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A physical view of sustainability

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ABSTRACT

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We assume that natural ecological communities tend to maximize the amount of stored biomass on a given area, thereby creating the highest sustainable rate of entropy formation possible from that area. We take this climax condition to define sustainability. Human intervention, through agriculture, reduced the ecosystem in given areas to a juvenile state, a state which seems to produce entropy at a lower rate than that of the natural climax condition. The gap in entropy production rates between the natural and the agricultural system would eventually be overcome by the direct and indirect use of fossil fuels. These fossil fuels are consumed much faster than they are being formed and, therefore, a social structure based on their extensive use cannot be sustainable. What type of social structure does meet our definition of sustainability? That is, what style and size of social activity will generate entropy at a rate no greater than that of the climax ecosystem in a particular area?

During the last two decades, studies of economic activities and their environmental repercussions were limited to the possible costs and benefits of pollution control and to the economically optimal extraction rates of mineral resources. The intrusion of human activities into the environment became increasingly apparent through the depletion of natural resource stocks and decreasing environmental quality. In the 1990s, sustainability of the socio-economic system within the global ecosystem has become the pressing issue. Although research is increasingly concerned with the question of sustainability, a definition based on physically measurable evidence is missing. Such a definition is proposed in this paper and an example application is given for a particular area.

1. BACKGROUND

Living systems are open ones that maintain their structure and function by using low entropy from their environment and releasing waste heat into

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the atmosphere. The Second Law of Thermodynamics directs all systems towards equilibrium with their surroundings. As a result of the immersion of living systems in low-entropy flows, low-entropy biomass is created locally at the expense of the high entropy in their surrounding environment. Life is a process that is far from equilibrium and seems to resist the directive of the second law. However, the emergence and evolution of complex living structures can be shown to increase overall entropy production over that which occurred in the absence of these structures (Schrödinger, 1944; Ulanowicz and Hannon, 1987). The second law is not violated by the local decrease in entropy caused by living systems. Within the plant is a new order which did not exist before the plant came into being. So the plant itself, with its structure and its complex set of chemical molecules, represents a decrease in entropy. But the process of constructing, operating and maintaining the plant results in the generation of entropy which more than offsets the entropy effect of the plant itself. The amount of entropy in the universe is increased by the presence of the plant.

The emergence and evolution of living organisms might be viewed as a "solution" to the thermodynamic problem of erasing the free energy gradients induced on earth by the influx of solar and geothermal radiation. Thus, ecosystems move temporarily away from thermodynamic equilibrium and become increasingly organized and effective at dissipating these free energy endowments. This dissipation process reaches a steady-state maximum as the ecological structure reaches such size and complexity that all captured energy is used for operation of the biological processes and maintenance of the biological structure. This steady-state system is called the climax ecosystem.

2. PROBLEM STATEMENT

Present-day definitions of sustainability are varied and vague. Often the phrase "sustainable development" is used in political circles in an apparent attempt to indicate to the listener that they can have it both ways. The ominous sound of "sustainable" must be modified to somehow make it acceptable. Listen to the definitions of sustainable development by the World Commission on Environment and Development (1987):

> ...sustainable development is a process of change in which the exploitation of resources, the direction of investment, the orientation of technological development, and institutional change are all in harmony and enhance both the current and future potential to meet human needs and aspirations.

or to Goodland and Leduc (1986) of the World Bank:

> ...a pattern of social and structural economic transformations which promises the benefits available in the present without jeopardizing the likely potential for similar benefits in the future.

or to the economists Pearce and Turner (1990),

> [a process that] ...involves maximizing the net benefits of economic development, subject to maintaining the services and quality of natural resources over time.

These definitions are hardly useful to those who seek guidance on where they stand with regard to the question of sustainability in their country, state, city, village or farm.

In order to provide an operational definition of sustainability, we see the need to define a reference system to which alternative states of the living system can be compared. We choose that reference system to be an ecological one, one that has proved to be sustainable over many hundreds of years. Such a reference system can be defined by the climax community in a given area. The climax ecosystem, provided consistency of climate and patchy disturbance, is a stable system in time. It is the reference system in our definition of sustainability.

In the climax community, living systems maximize the rate of entropy production relative to that production in the absence of life. For example, in our part of the world, the tall-grass prairie with periodic fires was such a climax community. Over thousands of years, the soil and the development of the organic system resulted in the enlargement of the biological activity on each piece of ground.

We assume that maximizing entropy formation is a consequence of the evolutionary and successional change of an ecosystem on any particular area given a particular climate and soil structure. In effect, we assume that the maximum rate of entropy production of the climax community (spatially averaged) on a given area is the highest possible sustainable rate attainable for that area. This is why we choose the climax ecosystem as our reference system. In the example below, we compare estimated entropy created by human-managed ecosystems to this reference system. If the entropy rates of human system exceeds the rate for the reference system, then these human systems cannot be sustainable.

We choose not to use some of the standard biological measures as Gross or Net Primary Production because these measures do not include all metabolic processes of the ecosystem (for example, those of the autotrophic and heterotrophic organisms). The energetic efficiency of the plant community is not captured by these standard measures and, therefore, they cannot serve as the bases for a proper reference system.

We are also faced with the problem that agriculture has the potential to reduce the maximum rate of entropy formation in a given area. In other words, farming can, particularly if carried on without regard to soil loss and chemical impairment of the soil ecosystem, temporarily or permanently reduce the climax biological activity on a given area, were that area to return to nature. The forests of Southern Illinois are a good example. Prior to the late 1700s, magnificent hardwood forests covered this region. Farming began in the early 1800s in the area as westward-moving farmers settled along the Ohio river. By 1900 much of the A horizon of the soil was degraded, farming ceased, and the forests of today struggle for survival in the rocky remnants. As a result, the sustainability of the reference system has been reduced significantly. The new reference system here, while it is likely sustainable, is capable of sustaining a significantly lower level of biomass than that originally supported. Therefore, its maximum entropy production rate is lower in Southern Illinois and, consequently, there is a smaller entropic "gap" for a sustainable crop system.

The entropy created on a unit area is determined by the quantity of solar radiation received by the ecosystem and the structure of the recurring climax biological community. The amount of radiation at each frequency of light received by the ecosystem can be calculated easily. In the complete absence of life (e.g., in a desert area), the land surface is highly reflective of incoming radiation and, we assume, does not increase the entropy rate significantly. In contrast, ecological systems are capable of capturing some of the incoming radiation, radiating back some of the radiation (e.g., from leaf surfaces), reradiating physically absorbed heat, and radiating the heat of biochemical reactions via respiration. Thus it can be shown that the dissipation rate or the rate of high entropy formation is higher at climax conditions than at any earlier successional stages (Ulanowicz and Hannon, 1987). They explain this procedure through satellite measure of the quantities of radiation at each frequency in the radiation spectrum from the ecosystem and their comparison with the radiation spectrum reflected during alternative successional stages.

Does the development of structure in the system increase the rate of high entropy formation? The behavior of the heat convection cell is a physical example (Schmidt and Silveston, 1958) of a self-organizing system that increases the rate of entropy as the system structure increases in complexity. If a heat source is placed under a uniform container which holds a thin layer of fluid, density patterns begin to emerge. First the patterns are simple ones, but they become more complex with time. The heat flow through the cell increases as the first pattern forms and increases still further as each more complex pattern is formed. These density patterns are local stores of low entropy formed from the available free energy of the heat source. The patterns are analogous to the low entropy stores in the biomass of an ecosystem. In our analogy, the increasingly complex patterns of the convection cell are similar to the increasingly complex biological structure in the successional and mature ecosystem.

Are such climax systems optimal? Recent advances in system theory indicate that complex systems, poised between order and chaos, can adapt most readily (Kauffman, 1991) and that large interactive systems naturally move toward an optimal condition in which the slightest disturbance can introduce chaos into the system (Bak and Chen, 1991). Examples of the latter class are avalanches and earthquakes. The combination of these ideas suggests that natural systems may evolve toward increasing adaptability to environmental change and that adaptability is maximized when the system has evolved to the verge of chaos. This condition is analogous to that of a mature prairie or forest which is experiencing fires. The conditions for the support of occasional fire become optimal as the system reaches maturity. The recurrence of fire is the sign that the system has reached the height of adaptability, the optimal or mature state. We offer this analogy to support our assertion that the prairie and forest which are experiencing natural fires have reached an optimal condition from which they are unlikely to change. The entropy production rate of these sustainable reference systems is the maximum sustainable by nature and, we claim, the maximum sustainable by nature with humans.

3. ASSUMPTIONS

It seems safe to assume that the difference between long-term radiation from totally inorganic land and radiation from a heavily populated natural ecosystem is a good approximation of the entropy generated by life. Here, however, we are only interested in comparing a current agricultural system with a potential natural climax ecosystem growing on the same area (the reference system). We argue that the most significant differences in energy radiation (and therefore in entropy production) between the two systems will be in the total heat liberated through respiration on an average annual basis. For modern agricultural systems, we must add the heat liberated through the use of fossil or nuclear fuels (an approximate entropy measure) directly or indirectly in support of the agricultural process. Therefore, we assume that the difference between the plant, animal, and saprobe respiration of each system is a good approximation of the entropy difference of the two systems. We assume that the natural climax system is sustainable. If the total respiratory heat generated by the agricultural system is less than that of the natural climax system, then it too is sustainable; if it is greater, the agricultural system is not sustainable. The juvenile state (an agricultural system) respires less than the mature climax ecosystem would on the same area. This is true possibly because the juvenile condition is more reflective. We are ignoring the entropy caused by probably greater soil erosion in the agricultural case. We assume that the entropy caused by the scattering of the soil particles is small compared to the respiration energies.

Most of the heat radiating from an ecosystem, however, is the heat reflected and reradiated from the plant and the soil (Ehleringer, 1991). Much of the light absorbed in photosynthesis is not usable (e.g., mid-day, full sunlight) and it is reradiated as heat to, in part, drive evapo-transpiration. Light absorbed by the soil is reradiated as heat after warming the soil. We assume that these rejected heat quantities total the same in both the agricultural and natural climax system. The main support for this assumption is the fact that the coefficient of emittance to longwave radiation is the same for soil and vegetation (Ehleringer, 1991).

Differences in variables such as the reflection of light from the senescent prairie or forest and an agricultural crop residue will also be neglected. Direct heating by infrared radiation is smaller on the plant leaf than on the soil. Since crops have more barren ground in the early stages, the crop system absorbs more direct heating. However, the entropy gain produced while absorbing infrared and reradiating it as lower temperature heat is probably not large because of the relatively small effective temperature difference. Therefore, we tentatively eliminate the direct heating from our calculations.

Finally, we restrict our examination of the reference system to the natural entropy created on site, that is, we neglect the natural off-site energy used by the reference system (e.g., the making of rain). These indirect supporting flows can be accounted for in a more sophisticated analysis (Hannon et al., 1991) and their inclusion here would obscure the utility of the reference ecosystem approach. Furthermore, such natural off-site energy subsidies to the reference ecosystem are also present for the agricultural system. The omission of natural off-site energy subsidies should not affect the outcome of our sustainability comparison.

In summary, we assume that nature has, through millions of years of "experimentation", found an upper limit on a sustainable rate of entropy flow from a given area on earth. We argue that the entropy rate of the climax ecosystem provides an upper bound on the entropy rate that can be sustainably produced by a human socio-economic system, a sustainable reference system. We note that the limiting rate given by the reference system can be decreased, for example, due to poor farming practices. We assume that the total respiratory heat from the reference system is to be compared to the same measure of the agricultural system as a test of agricultural sustainability.

4. AN EXAMPLE FOR THE SUSTAINABILITY OF AN AGRICULTURAL SYSTEM

The focus on the measures of annual respiratory heat allows us to find preliminary measures to demonstrate the idea of the sustainable reference system. We further restrict our example calculation to the conversion of the

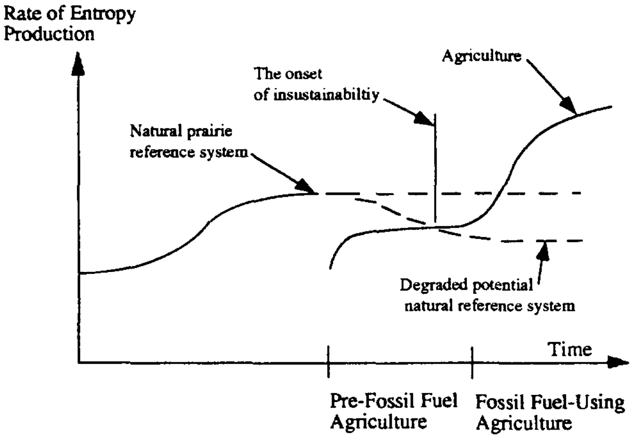

Fig. 1. Rate of entropy production in pristine, stable ecosystem (e.g., prairie) and human-managed ecosystem (e.g., modern agriculture) on a unit land area.

tallgrass prairie to agriculture, in order to simplify the demonstration of our proposition. Again, for simplicity, we ignore the effects of fire and other catastrophes on the performance of the reference ecosystem. In the case of the prairie ecosystems, periodical fires are actually part of the organizing forces that maintain the climax state.

At early stages of agriculture, prior to fossil fuel use in agriculture, the prairie ecosystem was reduced in complexity. This reduction was present in the use of uniform, even-aged crop stands whose structure and function is comparable to that of an early successional stage. Through agriculture, the more than 250 perennial prairie plants were replaced by less than a dozen domesticated annual plants (crops). As a result, the entropy production occurred at a lower rate than in the reference prairie state (see Fig. 1). Besides increasing soil erosion, agriculture may lead to a net loss of soil organic matter because the input of new organic matter is reduced and because the soil temperature is increased.

Similarly, the kind of animal stock was changed dramatically from one which aided in maintaining the prairie in a climax state to one consisting of sources of protein and farm work. The consumption by buffalo is not included in our calculations below. Farm animal respiration is included in the total respiration rates for they consumed most of the seed production from Central Illinois agriculture. The normal density of buffalo on the prairie is low and their impact on the total prairie respiration is thought to be negligible.

We suspect that the entropy rate created by these domesticated crops and animals was at least initially less than the rate created by the climax prairie. An entropy rate difference existed between the entropy flow rate generated by the subsistence farm family and that of the displaced prairie (the calculation below supports this view). It seems reasonable to speculate that this gap provided the energetic basis for the increase in human activities, such as experimental agricultural methods, to increase yield and perhaps even engage in trade of grain for the off-site manufacturing of farm machinery. The same process of creating an entropy gap occurred when the climax forest ecosystem, including its characteristic disturbances, was converted to agriculture.

However, as the agricultural process continued, the original reference state of the prairie was reduced through soil erosion and nutrient flow reversals. Soil erosion in Central Illinois is about 2 to 5 tons per acre per year (USDA, 1986). Consequently, the corresponding maximum potential rate of entropy production is likely to decline (see Fig. 1). When the rate of entropy production from the long-term (declining) reference system reaches the (possibly rising) rate of entropy production in the area, agriculture is no longer sustainable. This process could have happened before the advent of commercial hybrid seeds, chemical and mechanized farming (apparently Southern Illinois) or after the introduction of modern farming (Central Illinois).

5. BASIS OF THE EVALUATION

For a relatively stable ecosystem (i.e., in the absence of major catastrophes such as earthquakes, but in the presence of disturbances vital to the maintenance of the ecosystem structure and function), we expect that the rate of entropy production in a given ecosystem, such as the mature tall-grass prairie, is being maximized.

We might view the advent and evolution of human societies as a means to further degrade gradients, i.e., increase entropy. Modern societies contribute significantly to an increase in the entropy rate by tapping the earth's low-entropy storage, e.g., fossil fuels. Some of these fuels are used to substitute human-managed agriculture for climax ecosystems. The process of simplifying ecosystems is readily apparent in the transformation of the Midwestern prairie and forest lands into crop monocultures. Given the tendency of human agriculture to simplify ecosystems, we must ask:
To what degree does historic and modern agriculture increase the rate of entropy production, considering the direct and indirect fossil energy use for agricultural production?

If we consider a very long time horizon, fossil and nuclear fuels will be exhausted. If we assume further, with today's unavoidable myopia, that no new technologies will be available to supply energy from finite resource stocks, then the only sustainable human society is one based on the upper limit of entropy generated by the climax ecosystem. We may be able to wedge ourselves successfully into the entropy generation spectrum. In this *yeoman* view, we see ourselves as part of nature through succession. Humans could be seen to have simply displaced "inferior" species of plants and animals to make a place for themselves in the ecosystem.

If we take a rather short-range view of the future, or a view that assumes everlasting fossil fuel supply or the emergence of similar substitutes, then we can be seen as *utopian*. In this way we can see ourselves as an "invention" of nature which has increased successfully the overall rate of entropy-production of the living system. The question of sustainability depends then on our time horizon, or our discount rate: the shorter our time horizon, the higher the rate of discounting the future. The utopians are the high discounters; the yeoman have the lowest rates. The utopians have such a short time horizon that long-term planning is of little importance to them. The only interesting case is that of the yeoman. The yeoman sees the fossil fuels as having accelerated the human population level to an ultimately unsustainable level, and, assuming the yeoman is right, the interesting question becomes:

How do we establish a transition from a high population to a low one, one that can live within the sustainable level set by the climax ecosystem?

Depending on the time horizon, two scenarios (Fig. 2) for the entropy production in the ecosystem may follow: (a) a temporary increase in the rate of entropy production and maintenance on a high level (utopian

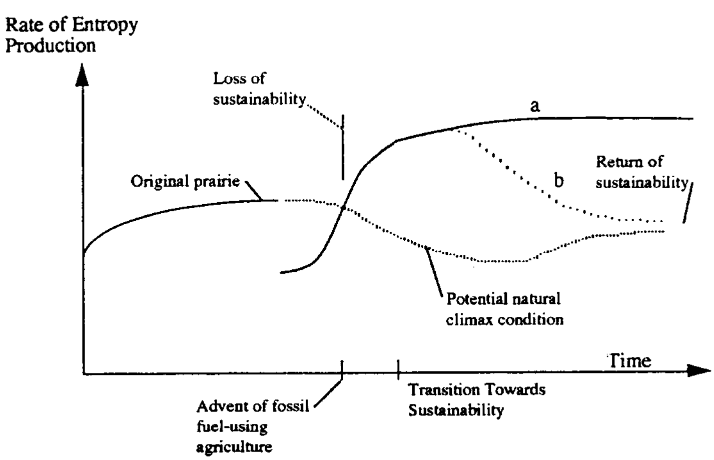

Fig. 2. Rate of entropy production in a complex ecosystem (e.g., prairie) and human-managed ecosystem (e.g., modern agriculture) before (a) and after (b) transition towards sustainability.

perspective); (b) decrease in the rate of entropy production to the sustainable limit (yeoman perspective).

6. EVALUATION

In order to estimate the rate of entropy production we must know the following data:

- respiration rates of prairie;
- respiration rates on agricultural land;
- direct and indirect fuel use for intensively managed agricultural lands.

Additionally, we should know the rates of reflection of solar radiation from prairie lands and agricultural lands (depending on type of plant cover and density of cover) and short- and medium-term fluctuations in back radiation (short-term: seasonal fluctuations; long-term: fluctuations over a period that is long enough to average the effects of periodical burning of prairie land). These additional pieces of information may be necessary to back some of the assumptions made in Section 2. But for this example, we adhere to the assumptions made above.

The annual respiration rate of a virgin, dry-land, tall grass prairie (Konza Prairie, in Kansas, 1987, 3400 ha) was calculated from Kim et al. (1992). We found the rate to be 3.93 kg CO_2 m^{-2} $year^{-1}$ (the sum of day and night soil respiration and plant respiration). In order to compare Central Illinois corn production to the original prairie productivity, we increased this respiration rate to reflect the greater level of productivity in Illinois where the annual average rainfall is greater. Translating this number into energy terms [1] and correcting for the differences in rainfall between the Konza prairie site to our local farming area gives about 115 million kcal/ha.

Hesketh (pers. commun., 1992) has calculated the comparable respiration rate for a typical Illinois cornfield whose production rates were 9.43

[1] The conversion from CO_2 in kg m^{-2} $year^{-1}$ to million kcal ha^{-1} $year^{-1}$: 686 kcal/mole of glucose; when 1 mole of glucose is burned, 6 moles of CO_2 are released. Therefore, 2600 kcal/kg CO_2 is released as heat. With 3.93 kg CO_2 m^{-2} $year^{-1}$ released on the Konza prairie, 102.2 million kcal/ha is liberated as respiratory heat. Annual average rainfall at the Konza prairie is 835 mm and at Champaign, the value is 1008 mm (Angel, pers. commun., 1992). In 1987, the year of record for the respiration data, the Konza prairie received 860 mm of precipitation. We transformed the Konza respiration (Leith, 1975b) data to the expected level of respiration of a virgin prairie in the Champaign, Illinois area using the production-precipitation equation, assuming respiration is linearly proportional to biomass production.

Mg/ha (150 bushels/acre). At this level of production, the annual respiration rate of the modern cornfield is 111 million kcal/ha (see Table 1). This figure includes the metabolism of the corn plant plus the biomass stock created (consumed by humans, animals, insects and bacteria and emitted as respiration) every year, on the average. The figure is surprisingly close to the expected climax prairie respiration level, but note that this value of cornfield respiration is made possible by fossil fuel use, directly and indirectly.

Records of the yields of Central Illinois cornfields have been kept since 1888 (University of Illinois College of Agriculture, 1982). One can estimate the initial corn production rate on the newly turned prairie sod. After about 12 years of continuous corn, the yield was about 4.72 Mg/ha (75 bushels/acre), dropping to about 1.89 Mg/ha (30 bushels/acre) by the 1950s if open pollinated corn was continuously planted on the same soil. The ratio of these production rates is an approximate measure of the soil degradation caused by agriculture were it not for human-introduced hybridization, crop rotation, fertilization and tillage.

If only occasional mineral fertilization, regular animal manure and crop rotation with hybridized seed is used, the yield can be increased to 7.23 Mg/ha (115 bushels/acre), as is the case in nearby (Arthur, IL) Amish farming (Johnson et al., 1977). This level is probably closer to the initial prairie yield as it involves almost entirely local natural fertilizers and modern understanding of plant genetics in support of the constant soil fertility. Coupled with a modern use of soil erosion control, nothing about this particular production plan is clearly unsustainable. At least it will last until the 2 to 3 feet of topsoil has eroded. The Amish are the yeoman in this example.

The nearby modern farmers, on the other hand, had average corn yields of 10.4 Mg/ha (165 bushels/acre) (Johnson et al., 1977). These farmers are truly modern, using the profit-maximizing amounts of pesticides and man-made fertilizers. Clearly, these inputs are not sustainable if stored energy such as the fossil fuels are a fixed endowment. These modern farmers must be classed as utopians, those hoping that a suitable replacement will be found for the stocks of fossil and nuclear fuels.

If we assume that we can scale the respiration rate of the cornfields by the yield rates, the Amish have fields that give an annual total respiration of 85 million kcal/ha (Hesketh, pers. commun., 1992). The modern farmer has an annual corn respiration rate of 122 million kcal/ha (Hesketh, pers. commun., 1992). Both the Amish and modern farmer use fossil fuels directly and indirectly every year: about 4.6 million kcal/ha for the Amish (Johnson et al., 1977) and 18.8 million kcal/ha for the modern farmer (Chambers et al., 1979). Rough estimates of the non-farm fossil depend-

TABLE 1

The respiration costs of cornfield and prairie, million kcal ha^{-1} $year^{-1}$ (Hesketh, pers. commun., 1992 [a]; Kim et al., 1992, respectively)

	Respiration costs	Biomass	Standard respiration	Agricultural respiration	Fossil fuel costs	Life style costs	Total respiration
Stalk and root	15.2	45.6	60.8				
Seed	13.2	36.6	49.8				
Modern cornfield				121.7	18.8	1.8	142.3
Amish cornfield				84.8	4.6	0	89.4
Prairie							
Konza (Kansas)							102.2
Illinois (estimate)							115.0

The stalk, root and seed standard respiration values are for 9.43 Mg/ha corn in Central Illinois. The Amish average yield there is 7.23 Mg/ha and the nearby modern farm averages 10.4 Mg/ha (Johnson et al., 1977). The same calculation procedure yields about 71 million kcal ha^{-1} $year^{-1}$ as the standard respiration for soybeans with an average yield of 3.14 Mg/ha (Hesketh, pers. commun., 1992), well below the climax prairie respiration level.
[a] J. Hesketh based his calculations on data found in Leith et al. (1975a) and Loomis (1983).

ency of the modern farmer is about 1 to 2 million kcal/ha [2] and very little extra is needed for the Amish lifestyle (Johnson et al., 1977). So the total respiration for the corn crop on the modern farm is about 142 million kcal/ha and the same measure for the Amish farm is about 90 million kcal/ha. Comparing these numbers to the annual total respiration rate of the local climax ecosystem, we conclude that the Amish farm is sustainable and the modern farmer is not. We note that the ratio of Amish level of cornfield respiration to the prairie respiration is about 0.78, indicating the juvenile nature of the cornfield relative to the climax natural ecosystem of the same area. The data are summarized in Table 1.

Neither farm is completely planted in corn. The modern farmers alternate their fields between corn and soybeans. The Amish farmer has a more complex rotation pattern. On the modern farm, soybeans do not respond significantly to fertilization: the bulk of the energy-rich nitrogen fertilizers

[2] This figure is obtained by taking rough estimates of the per capita U.S. energy use and assuming that the modern farm is a four-person family. This is definitely the lower bound. For the point of view taken in this paper, the sustainability of the US society depends in part on our sunlight capturing ability. Therefore, the fossil energy use of the entire society might be seen as "needed" to support modern farming! A more reasonable way of estimating the legitimate assignment of the fossil fuel use to farming is to use the direct and indirect labor demand of the farming process and assign the per capita fuel use of those people and their families to the farm operation.

are applied only to the corn. We averaged these energy costs over the entire farm since we did not know the corn–bean division in the Johnson et al. (1977) data and, therefore, we may be understating the fossil energy cost of corn production on the modern farm.

What about the "respiration cost" of the rest of society, the energy used by the population not directly or indirectly connected through the workplace to agriculture? Should not their energy use be somehow distributed over agricultural activities to insure sustainability of the whole society, including the farm operations? Given our view of sustainability, we think that some distribution of this sort should occur. One reasonably accurate way to assign this energy cost to agricultural products is to reorganize the input–output accounts of the country. With this scheme, agriculture and net exports would be the only net outputs of the economy. The customary components of net output (GNP) of the U.S. economy are household and government consumption, new capital formation and net exports. If all but the net exports are internalized in the matrix of economic exchange (Costanza, 1980; Costanza and Herendeen, 1984), and the consumption by agriculture is joined with the net exports to form the economy's net output, the true total energy cost of agriculture can be found. It would then be possible to unambiguously assign all of the fossil and nuclear energy to the various parts of the agricultural spectrum. This rearrangement for the, say, 1982 economy (the latest available data) is a fairly large undertaking, but it is certainly feasible and theoretically correct. For those agencies that have the input–output data for the whole economy, it would be a simple exercise. The energy cost of the standard definition of net economic output has been done for earlier years (Casler and Hannon, 1989).

We expect our estimates to be viewed cautiously. We have many assumptions to allow us to produce this example. The primary assumption was that any heat liberated by a living system on a particular area was the same whether it came from an agricultural or a natural system, except for the plant and decomposer respiration. The critical distinction between natural and man-made systems is (we assume) due to differences in these respiration rates. We make this assumption since we cannot find evidence that shows the overall entropy balance on prairies and cornfields, and because the assumption seems to be a good first approximation. More research is needed here.

The important observation from Table 1 with regard to potential sustainability of the agricultural process is not only the fossil energy used directly, but also the effect that the energy has on yield. Modern agriculture is able, through the use of fossil fuels, to boost the total annual respiration rates above that of the displaced climax prairie ecosystem. A second important observation (from the Amish farms) is that some fossil fuel use may be possible in the sustainable agricultural system. However, the Amish use of fossil fuels is not directly or indirectly related to yield. Their fuel use is strictly for labor-saving machinery. They would be able to maintain their corn yields without any fossil fuel use. This is not true for the modern farmer. Energy intensive fertilizers and pesticides directly raise yields significantly. A third observation is that the total annual respiration rate of soybeans is well below that of the prairie rate. Both types of farmers are apparently sustainable in raising soybeans, mainly because this crop is not very sensitive to artificial fertilizers.

The Amish and modern agriculture are two extremes in the array of processes for the capture of solar energy. Our approach allows us to compare also other social arrangements with regard to their sustainability and provide, ultimately, instruments for the choice of alternatives.

Before we venerate the Amish lifestyle too much, we should realize how they keep their fossil fuel use so low. While modern farming is still labor intensive compared to manufacturing, the Amish farm is very labor intensive. Large families have economic value through their contribution to farm labor. The average Amish farm has seven children (Stoltzfuss, 1973). The natural attrition of Amish young people to modern society and mainly to other newer settlements keeps their local community population nearly steady. The Amish are apparently sustainable as a family farm, but not necessarily as a society. Does farming have to be this labor/population intensive to be sustainable? Perhaps in a world without fossil and nuclear fuels, it does, but perhaps much of that labor could come from the rest of society rather than the farm family. The fossil fuel–labor substitution is a real dilemma for the Amish. They try to use a small amount of fossil energy as a substitute for some on-farm labor. If they use too much energy, they are not sustainable. If they do not somehow find labor-saving technologies without the use of fossil fuels, they are not a model for the sustainable future of the whole society. The dilemma is really a global one.

There is no known physical law which says that our definition of sustainability must be met. We propose it as a guide for the direction of technological and perhaps ultimately, social change, beginning with sunlight capture and food production. Boyer (1982) gives an excellent discussion of the technological impacts on prairie-based agriculture, both historical and projected.

We suggest that our definition could be one part of a plan for intergenerational equity. Following Page (1977), we suggest that to be equitable to future generations, we should pass on to each generation a population level, a set of technologies and a stock of fertile land and fossil fuels which would enable them to at least do what we have done. In other words, we are fair to future generations if we are sustainable in our production and consumption systems. A process of developing a sustainable agriculture is the first step.

Our results suggest that the rate of energy liberated through respiration and fuel use may be one measure, a strictly physical one, by which ecosystems such as agriculture can be compared with the natural systems they replaced. Assuming that the natural ecosystem was sustainable, our approach provides a sustainable standard or reference system to which humans can aspire to achieve. Other measures, such as population stability, species diversity, soil productivity, and vegetative structure may also be important.

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