AGRO-ECOSYSTEM HEALTH: AGGREGATION OF SYSTEMS IN TIME AND SPACE

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Summary

Analogies between systems are bound to occur because all systems behave according to the same laws. This explains the analogy between the concepts of agro-ecosystem health and sustainability, and it implies the existence of basic principles to which system behavior conforms. Two such principles are identified in this paper. The first one stresses the importance of relations among subsystems, and the second stresses the importance of context and observer. The importance of relations is here called *ceteris imparibus* and it refers to tension between health of aggregated (sub)systems. The growth, health or strength of an individual subsystem (organ or the output of a plant and/or a cow) may need to be adjusted in time and space to achieve maximum total system output, due to relations, i.e. conflicts of interest between subsystems. The second principle expresses the effect of context and observer by stating that *beauty is in the eye of the beholder*. It implies that the choice of proxies (indicators) for health and/or sustainability depends on the observer and the context. Thus, health can be measured in different ways and at many levels, e.g. as the strength of a bone in vertebrates, as the growth of cell walls or reproductive tissue in a plant, as grain yield of a crop or as the health, strength or liveweight gain of an animal or herd. Such theoretical issues are applied to practice at different levels of system hierarchy in space and time: the plant, the animal, the plot, the herd, the farm and the region. The final part of this paper carries the arguments further by focusing on conflict among subsystem interests in time, among others by applying methodologies from non-linear system dynamics, in this case the predator-prey relations.

Introduction

The recent concern about agro-ecosystem health arises from the observation that aggregation of apparently healthy subsystems can lead to a total system that appears to be "unhealthy", e.g. polluted, stressed or exhausted. Basically, the drive to achieve "healthier" systems is similar to the drive to achieve more sustainable systems. However, the use of the term "health" allows researchers, policy makers and others in society to approach this problem with knowledge about principles from public health (Waltner-Toews & Nielsen, 1994). The need for sustainable development and/or health of agro-ecosystems is due to failures and side-effects of the developments that have focused on the well-being of system components rather than on their aggregated whole. That tradition is rooted in philosophic paradigms of reductionism which implicitly assume that the well-being of a subsystem can be studied without considering its relations with the surroundings. In other words, the reductionist tradition tends to emphasize the measurement of values of components with insufficient attention to the context. The essence of this paper is that solutions to current problems can only be found by taking a different look. Old approaches may have to be supplemented with new methodology and prevailing paradigms have to be reconsidered. The topic of aggregation subsystems provides a good opportunity to discuss these issues.

This paper starts by providing a set of working definitions concerning system health. As a conceptual step in system thinking, we then propose to adopt two principles that govern system behavior. The first is the assumption of *ceteris imparibus*, which is explained to refer to the importance of relations among (sub)systems. The second principle states that *beauty is in the eye of the beholder*. It underlines that context and observer play an important role in the setting of values and choice of criteria. The combination of these two principles explains the tension between aggregates of (sub)systems on scales of space and time. The second part of this paper illustrates these theoretical aspects with results from practical cases and scenario studies dealing with aggregation of systems in space. The third part discusses aggregation of systems in time by using simple cases and by introducing concepts and methodology from non-linear system dynamics, i.e. the predator-prey relation.

Agro-ecosystem health: concepts, paradigms and analogies

The discussion about ecosystem health requires definition of concepts and we propose to use the following working definition of a system*: a system is a unit of interrelated parts that transforms inputs into outputs*. This definition implies that concepts such as system, systems analysis and system behavior can be applied to what are, anthropocentrically, called abstract as well as concrete systems. For example it encompasses farms as well as health, cows as well as cities, and political systems as well as religions (Odum, 1971; Kramer & De Smit, 1987). Accordingly, this paper uses analogy as a tool to explain and understand the issue of aggregation of subsystems. Analogies between agro-ecosystem health and sustainability are here assumed to occur by principle, not by chance. As an illustration, definitions of health and sustainability are quite similar. WHO defines health as: *the extent to which an individual or group is able, on the one hand, to realize aspirations and satisfy needs and, on the other hand, to change or cope with the environment. Health is therefore seen as a resource for everyday life, not as the objective of living; it is a positive concept emphasizing social and personal resources, as well as physical capacity* (Nielsen, 1992). This definition shows that health is a combination of objectives of different subsystems. The definition of sustainable development by WCED (1987) is similar even though it puts more emphasis on the time aspect of system behavior, by stating that: *sustainable development is not a fixed state of harmony, but rather a process of change in which the exploitation of resources, the direction of investments, the orientation of technological developments, and the institutional changes are made consistent with future as well as present needs*. Ultimately therefore, and in spite of the risk of using analogies, we believe that the discussion about agro-ecosystem health is similar to that on agro-ecosystem sustainability. The advantage is that knowledge and concepts of sustainability can be applied to those of system health, including stress on the importance of time aspects.

Paradigms and principles

Not only definitions but also paradigms that underlie the discussion need to be explicitized. We propose to recognize at least two principles of system behavior that stress both the importance of relations and context:
* *principle 1: ceteris imparibus*. This is the opposite of the commonly held reductionist assumption *ceteris paribus* (while one component is changed, all other things remain equal). It reflects the idea of Spedding (1988) that all systems are interrelated, i.e. a change of one part of the system affects the system parts elsewhere.
* *principle 2: beauty is in the eye of the beholder*. It expresses that the value of a phenomenon depends on its context (its place in the system) and on the interest of the observer. This goes against the reductionist belief in values, truths and solutions that are universally true irrespective of time and place.
We will explain that the first principle implies tension between health of individual (sub)systems that are aggregated at different levels of system hierarchy. In addition, application of the second principle to (ecosystem) health implies that any definition of health and interpretation of proxies for health require explicit description of the context (boundary conditions) in which it is to be applied.

First implications of the two principles

For our arguments in this paper, it is best to start with a discussion of the second principle, i.e. the fact that agro-ecosystem health can be described by any (set of) indicator(s), hereafter called proxies. The reason is that the validity and/or usefulness of a proxy depends on the place, the perception and the boundary setting of the observer *(beauty is in the eye of the beholder*). In that sense, one could suggest that the strength of a bone or the flow of blood through the portal vein to the liver be considered to be proxies for health at body level. By analogy with the flow rate of blood in a vein, the health of a plant could be expressed as the flow of nutrients from stem to grain, in terms of the strength of a stem (resistance to lodging), or for example as the yield of grain. In the same manner the health of an animal may be expressed in terms of milk yield or litter size. At plot or herd level, we could express system health as grain yield per plot, milk yield per herd, liveweight per hectare or average number of piglets. At farm or regional level one can use cash flow, milk yield or Gross National Product to measure system health. At all these levels the context is of paramount importance. For example, the required strength of a given bone in a vertebrate differs drastically between the baby or adult context in humans, and between the context of a human, an elephant or a sparrow. This, we believe, sufficiently illustrates the principle of beauty in the eye of the beholder. The effect of the first principle about relations i.e. *ceteris imparibus*, can be illustrated by discussing the issue of aggregation of systems in space, the topic of the next section.

Aggregation of subsystems in space

We state that the conflict of interest that is associated with the aggregation of subsystems, is the result of relations between systems. A nice example of competition at organism level between the bone and the muscle system. Indeed, organisms optimize their resource allocation by sacrificing bone strength to achieve more muscle strength, or conversely, by sacrificing muscle strength for better bone strength. As resources are limited, stronger bones go at the expense of muscles and vice versa, illustrating the existence of relations and conflict of interest between (sub)systems. Such conflict is evident at plot level in cropping systems where the maximum yield of an individual plant has to be sacrificed in order to achieve a higher total plot yield. This aspect of aggregation of (sub)systems was first brought to our attention by B. Deinum (pers. comm., 1988), who explained that spacing of plants for maximum individual plant yield is wider than for maximum plot yield. The issue is worked out in much greater detail by De Wit (1960). In a more philosophical way it has been elaborated by Donald (1981) who explains that the design of an individual wheat plant as evolved in the struggle for survival may be ill suited for its performance in a community. In order to achieve higher yields per plot it is necessary that the plant is redesigned: its leaves should be more erect; height is no longer an important characteristic and individual yields are made subject to total plot yield. The term communal ideotype is thus coined by Donald for a plant type defined as follows:

> *[...] communal plants may give low individual plant yields, but when grown in a pure stand at densities sufficient to induce interplant competition and full exploitation of the environment, they are capable of high crop yields. It is proposed that any ideotype for wheat or barley crops should be based on communal plants.*

The principle of the communal ideotype, i.e., the competition between production of an individual and that at system level has also been described for animal production in the context of heterogeneous feed resources (Jones & Sandland, 1974). It is illustrated in figure 1 where individual liveweight gain is maximum at stocking rates < M_i, while decreasing at higher animal densities where the liveweight gain per ha can continue to increase. Thus, output per area unit can increase when output per individual animal declines, and the maximum output of the aggregated system per hectare is achieved at point M_c where output per individual animal subsystem is below its biological maximum.

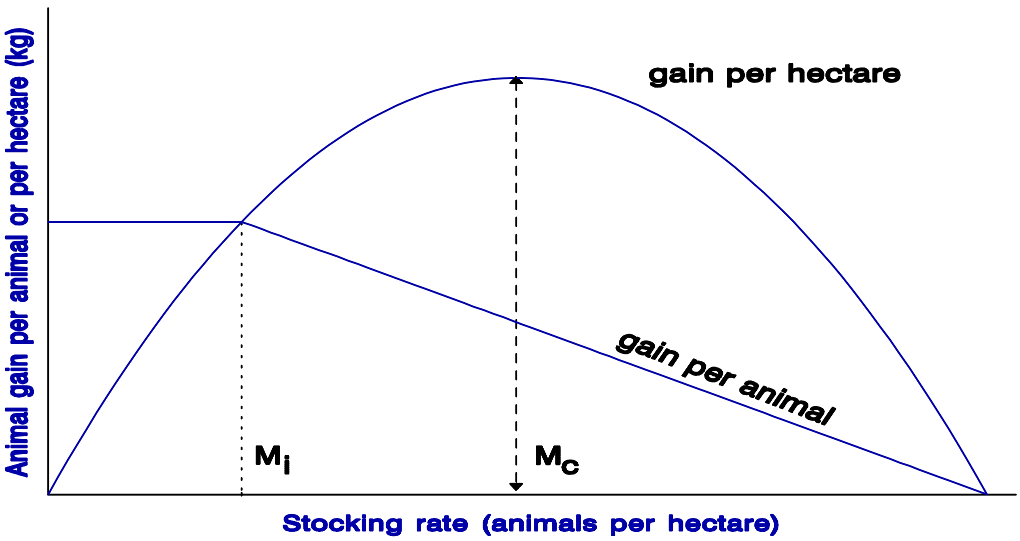

Figure 1: The yield of an aggregate system as related to the yield of individual (sub)system on a scale of increasing density (source: Jones & Sandland 1974)

Many more examples can be shown where subsystem yield needs to be adjusted for maximum system yield, e.g. in mixed grass/legume tree cropping, (Mureithi et al., 1995; Trenbath et al., 1990), mixed farming of crops and livestock (Kidane 1984; Patil et al., 1993) and even in seemingly farfetched issues such as the adjustment of animal dung quality to the crop growth requirements (J. van Bruchem, pers. comm., 1996). The point has also been elaborated by by Zemmelink et al. (1992) and Schiere et al. (1995) who show that high yield targets of individual cows may lead to lower aggregated system yield when they exceed total resource endorsement of the system in terms of quality and quantity. The practical implication of the communal ideotype concept is that, depending on resource potential, the design of plant, animal or farm ideotypes or prototypes has to be based on a balance between the interest of the individual and the interest of their aggregated whole.

Aggregation of subsystems in time

The essence of principle 1 is that a change in one part of the system affects the system elsewhere. This was illustrated with examples from high-yielding subsystems that negatively affect the production of its aggregate system. We will now show that this principle also holds in the time domain, first by discussing optimal densities of a maize crop grown in a wet and a semi arid climate, i.e. two different contexts. The recommended density for maize in humid regions tends to be higher than in semi-arid regions because of different competition of plant systems for moisture in time. In semi-arid regions, moisture availability in the period of grain fill is generally inadequate if growth during the vegetative period has consumed most of the available moisture (B. Deinum, pers. comm., 1996). Thus, the ideal density of plants, animals etc. depends on present *and* future access to resources. This is a familiar and urgent ring in discussions about sustainability expressed as interspatial and intertemporal equity (De Wit et al., 1995). For animal production this phenomenon was noted by Columella who wrote for Roman farming 2000 years ago that:

> *where fodder is scarce, cows should only be allowed to calve every second year, particularly when cows are used for farm work, to enable the cow to have an ample supply of nourishment for her calf and to save her the double burden of work and pregnancy* (White, 1970)

The time aspect in system behavior and resource flow is always present due to the effect of a lag time, i.e. the fact that it always takes some time for systems to respond to an effect elsewhere. The time aspect is thus more prevalent than one may have realized in the previous parts which emphasized on competition in space. More practically, we have oversimplified the measurement of health so far by looking at proxies such as yield and cash flow at a given point in time. We deliberately ignored time effects and system dynamics, an issue that implies attention to, for example, yield and resource flow per remaining resources: a core issue in the discussion of sustainability.

The reference here to remaining resources assumes clearly that resources such as fossil fuel or natural fertility can be exhausted. In contrast to national economies, private business tends to look at this aspect by considering cash flow *and* assets, whereas national economies tend to look at resource flow only, generally in terms of GNP. However, GNP can be replaced with the so-called Index Sustainable Economic Welfare (ISEW), which incorporates both losses of remaining resource stocks (assets) *and* resource flow (Daly & Cobb, 1990). The decision on whether to include such a time effect in the measurement of (national) well-being illustrates again that beauty is in the eye of the beholder. Inclusion of attention to remaining resources shows a different picture for what tends to be called "system health" in current newspaper language: the "growth" of an economy is negative rather than positive (Table 1). It also illustrates competition among subsystems on short and long term, i.e. on scales of time.

Table 1. "Health" of a national economy expressed as growth/capita/year in terms of resource flow (GNP), and with "corrections" for resource depletion (ISEW)

	Gross National Product (GNP)	Index Sustainable Economic Welfare (ISEW)
1951 - 1960	0.97 %	0.84 %
1960 - 1970	2.64 %	2.01 %
1970 - 1980	2.04 %	-0.14 %
1980 - 1986	1.84 %	-1.26 %

Source: Daly & Cobb (1990)

System dynamics

So far, the reasoning on tension among systems in time has been straight forward, hardly doing justice to the interesting dynamics that are inherent to the behavior of complex systems consisting of aggregated parts. This omission can be remedied by introducing elements of non-linear system dynamics, a relatively new branch of science that is popularly called chaos theory (Gleick, 1987; Cohen & Steward, 1994). It is necessary for this purpose to introduce a measure of density, for example by expressing yield as a function of resource stocks. In this sense it is useful to refer to the work of Giampietro et al. (1992), who use yield per biophysical capital as a measure of sustainability. The principles of this approach are applied in animal science, for example, when milk yield/animal is interpreted in the (time!) context of changing body weights. Similarly, maize yield in successive years can be plotted against remaining resource stocks such as soil nutrients, and animal output over several seasons can be plotted against remaining feedstocks. While elaborating on these aspects of system dynamics we were almost automatically led to the use of predator prey-relations.

The fox-rabbit relationship

A well-known predator-prey relationship was developed long ago by Lotka and Volterra (cf. Cohen & Stewart, 1994). It is illustrated in Figure 2 where the number of predators (foxes in this case) are plotted versus the number of preys (rabbits) for various points in time ($t_0...t_6$). Both densities are positively correlated up to the point where fox density starts to negatively affect the size of the rabbit population. As a result, the number of rabbits starts to decline from there on, while the number of foxes continues to increase until t_3, due to the time lag. At that point, the size of the fox population stabilizes while the rabbit population further declines (t_4), but fox populations actually decline (t_5) when rabbit stocks become critical. When fox numbers become very low, e.g. at t_6, the rabbit population can increase again and the cycle starts at t_0 or a similar point. The general shape of this relationship can be described as an attractor, mathematical systems that occur in several forms. Attractors have properties as depicted in Figure 3, 4 and 5, they can stabilize at an equilibrium point (Fig. 3a), at a so-called limit cycle (Fig. 3b), or they can follow an irregular path of a so-called strange attractor (Fig. 3c).

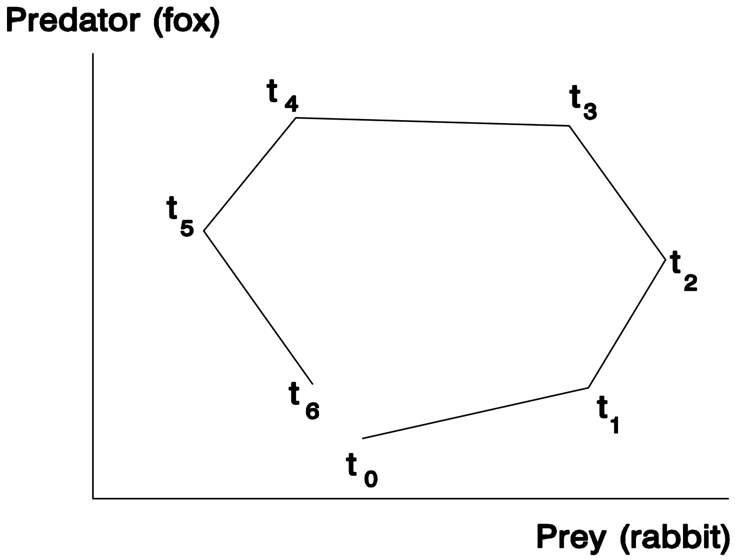

Figure 2: The general shape of the Lotka-Volterra predator-prey relationship

The stable configuration (any of the three possibilities of Figure 3) can be disturbed either by random forces or by a systematic change (shift in system parameters). This may result in an extinction of the predator or the prey. The difference between these two outcomes is large for system health and sustainability. Extinction of the predator leaves the prey at a

level such that re-introduction of the predator restores the stable state of coexistence (Fig. 4a). If the prey gets extinct in the collapse model the predator will follow and the system collapses completely (Figure 4b). In Figure 5, we sketch the effect of a changing land use that can destabilize the coexistence of humans, animals, vegetation and soil type. We have for convenience sake superimposed the essence of Figures 3 and 4 into one while deleting the strange attractor of Fig. 3c. To spark discussion we do provide some practical cases of systems that might behave according to the simple predator-prey systems (Figure 5). The details may differ but we hypothesize that technologies such as liming in medieval agriculture and digging of wells for irrigation of crops or for watering of nomadic herds may bring systems onto the "C" trajectory. Traditional nomadism, infield/outfield systems, irrigated paddy fields and grass leys may follow the A trajectory. Outbreaks of "Black death" or rinderpest may be either expressions of system behavior on the A trajectory, or they may cause a temporal extinction of animals or men (B trajectory).

The analogy to the predator-prey relation in this context raises exciting issues for the discussion about tension between health of aggregated subsystems. For example:

- it is the predator's interest that sufficient prey is maintained, a strange tension between aggregated subsystems in the form of a love-hate affair over time,
- system health, expressed as output per (biophysical) reserves, tends to be a range rather than a fixed point,
- the behavior of the predator-prey relation at one level in the hierarchy should be considered in the context of predator-prey relation at higher or lower levels. Apparently healthy systems can collapse due to problems at other levels: ceteris imparibus par excellence (figure 6a-c).

More specifically, the fox-rabbit relation can serve as an analogy for systems in which a) humans prey on animals, b) animals prey on feed/plant biomass, and/or c) plant biomass preys on soil fertility (figure 6a-c). In this cascaded sequence, the effect of an intervention for increased system health at one level may be either magnified or reduced as a result of system behavior at other levels.

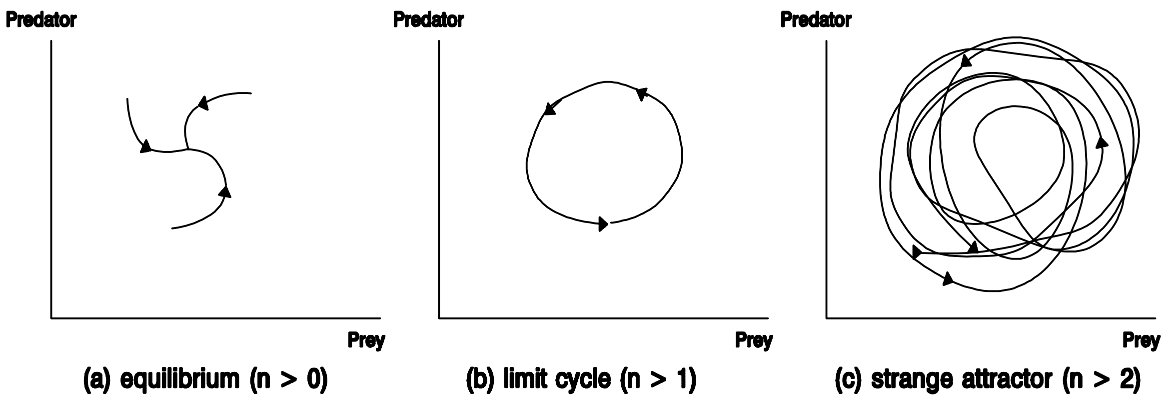

Figure 3: Two-dimensional projections of different types of attractors with the dimension of the state space of the process (= n).

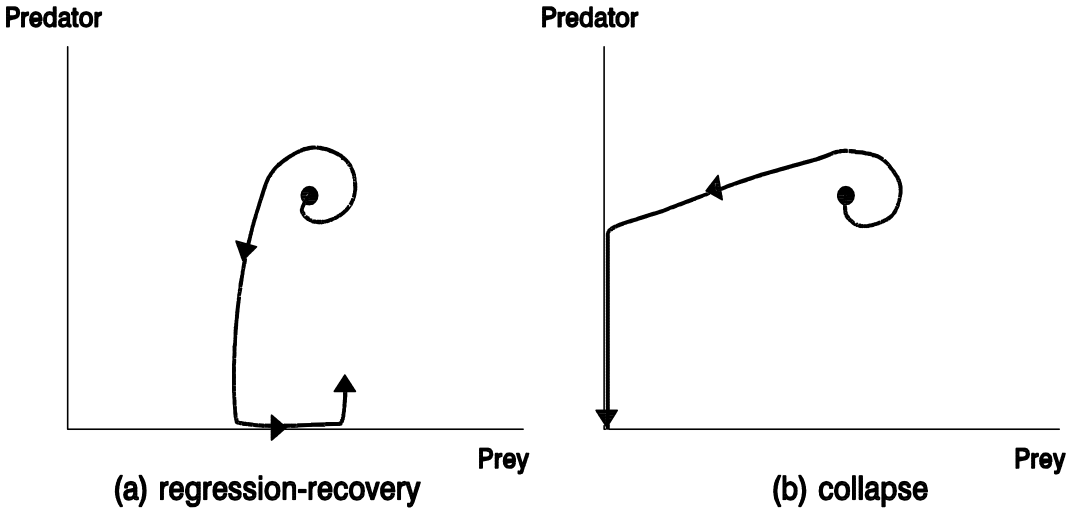

Figure 4: Extinction due to random causes or systematic change

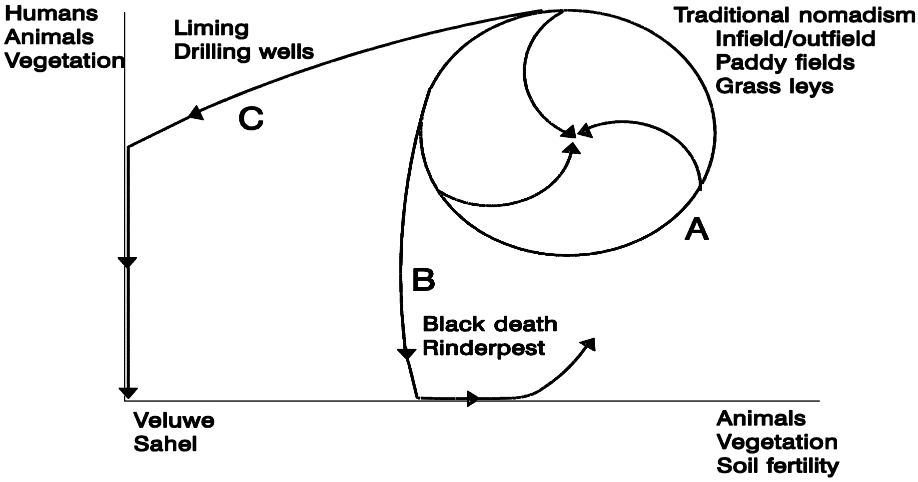

Figure 5: The fox-rabbit concept applied to the problem of sytem health (see figure 6 for the relation between the Y and the X-axis)

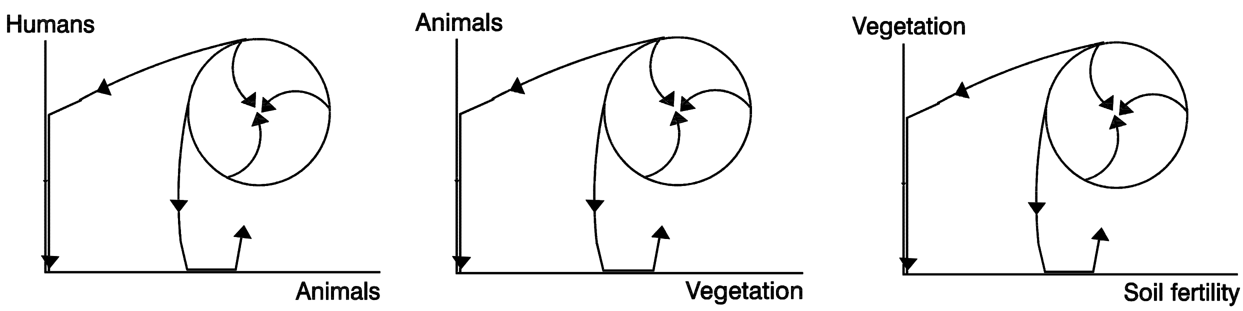

Figure 6a-c. The predator-prey relation in a cascade of systems at different levels of the hierarchy.

Much more is known about attractors and so-called chaotic system behavior than can be summarized here. Complications are that there are various types of predators, preys and even predators and preys that feed on each other. Beyond that, instability at one level may originate from other system levels as suggested in Figures 6a-c. However, we believe that this simplified discussion about conflict of interest among aggregated (sub)systems in space and time has sufficiently set the stage for further research, understanding and challenges about prevailing paradigms and to issues of agro-ecosystem health/sustainability. Research in various fields supports the points made here, see for example the work by Ellis & Swift (1988) and Noy-Meir (1975).

Conclusions

All systems can be hypothesized to be subject to the same laws, whether at the level of an individual organ, individual, farm or region. Testing of analogies is always necessary, but the analogy between system health and sustainability is probably a matter of principle rather than chance. In that sense, the work on health and sustainability both originate from the same concern about system behavior that seems to have gone astray due to excessive reliance on reductionist approaches that overlook the importance of relations, observer and context. We propose, therefore, to distinguish two principles of system behavior that counteract assumptions of reductionist approaches by stating that:

(i): *ceteris imparibus*, i.e., a change in one place affects the system elsewhere,

(ii): *beauty is in the eye of the beholder*, i.e., interpretation of measurements requires definition of context.

Application of analogies allows application of concepts from sustainability to the issue of agro-ecosystem health. Apart from the difficulty that interpretation of criteria for health/sustainability depends on "the beholders perception of beauty" there is tension between individual and collective interest in space and time, even when only one criterion of sustainability is used, e.g. yield per subsystem. This implies that the design of "sustainable cows", "sustainable farms" or sustainable ideotypes cannot be done without balancing the interest of the individual subsystems with that of the aggregated systems. Study on time effects of conflict between subsystems can use concepts from non-linear system dynamics. These show that system health is often not a fixed point but it can be a range of values beyond which the system is either non existent or bound for collapse. Moreover, the sustainability of a system can be threatened by problems at other levels than the one under study. For example, the sustainable ratio of humans over animals can be ultimately determined by the regional soil fertility, once again illustrating that the well-being of one part of the system is inseparably related with that of another part. Finally, further knowledge of theory on system dynamic indicates fundamental uncertainty about system behavior even though ranges and probable attractor trajectories of system behavior can be predicted.

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