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Entropy and sustainability

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Summary

Soil–plant systems exchange both energy and matter with their surroundings and are consequently open systems thermodynamically. They should therefore tend towards a steady state described by non-equilibrium thermodynamics and characterized by minimum production of entropy. The theory surrounding the principle of minimum entropy production provides a good analogue of the behaviour of natural and agricultural ecosystems subjected to perturbations. Entropy-increasing processes are those that degrade complex, ordered structures of large molecular weight to small molecules such as CO_2, NH_3 and H_2O. Processes such as photosynthesis that build small molecules into larger ones lessen entropy. These ordering processes are permitted by thermodynamic work performed when heat is transferred from the sun. They depend critically on the capacity of the system for self-organization, which is identified with its biological potential. Several of the small molecules are environmentally undesirable in excess. This, together with the theoretical considerations above, suggests that minimum production of entropy should be a criterion of sustainability. It implies that agricultural systems should be allowed to become steady states where possible and that maintaining the biological potential is essential. An 'audit of small molecules' is suggested as a way of assessing sustainability.

Introduction

Thermodynamic models have been used in soil science since the time of Schofield (1935, 1955) and possibly earlier, mainly to describe the behaviour of water or nutrients. Using such models necessitates the placement of the soil in the correct thermodynamic system, there being three possibilities. An *adiabatic* system can exchange neither energy nor matter with its surroundings, a *closed* system can exchange energy but not matter and an *open* system can exchange both. An adiabatic system is a theoretical concept that can only be approximated in experiments, but a closed system can be realized quite easily. Most of the biosphere, however, comprises open systems that exchange both energy and matter with their surroundings, and the soil is clearly an open system (Johnson & Watson-Stegner, 1987).

Possibly the first example of thermodynamic soil model centred on entropy concepts was that of Runge (1973), who was concerned with the development of the soil profile. Runge's basic idea, derived from the First and Second Laws of Thermodynamics, was that entropy was lessened, and the profile therefore made more ordered, by an input of energy from outside the system. He considered water flow to be the principal source of the energy. Hoosebeek & Bryant (1992) correctly pointed out that Runge used thermodynamics appropriate to closed systems, whereas the soil is an open system. Indeed Runge's assumption that water flow provided the energy input implied that the soil was an open system, and it is not only water that flows into and out of the soil. For a soil model we need a form of thermodynamics that deals with flows of matter in open systems, and this leads us to non-equilibrium thermodynamics rather than the equilibrium thermodynamics on which Runge's approach was based. Equilibrium thermodynamics describes a *closed system* that tends towards an *equilibrium* characterized by minimum energy and *maximum entropy*. Non-equilibrium thermodynamics describes an *open system* that tends towards a *steady state* characterized by *minimum production of entropy* (Prigogine, 1947; Katchalsky & Curran, 1967). There is obviously an important conceptual difference between a system that tends to maximum entropy and one that seeks a state of minimum entropy production. The soil–plant system is clearly the latter type of system, and this paper explores some of the implications of the Principle of Minimum Entropy Production for sustainability in soil–plant systems and discusses these in the context of the debate about intensification and extensification in land use.

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Entropy, information and work

Entropy is *inter alia* a measure of disorder or randomness. The molecules of a solid, for example, have a more ordered

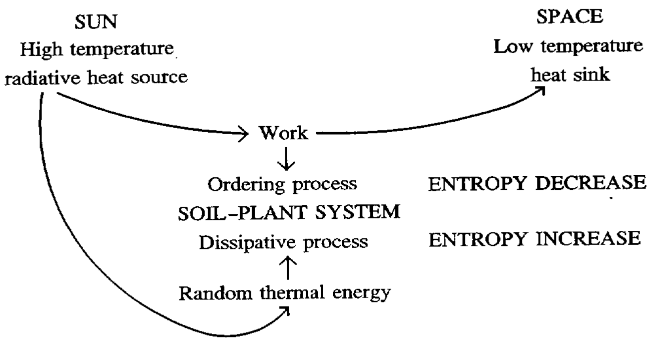

Fig. 1. Performance of work and production of entropy in ordering and dissipative processes that influence the soil–plant system.

configuration than the corresponding liquid, so melting a solid leads to an increase in entropy (Glasstone, 1947). An ordered state contains information, so there is a degree of equivalence between entropy and information, such that entropy increases when order is lost. Information is also related to thermodynamic work with a two-way interchangeability, work being converted to information in some circumstances and information to work in others. Continuous work therefore permits the self-organization of systems, and this principle forms the basis of the ordering of the biosphere (Morowitz, 1970).

Thermodynamic work is performed when energy in the form of heat is transferred from a source at a high temperature to a sink at a low temperature. Continuous work, therefore, requires effectively infinite isothermal reservoirs at high and low temperatures, which are provided for the biosphere by the sun and outer space respectively (Fig. 1). During the performance of this work energy flows from the sun to outer space and entropy is produced, but the work done in processes on the surface of the earth may lead to considerable increases in order and, therefore, decreases in entropy at a local scale. In addition to the ordering processes permitted by continuous work there are also dissipative processes that produce entropy at the local scale as well as the scale of the solar system. These result from the random distribution of heat energy. Biology provides the most obvious examples of these ordering and dissipative processes. Photosynthesis and its associated processes build complex ordered structures containing substances of large molecular weight from small molecules such as CO_2, H_2O and NH_3, while dissipative processes such as respiration and senescence degrade these structures back into the small molecules. Table 1 lists processes likely to have ordering or dissipative effects in the soil–plant system. The pairs listed are not necessarily exact opposites, and they are discussed further by Addiscott (1994). Morowitz (1970) perceived the great ecological cycles of the biosphere to be driven by such ordering and dissipative processes. The soil–plant system is a key component of many of these cycles, and the sustainability of our agricultural systems depends on maintaining a proper balance between order and dissipation. The same is almost certainly true of all systems in which man is involved, but this paper concentrates on agricultural sustainability.

Forces, flows and entropy production

The laws of Ohm and Darcy are familiar examples of force–flow relationships in which there is just one force and one flow. Where there are several forces and several flows in one system all the flows are influenced by all the forces. This principle was first enunciated by Lord Rayleigh for mechanical forces and flows in his treatise on sound. Onsager (1931) extended it to thermodynamic forces and flows in his phenomenonological equations which relate flows J_i to their conjugate forces X_i. For three forces and three flows, for example, the equations are as follows:

$$J_1 = L_{11}X_1 + L_{12}X_2 + L_{13}X_3 \qquad (1a)$$

$$J_2 = L_{21}X_1 + L_{22}X_2 + L_{23}X_3 \qquad (1b)$$

$$J_3 = L_{31}X_1 + L_{32}X_2 + L_{33}X_3 \qquad (1c).$$

The conjugate force must be appropriate to the flow, and this is ensured by the condition that the product of the flow and the force, J_iX_i, has the dimensions of entropy production, or decrease in free energy, per unit time. This is analogous to the relationship that shows the heat produced in (and dissipated from) a wire in which an electric current flows to be the product of the current and the electromotive force.

The coefficients L_{ij} that link the flows and forces are equivalent to the conductivity in the electrical analogue and are of two kinds, 'straight' ($i=j$) and 'coupling' or 'cross-linking' ($i \neq j$). Onsager simplified the matrix by proving that, where i is not equal to j, $L_{ij}=L_{ji}$. These cross-linking coefficients provide a useful reminder that few flows occur

Table 1. Ordering and dissipative processes in the soil–plant systems categorized as biological or physical. The pairs are not necessarily exact opposites. (From Addiscott, 1994).

Ordering processes Entropy decreases	Dissipative processes Entropy increases
Biological	
Photosynthesis	Respiration
Growth	Senescence
Formation of humus	Decomposition of humus
Physical	
Water flow (profile development)	Water flow (erosion, leaching)
Flocculation	Dispersion
Aggregation	Disaggregation
Development of structure	Breakdown of structure
Larger units	Smaller units
Fewer of them	More of them
More ordered	Less ordered

in the soil–plant system without interacting with other flows. The interaction between the flows of water and heat was investigated both theoretically and experimentally by Cary & Taylor (1962), who were able to show that these flows obeyed Onsager's theory reasonably closely. These coefficients are also important because each flow with its conjugate force makes a contribution to entropy production and these contributions are additive, so the entropy production per unit time from the matrix above is:

$$\sigma = J_1 X_1 + J_2 X_2 + J_3 X_3 \qquad (2).$$

This relationship is not as simple as it may appear because, unless the cross-linking coefficients are zero, J_1 is influenced by X_2 and X_3 as well as X_1, and similarly for J_2 and J_3. Thus interactions between flow processes influence entropy production, providing, perhaps, a warning against the over-simplistic use of this theory in circumstances in which not all the forces and flows are known. However, one of the consequences of Equation (2) is the proof (e.g. Katchalsky & Curran, 1967) that, in an open system allowed to mature, entropy production will decrease with time and reach a minimum. This is, of course, the principle to which reference was made in the Introduction. Katchalsky & Curran also show another consequence of Equation (2); that if a flow is perturbed by a change in its conjugate force, the flow will act to decrease the perturbation so that the system returns towards its original state. Their theory also implies that the perturbation causes an increase in entropy production.

Steady states and perturbations

Katchalsky & Curran (1967) were interested in the implications for processes in the biosphere of the theory outlined above. "There are several remarkable analogies", they wrote, "between an open system approaching a steady state and living organisms in their development towards maturity". They went on to suggest that the Principle of Minimum Entropy Production could be the physical principle underlying the evolution of the phenomena of life and to point out that living organisms have regulatory mechanisms that preserve the steady state by countering perturbations as in the thermodynamic system described above. There are, however, two major perturbations that all living organisms experience, birth and death, and these limit the usefulness of steady-state concepts for individual organisms. It is probably more relevant to apply these ideas to communities of organisms, or to the ecosystems of which they are a part. For a given set of forces, or constraints, an ecosystem will during a period of time mature to a particular steady state. The soil is initially one of the constraints determining the direction in which the ecosystem matures but it remains part of the ecosystem and is changed during the process of maturing.

If the ecosystem is perturbed, the thermodynamic analogue suggests that the flows in the system will act to counter the perturbation and restore the steady state and this will probably involve the soil. Two questions arise:

1. How long does an ecosystem take to restore itself to the steady state following a perturbation?

2. Can there be a catastrophic perturbation as a result of which the system is unable to redirect itself towards any steady state?

To answer these questions we need to consider an example of an ecosystem in a steady state, of which the clearest example is the system sometimes described as climax vegetation but probably better described as steady-state vegetation. In many parts of the world this is some form of forest in which the soil is an integral part of the ecosystem and would be totally different without the rest of the ecosystem.

Question 1 above cannot be answered without considering the extent to which the system is perturbed, but the study by Nye & Greenland (1960) of traditional shifting cultivation in west Africa illustrates the kind of answers that may be found. In this system, areas of soil were cleared of the steady state vegetation and cultivated for a few years, during which the fertility declined because of the loss of organic matter. When yields became too small the areas were allowed to revert to the natural vegetation and the fertility was gradually restored. The time needed for this recuperation depended on the extent of the perturbation. Where the soil was untilled and crops were planted in holes made with 'dibbling sticks', the soil was restored to its original form and fertility in about 10 years, but if it was tilled, that is, turned over with hoes, the recuperation took about 50 years. The soil fauna played a vital role in the recuperative process following both degrees of perturbation (P.H. Nye, personal communication).

Question 2 can be answered in a more specific way. A catastrophic perturbation can probably be defined as one in which the capacity of the system for self-organization is seriously damaged or destroyed. A perturbation to a forest ecosystem that resulted in a serious loss of soil would be potentially catastrophic, as we have seen in Amazonia. The comment by Nye above suggests that the critical loss in a tropical forest would be that of the soil fauna. These organisms play a key role in all the natural cycles involving the soil, particularly in the turnover and re-cycling of organic matter and nutrients, and they must be vital to the capacity of these systems for self-organization.

Gradual change in temperate systems

Many areas of the world have lost their steady-state vegetation but have not reacted catastrophically. The reason for this is gradual change, and it may be no coincidence that the theory outlined above, which Katchalsky & Curran saw as a model for biosphere processes, holds only for perturbations that are not too rapid and which do not push the system too far from its steady state. The key point is that the system retains its capacity for self-organization, which in the present context means that the biological potential is maintained. Rothamsted has very long-term data which permit comment on steady states and their perturbation on a gradual basis. The steady-state vegetation of the Rothamsted area is thought to be deciduous woodland and there have been two main perturbations which probably happened in succession:

1. Tree clearance which started in Saxon times and had brought about a timber famine by the seventeenth century (Hoskins, 1977). Grazing would have inhibited regrowth in many places.

2. Ploughing of old grassland. Some of the resulting arable land has been in this use for centuries.

We saw above that the perturbation of a steady state should in theory lead to an increase in entropy production. This almost certainly happened with the timber clearance because much of the wood would have been used as fuel and the ordered structure of the wood degraded to small molecules such as CO_2. A similar fate would have befallen any smaller pieces of wood that fell to the ground and were decomposed by the soil micro-organisms, although the increase in entropy would have been offset partly by the ordering resulting from the growth of microbial cells. The ploughing of grassland for arable use also caused an increase in entropy production, as organic matter of large molecular weight was decomposed to small molecules. The ploughing of some very old grassland at Rothamsted led to the loss of 4 t ha^{-1} of nitrogen from the soil in the first 20 years, and much of this could be found in the chalk beneath the site as nitrate. About 40 t ha^{-1} of carbon must have been lost as carbon dioxide. The soil profile would have become less ordered, but this probably made a smaller contribution to entropy production than the much enhanced production of small molecules.

The theory shows not only that perturbing a steady state causes an increase in entropy production but also that when the perturbation is removed the system returns towards the steady state, with entropy production declining towards an eventual minimum. That this can happen in ecosystems is shown by two very interesting sites at Rothamsted. In the 1880s two areas which had long been in arable use were left uncultivated and remain so to the present day. The theory suggests that these sites should have reverted towards the steady state vegetation. In 1957, Thurston (1958) wrote of the more acid of the two sites: "The area has reverted to woodland, consisting chiefly of elm, ash and oak. The largest tree is an oak 81 inches (2.06 m) in diameter at 4 feet (1.22 m) from the ground, growing near the middle of the area that was cultivated. Of the 46 species of angiosperms present in 1957, thirty-two had been recorded previously and 14, including eight woodland species, had come in since 1913. In the same period, 55 species, all characteristic of grassland, had disappeared. All the arable weeds had already gone by 1913". The steady state had clearly been restored to a very large extent. Woodland also reasserted itself on the other site, but the calcareous nature of the soil there resulted in a differing distribution of species, with hawthorn rather than oak predominant (Jenkinson, 1971).

The restoration of the steady state should have been accompanied by a decline in entropy production, and this was observed. By the time of Jenkinson's 1971 report, the acid site had accumulated 180 t ha^{-1} of trees and the calcareous site 274 t ha^{-1} of trees, both representing a massive ordering of small molecules, including, Jenkinson estimated, about 0.7 and 1.1 t ha^{-1} of N respectively. A further ordering of small molecules occurred in the accumulation of an average of 530 kg ha^{-1} of C and 45 kg ha^{-1} of N in organic matter in the soil each year in the calcareous site and rather less in the acid site. Another, rather smaller, decline in entropy production came from a greater degree of ordering in the soil. The accumulation of C and N and the ordering of the profile are discussed in greater detail elsewhere (Addiscott, 1994).

Perturbations that become constraints

Tree clearance and arable cultivation were discussed above as perturbations, albeit very long-term ones, of the steady state, that is, the steady-state vegetation. The sites that were allowed to revert to the steady state form only a small percentage of the land at Rothamsted; most of the land has remained in arable use or, to a much lesser extent, as grazed or cut grassland. These 'perturbations' have now continued for centuries and have effectively become constraints, so that the grass and the arable land have themselves become steady states. Indeed, one experiment at Rothamsted has now received the same fertilizer inputs for exactly 150 years, and several others have been treated with similar consistency for nearly as long. Here the inputs have become constraints, and the plots receiving them steady states. Jenkinson (1991) identified these steady-state plots with specific annual inputs of nitrogen from fertilizer as valuable resources for studying the flows of nitrogen in arable ecosystems and Powlson *et al.* (1986) obtained interesting and important data from ^{15}N-labelled fertilizer applied to these plots.

Sustainability in agriculture

'Sustainable' agriculture is currently the topic of much debate, and there is also a fair amount of discussion about what 'sustainable' means. The Principle of Minimum Entropy Production provides a useful framework within which sustainability can be discussed. Natural ecosystems are sustainable not least because they become steady states characterized by minimum production of entropy. One manifestation of entropy production is, as we saw above, the degradation of substances with ordered structures and large molecular weights, which results in the production of small molecules such as CO_2, CH_4, N_2O and NO_3^-, all of which are environmentally undesirable when in excess (and H_2O, which is not likely to become a problem in this way). This suggests strongly that one of the criteria of sustainability should be minimum entropy production and that we should seek agricultural systems that permit the establishment of steady states. Continuous arable agriculture, or even monoculture, may therefore be one of the more sustainable options available, but with four provisos:

1. The system must achieve a steady state.
2. The flows within the system, particularly that of nitrogen, must be of appropriate magnitude.
3. The capacity for self-organization must be retained in the system; this means making sure that the biological potential is maintained.
4. The maintenance of the steady state must not involve excessive expenditure of energy, and entropy production, outside the system, in fertilizer manufacture, for example. (This point is covered in the section that follows).

Ley–arable rotations are widely perceived as the most sustainable option, particularly by those practising organic farming, who use grass–clover leys to introduce nitrogen into the system. Such rotations played a vital role in increasing agricultural productivity in the eighteenth century without the use of fertilizers. They do, however, involve the regular ploughing up of grassland, so that neither the grassland nor the arable land achieves a steady state. There is also the problem that the ploughing up of the grassland encourages the production of small molecules, mainly CO_2 and NO_3^-. Careful management of a rotational system can minimise losses of NO_3^- from the system and taking a long-term view of such a system may show it to be in a steady state characterised by small periodic fluctuations and therefore sustainable in the longer term.

The balance of advantage between continuous arable and ley–arable systems probably depends on the type and location of the soil. The achievement of the steady state and the control of the flows of nitrogen and other materials within the system should be easier in the continuous arable system. It could be, however, that the maintenance of the capacity for self-organization is more effective in the mixed system. This could be critical where there is a risk of catastrophic perturbation, for example, in some tropical soils.

Assessing sustainability by an audit of small molecules

The sustainability of our agricultural systems depends on maintaining a proper balance between dissipative and ordering processes, that is, between processes that produce entropy and those that lessen it. Since in the biosphere small molecules, such as CO_2, H_2O and NH_3, are produced when dissipative processes degrade complex, ordered structures and removed when such structures are built, an audit of small molecules appears to offer a way of assessing sustainability. It does not, of course, give a complete assessment, and the information required will rarely be available in full. Bertilsson (1992), however, assembled some very useful data on flows of energy and material in Swedish agriculture and information from his paper is used here to show the kind of results that might be obtained from an audit of small molecules.

Bertilsson was interested in farming systems of high and low intensity and he addressed a question of widespread importance. "Is it better to farm more land less intensively or to farm less land more intensively, using the spare land for 'nature' or for the production of bioenergy?" He discussed too another key question, also raised by Addiscott *et al.* (1991). "Should we consider losses of nitrate, for example, as kilograms per unit area or kilograms per unit of production?" The second question presumes that the production is a means to an end rather than an end in itself, and its significance will, I hope, become clearer shortly.

The farming system considered by Bertilsson was the whole of Sweden. In a somewhat simplified study he divided this into a milk (and meat) production system, which depended on a rotation that included a grass/clover ley and feed crops, and a crop production system. These production systems were assigned to three N-use systems, Normal N, Low N or Zero N (Table 2). There was a target production that had to be met by all three N-use systems; this was set in terms of milk and beef production, grain for sale and potatoes. (The potato target included, sugar beet, vegetables and other crops in this simplified study.) A key feature of the study was that the area in agricultural production was not fixed, so that where an N-use system met the target without using all the land, spare land could be devoted to 'nature' or to the production of willows for biofuel. Further details are given by Bertilsson (1992) or, in a summary, by Addiscott (1993).

Table 2. The Normal-, Low- and Zero-N applications of N fertilizer assumed for the milk and crop production systems in the calculations of Bertilsson (1992).

	N application/kg ha^{-1}		
System	Normal-N	Low-N	Zero-N
Milk production[ab]	85	25	0
Crop production[b]	100	60	0

[a]Rotation: ley (grass–clover), ley, oats, barley, potatoes, peas, barley, potatoes. Stocking rate 0.53 ha cow^{-1}.
[b]Effective use of farmyard manure assumed. Use of peas and forage crops adjusted to match the requirements of the system.

Bertilsson calculated for each N-use system the energy demand, which is not discussed in detail here, and the emission of carbon dioxide, nitrogen oxides, ammonia, nitrate and phosphate. All these are small molecules which are environmentally undesirable when in excess and are relevant to an audit of small molecules, although others, notably methane, could be added. His estimates were either on a per hectare basis (Table 3) or for the total target production of agricultural commodities (Table 4). To sum the emission of small molecules collectively the emission of each was expressed on a molar basis, mol ha^{-1} in Table 3 and as total moles for the target production of agricultural commodities in Table 4.

Table 3. Emissions of small molecules from the Normal-, Low- and Zero-N systems of Bertilsson (1992). Calculations made on a per hectare basis.

	Emissions					
	/kg ha^{-1}			/10^3 mol ha^{-1}		
	Normal	Low	Zero	Normal	Low	Zero
CO_2-C	144	133	86	11.99	9.41	7.16
NO_x-N	5.3	5.1	5.2	0.38	0.37	0.37
NH_3-N	16	12	13	1.14	0.86	0.93
NO_3-N	34	29	27	2.43	2.07	1.93
PO_4-P	0.26	0.25	0.24	0.01	0.01	0.01
Sum				15.94	12.71	10.39

Table 4. Emissions of small molecules from the Normal-, Low- and Zero-N systems of Bertilsson (1992). Calculations made for the whole of Swedish agriculture.

	Emissions					
	/10^3t			/10^9 mol		
	Normal	Low	Zero	Normal	Low	Zero
CO_2-C	216	224	189	18.0	18.7	15.7
NO_x-N	8	10	11	0.6	0.7	0.8
NH_3-N	24	24	25	1.7	1.7	1.8
NO_3-N	51	58	60	3.6	4.1	4.3
PO_4-P	0.4	0.5	0.5	0.0(1)	0.0(2)	0.0(2)
Sum				23.9	25.2	22.6
With willows grown on spare land						
CO_2-C	−1448	−241	189	−120.6	−20.1	15.7
Sum				−114.6	−13.5	22.6

Examining the small molecule emission in the N-use systems on a mol ha^{-1} basis showed that the Normal-N system was clearly the largest emitter of small molecules and, by inference, producer of entropy; it was, therefore, the least sustainable. The Low-N system was intermediate and the Zero-N system the smallest emitter of small molecules—and ostensibly the most sustainable (Table 3). However, considering small molecule emission in terms of the achievement of the target production of agricultural commodities showed a very different picture (Table 4). The Zero-N system remained the smallest emitter of small molecules, but only by a very small margin, and the Low-N system became the largest emitter and thence the least sustainable, with the Normal-N system intermediate.

The 'spare' land had a very large influence on *net* small molecule emission. If it was devoted to 'nature', the pattern remained as described above, but if it was used to grow willows for biofuel the pattern changed greatly because the willows were assumed to replace a fossil fuel source. Burning willows releases only the CO_2 recently fixed in photosynthesis, but burning fossil fuel releases CO_2 long kept out of the atmosphere. Growing willows therefore made possible a net decrease in CO_2 emission. The Normal-N system had plenty of spare land and the low-N system had a little, but the Zero-N system had none because all the land had been used for agricultural production. Consequently, when willows were grown, the Normal-N system became a large *net* fixer of small molecules, rather than an emitter, and the Low-N system became a small net fixer, but the Zero-N system remained an emitter of small molecules (Table 4). With willow production, therefore, the Normal-N system became, on this basis, the most sustainable. Considering energy demand or net production (Bertilsson, 1992) gave the same conclusion.

Discussion

The relationship between order and disorder is central to many aspects of life. It is also an area of thought in which the physical and biological sciences have a very productive interface. The distinguished quantum physicist Schrödinger commented some decades ago that a living organism has "the astonishing gift of concentrating a 'stream of order' on itself and thus escaping the decay into atomic chaos" (Schrödinger, 1967). Another branch of the physical sciences, thermodynamics, shows this 'astonishing gift' to result from the self-organization of systems permitted by the continuous thermodynamic work that is performed as heat is transferred from a high-temperature source (the sun) to a low-temperature sink (space) (Morowitz, 1970). In Schrödinger's parlance, sustainability could be defined in almost mystical terms as the stewardship of the gift. In more practical terms, we are concerned to ensure the continuation of the capacity for self-organization and the thermodynamic work. We have already seen that the former involves the maintenance of the biological potential, and more or less the same conclusion was reached by Wilson (1992) in saying that sustainable development must avoid the loss of native biodiversity. The thermodynamic work will occur with or without our intervention, but care does need to be taken to ensure that our planet remains able to obtain full benefit from it.

Natural ecosystems are open systems from a thermodynamic view-point, and the non-equilibrium thermodynamic theory that describes open systems has been shown to provide a good general description of these systems. Two associated features of such systems need to be noted, the seeking of a steady state and the minimization of entropy production. Agriculture usually involves the replacement of one ecosystem by another, and as suggested earlier, it is important that it achieves a steady state and minimizes entropy production. The maintenance of the capacity for self-organization is, of course, essential for the latter.

Minimizing entropy production presupposes that entropy production can be assessed. The assessment will often need to be of a qualitative nature, for lack of detailed information, but the proposed 'audit of small molecules' provides one approach where data are available. This is an oversimplified approach because it implies that the entropy contributions of all small molecules are the same, whereas in practice they are not all the same and the entropies of gases and ions are assessed by differing means. However, Glasstone (1947) gives values for the virtual molar entropies of the gases CO_2, NO, NO_2, N_2O, NH_3 and H_2O that all fall in the range 44–52 entropy units (184–220 J mol^{-1} K^{-1}) and a standard entropy of NO_3^- (calculated from the entropies of salts) of 35 entropy units (146 J mol^{-1} K^{-1}), all at 25°C. Thus the audit of small molecules does not seem to be a gross over-simplification, although no value is given for phosphate, and if sulphate had been included, its entropy of 4 entropy units would have been seen to be far out of this range.

It is interesting to try to relate the thermodynamic ideas discussed in this paper to two other descriptions of complex systems, the Gaia hypothesis (Lovelock, 1979) and Chaos Theory (e.g. Gleick, 1988). All three approaches are concerned with the emergence of order within disorder, but the underlying assumptions are not exactly the same. The Gaia hypothesis suggests that the conditions needed for life are created and maintained by life itself in a self-sustaining process of dynamic feedback. The overall conclusions reached in this approach are broadly similar to those reached in the thermodynamic approach but the latter is more specific about the process by which the biosphere is ordered.

Chaos Theory describes systems that are in a state of pure disorder but in which order and even beauty are to be found. Various branches of the theory exist and they have been shown to give useful descriptions of phenomena as different as the formation of snowflakes and the changes in populations of species. The concept of self-organization emerges from this theory principally as the result of the interactions between processes at different scales, but how exactly it occurs is not yet clear. The interface between Entropy Theory and Chaos Theory is beginning to be explored (e.g. Çambel, 1993) and it promises to be an interesting one.

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References

Addiscott, T.M. 1993. How high should low-intensity be on the agenda? A view from Sweden. *The Agronomist* No. 2, 1993, pp. 4–5 and 16.

Addiscott, T.M. 1994. Simulation, prediction, foretelling or prophesy? Some thoughts on pedogenetic modelling. In: *Quantitative Modeling of Soil Forming Processes*, SSSA Special Publication No. 39 (eds R.B. Bryant & R.W. Arnold), pp. 1–15, Soil Science Society of America, Madison, WI.

Addiscott, T.M., Whitmore, A.P. & Powlson, D.S. 1991. *Farming, Fertilizers and the Nitrate Problem*. CAB International, Wallingford.

Bertilsson, G. 1992. Environmental consequences of different farming systems using good agricultural practices. *Proceedings of an international conference of the Fertilizer Society, Cambridge*, 16–17 December 1992. 27 pp.

Çambel, A.B. 1993. *Applied Chaos Theory: A Paradigm for Complexity*. Academic Press, London.

Cary, J.W. & Taylor, S.A. 1962. The interactions of the simultaneous diffusions of heat and water vapor. *Soil Science Society of America Proceedings*, **26,** 413–416.

Glasstone, S. 1947. *Textbook of Physical Chemistry*. Macmillan, London.

Gleick, J. 1988. *Chaos: Making a New Science*. Penguin Books, Harmondsworth.

Hoosbeek, M.R. & Bryant, R.B. 1992. Towards the quantitative modelling of pedogenesis—a review. *Geoderma*, **55,** 183–210.

Hoskins, W.G. 1977. *The Making of the English Landscape*. Hodder & Stoughton, London.

Jenkinson, D.S. 1971. The accumulation of organic matter in soil left uncultivated. *Rothamsted Experimental Station Report for 1970*, Part 2, pp. 113–137. Rothamsted Experimental Station, Harpenden, England.

Jenkinson, D.S. 1991. Rothamsted long-term experiments: are they still of use? *Agronomy Journal,* **83,** 1–10.
Johnson, D.L. & Watson-Stegner, D. 1987. Evolution model of pedogenesis. *Soil Science,* **143,** 349–366.
Katchalsky, A. & Curran, P.F. 1967. *Non-Equilibrium Thermodynamics in Biophysics.* Harvard University Press, Cambridge MA.
Lovelock, J.E. 1979. *Gaia: A New Look at Life on Earth.* Oxford University Press, Oxford.
Morowitz, H.J. 1970. *Entropy for Biologists.* Academic Press, New York.
Nye, P.H. & Greenland, D.J. 1960. *The Soil under Shifting Cultivation,* Technical Communication **51.** Commonwealth Agricultural Bureau, Farnham Royal, Bucks, England.
Onsager, L. 1931. Reciprocal relations in irreversible processes. I & II. *Physical Reviews,* **37,** 405–426 and **38,** 2265–2279.
Powlson, D.S., Pruden, G., Johnston, A.E. & Jenkinson, D.S. 1986. The nitrogen cycle in the Broadbalk wheat experiment: recoveries and losses of ^{15}N labelled fertilizer applied in spring and impact of nitrogen from the atmosphere. *Journal of Agricultural Science,* **107,** 591–609.
Prigogine, I. 1947. *Étude Thermodynamique des Processus Irreversibles.* Desoer, Liège.
Runge, E.C.A. 1973. Soil development sequences and energy models. *Soil Science,* **115,** 183–193.
Schofield, R.K. 1935. The pF of the water in soil. *Transactions of the 3rd International Congress of Soil Science,* **2,** 37–48.
Schofield, R.K. 1955. Can a precise meaning be given to available soil phosphorus? *Soils and Fertilizers,* **18,** 373.
Schrödinger, E. 1967. *What is Life?* Cambridge University Press, Cambridge.
Thurston, J.M. 1958. Geescroft wilderness. *Rothamsted Experimental Station Report 1957,* p. 94. Rothamsted Experimental Station, Harpenden, England.
Wilson, E.O. 1992. *The Diversity of Life.* Harvard University Press, Cambridge, MA.