

2.15 Case Studies: Soil as the Interface of the Ecosystem Goal Function and the Earth System Goal Function

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Abstract

Ecosystem boundaries are chosen such that a domain is defined where a single ecosystem goal operates as the system attractor. Other goals may still operate on this area because the ecosystem contains semi-autonomous parts which are the organisms in a food web. It is possible for parts to have separate goals when the parts are separated from the whole by buffers or stores. The directed movement of water is defined here as the earth system goal. Ecosystems as goal directed objects are defined as the abundance of different sized organisms on the territory of the top predators. Fat decouples organisms from the ecosystem food web; the ecosystem food web is decoupled from climate by water storage in soil. Because the ecosystem is decoupled from its parts it can possess a goal; goal function equations for ecosystems and for water transfer in soil are given.

2.15.1 Introduction

You cannot serve both God and Mammon

St Matthew : 24

The quotation above illustrates the religious hypothesis that a system can have only a single goal at any one time. Any single goal can be described mathematically by a single goal function. Yet the world is obviously complex, with many goal orientated processes going on simultaneously. How can we bridge these two views of reality? We use the example of the soil as a system which appears to possess more than one goal function to examine general principles of system goals and to show the value of these principles to system modelling. The objective of this paper is to define the conditions under which the ecosystem (Cousins 1990) can possess a goal and to identify candidate goal functions for the ecosystem thus defined. It is shown that real world separation of the dynamics of systems is necessary to allow a system goal to operate. The soil provides

this means of separation of the ecosystem from the global climate referred to as the Earth system in the title, and so allows the ecosystem to possess a goal function.

2.15.2 Systems and Goal Functions

If we take an arbitrary area on the Earth's surface and call that area *The System*, then we can call the remaining larger area of the Earth, the System's Environment. The line enclosing the system, as we have defined it, is the System Boundary. It is unclear in this case whether the system as a whole has a goal or indeed whether it has several goals because the system has been arbitrarily, perhaps even randomly, constructed. However there may be other ways of more carefully choosing the boundary position such that only a single goal is exhibited by the system as a whole. Thus it is proposed that the search for goal functions is directly linked to where system boundaries are placed and therefore to the task of system definition. Similarly the search for the goal function of the ecosystem is directly linked to the location of ecological system boundaries and to the definition of what an ecosystem *is*.

The presently dominant definition of ecosystem (Lindeman 1942), that it contains biotic and abiotic (i.e. everything) and exists at every scale from microscopic to planetary, is not constructive for the identity of goal functions since perhaps 'every' goal function could be included under these conditions. In short, the meaning of the word 'system' within the word 'ecosystem' is totally subjective allowing the ecologist to draw a boundary in whatever arbitrary or informed way he or she may choose.

The alternative approach as suggested above is to invert this problem and construct system boundaries such that they are defined by a single goal, this single goal being characteristic of each system and the boundary enclosing the domain of action of the goal, where the goal operates as a system attractor.

A further concept is needed to deal with the reality that there are many simultaneous goals being pursued in the physical space occupied by a system. Because of containment, that is, ecosystems contain organisms which contain cells and so on, the ecosystem goal may differ to the goal of the organism and of the cell. The concept of containment resolves this particular problem, by showing there may be multiple goal functions active within the space occupied by the ecosystem, while the ecosystem itself has a single goal. This may be generalized as the whole has a single goal function but the whole is made up of parts which each have a single goal function and so on in a hierarchy.

The problem that remains is how can these separate goals interact and yet be preserved as separate goals. Simon (1973) provides a description of what is required which he defines as semi-autonomy. Thus in a hierarchy of contained systems, each system is semi-independent of the levels above and below, that is, independent within certain thresholds of behaviour.

The identity of a hierarchy is at least as controversial as the identity of system boundaries (Allen and Starr 1982). However goal functions may play a similar role in the non-arbitrary definition of hierarchy as they have for system boundary definition above. Thus we may say that in the real world, nature is constructed by a hierarchy of systems where each system is in possession of a single goal function and is semi-autonomous from the large system in which it is contained and is itself made up of parts which are single goal function semi-autonomous systems, and so on. The identification of single goal functions and their domains thus defines objective hierarchies of structure in nature.

In this paper we put some flesh on these theoretical bones using soil as focus but with the objective of defining the ecosystem goal function. The hydrological properties of soil are central to the soil's role as a growth medium for plants and we begin there.

2.15.3 Hydrological Systems

Let us consider the movement of water as part of the global water cycle. Overall water minimises its energy level both in the transition between phases and within each phase; sorption of water in soils minimises energy also. Water at the surface is energised by solar energy causing a phase change to water vapour. In this gas phase water moves to regions of lowest pressure which we take to be the goal of all air flow. However when the water vapour is returned to the liquid phase as rain, its goal is to move downwards in response to gravity. This goal is expressed by directed movement down the maximum slope available on the land surface. The goal of water minimising its potential energy can be used to define the boundary of the waterflow system. This is identified as the watershed and the area over which water travels is the catchment. Thus the goal is achieved in catchments by the movement of water through a network of drainage channels to the river and ultimately to the river mouth. The rate at which this occurs is due to the characteristics of the land surface e.g. soils and vegetation.

It is important to observe that the catchment boundary is uniquely defined by the water flow goal and the catchment has an intrinsic scale. That is to say, the size of the catchment is independent of the observer and the system defined from its single goal function is independent of the observer also.

Finally it is also relevant to note that the intrinsic scale of the system changed when the water changed phase from liquid to gas or vice versa, and the scale change was determined by the change in goal. At a more general level this phase change may be thought of as a change in the currency of the flows which are proceeding to the goal of each system.

We can now examine a second relevant system, the ecosystem, in which a completely different currency is transferred to the ecosystem goal.

2.15.4 Ecological Systems

We have already touched on the problems that arise in identifying ecosystem goals due to the highly subjective approach to the definition of ecosystem proposed by the founding fathers of ecology (Tansley 1935; Lindeman 1942). Here we take the hypothesis that nature is structured as nested (contained) domains of single goal systems. We search for a single goal function which describes the key properties of ecosystems and from which to define objective ecosystem boundaries which correspond to the domain of that goal.

An approach to this problem is provided by McNaughton et al. (1989) 'Ecosystems are structurally organised as food webs'. Thus we can reframe the ecosystem goal by seeking the goal function of food webs. When we do this a solution analogous to the watershed is produced.

Cousins (1990, 1996) describes ecosystems as objects defined by energy flowing through the food web to the top predator. These objects are bounded by the territory edge of the top predator, such that if solar energy (photons) fall on one side of the boundary the energy will tend to move to one top predator, and if it falls on the other side it will flow to the other top predator. Little of the energy reaches the top predator but is consumed and respired by intermediate organisms in the food web. In this framework ecosystems as functioning objects only contain live organisms and food items. The abiotic is specifically excluded and assigned to some other (abiotic) goal orientated system, e.g. the watershed.

Before leaving this question of how to view ecosystems, their boundaries and their goal functions, we note that it has been traditional to study ecology 'at the ecosystem level' precisely as the study of the abiotic, or as the study of nature using energy and materials as currencies. Population ecology has adopted live organisms as its currency but studies tend to be limited to only a subset of species in an ecosystem. However as Martinez (1995) observes, there is nothing unique about the ecosystem level in its use of energy and materials. Cells use energy and pass materials across their boundaries; single organisms and therefore populations do also. What is unique about ecosystems is that they are structured by feeding interactions; food is their currency.

The behaviour and goal function of ecosystems is in many ways similar to catchment hydrology. Catchments trap incoming rainfall and ecosystems trap incoming radiation. In catchments water is transferred through a hierarchical network of drainage channels to the river and in ecosystems energy is transferred through hierarchical sequences of organisms to the top predator (a food web). The boundary of the catchment is the watershed and the boundary of an ecosystem is the photonshed, in which the photonshed is defined by the territory of the top predator (its feeding area), and that within a photonshed the energy from intercepted radiation is statistically most likely to be directed toward the top predator.

2.15.5 Soils as the Interface

Biological and hydrological systems interact because they are not totally autonomous. So that each system impinges on the ability of the other system to achieve its own goal function.

Table 2.15.1. Mean values of available water for some common British soil profiles (adapted from Hall *et al.* 1977 and Mackney *et al.* 1983)

Soil series	Parent material	Depth of integration (cm)	Total available water (mm) (0.05-15 bar)	Easily available water (mm) (0.05-2 bar)
Aberford	Permian, Jurassic and Eocene limestone	60	110	70
Ardington	Cretaceous glauconitic sand, loam and clay	100	150	100
Bardsey	Carboniferous mudstone with interbedded sandstone	100	130	80
Bridgnorth	Permo-Triassic and Carboniferous reddish sandstone	80	85-105*	65-90*
Bromsgrove	Permo-Triassic and Carboniferous sandstone and siltstone	80	105	75
Clifton	Reddish till	100	150	100
Crewe	Reddish Glaciolacustrine drift and till	100	140	75
Denchworth	Jurassic and Cretaceous clay	100	160	82
Eardiston	Devonian and Permo-Triassic sandstone	60	105	70
Elmton	Jurassic limestone	30	65	40
Flint	Reddish till	100	120	70
Gresham	Aeolian drift and till	100	140	80
Marcham	Jurassic limestone	35	45	30
Newport	Glaciofluvial drift	100	75-150*	65-130*
Oak	Reddish till	100	130	65
Ragdale	Chalky till	100	130	75
Salop	Reddish till	100	135	80
Sherborne	Jurassic limestone and clay	35	55	30
Wick- Arrow- Quorndon	Glaciofluvial drift	100	100-200*	70-160*
Wilcocks	Drift from Palaeozoic sandstone, mudstone and shale	100	215	135
Worcester	Permo-Triassic reddish mudstone	100	115	60

*varies greatly according to content of 60-100 μm sand and surface organic matter levels

** (to 100 cm or to rock if shallower)

It is the contention of this paper that soils provide the interface between the goal functions of these two systems; the ecosystem goal function and the Earth system goal function for water distribution.

Because a wide range of soil types and properties occur in nature, the ability of soils to act as an interface depends largely on these properties and their distribution in space. For example, differences in soil types have a number of influences on the movement of water in catchments, including:

- infiltration (soil structure and porosity);
- surface runoff (surface roughness, soil water content);
- lateral flow (hydraulic conductivity);
- evapotranspiration (soil effects on plant growth and distribution).

Some examples of the differences in the physical properties of soil types are given in Tables 2.15.1 and 2.15.2. These examples are illustrative and data for other sites can be found elsewhere (Schlesinger 1985, 1991).

Table 2.15.2. Topsoil porosity classes for textural groupings with a medium packing density ($1.4\text{--}1.75\text{ g cm}^{-3}$) (after Hall et al. 1977).

Particle size class	Air capacity (%)	Porosity class
Clay	5.0-9.9	Slightly porous
Sandy clay	-	-
Silty clay	10.0-14.9	Moderately porous
Sandy clay loam	10.0-14.9	Moderately porous
Clay loam	5.0-9.9	Slightly porous
Silty clay loam	5.0-9.9	Slightly porous
Silt loam	10.0-14.9	Moderately porous
Sandy silt loam	10.0-14.9	Moderately porous
Sandy loam	15.0-20.0	Very porous
Loamy sand	>20.0	Extremely porous
Sand	>20.0	Extremely porous

Soil formation and the development of soil properties have been described using a functional relationship first proposed by Jenny (1941):

$$s = f(\text{parent material, climate, organisms, topography, time}) \quad (2.15.1)$$

in which s is a soil property. It is interesting to note from Equation (2.15.1) that both the biological (*organisms*) and hydrological (*climate*) systems contribute to the development of soils. In doing so, they influence the interface between their goal functions. For example, the biological system influences the hydrological system by:

- extracting and transpiring soil water;

- enhancing soil water retention (through returns of organic material or the effect of roots on soil structure);
- reducing surface runoff (through interception) and thus, enhancing infiltration.

In each of these examples the ability of the hydrological system to achieve its goal function is impaired, whereas the biological system benefits. Table 2.15.3 gives some examples of how different vegetation types influence the organic carbon content of soils.

Table 2.15.3. Examples different soil organic carbon contents under different land uses or vegetation types (after White 1981).

Land use or vegetation type	Organic carbon (t ha ⁻¹)
Alpine and arctic forest	0.1
Arable farming (cereals)	1-2
Temperate grassland	2-4
Coniferous forest	1.5-3
Deciduous forest	1.5-4
Tropical rainforest (Columbia)	4-5
Tropical rainforest (Africa)	10

2.15.6 Soil Water Goal Function

In its simplest form, soil water movement can be described as follows. Water movement through porous materials is expressed by Darcy's equation:

$$v = -k \text{ grad } \psi \quad (2.15.2)$$

where v is the volume of water per unit time crossing an area A perpendicular to the flow, $\text{grad } \psi$ denotes the change in water potential per unit distance in the direction of flow (which may be horizontal or vertical), and k is a constant (at saturation) called the hydraulic conductivity (defined as the reciprocal of the flow resistance).

The main components of the soil water potential (ψ) in head units (h) are the pressure head (p), where $-p =$ suction for soil water under tension, and the gravitational head (z), thus:

$$h = p + z \quad (2.15.3)$$

So that, Equation (2.15.2) becomes:

$$v = -k \text{ grad } h \quad (2.15.4)$$

Thus, as a plant extracts soil water through its roots (by transpiration), the pressure head in the immediate vicinity of the roots declines, and grad h increases. Water will then move toward the rooting zone at a rate that is defined by the size of the pressure gradient (grad h) and by the hydraulic conductivity (k). The value of k varies greatly between different soil types, see Table 2.15.4. Thus, the properties of different soils determine the efficiency of the plant 'water pump'.

Table 2.15.4. Saturated hydraulic conductivity (using the auger hole method) for some selected soils in England and Wales

Soil series	Horizon	Depth (cm)	Clay (%)	Saturated hydraulic conductivity (cm day ⁻¹)
Bignor	Eb(g)	16-40	23	74
Bignor	2Btg	40-55	30	45
Bignor	Bt(g)	45-61	29	36
Denchworth	Bw(g)	19-38	53	0.5
Everingham	Bg2	37-60	8	183
Evesham	Bw(g)	50-70	75	1.4
Evesham	Bw(g)	32-52	88	6
Evesham	BCgk1	52-76	87	2
Evesham	BCgk2	94-100	85	0.5
Stow	Bg	45-70	38	0.1
Whimble	Bt(g)	27-50	40	2
Whimble	2BCt	70-90	30	0.02
Winsdor	Bg	50-70	45	0.3

2.15.7 Ecosystem Goal Function

We have described ecosystems as the outcomes of interactions within a food web. These interactions occur within the area of the top predator territory. For lions or for Wolves such a territory is of the order of 100km². The net result of feeding interactions is the growth and reproduction of the feeders and when the populations of all species on the territory are observed, the relative abundance of all the organisms on the territory.

Peters (1983) plot of the abundance of different species of different body mass shows a steep decline in abundance of species of progressively larger size. Elton (1927) was the first to observe that it was the faster reproduction and growth rates of small organisms that fuelled the food web in which larger predators ate smaller prey.

The equation for the 'Peters' line is

$$D = 3 w^{-1} \quad (2.15.5)$$

where D is the population density of a species in number km^{-2} and w the mean weight in kg.

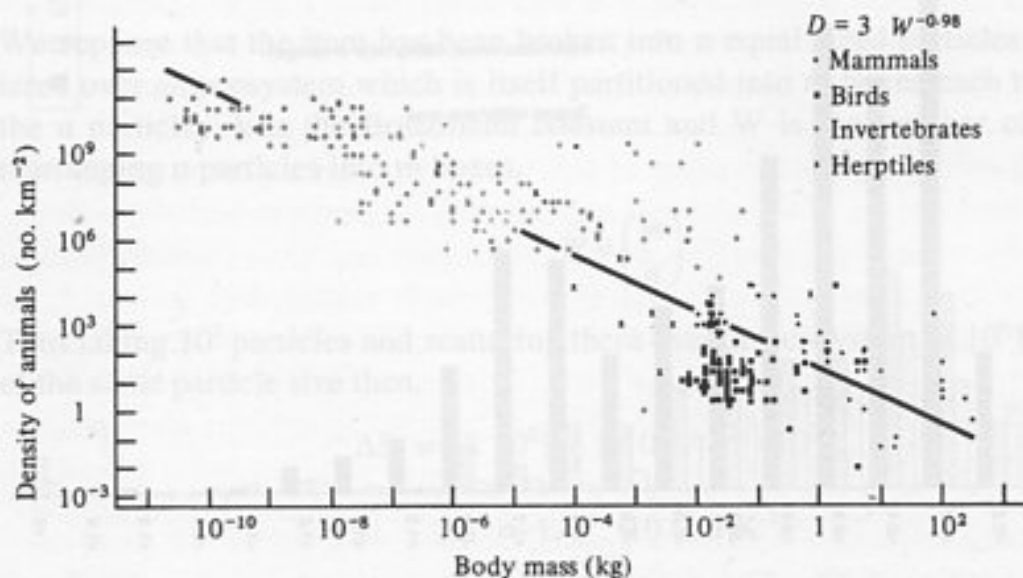


Fig. 2.15.1. The general relationship between animal body size and population density in published studies. With Permission (Peters 1983)

However, species are not the appropriate variable to parameterize the goal function since it is individuals who eat or are eaten in a food web not species. Members of a species may exist at very different sizes within the same ecosystem and can be cannibalistic. The alternative is to multiply equation (2.15.5) by the number of species at that weight to give the number of individuals at any weight. In practice it is easier to measure this quantity directly without identifying species. This approach has been most thoroughly pursued in the marine environment where automatic particle counters can be towed through the ocean. Again smaller organisms are eaten by progressively larger ones as energy passes in the direction of the top predator. The resulting abundance distribution of biomass is described by

$$b(w) = k w^{-2.2} \quad (2.15.6)$$

Where b , is the biomass of organisms of size $w + dw$ kg, and k is a constant. Platt et al. (1984) found equation (2.15.6) to be a good fit for data collected in the central gyre of the north Pacific ocean.

This distribution of animal number by size of organism is proposed as the attractor to which the ecosystem converges and equation (2.15.6) is proposed as

the form of the ecosystem goal function. Equations for the dynamics of this distribution are given elsewhere (Silvert and Platt 1980, Cousins 1985).

The operation of the ecosystem goal function within soil is illustrated in Fig. 2.15.2 showing the size and abundance of soil organisms found on long term experimental agricultural and grazing plots at Rothamstead, UK.

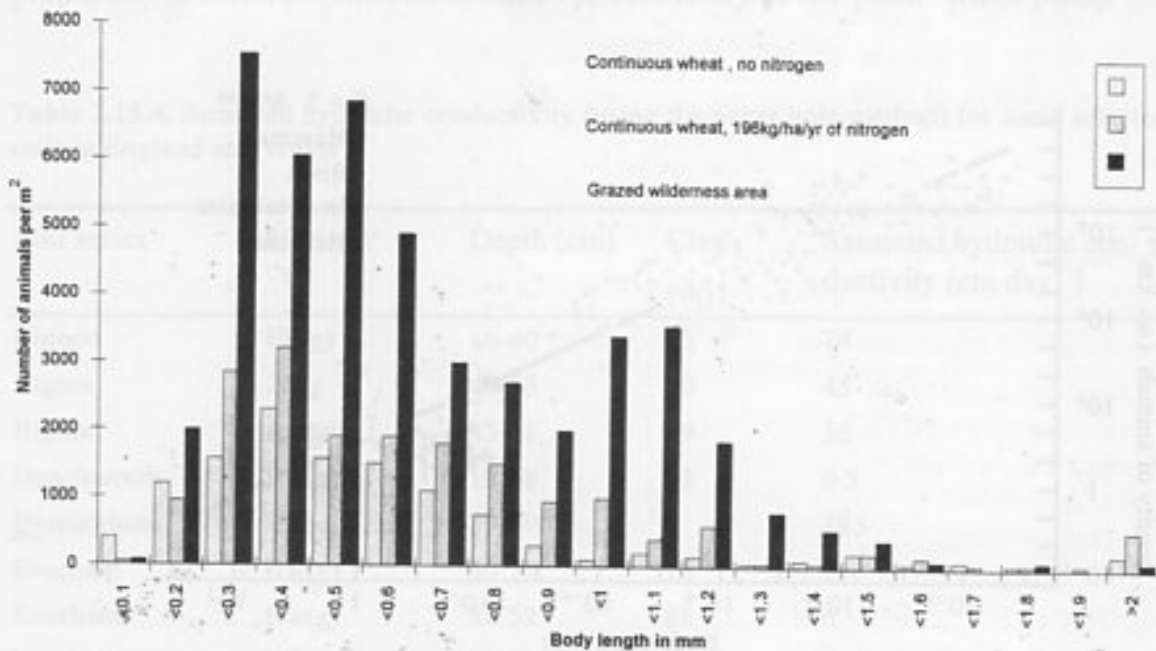


Fig. 2.15.2. The abundance of individuals in body size classes for all arthropods (0-2mm) from soil derived from three different long term farming regimes at Rothamstead. With Permission (Park and Cousins 1995)

Finally, we can ask what relationship the proposed ecosystem goal function has to other goal functions proposed such as minimising entropy loss or maximising energy.

2.15.8 Negentropy Change in the Food Web

The objective of this section is to illustrate that the proposed ecosystem goal function can be described in thermodynamic terms.

We may consider the operation of a food web over the top predator territory as energy capture via photosynthesis then movement of this energy by the plant, and fungi as well as concentration of energy into large body masses in the animal food chain. In the plant translocation and chemical transformation create locally energy dense states (e.g. seeds as an extreme example; fruiting bodies in fungi).

We may in general consider the operation of the food web and plant growth to create an ecosystem populated by statistically unlikely occurrences of local en-

ergy dense states, the organisms (or plant parts) themselves. These locally energy dense states arise within a uniform field of solar energy input to the system. We can calculate the change in entropy which is associated with the aggregation of food into larger particles. Suppose we take a uniform food item and break it into smaller parts and scatter them over an ecosystem. This act produces a change in entropy ΔS where

$$\Delta S = -k \cdot \ln W \quad (2.15.7)$$

We suppose that the item has been broken into n equal sized particles and scattered over an ecosystem which is itself partitioned into m boxes each the size of the n particles. k is the Boltzmann constant and W is the number of ways of rearranging n particles into m boxes,

$$W = \binom{m}{n} \quad (2.15.8)$$

Thus taking 10^2 particles and scattering them over an ecosystem of 10^6 boxes of the same particle size then,

$$\Delta S = -k 10^6! / [(10^6! - 10^2!) 10^2!] \quad (2.15.9)$$

$$\Delta S = 1.4 \cdot 10^{-20} \text{ J K}^{-1} \quad (2.15.10)$$

This can be compared to the energy change due to the oxidation of 1 g glucose

$$\Delta S = 1.4 \times 10^3 \text{ J K}^{-1} \quad (2.15.11)$$

However, it is important to contrast the small but calculable change in negentropy caused by the aggregation of animal biomass into larger particles with the inefficiency (and hence thermodynamic irreversibility) of the food web which collect the food together into larger particles.

A reference state of all biomass being distributed evenly in particles of the size of the smallest organism can be compared with the distribution of the same biomass in body sizes according to equation 2.15.6 to provide a measure of entropy change from ecosystem organisation.

2.15.9 Semi-Autonomy and Rules for System Identification

So far we have identified goal functions for the water and ecological systems and from these we have identified the system boundaries defined by the domains of these goals. The remaining issue concerns how these goal directed systems remain sufficiently independent of each other to allow their goals to operate. For ecosystems we have identified the 'whole' as the relative abundance of organisms within a spatially defined food web. Here the components are the individual organisms. The degree to which the organisms are independent of the food web, or are entrained by it, is given by the size of energy store the organism possesses.

Fat stores allow the organism to pursue other activities than just eating. Without those stores every expenditure of energy would have to be balanced by an immediate intake of food to compensate.

A general view of this process is that stores and buffers allow parts to decouple from the whole and therefore allow the parts to possess separate goals. In a hierarchy of contained systems where we focus on ecosystem (as defined above) we now see that it is decoupled from its parts, the organisms, by their energy stores. However a bounded ecosystem is also contained in a larger system which we will call the Earth and its property known as climate. For ecosystems to possess a goal function it is necessary to have some autonomy with respect to climate.

We can now see the importance of soil to the ecosystem goal function. The principle components of climate are rainfall and temperature and these determine the life zones on Earth (Holdridge 1947). Here we have shown that it is through the biological system increasing soil organic matter, that the supply of water to the plant can be moderated. Soil organic matter acts as a water store, decoupling the ecosystem from the climate. This decoupling is not total and acts to smooth out variation and allows the plant to respond to the long term average of temperature and rainfall.

2.15.10 Conclusions

We concluded that systems must have some autonomy in order for them to possess goal directed behaviour. If the system contains parts, then these parts can have their own goals if the parts have some autonomy from the whole. Thus the ecosystem has to be decoupled from the climate of the global system and from its own parts, the organisms. One mechanism to achieve autonomy is storage of the material that links the part and the whole. Fat decouples organisms from the ecosystem food web; the ecosystem food web is decoupled from climate by the possession of water storage in soil organic matter and in mineral soil components.

Although soil is normally treated as a system in its own right, it is shown here to be the interface between two system objects each with their own goal function, given by equations (2.15.4) and (2.15.6), for the water catchment and the food web respectively. The interaction of the two system goal functions is consistent with organisms as 'ecosystem engineers' (Lawton and Jones 1995). The parameters of the soil water movement equation for different parent soils are shown to vary widely and so determine the characteristics of the interface between the two systems.

It is also proposed that system boundaries can be identified by the area of operation of the system goal and that this process can be used also to define objective hierarchies in nature. The use of goal functions may simplify modelling and

in this case the existence of hierarchical catchment models may inform energy catchment models of the food web.

The major conclusion of this paper is that soil allows ecosystems to be semi-autonomous and therefore goal directed and described by a goal function. It will be for others to determine how an awareness of these system goals is useful to resource management or helps the expression of human preferences.

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References

- Allen TFH and Starr TB (1982) *Hierarchy: perspectives for ecological complexity*. Chicago University Press, Chicago
- Cousins SH (1985) The trophic continuum in marine ecosystems: structure and equations for a predictive model. *Can Bull fish and Aq Sci* 213:76-93
- Cousins SH (1990) Countable ecosystems deriving from a new food web entity. *Oikos* 57:270-275
- Cousins SH (1996) Food webs: from the Lindeman paradigm to a taxonomic general theory of ecology. In: Polis GA and Winemiller KO (eds) *Food webs: integration of patterns and dynamics*. Chapman and Hall, New York
- Hall DGM, Reeve MJ, Thomasson AJ and Wright VF (1977) Water retention, porosity and density of field soils. *Soil Survey Technical Monograph No. 9*. Soil Survey of England and Wales, Harpenden
- Holdridge LR (1947) Determination of world plant formulations from simple climatic data. *Science* 105:367-368
- Jenny H (1941) *Factors of soil formation*. McGraw-Hill, New York
- Lawton JH and Jones CG (1995) Linking species and ecosystems: organisms as engineers. In: Jones CG and Lawton JH (eds) *Linking species and ecosystems*. Chapman & Hall, New York
- Lindeman, RL (1942) The trophic dynamic aspect of ecology. *Ecology* 23:399-418
- Mackney D, Hodgson JM, Hollis JM and Staines SJ (1983) Legend for the 1:250,000 soil map of England and Wales. Soil Survey of England and Wales, Harpenden
- Martinez ND (1995) Unifying ecological subdisciplines with ecosystem food webs. In: Jones CG and Lawton JH (eds) *Linking species and Ecosystems*. Chapman and Hall, New York
- McNaughton SJ, Oesterheld M, Frank DA and Williams KJ (1989) Ecosystem patterns in primary productivity and herbivory in terrestrial habitats. *Nature* 341:142-144
- Park J and Cousins SH (1995) Soil biological health and agro-ecological change. *Ag Ecosys Env* 56:137-148
- Platt T, Lewis M and Geider R (1984) Thermodynamics of the pelagic ecosystem: Elementary closure conditions for biological production in the open ocean. In: Fasham MJR (ed) *Flows of energy and materials in marine ecosystems: theory and practice*. Plenum Press, London
- Peters RH (1983) *The ecological implications of body size*. Cambridge Univ Press, Cambridge
- Schlesinger WH (1985) Changes in soil carbon and associated properties with disturbance and recovery. In: Trafletka JT, Reichle DE (eds) *The carbon cycle: a global analysis*. Springer-Verlag, New York
- Schlesinger WH (1991) *Biogeochemistry: an analysis of global change*. Academic press, New York

- Silvert W and Platt T (1980) Dynamic energy flow model of the particle size distribution in pelagic ecosystems. In: Kerfoot WC (ed) Evolution and ecology of zooplankton communities. University Press of New England, New Hampshire
- Simon HA (1973) The organisation of complex systems. In: Pattee HH (ed) Hierarchy theory. Braziller, New York
- Tansley AG (1935) The use and abuse of vegetational concepts and terms. Ecology 16:284-307
- White RE (1981) Introduction to the principles and practices of soil science. Blackwell Scientific, Oxford