sively on proving the impossibility of growth, they were easily deluded by a simple, now widespread, but false syllogism: since exponential growth in a finite world leads to disasters of all kinds, ecological salvation lies in the stationary state [42; 47; 62, 156–184; 6, 3f, 8, 20].[46] H. Daly even claims that "the stationary state economy is, therefore, a necessity" [21, 5].

This vision of a blissful world in which both population and capital stock remain constant, once expounded with his usual skill by John Stuart Mill [64, Bk. 4, Ch. 6], was until recently in oblivion.[47] Because of the spectacular revival of this myth of ecological salvation, it is well to point out its various logical and factual snags. The crucial error consists in not seeing that not only growth, but also a zero-growth state, nay, even a declining state which does not converge toward annihilation, cannot exist forever in a finite environment. The error perhaps stems from some confusion between finite stock and finite flow rate, as the incongruous dimensionalities of several graphs suggest [62, 62, 64f, 124ff; 6, 6]. And contrary to what some advocates of the stationary state claim [21, 15], this state does not occupy a privileged position vis-à-vis physical laws.

To get to the core of the problem, let S denote the actual amount of accessible resources in the crust of the earth. Let P_i and s_i be the population and the amount of depleted resources per person in the year i. Let the "amount of total life," measured in years of life, be defined by $L = \Sigma P_i$, from $i = 0$ to $i = \infty$. S sets an upper limit for L through the abvious constraint $\Sigma P_i s_i \leqslant S$. For although s_i is a historical variable, it cannot be zero or even negligible (unless mankind reverts sometime to a berry-picking economy). Therefore, $P_i = 0$ for i greater than some finite n, and $P_i > 0$ otherwise. That value of n is the maximum duration of the human species [31, 12f; 32, 304].

The earth also has a so-called carrying capacity, which depends on a complex of factors, including the size of s_i.[48] This capacity sets a limit on any single P_i. But this limit does not render the other limits, of L and n, superfluous. It is therefore inexact to argue—as the Meadows group seems to do [62, 91f]—that the stationary state can go on forever as long as P_i does not exceed that capacity. The proponents of salvation through the stationary state must admit that such a state can have only a finite duration—unless they are willing to join the "No Limit" Club by maintaining that S is inexhaustible or almost so—as the Meadows group does in fact [62, 172]. Alternatively, they must explain the puzzle of how a whole economy, stationary for a long era, all of a sudden comes to an end.

Apparently, the advocates of the stationary state equate it with an open *thermodynamic* steady state. This state consists of an *open* macrosystem which maintains its entropic structure constant through material exchanges with its "environment." As one would immediately guess, the concept constitutes a highly useful tool for the study of biological organisms. We ~~must, however~~, observe that the concept rests on some special conditions introduced by L. Onsager [50, 89–97]. These conditions are so delicate (they are called the principle of *detailed* balance) that in actuality they can hold only "within a deviation of a few percent" [50, 140]. For this reason, a steady state may exist in fact only in an approximated manner and over a finite duration. This impossibility of a macrosystem not in a state of chaos to be perpetually durable may one day be explicitly recognized by a new thermodynamic law just as the impossibility of perpetual motion once

[46] The substance of the argument of *The Limits* beyond that of Mill's is borrowed from Boulding and Daly [8; 9; 20; 21].

[47] In *International Encyclopedia of the Social Sciences*, for example, the point is mentioned only in passing.

[48] Obviously, any increase in s_i will generally result in a decrease of L and of n. Also, the carrying capacity in any year may be increased by a greater use of terrestrial resources. These elementary points should be retained for further use (Section X).

was. Specialists recognize that the present thermodynamic laws do not suffice to explain all nonreversible phenomena, including especially life processes.

Independently of these snags there are simple reasons against believing that mankind can live in a perpetual stationary state. The structure of such a state remains the same throughout; it does not contain in itself the seed of the inexorable death of all open macrosystems. On the other hand, a world with a stationary population would, on the contrary, be continually forced to change its technology as well as its mode of life in response to the inevitable decrease of resource accessibility. Even if we beg the issue of how capital may change qualitatively and still remain constant, we would have to assume that the unpredictable decrease in accessibility will be miraculously compensated by the right innovations at the right time. A stationary world may for a while be interlocked with the changing environment through a system of balancing feedbacks analogous to those of a living organism during one phase of its life. But as Bormann reminded us [7, 707], the miracle cannot last forever; sooner or later the balancing system will collapse. At that time, the stationary state will enter a crisis, which will defeat its alleged purpose and nature.

One must be cautioned against another logical pitfall, that of invoking the Prigogine principle in support of the stationary state. This principle states that the minimum of the entropy produced by an Onsager type of open thermodynamic system is reached when the system becomes steady [50, ch. xvi]. It says nothing about how this last entropy compares with that produced by other open systems.[49]

The usual arguments adduced in favor of the stationary state are, however, of a different, more direct nature. It is, for example, argued that in such a state there is more time for pollution to be reduced by natural processes and for technology to adapt itself to the decrease of resource accessibility [62, 166]. It is plainly true that we could use much more efficiently today the coal we have burned in the past. The rub is that we might not have mastered the present efficient techniques if we had not burned all that coal "inefficiently." The point that in a stationary state people will not have to work additionally to accumulate capital (which in view of what I have said in the last paragraphs is not quite accurate) is related to Mill's claim that people could devote more time to intellectual activities. "The trampling, crushing, elbowing, and treading on each other's heel" will cease [64, 754]. History, however, offers multiple examples—the Middle Ages, for one—of quasi stationary societies where arts and sciences were practically stagnant. In a stationary state, too, people may be busy in the fields and shops all day long. Whatever the state, free time for intellectual progress depends on the intensity of the pressure of population on resources. Therein lies the main weakness of Mill's vision. Witness the fact that—as Daly explicitly admits [21, 6–8]—its writ offers no basis for determining even in principle the optimum levels of population and capital. This brings to light the important, yet unnoticed point, that *the necessary conclusion*

[49] The point recalls Boulding's idea that the inflow from nature into the economic process, which he calls "throughput," is "something to be minimized rather than maximized" and that we should pass from an economy of flow to one of stock [8, 9f; 9, 359f]. The idea is more striking than enlightening. True, economists suffer from a flow-complex [29, 55, 88]; also, they have little realized that the proper analytical description of a process must include *both flows and funds* [30; 32, 219f, 228–234]. Entrepreneurs, as far as Boulding's idea is concerned, have at all times aimed at minimizing the flow necessary to maintain their capital funds. If the present inflow from nature is incommensurate with the safety of our species, it is only because the population is too large and part of it enjoys excessive comfort. Economic decisions will always forcibly involve both flows and stocks. Is it not true that mankind's problem is to economize S (a stock) for as large an amount of life as possible, which implies to minimize s_i (a flow) for some "good life"? (Section XI).

of the arguments in favor of that vision is that the most desirable state is not a stationary, but a declining one.

Undoubtedly, the current growth must cease, nay, be reversed. But anyone who believes that he can draw a blueprint for the ecological salvation of the human species does not understand the nature of evolution, or even of history—which is that of a permanent struggle in continuously novel forms, not that of a predictable, controllable physico-chemical process, such as boiling an egg or launching a rocket to the moon.

IX. SOME BASIC BIOECONOMICS[50]

Apart from a few insignificant exceptions, all species other than man use only *endosomatic* instruments—as Alfred Lotka proposed to call those instruments (legs, claws, wings, etc.) which belong to the individual organism *by birth.* Man alone came, in time, to use a club, which does not belong to him by birth, but which extended his endosomatic arm and increased its power. At that point in time, man's evolution transcended the biological limits to include also (and primarily) the evolution of *exosomatic* instruments, i.e., of instruments produced by man but not belonging to his body.[51] That is why man can now fly in the sky or swim under water even though his body has no wings, no fins, and no gills.

The exosomatic evolution brought down upon the human species two fundamental and irrevocable changes. The first is the irreducible social conflict which characterizes the human species [29, 98–101; 32, 306–315, 348f]. Indeed, there are other species which also live in society, but which are free from such conflict. The reason is that their "social classes" correspond to some clear-cut biological divisions. The periodic killing of a great part of the drones by the bees is a natural, biological action, not a civil war.

The second change is man's addiction to exosomatic instruments—a phenomenon analogous to that of the flying fish which became addicted to the atmosphere and mutated into birds forever. It is because of this addiction that mankind's survival presents a problem entirely different from that of all other species [31; 32, 302–305]. It is neither only biological nor only economic. It is bioeconomic. Its broad contours depend on the multiple asymmetries existing among the three sources of low entropy which together constitute mankind's dowry—the free energy received from the sun, on the one hand, and the free energy and the ordered material structures stored in the bowels of the earth, on the other.

The *first* asymmetry concerns the fact that the terrestrial component is a *stock,* whereas the solar one is a *flow.* The difference needs to be well understood [32, 226f]. Coal *in situ* is a stock because we are free to use it all today (conceivably) or over centuries. But at no time can we use any part of a future flow of solar radiation. Moreover, the flow rate of this radiation is wholly beyond our control; it is completely determined by cosmological conditions, including the size of our globe.[52] One generation, whatever it may do, cannot alter the share of solar radiation of any future generation. Because of the priority of the present over the future and the irrevocability of entropic degradation, the opposite is true for the terrestrial shares. These shares are affected by how much of the terrestrial dowry the past generations have consumed.

Second, since no practical procedure is available at human scale for transforming energy into matter (Section IV), accessible material low entropy is by far the most critical element from the bioeconomic viewpoint.

[50] I saw this term used for the first time in a letter from Jiří Zeman.

[51] The practice of slavery, in the past, and the possible procurement, in the future, of organs for transplant are phenomena akin to the exosomatic evolution.

[52] A fact greatly misunderstood: Ricardian land has economic value for the same reason as a fisherman's net. Ricardian land catches the most valuable energy, roughly in proportion to its total size [27, 508; 32, 232].

True, a piece of coal burned by our forefathers is gone forever, just as is part of the silver or iron, for instance, mined by them. Yet future generations will still have their inalienable share of solar energy (which, as we shall see next, is enormous). Hence, they will be able, at least, to use each year an amount of wood equivalent to the annual vegetable growth. For the silver and iron dissipated by the earlier generations there is no similar compensation. This is why in bioeconomics we must emphasize that every Cadillac or every Zim—let alone any instrument of war—means fewer plowshares for some future generations, and implicitly, fewer future human beings, too [31, 13; 32, 304].

Third, there is an astronomical difference between the amount of the flow of solar energy and the size of the stock of terrestrial free energy. At the cost of a decrease in mass of 131×10^{12} tons, the sun radiates annually 10^{14}Q—one single Q being equal to 10^{18}BTU! Of this fantastic flow, only some 5,300 Q are intercepted at the limits of the earth's atmosphere, with roughly one half of that amount being reflected back into outer space. At our own scale, however, even this amount is fantastic; for the total world consumption of energy currently amounts to no more than 0.2 Q annually. From the solar energy that reaches the ground level, photosynthesis absorbs only 1.2 Q. From waterfalls we could obtain at most 0.08 Q, but we are now using only one tenth of that potential. Think also of the additional fact that the sun will continue to shine with practically the same intensity for another five billion years (before becoming a red giant which will raise the earth's temperature to 1,000°F). Undoubtedly, the human species will not survive to benefit from all this abundance.

Passing to the terrestrial dowry, we find that, according to the best estimates, the initial dowry of fossil fuel amounted to only 215 Q. The outstanding recoverable reserves (known and probable) amount to about 200 Q. These reserves, therefore, could produce only two weeks of sunlight on the globe.[53] If their depletion continues to increase at the current pace, these reserves may support man's industrial activity for just a few more decades. Even the reserves of uranium-235 will not last for a longer period if used in the ordinary reactors. Hopes are now set on the breeder reactor, which, with the aid of uranium-235, may "extract" the energy of the fertile but not fissionable elements, uranium-238 and thorium-232. Some experts claim that this source of energy is "essentially inexhaustible" [83, 412]. In the United States alone, it is believed, there are large areas covered with black shale and granite which contain 60 grams of natural uranium or thorium per metric ton [46, 226f]. On this basis, Weinberg and Hammond [83, 415f] have come out with a grand plan. By strip-mining and crushing all these rocks, we could obtain enough nuclear fuel for some 32,000 breeder reactors distributed in 4,000 offshore parks and capable of supplying a population of twenty billion for millions of years with twice as much energy per capita as the current consumption rate in the USA. The grand plan is a typical example of linear thinking, according to which all that is needed for the existence of a population, even "considerably larger than twenty billion," is to increase all supplies proportionally.[54] Not that the authors deny that there also are non-technical issues; only, they play them down with noticeable zeal [83, 417f]. The most important issue, of whether a social organization compatible with the density of population and the nuclear manipulation at the

[53] The figures used in this section have been calculated from the data of Daniels [22] and Hubbert [46]. Such data, especially those about reserves, vary from author to author but not to the extent that really matters. However, the assertion that "the vast oil shales which are to be found all over the world [would last] for no less than 40,000 years" [59, 99] is sheer fantasy.

[54] In an answer to critics (*American Scientist,* LVIII, No. 6, p. 619), the same authors prove, again linearly, that the agro-industrial complexes of the grand plan could easily feed such a population.

grand level can be achieved, is brushed aside by Weinberg as "transscientific" [82].[55] Technicians are prone to forget that due to their own successes, nowadays it may be easier to move the mountain to Mohammed than to induce Mohammed to go to the mountain. For the time being, the snag is far more palpable. As responsible forums openly admit, even one breeder still presents substantial risks of nuclear catastrophes, and the problem of safe transportation of nuclear fuels and especially that of safe storage of the radioactive garbage still await a solution even for a moderate scale of operations [35; 36; especially 39 and 67].

There remains the physicist's greatest dream, controlled thermonuclear reaction. To constitute a real breakthrough, it must be the deuterium-deuterium reaction, the only one that could open up a formidable source of terrestrial energy for a long era.[56] However, because of the difficulties alluded to earlier (Section IV), even the experts working at it do not find reasons for being too hopeful.

For completion, we should also mention the tidal and geothermal energies, which, although not negligible (in all 0.1 Q per year), can be harnessed only in very limited situations.

The general picture is now clear. The terrestrial energies on which we can rely effectively exist in very small amounts, whereas the use of those which exist in ampler amounts is surrounded by great risks and formidable technical obstacles. On the other hand, there is the immense energy from the sun which reaches us without fail. Its direct use is not yet practiced on a significant scale, the main reason being that the alternative industries are now much more efficient economically. But promising results are coming from various directions [37; 41]. What counts from the bioeconomic viewpoint is that the feasibility of using the sun's energy directly is not surrounded by risks or big question marks; it is a proven fact.

The conclusion is that mankind's entropic dowry presents another important differential scarcity. From the viewpoint of the extreme longrun, the terrestrial free energy is far scarcer than that received from the sun. The point exposes the foolishness of the victory cry that we can finally obtain protein from fossil fuels! Sane reason tells us to move in the opposite direction, to convert vegetable stuff into hydrocarbon fuel—an obviously natural line already pursued by several researchers [22, 311–313].[57]

Fourth, from the viewpoint of industrial utilization, solar energy has an immense drawback in comparison with energy of terrestrial origin. The latter is available in a concentrated form, in some cases, in a too concentrated form. As a result, it enables us to obtain almost instantaneously enormous amounts of work, most of which could not even be obtained otherwise. By great contrast, the flow of solar energy comes to us with an extremely low intensity, like a very fine rain, almost a microscopic mist. The important difference from true rain is that this radiation rain is not collected naturally into streamlets, then into creeks and rivers, and finally into lakes from where we could use it in a concentrated form, as is the case with waterfalls. Imagine the difficulty one would face if one tried to use *directly* the kinetic energy of some microscopic rain drops as

[55] For a recent discussion of the social impact of industrial growth, in general, and of the social problems growing out of a large scale use of nuclear energy, in particular, see [78], a monograph by Harold and Margaret Sprout, pioneers in this field.

[56] One percent only of the deuterium in the oceans would provide 10^8 Q through that reaction, an amount amply sufficient for some hundred millions of years of very high industrial comfort. The reaction deuterium-tritium stands a better chance of success because it requires a lower temperature. But since it involves lithium-6, which exists in small supply, it would yield only about 200 Q in all.

[57] It should be of interest to know that during World War II in Sweden, for one, automobiles were driven with the poor gas obtained by heating charcoal with kindlings in a container serving as a tank!

they fall. The same difficulty presents itself in using solar energy directly (i.e., not through the chemical energy of green plants, or the kinetic energy of the wind and waterfalls). But as was emphasized a while ago, the difficulty does not amount to impossibility.

Fifth, solar energy, on the other hand, has a unique and incommensurable advantage. The use of any terrestrial energy produces some noxious pollution, which, moreover, is irreducible and hence cumulative, be it in the form of thermal pollution alone. By contrast, any use of solar energy is *pollution-free*. For, whether this energy is used or not, its ultimate fate is the same, namely, to become the dissipated heat that maintains the thermodynamic equilibrium between the globe and outer space at a propitious temperature.[58]

The *sixth* asymmetry involves the elementary fact that the survival of every species on earth depends, directly or indirectly, on solar radiation (in addition to some elements of a superficial environmental layer). Man alone, because of his exosomatic addiction, depends on mineral resources as well. For the use of these resources man competes with no other species; yet his use of them usually endangers many forms of life, including his own. Some species have in fact been brought to the brink of extinction merely because of man's exosomatic needs or his craving for the extravagant. But nothing in nature compares in fierceness with man's competition for solar energy (in its primary or its by-product forms). Man has not deviated one bit from the law of the jungle; if anything, he has made it even more merciless by his sophisticated exosomatic instruments. Man has openly sought to exterminate any species that robs him of his food or feeds on him—wolves, rabbits, weeds, insects, microbes, etc.

But this struggle of man with other species for food (in ultimate analysis, for solar energy) has some unobtrusive aspects as well. And, curiously, it is one of these aspects that has some far-reaching consequences in addition to supplying a most instructive refutation of the common belief that every technological innovation constitutes a move in the right direction as concerns the economy of resources. The case pertains to the economy of modern agricultural techniques.

[58] One necessary qualification: even the use of solar energy may disturb the climate if the energy is released in another place than where collected. The same is true for a difference in time, but this case is unlikely to have any practical importance.

X. MODERN AGRICULTURE: AN ENERGY SQUANDERER

Given the extant spectrum of green plants and their geographical distribution at any one time, the biological carrying capacity of the earth is determined, even though we could compute it only with difficulty and only approximately. It is within this capacity that man struggles with other life-bearing structures for food. But man is unique among all species in that he can influence, within limits, not only his share of food but also the efficiency of the transformation of solar energy into food. With time, man learned to plow deeper, to rotate the use of land, to fertilize the soil with manure, and so on. In his farming activity, man also came to derive an immense benefit from the use of domesticated draft animals.

Two evolutionary factors have influenced farming technology over the years. The oldest one is the continuous pressure of population on the extant land under cultivation. Village swarming, at first, and later migration, were able to relieve the pressure. Means of increasing the yield of land also helped ease the tension. The main source of release, however, remained the clearing of vast tracts of land. The second factor, a by-product of the Industrial Revolution, was the extension to agriculture of the process by which low entropy from mineral sources was substituted for that of biological nature. The process is even more conspicuous in agriculture. Tractors and other agricultural machines have taken the place of man and draft animals, and chemical fertilizers, that of manuring and fallowing.

However, mechanized agriculture does not fit small family farms which have at their disposal a large supply of free hands. Yet even in this case it had to come. The peasant who practices organic agriculture, who uses animals for power and manure as fertilizer, must grow not only food for his family but also fodder for his helpers. The increasing pressure of population thus forced even the small farmer, practically everywhere, to do away with the beasts of burden so as to use his entire land for food [27, 526; 31, 11f; 32, 302f].

The point beyond any possible doubt is that, given the pressure of population in the greater part of the globe, there is no other salvation from the calamities of undernutrition and starvation than to force the yield on the land under cultivation by an increasingly mechanized agriculture, an increasing use of chemical fertilizers and pesticides, and an increasing cultivation of the new high-yield varieties of cereal grains. However, contrary to the generally and indiscriminately shared notion, this modern agricultural technique is in the longrun a move against the most elementary bioeconomic interest of the human species.

First, the replacement of the water buffalo by the tractor, of fodder by motor fuels, of manure and fallowing by chemical fertilizers substitutes scarcer elements for the most abundant one—solar radiation. Secondly, this substitution also represents a squandering of terrestrial low entropy because of its strongly decreasing returns.[59] What modern agricultural technique does is to increase the amount of photosynthesis on the same piece of cultivated land. But this increase is achieved by a more than proportional increase in the depletion of the low entropy of terrestrial origin, which is the only critically scarce resource. (We should note that decreasing returns in substituting solar for terrestrial energy would, on the contrary, constitute a good energetic deal.) This means that, if half of the input of terrestrial energy (counted from the mining operation) required by modern agriculture for one acre—cultivated, say, with wheat—is used each year, in two years the less industrialized agriculture would produce more than twice as much wheat from the same piece of land. This diseconomy—surprising as it may seem to the worshipers of machinery—is especially heavy in the case of the high-yield varieties which earned their developer, Norman E. Borlaug, a Nobel Prize.

A highly mechanized and heavily fertilized cultivation does allow a very large population, P_i, to survive, but the price is an increase of the per capita depletion of terrestrial resources s_i, which *ceteris paribus* means a proportionally greater reduction of the future amount of life (Section VIII). In addition, if growing food by "agro-industrial complexes" becomes the general rule, many species associated with old-fashioned, organic agriculture may gradually disappear, a result which may drive mankind into an ecological cul-de-sac from which there would be no return [31, 12].

The above observations bear upon the perennial question of how many people the earth could support. Some population experts claim that there would be enough food even for some forty billion people at a diet of some 4,500 kilocalories provided that the best farming methods were used on every acre of potentially arable land.[60] The logic rests on multiplying the amount of potentially arable land by the current average yield in Iowa. The calculations may be as "careful" as boasted—they represent, nonetheless, linear thinking. Clearly, neither these authors nor those less optimistic have thought of the crucial question of *how long* a population of forty billion—nay, even one of only one million for that matter—can last [31, 11; 32, 20, 301f]. It is this question which, more

[59] Between 1951 and 1966, the number of tractors increased by 63 percent, phosphate fertilizers by 75 percent, nitrate fertilizers by 146 percent, and pesticides by 300 percent. Yet the crops, which may be taken as a good index of yield, increased by only 34 percent! [6, 40]

[60] This position has been advanced, for example, by Colin Clark in 1963 [see 31, 11; 32, 20], and very recently by Revelle [70].

than most others, lays bare the most stubborn residual of the mechanistic view of the world, which is the myth of the optimum population "as one that can be sustained indefinitely" [6, 14; also 62, 172f; 74, 48].

XI. A MINIMAL BIOECONOMIC PROGRAM

In "A Blueprint for Survival" [6, 13], the hope is expressed that economics and ecology will one day merge. The same possibility has already been considered for biology and physics, with most opinions agreeing that in the merger biology would swallow up physics [32, 42]. For essentially the same reason—that the phenomenal domain covered by ecology is broader than that covered by economics—economics will have to merge into ecology, if the merger ever occurs. For, as we have seen in the preceding two sections, the economic activity of any generation has some influence on that of the future generations—terrestrial resources of energy and materials are irrevocably used up and the harmful effects of pollution on the environment accumulate. One of the most important ecological problems for mankind, therefore, is the relationship of the quality of life of one generation with another—more specifically, the distribution of mankind's dowry *among all generations*. Economics cannot even dream of handling this problem. The object of economics, as has often been explained, is the administration of scarce resources; but to be exact, we should add that *this administration regards only one generation*. It could not be otherwise.

There is an elementary principle of economics according to which the only way to attribute a relevant price to an irreproducible object, say, to Leonardo's Mona Lisa, is to have absolutely everyone bid on it. Otherwise, if only you and I were to bid, one of us could get it for just a few dollars. That bid, i.e., that price, would clearly be parochial.[61] This is exactly what happens for the irreproducible resources. Each generation can use as many terrestrial resources and produce as much pollution as its own bidding alone decides. Future generations are not, simply because they cannot be, present on today's market.

To be sure, the demand of the present generation reflects also the interest to *protect* the children and perhaps the grandchildren. Supply may also reflect expected future prices over a few decades. But neither the current demand nor the current supply can include even in a very slight form the situation of more remote generations, say, those of A.D. 3,000, let alone those that might exist a hundred thousand years from now.

Not all the details, but certainly the most important consequences of allocation of resources among generations by the market mechanism may be brought to the fore by a very simple, actually a highly simplified diagram. We shall assume that demand for some mineral resource already mined (say, coal-on-the-ground) is the same for each successive generation and that each generation must consume at least one "ton" of coal. The demand schedule is also assumed to include the preference for protecting the interests of a few future generations. In Figure 1, D_1, D_2, $\ldots D_{15}$ represent the aggregate demands of successive generations, beginning with the present one. The interrupted line *abcdef* represents the average cost of mining the deposits of various accessibilities. Total reserves amount to 15 tons. Now, if we ignore for a moment the effect of the interest rate on the supply of the coal *in situ* by the owners of the mines, then the first generation will mine the amount $a'b'$, the shaded area representing the differential rent of the better mines. We may safely regard aa' as the price of the coal contained in these mines. The second generation will mine the amount $b'c'$. But

[61] Yet the economist's myth that prices reflect values in some generally relevant sense is now shared by other professions as well. The Meadows group, for example, speaks of the cost of resource depletion [62, 181], and Barry Commoner, of the cost of environmental deterioration [18, 253f and *passim*]. These are purely verbal expressions, for there is no such thing as the cost of irreplaceable resources or of irreducible pollution.

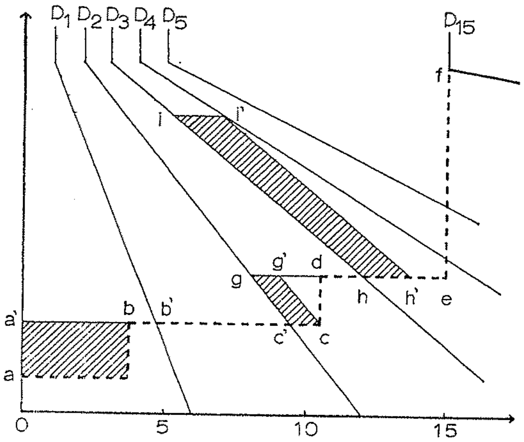

FIGURE 1

since no mine will earn a differential rent, the price of the coal *in situ* will be zero. During the third generation, the marginal cost of mining will be at the level of h; the quantity mined will be gh, with the quantity $c'c = gg'$ earning the rent shown by the shaded area. Finally, the fourth generation is left with the amount hh' (determined by the condition that $g'd = h'e$), which will earn a pure scarcity rent, represented by the shaded area $hh'i'i$. Nothing will be left for the following generations.

Several things are now obvious. First, the market mechanism *by itself* results in resources being consumed in higher amounts by the earlier generations, that is, faster than they should be. Indeed, $a'b' > b'c' > gh > hh'$, which confirms the dictatorship of the present over the future. Should all the generations bid from the outset for the total deposit of coal, the price of coal *in situ* will be driven up to infinity, a situation which would lead nowhere and only explode the entropic predicament of mankind. Only an omniscient planner could avoid this situation by simply allocating one ton of coal *in situ* to each of the first fifteen generations, each ton consisting of the same qualitative composition.[62]

Bringing in the interest rate modifies the picture somewhat and allows us to see even more clearly the impotence of the market to prevent the excessive depletion of resources by the earlier generations. Let us consider the case which I earlier called a bonanza era. Specifically, it is the situation in which the best quality of coal mine suffices to satisfy the present demand as well as that of the future generations *as far as the* present economic time horizon goes. Within this horizon, then, there is no rent at any time and hence no inducement to save coal *in situ* for future generations. Coal *in situ* can thus have no price during the present generation.

The question ignored by the few economists who have recently tackled some market aspects of natural resources [e.g., 75] is why resources *in situ* may, after all, have a positive price even if there are no self-imposed restrictions by the mine owners. The answer is that if present resources have a price, it is not ordinarily because of present scarcity, but because of some expected differential scarcity within the present time horizon. To illustrate the rationale of this process, let C_1, C_2, C_3 be coal mines of different qualities, the costs of mining one unit of coal being $k_1 < k_2 < k_3$, respectively. Let us further assume that C_1 is expected to be exhausted during the third generation after the present one, when C_2 will become economically efficient. Let us also assume that C_2, in turn, will be exhausted during the second generation thereafter, and that C_3 will then suffice for the remainder of the time horizon. During the third future generation, C_1 will prove to enjoy a differential rent $r_1 = k_2 - k_1$ with respect to C_2, and after two more generations the differential rent of C_2 over C_3, $r_2 = k_3 - k_2$, will become manifest. Only C_3 has no differential rent, and hence, as we have seen in the previous paragraph, its price is zero throughout. On the other hand, because C_2 necessarily earns a rent in the fifth generation from now, it must have a present positive price, namely, $p_2^0 = r_2/(1 + i)^5$, where i is the interest rate (assumed constant throughout the time horizon). In the j-th

[62] In a pioneering work [45], Hotelling demonstrated once for all that one cannot speak of optimum allocation of resources unless the demand over the entire future is known.

generation from now, the price will be $p_2^j = r_2/(1 + i)^{5-j}$. A similar logic determines the present price of C_1. Only, we must observe that during the generation when the differential rent of C_1 becomes manifest, the price of C_2 is $p_2^3 = r_2/(1 + i)^2$. The rent must therefore be added to this price. Hence, the present price of the coal of C_1 is $p_1^0 = (r_1 + p_2^3)/(1 + i)^3$.

The formulae just established show that the effect of the interest rate in the presence of a qualitative spectrum of mines is to extend the use of coal mined from more accessible sources (in comparison to the quantities determined by Figure 1). In some rather idle way, we may say that the existence of the interest rate helps the economy of resources. But let us not ignore the far more important conclusion of the foregoing analysis, which is especially striking in the case of an era of bonanza. Serious scarcities may become effective (as will certainly happen) beyond the present time horizon. That future fact can in no way influence our present market decisions; it is virtually inexistent as far as these decisions are concerned.

Nothing need be added to convince ourselves that the market mechanism cannot protect mankind from ecological crises in the future (let alone to allocate resources optimally among generations) even if we would try to set the prices "right." [63] The only way to protect the future generations, at least from the excessive consumption of resources during the present bonanza, is by reeducating ourselves so as to feel some sympathy for our *future* fellow humans in the same way in which we have come to be interested in the well-being of our *contemporary* "neighbors." This parallel does not mean that the new ethical orientation is an easy matter. Charity for one's contemporaries rests on some objective basis, namely, the individual self-interest. The difficult question one has to face in spreading the new gospel is not "what has posterity done for me?"—as Boulding wittily put it—but, rather, "why should I do anything for posterity?" What makes you think, many will ask, that there will be any posterity ten thousand years from now? And indeed, it would certainly be poor economics to sacrifice anything for a nonexistent beneficiary. These questions, which pertain to the new ethics, are not susceptible of easy, convincing answers.

Moreover, there is the other side of the coin, also ethical and even more urgent, on which Kaysen [51] and Silk [72], in particular, have rightly insisted. The nature of Mohammed-men being what it is, if we stop economic growth everywhere, we freeze the present status and thus eliminate the chance of the poor nations to improve their lot. This is why one wing of the environmentalist movement maintains that the issue of population growth is only a bogy used by the rich nations in order to divert attention from their own abuse of the environment. For this group, there is only one evil—inequality of development. We must proceed, they say, toward a radical redistribution of productive capacity among all nations. Another view argues that, on the contrary, population growth is the most menacing evil of mankind and must be dealt with urgently and independently of any other action. As expected, the two polarized views have never ceased clashing in useless and even violent controversies—as happened especially at the Stockholm Conferences in 1972, and, quite recently, at the Bucharest Conference on Population.[64] The difficulty is again seated in human nature: it is mutual, deep-rooted

[63] The economist's characteristic confidence in the omnipotence of the price mechanism (Section IV, note 15) led many of my auditors to counter that the choice between satisfying present or future needs, with the usual reward for postponing consumption, will set the prices right for optimal use of resources. The argument fails to take into account precisely the limitation of our time horizon, which does not extend beyond a couple of decades [10, 10]. Even Solow, in an illustration defending the standard position [74, 427], assumes a horizon of thirty years only.

[64] For a highly interesting account of the crosscurrents at the Stockholm Conference, see [2].