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NATURAL AREAS AS NECESSARY COMPONENTS OF MAN'S TOTAL ENVIRONMENT

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Our theme is that natural environment is an essential part of man's total environment. Preservation of a substantial portion of the biosphere in a natural state, while not a panacea for all the ills of mankind, is, nevertheless, a necessity if we base the carrying capacity of the earth on the quality of human life. First, we define "natural environment" as that part of our environment which is essentially self-supporting, in that a minimum of human management is required for maintenance. In terms of function, "natural environment" is that part of man's life support system that operates without energetic or

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[1] In the absence of the authors, this paper was read by Dr. E. L. Cheatum, session chairman.

economic input from the power flows directly controlled by man. "Natural environment" is a more restricted category than "open space," a term widely used by planners to mean any part of the landscape, whether natural or man-made, that is free of building structures. In this context "natural environment" includes ecological systems ranging from little-used wildernesses to moderately used forests, grasslands, rivers, estuaries, and oceans, which produce useful products and recycle wastes on a continuous basis, but *without appreciable economic cost to man.* These self-maintaining ecological systems run on sun energy, including the energy of rain, wind or water flow that are derived from sun power. In contrast, what we choose to call "developed environment" includes ecosystems that are structured and maintained by large auxiliary power flows from fossil or other concentrated fuels that supplement or replace the natural energy flow of the sun. A city, of course, is the ultimate developed ecosystem, but golf courses, suburban developments, agricultural fields and channelized rivers are also developed ecosystems since they require a diversion of energy from man-controlled power flows to maintain them in the developed state even though natural elements (water, trees, grass, bacteria) may have important roles in such systems. Developed systems generate economic wealth but *the economic cost of maintenance increases as a power function of the intensity of development.* For example, it is well known that the cost of maintenance (C) of a network of services increases roughly as the square of the number of units (N) in the network, as shown in the following equation:

cost of maintenance

$$C = \frac{N\,(N\text{-}1)}{2} \quad \text{or approximately } C = \frac{N^2}{2}$$

Thus, if a city doubles from 10 to 20 million units the cost goes up 4 times. Furthermore, the stress on supporting natural life support systems increases markedly, again as some kind of multiplier, as the size and power demand of developed systems increases. *Because the multiplying maintenance costs are too often not anticipated and the useful work of nature totally undervaluated, developed systems have an inherent tendency to grow beyond optimum size, and at the expense of natural systems.*

In some parts of the world aesthetic and recreational values (and associated economic dividends) have been sufficient to justify preservation of large natural areas in parks and refuges. In some countries preservation of greenbelts and other natural areas have been a cultural or religious tradition. However, in the future neither aesthetic values nor ethnic traditions will be adequate basis for preservation of natural environment because rapid technological and population growth produces a strong drive to convert natural environment into developed environment. General public awareness that natural environment is important is, by itself, not enough. So powerful is the positive feedback within the urban system, and the economic "forcing function" from outside that there has to be equally strong negative feedback control built into economic and political systems to prevent over-development. To suggest that cities and other highly developed ecosystems have an inherent tendency to grow beyond the optimum (*i.e.* to "overdevelop") is not to embrace an anti-human, anti-urban or anti-development philosophy. Because cities and other developed environments are so valuable to man they must be protected from exploitation just as is necessary for any valuable resource. Specifically, cities need the protection of an adequate life support system, many elements of which natural environment provides free of charge. Without natural recycling and other work of nature, the cost of maintaining quality life in cities would be prohibitive. Later in this paper we will show by actual calculation that the per capita cost of treating human wastes, which are only one small part of the pollution disorder generated by cities, would be more than doubled if there were no natural environment available and able to carry out the work of tertiary treatment of these wastes.

A first step towards redressing the inbalance in valuation of natural versus developed environment would be to determine the real value of "natural environment" in comparable monetary terms as are used to determine the worth of developed environments. The example of the previous paragraph suggests one approach, and we will have more to say about this later in the paper. However—and this is our most important theme—*the true value of a man's total environment is determined by the diversity interaction between the "developed" and the "natural" environment and not only by the worth of each as a separate component.* Yet, at the present time society does not evaluate in any effective manner total environment, but bases human values on the monetary worth of separate components, largely the highly developed ones. If power-hungry developed systems spread in an unrestricted and unplanned manner at the expense of the natural environment, then a point is soon reached where the latter is unable to perform its "free" life support functions. Then, not only does the quality of the remaining natural self-supporting environment decline, but, more important, the quality of the highly developed environment also deteriorates as the costs of pollution and other disorder abatement rises percipitously in non-linear, multiplying fashion. *Accordingly, there has to be some optimal proportion between the* *natural and developed environments* (since 100 percent of either would be unthinkable). Once a rational ratio for a given region is determined there has to be an agreed upon "environmental-use plan" (= "land-use plan" as this term is generally understood by planners and conservationists), with sufficient legal and political sanction to counteract the overdevelopment syndrome. We aim to show that it should now be feasible to model environmental decision-making so as to predict the total consequences of varying the proportion of developed to natural environment (1:1; 2:1 and so on) and thereby find an optimum range in terms of quality of the total environment. After we have presented a very simplified and theoretical working model for such ecosystem management, we will then discuss more pragmatic approaches which we hope planners will find useful until such time as realism can be built into total models.

THE ECOSYSTEM MANAGEMENT MODEL

Figure 1 pictures the essential elements, energy flows and human values that must be considered in modeling environmental-use options designed to maintain an optimum balance between natural and developed ecosystems in counties, watersheds, states, regions or other relatively large areas of the biosphere. The symbols used in this model are part of an "energy language" devised by H. T. Odum and described in detail elsewhere (H. T. Odum, 1967, 1968, 1971). Circles represent energy sources while the tank-shaped, round bottom modules represent stored or potential energy or resources. Natural ecosystems are depicted as bullet-shaped, autotrophic modules, that are self-nourishing and developed ecosystems as hexagonal, heterotrophic or consumer modules that require an energy input for nourishment. Both natural and developed ecosystems have storage capacities important for maintaining function during period of reduced energy inflow. Downward-directed arrows into heat sinks (like electrical "ground" symbols but only one-way flow) show where energy is lost during conversion from one form to another as required by the second law of thermodynamics. Modules containing a large "X" stand for a multiplicative function during work transfer or exchange as discussed in the preceding section of this paper. Especially important is the energy drain and reduction in storage capacity that developed systems impose on natural systems, as shown by the "stress" arrow in Figure 1. Note that except for original energy sources and land resources all modules have at least one input, or source of energy, and at least two outputs, one representing a heat loss or energy drain and the other is passed on as an input to another unit in the system. Seen graphically in this manner, the interrelationships and interdependence of components as working parts of the whole can be clarified. Finally, the model identifies the three environmental values as previously mentioned, namely: (1) the value of natural ecosystems as such, (2) the value of developed ecosystems as such, and (3) the value of man's total environment as determined by "diversity interactions" between 1 and 2.

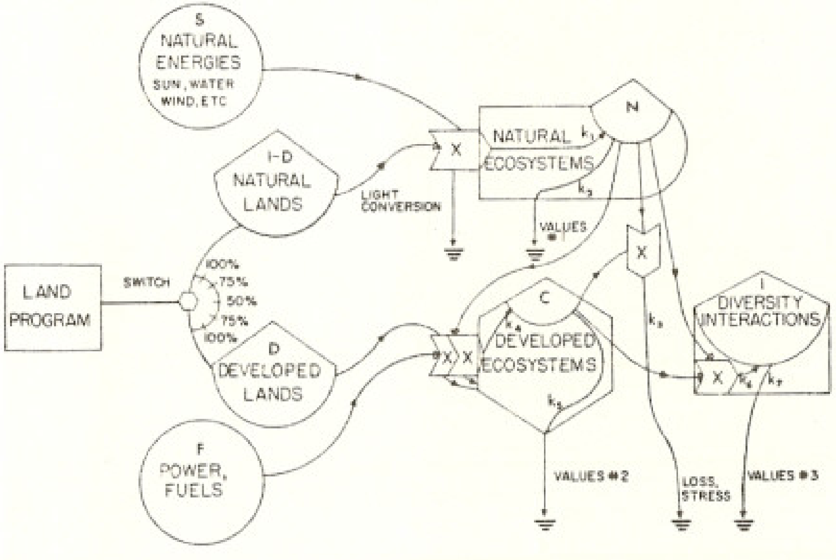

Figure 1.—A Model for Land Management in which the Proportion of Natural and Developed Lands can be Varied in Order to Determine the Optimum Balance in Terms of Value of the Total Environment (sum of values 1, 2, and 3). See Text for Explanation of Symbols.

If all of the inputs and outputs of components in the ecosystem model can be quantitated in common-denominator energy units (which can be converted to monetary units as will be discussed in the next section) different options in land-use planning can be simulated with analog or digital computers. The switching module in Figure 1 shows how a land-use program could theoretically vary the percentage of land that is developed in order to predict interactions, and to determine an optimum proportion between developed and undeveloped land in terms of the quality of the total environment (Value No. 3, Figure 1). To be realistic the oversimplified model of Figure 1 would have to be expanded to include separate modules for different types of both developed and natural systems since energy requirements and outputs vary widely within each of these two general classes of ecosystems. For example, as already noted a high-density city has a much greater power requirement, and, therefore, exerts a much greater stress on its surrounding environment, than does a low-density suburban development.

Since the metabolism of a modern city with its automobiles, industries and high electric power consumption is about 100 times greater than the metabolism of most natural ecosystems (4000 as compared to 40 kcal/M²/day) it is easy to see why high-powered systems tend to be destructive of lower-powered systems in contact with them. Even the simplest models clearly demonstrate that high-powered systems, such as cities, require an abundant life support from nature. If large areas of natural environment are not preserved to provide the needed input from nature then the quality of life in the city declines and the city can no longer compete economically with other cities that have an abundant life support input. Frequently, it is not energy itself that becomes the limiting factor, but some basic natural resource required to maintain the high rate of energy flow. In south Florida water seems now to that limiting input. Continued urban or industrial growth in many areas will depend on developing special water sources such as by desalination, or pumping water from underground or distant sources. If such special sources are developed the city's energy cost rises until it can no longer compete with cities that do not have to pay this extra cost. It is a sad situation when cities grow beyond their means and can no longer pay for their own maintenance. They borrow money or demand federal grants in order to grow ever larger and more demanding of their life support system when they ought to be diverting more of their energy to maintaining the quality and efficiency of the environment already developed, and to reducing the stress on vital life-supporting natural environment. Preliminary simulation of the south Florida situation indicates that a 1:1 ratio of natural to developed environment would provide a basis for an optimum environmental-use program. Until this kind of systems analysis procedure can be refined and become a basis for political action, it would be prudent for planners everywhere to strive to preserve 50 percent of the total environment as natural environment.

CALCULATING THE MONETARY VALUE OF NATURAL ENVIRONMENT

ecosystem management

As indicated in the preceding section, it will be a long time before total ecosystem management will be accepted as an economic and political reality. In the meantime, we have to justify and manage on the basis of separate values (Values No. 1 and 2 in Figure 1). A stronger economic basis for justifying the preservation of natural environment is obtained if we calculate the work of nature in terms of dollars or other currency units. Since money and energy flow in opposite directions, which is to say that money outputs is exchanged for energy input, H. T. Odum (1971) has suggested that the ratio of Gross National Product (GNP) to National Power Consumption can be used to convert calories to dollars. For the United States this works out to be approximately 10,000 kilocalories equals one dollar. Using this conversion Lugo *et al.* (1971) calculated the work done by a tree with a 50 M² crown as being worth $128 per year, and $12,800 over a 100-year life span of the tree. The useful work done by an acre of forest, then, would be $10,360 per year and $1.04 million over a 100-year period. This value may be regarded as somewhat inflated by egocentric man, since he might not consider all work done by a forest useful to man. However, we believe it comes closer to the real value than conventional economic cost-accounting which values a forest only in terms of yield of wood or other consumer products and ignores its life support value.

Another approach to economic justification for preservation of natural environment involves evaluating the work of nature in treatment and recycling of wastes. Again, conventional accounting rarely includes placing a dollar value on such useful work. This can be done by calculating how much it would cost cities to completely treat wastes by artificial means if there were no natural environment available to do at least part of the work. Experiments at Pennsylvania State University have shown that land areas covered by natural or semi-natural vegetation can be effective natural tertiary treatment areas for municipal wastes that have gone through secondary treatment (see Parizek, 1967; Sopper, 1968). While these studies suggest that 2 inches a week of waste water can be added without stress, we would suggest that about half of this, or 4 feet per year, would be a more judicious rate in terms of avoiding mineral buildup in the land filter. An acre of land could then absorb about 1.3 million gallons of treated waste water per year, which is about the amount of waste water produced by 35 city people (100 gallons per day per person or 36,500 gallons per year). If this waste were subjected to artificial tertiary treatment the cost would be 30¢ per 1000 gallons or about $400 for the 1.3 million gallons. Thus, an acre of natural environment could be worth at least $400/year for this one useful function alone. Most of all, if all wastes had to be carried through tertiary treatment in artificial systems because there was not enough natural environment to do this work free, then the taxpayer's bill for waste treatment would be doubled since tertiary treatment costs about twice as much as secondary treatment.

THE PER CAPITA APPROACH

In a recent study E. P. Odum (1970) attempted to determine the total environmental requirements for an individual as a basis for estimating the optimum population density for man. In this study, the State of Georgia was used as an input-output model for estimating the per capita acreage requirements on the assumption that this state is large enough and typical enough to be a sort of "microcosm" for the nation and the world. The basic question asked was: How many acres of environment does each person require to maintain a reasonably high standard of living on a continuing, self-contained equilibrium basis—in the sense that imports and exports of food, other energy and resources would be balanced? In other words, what does it take to support a quality human being in an area that can not count on being an ecological and economic "parasite" on some distant region. As it turned out, Georgia is a good microcosm for the United States because its human density, growth rate, food production, and the distribution of its human and domestic animal populations are all close to the mean situation for the whole nation.

The per capita area required for food was estimated by taking the diet recommended by the President's Council on Physical Fitness and determining how much crop, orchard and grazing land is required to supply the annual requirement for each item. If we would be satisfied with a diet based on intensive grain and soy bean culture perhaps as little as one-third of an acre could keep a person fed and reasonably well nourished, but the kind of diet Americans enjoy (including orange juice, bacon and eggs for breakfast and steaks for dinner) requires a great deal of land to produce, at least 1.5 acres per person. The impact of domestic animals on man's total environment is often overlooked in land-use planning. In Georgia, for example, domestic animals (cattle, pigs, chickens, etc.) consume primary production (food produced by plants) equivalent to that consumed by 21 million persons (compared to 4.8 million persons now living in the state). And this does not include pets, which for the nation as a whole consume enough food to feed five million people. While the impact of domestic animals on the environment is not nearly so great as that of an equivalent human biomass the stress they place on the natural environment is considerable, and must be accounted for. We could, of course, do away with domestic animals, but this would mean giving up meat in the diet (and associated options) and dehumanizing man himself to the level of a domestic animal. ?!

TABLE 1. MINIMUM PER CAPITA ACREAGE REQUIREMENTS FOR A QUALITY ENVIRONMENT

Food-producing land	1.5 acres	30%
Fiber-producing land	1.0 acres	20
Natural use areas	2.0 acres	40
Urban-Industrial Systems	0.5 acres	10
TOTAL	5.0 acres	

In a similar manner, the per capita acreage needed for fibers (paper, lumber, cotton, etc.), watersheds, tertiary treatment of wastes, recreation, parks, highways, urban and industrial living space were estimated. For some uses good data are available in statistical yearbooks, but for other needs (for example, outdoor recreation) we had to depend on recommendations of professional planners who deal with the particular human need. Our preliminary attempt to sum up total environmental needs in terms of the *minimum space required* is shown in Table 1.

It should be emphasized that this estimate of 5 acres (2 hectares) per person applies to a self-sustaining region with good soils, a temperate climate and abundant rainfall; requirements would be larger in areas with a less favorable climate. Since Georgians now enjoy 10 acres per person, we conclude that optimum population density (again on a self-sustaining basis at an American level of affluence) is no more than double the present population.

In this model (Table 1) about 2/5 of the total requirement is designated as natural environment. When we consider that food and fiber-producing lands contain considerable natural elements which contribute to life support and recycling, this estimate comes close to the 50 percent figure previously suggested as a working hypothesis for planners.

APPENDIX

To illustrate how the model of Figure 1 could be used, hypothetical data based on reasonable expectations for energy flows and exchange coefficients were fed into an analog computer and the output plotted as a performance curve, as shown in Figure 2. The "sum of values" on the Y-axis is the sum of the three values shown in Figure 1, and is plotted as a percentage of the maximum sum. In this highly generalized run the optimum plateau covers a broad range between one-third and two-thirds developed lands. Anything more than 60 percent developed (or anything less than 40 percent natural) environment resulted in a precipitous decline of the value of the total environment. It should be emphasized that the optimum mix between developed and natural environment could vary considerably from region to region depending on the intensity of development, the kind and

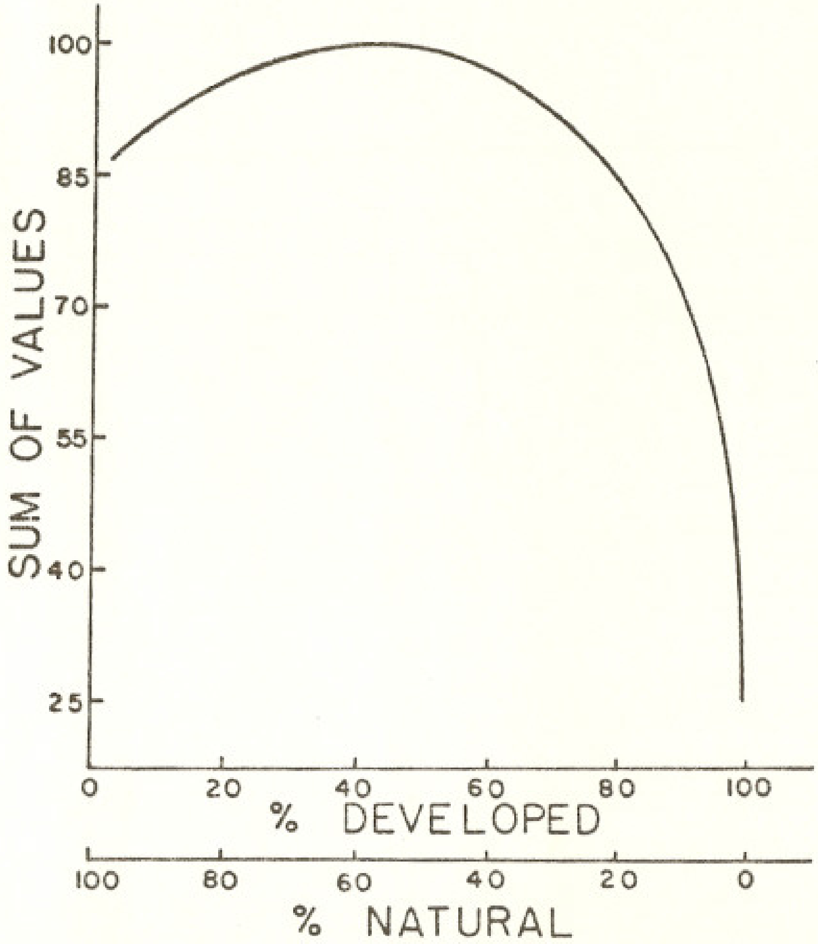

Figure 2.—Performance curve generated from the model of Figure 1 using hypothetical data based on reasonable values for energy flow in highly developed and natural environments. The "sum of values" is the sum of the three values shown in Figure 1 plotted as a percent of maximum. W. Smith, H. McKellar, and C. Littlejohn, of the University of Florida, obtained the diagram using analog computer using light settings of percentage of developed land.

amount of poisonous wastes produced, the capacity (productivity) of the natural environment, the density and behavior of the human population, and so on. However, performance curves of the type shown in Figure 2, appear to be characterized by rapid declines once one goes beyond the optimum plateau. If this is a true generalization it may explain why it is difficult to recognize overdevelopment before it is too late.

During the coming year it is hoped that data from actual situations can be used to further test and refine the procedure. Particularly desired are data on actual economic budgets, power flows and land use patterns in large metropolitan districts, or other regions or sections that have a functional unity. First attention will certainly be given to areas where research and planning inventories can provide accurate values, and where public opinion and government organization are sufficiently strong to promote serious planning aimed at preventing overdevelopment.

In addition to showing energy relationships, the energy diagram is a way of writing differential equations, and the differential equations are an intermediate step in putting the model on analog or digital computer. The translation of the Fig. 1 model is given as three linked equations below in which the natural energies are designated S; fossil fuels, F; the developed lands, D; the natural lands, (1-D); the natural ecosystems, N; the developed ecosystems and cities, C; and the interactions of diversity of man and nature, I; k's are the coefficients for each pathway which may be evaluated from data. Where the pathway has little drain action on its source, it is indicated by a small triangle and its outflow action omitted in the equations.

$$\dot{N} = k_1\, S(1\text{-}D) - k_2N - k_3CN$$
$$\dot{C} = k_4\, DFN - k_5CN$$
$$\dot{I} = k_6\, CN - k_7I$$

Value rates (V) are the sum of the energies of replacement and maintenance and, thus, are the sum of three rates of energy flow.

$$V = k_2N + k_5C + k_7I$$

The graph in Fig. 2 is the steady state sum of value flows found with one set of coefficients (k's) in the set of equations on an AD-30 analog computer.

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DISCUSSION

MR. WILLIAM BELLER (U. S. Environmental Protection Agency): Again I would like to caution against overuse of an analogy. The statement was made here that an acre of land would cost $400 for use in tertiary treatment but was worth $12,500 in terms of the energy that the trees contribute. Fine. But suppose you have an acre of land in the middle of a city and a developer comes up and says, "I'll give you that money; give me the acre of land." I am afraid you have yourself in a box and you must have higher values. So please don't establish a low value, because they may come and buy it from you.

DISCUSSION LEADER CALLISON: Thank you for that word of caution. Mr. Chairman, is there time for another comment?

DR. ROBERT WEEDEN (University of Alaska): Those of us who would like to preserve tundras and deserts would also like to supplement this system of monetary and energy interchange values. Clearly these are based on a biological productivity. Tundras and deserts are lower in biological productivity, and through this system alone, then, would have lower monetary values. I think that Dr. Hardin and many of us here can think of ways in which you can supplement this system, as proposed by Dr. Odum, with other types of value systems.

DR. EARL J. BELL (University of Washington): I have some experience in doing ecological modeling in the San Juan Islands area in the State of Washington, and I would like to urge you to more general caution. Now Dr. Odum's statement that analogue or visual stimulation can be carried out is a fantastic overstatement of the problem. Every one of those connections in that diagram requires some kind of functional determination of how that connection works. This requires an inordinate amount of basic research, number one, and every single one of those connections must be specifically introduced into the computer in some sort of mathematical function. Therefore, the tendency here is, I think, to raise hopes a little too much. I have read Dr. Odum's book and I would like to caution that this is not going to be any kind of panacea. Every single ecosystem that gets modeled is going to be the result of thousands and thousands of man hours of work. Thank you.

DR. CHEATUM: Both Odums, Gene and Tom, recognize this. And this one of the reasons I think Gene said that it will be a long time before we can really effectively fill in the little boxes in this model. It will take a tremendous amount of work, and it is going to cost a lot, but in the meantime we may be able to work more efficiently with new concepts, with at least what we have.