environmental Repercussions and the Economic Structure: An Input-Output Approach, *The Review of Economics and Statistics, 52:*3, August, 1970.
10. O. Herfindahl and A. Kneese, *Economic Theory of Natural Resources*, Chapter 11, Charles E. Merrill Publishing Co., 1974.
11. E. Laurent and J. Hite, *Economic-Ecologic Analysis in the Charleston*

Metropolitan Region: An Input-Output Study, Water Resources Research Institute, Clemson University, Clemson, South Carolina, Report No. 19, April, 1971.
12. P. Victor, *Pollution: Economy and Environment*, George Allen and Urwin Ltd., Great Britain, 1972.
13. W. Isard, On the Linkage of Socio-Economic and Ecologic Systems, *The Regional Science Association Papers*, *21*, 1968.
14. W. Isard, *Ecologic-Economic Analysis for Regional Development*, The Free Press, New York, 1972.
15. For the full twelve-page table, see the Isard book [14, Supra n. 14, pp. 96-108].
16. C. Russell and W. Spofford, A Quantitative Framework for Residuals Management Decisions, *Environmental Quality Analysis: Theory and Method in the Social Sciences*, A. V. Kneese and B. T. Bower, (eds.), John Hopkins Press, 1972.
17. C. Russell, *Residuals Management in Industry: A Case Study of Petroleum Refining*, John Hopkins Press, 1973.
18. A. Kneese, *Management Science*, *19:*10, June, 1973.
19. C. Russell, Application of Microeconomic Models to Regional Environmental Quality Management, *The American Economic Review*, R. Dorfman, (ed.), *63:*2, p. 253, May, 1973.
20. See the Isard book [14, Supra n. 14, p. 95].

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