# A Long-Term Perspective on Resilience in Socio-natural Systems

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# IN SOCIO-NATURAL SYSTEMS

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## Abstract

This paper argues that, both in the natural and life sciences and in the social sciences, we urgently need to develop a trans-disciplinary approach to environmental problems which does away with the presumed differences between "cultural" and "natural" processes. This may usefully be achieved by drawing upon the conceptual apparatus provided by the "Complex Systems" approach. In such a "socio-natural" perspective, the key concept is resilience (rather than sustainability). The resilience of socio-natural systems is in many situations dependent on the capacity of the human societies involved to process in the time available all the information necessary to deal effectively with the complex dynamics of the system as a whole.

The paper then sketches how human institutions may be conceived of as self-organising, information processing, flow-structures. It then asks how the dynamics of these affect the resilience of a socio-natural system, and defines a number of parameters that may be used to gauge that resilience. The first group of these concerns all the external parameters of a disturbance, and the second those that relate to the reactivity of the system to such a disturbance.

The paper ends with a brief outline of an example – the study of two successive crises in the Comtat area in France, one century apart. In the first crisis, the area was very resilient, and in the second it was not. The paper points to a number of the interacting factors that may be held accountable for the difference in response.

## Introduction: what is an (environmental) crisis?

As an archaeologist, the debate about global warming, the greenhouse effect and generally the idea that humanity is facing an environmental crisis makes me question whether it really is the first time that human societies have faced such a situation.

As usual, the answer depends on one's perspective. Whereas there is objectively no doubt that the present situation is unique in the sense that the scale of the problems facing us is global, earlier societies have had to face crises that they perceived as 'global'. The Maya and the Romans, for example, both faced major crises in their relationship to the environment. A number of Roman authors described such a crisis in the 2nd and 3rd centuries AD, for example, and some of them did indeed impute it to environmental change. The crisis affected the whole of the world that was known to them.

Reflecting on the parallels between the Roman situation and our own raises a number of interesting questions. How has humanity survived the many crises it seems to have encountered? Are crises inherent in the relationship between societies and their environments? Are they always caused by changes in the external environment? Are crises objectively measurable? What does the word 'crisis' mean? Does the scale of the disturbance matter?

If anything, the long-term perspective which archaeology brings to bear on such issues as environmental crises causes one to question the 'life or death' connotation that is attached to them. After all, humankind has gone through such moments of 'crisis' countless times since its existence on earth. Most of these crises occurred when the globe was sparsely populated by small groups of human beings that were much more likely to be eradicated than the present world population. In some cases, a 'solution' may have been found in the nick of time, whereas in others the disaster probably was complete for the group concerned, but because such groups led a relatively independent existence in different environmental circumstances, other groups survived, and so did the human race.

But the wealth of instances that are available to the archaeologist also makes the point that most, if not all societies have at one point stumbled in their relationship with the environment. Indeed, it seems as if crises are an inherent part of the dynamic relationship between societies and their environment, just as they are part of the dynamics of certain other species.

Are environmental crises due to changes in the external environment? Some interesting archaeological instances may throw light on the issue. Among the prehistoric populations on the Australian continent, those living in the (environmentally rich and friendly) Murray-Darling watershed regularly suffered famines, whereas the groups in the (environmentally poor) Australian desert almost never did. The only way one can explain this difference is by assuming that the desert populations respected the low carrying capacity of their environment and moved on before it was depleted, whereas the people living in the forests of the Murray and Darling did not. Did the richness of their environment incite the latter to overexploit the area, periodically bringing famine down upon themselves ? The implication seems to be that, in the case of human societies, their perception of the environment seems to have something to do with the genesis and nature of environmental crises. Crises seem to be the result of a conjunction of internal and external dynamics, in which the external dynamics are not always decisive.

Archaeology has more difficulty determining the relationship between the objective and the subjective aspects of crises. Most of its data on crises are of an 'objective' nature, so that the subjective experience of crises cannot really be explored by the discipline. But at least in some cases where we have both archaeological ('objective') and historical (written, 'subjective') data — such as the Roman one mentioned above — it seems that the sense of crisis that the written documents attest to does not match the 'objective' evidence. That observation is corroborated by many kinds of anthropological evidence. We would therefore suggest that whether or not a certain situation is experienced as a 'crisis', is at least in part dependent on the 'mind-set' of the populations concerned.

That leads us to redefine 'crisis' as a situation in which a society does not have the capacity to respond adequately to the situation which is developing. The lack of appropriate response may be due to any combination of factors, such as a lack of appropriate know-how or technology, an absence of the organisational or economic means to implement one, or a mismatch between the spatio-temporal scale of the problems and the solutions available.

All these questions, and the research on which a number of the above answers are based (cf. ARCHAEOMEDES 1998), have prompted us to look more closely at the way we look at the — worrying — changes in the environment which we have observed over the last 25 years. In particular, it seems that we must pay more attention to the social dynamics involved in what appear at first sight to be purely 'environmental' crises, but turn out to be 'socio-natural'.

## Environmental problems are socio-natural problems

In a brilliant essay, the German philosopher Luhman points out that "[…] society does not communicate with its environment, it communicates about its environment with itself […]" (1985). In his view, all human understanding is shaped in the interaction between the 'outside world' that we observe and our perceptual and cognitive apparatus. Consequently, 'environmental' problems are to a large extent socially defined. Luhman shows how, as a result, the definitions of such problems differ between disciplines. Descola (1994) makes essentially the same argument at the level of entire societies and cultures: each has its own way of constructing a conception of 'the environment'.

Evidence is mounting that most, if not all, of the 'environmental' problems we encounter are exacerbated by the 'nature'—'culture' opposition in our minds. Separating ourselves from what we consider to be 'nature', we have tended to favour human intervention in the natural domain as the way to 'solve' such 'environmental' problems — including saving our environment from ourselves. A growing awareness of this issue has triggered a shift in the debate on environmental matters in the scientific arena, but increasingly also in the political agenda and in the eyes of the general public.

It is difficult to pin the different steps of this evolution to specific dates, but the general tenor of the shift in perspective can be summarised by pointing out that the role of human beings in socio-environmental relations has gone from ***re***-active, via ***pro***-active, to ***inter***-active. The first two perspectives are anthropocentric: either we make exceptions of ourselves by taking no responsibility, or we do so by taking all the responsibility.

In the last perspective, humans become "*just another unique species*" (Foley 1987), and take

***part*** of the responsibility — which is much more difficult, as it necessitates determining, in every instance again, where the limits of our responsibility as human beings lie. As a result of this shift the 'tangled hierarchy' inherent in the disciplinary structure of our intellectual tradition, which for several centuries determined the relationship between 'nature' and 'culture' (ARCHAEOMEDES 1998, 26-41), is losing its grip on our thinking.

| **Pre-1980's** | **1980's** | **1990's** |
|---|---|---|
| Culture is natural | Nature is cultural | Nature and culture have a reciprocal relationship |
| Humans are *re*-active to the environment | Humans are *pro*-active in the environment | Humans are *inter*-active with the environment |
| Environment is dangerous to humans | Humans are dangerous for the environment | Neither are dangerous if handled carefully, both if that is not the case |
| Environmental crises hit humans | Environmental crises are caused by humans | Environmental crises are caused by socio-natural interaction |
| Adaptation | Sustainability | Resilience |
| Apply technofixes | No new technology | Minimalist, balanced use of technology |
| *'Milieu'* perspective dominates | *'Environnement'* perspective dominates | Attempts to balance both perspectives |

***Table 1:*** *Dimensions of the shift towards an interactive approach of the 'nature-culture' opposition.*

Recently, McGlade (1995) has thus argued : "there is no 'social system', and neither is there a 'natural system', there are only socio-natural interactions". It thus becomes possible to talk about 'socio-natural ***relations'*** and 'socio-natural ***problems'***, rather than about the relationship between social and natural ***systems***, stressing the interactions while accepting the differences in the nature of their dynamics.

Some other dimensions of this relatively recent shift in perspective are summarised in table 1. Among these, the principal one which concerns us here is that from 'adaptation' to 'sustainability' to 'resilience' as the core concept defining the nature of the relationship between the social and the natural aspects of the dynamics.

## 'Sustainability'

As a first approximation, one might say that in the case of 'adaptation', the social dynamics (the 'social system') is presumed to adapt itself to the natural dynamics. 'Sustainability', on the other hand, refers to an approach in which the social dynamics are presumed dominant, and where the survival of the combined dynamics depends on introducing long-term aims for human action and maintaining them. The third term, 'resilience', stresses the reciprocity between the social and the natural dynamics, and underlines the importance of change as a means of survival.

But as soon as one delves into the contrast between sustainability and resilience more deeply, a number of other differences emerge which, in this paper, need to be made explicit. 'Sustainable development', for example, differs from many other modern concepts and ideologies (e.g. 'eco-development', 'green development' or 'alternative development') in that it is not simply defended by a group of marginal supporters, but has become an officially recognised concept. First presented in 1980 in reports of the United Nations and the World Wildlife Fund, 'sustainability' did not attract general attention until the publication of the Brundtland report in 1987 (The World Commission on Environment and Development). It now comes back frequently, very often proffered as a solution to the global crisis.

In the huge literature on the subject one finds a large number of definitions[3]. However, because the aim of this paper is a comparison between 'sustainability' and 'resilience' rather than an exhaustive study of the different positions in the debate, we will here confine ourselves to two general definitions that are more or less typical for the subsequent ones. The first of these was formulated by 'World Conservation Strategy' in 1980. It states: "sustainable development is to live from the interest without using the capital." Seven years later, the definition proposed by the Brundtland Commission was the following:

> "Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs. [In this process] the exploitation of resources, the orientation of investments, the foci of technological development and the reform of institutions harmoniously contribute to the enrichment of the present and potential in order to respond to the future needs and aspirations of humanity."

## Criticisms of « sustainability »

Helmfrid (1992) makes the point that both these definitions manifest an anthropocentric perspective, as do most others. They intend to assure the well-being of human society and the individuals which constitute it, while the well-being of the natural environment, though closely linked, is secondary. This implies that a truly ecological perspective is absent from these definitions. According to the Brundtland definition, for example, the extinction of species that apparently are useless to humanity is acceptable. The consequences of accepting such implications are not unknown. Humid zones, for example, were formerly considered as useless and were often exploited after drainage. Too late, it became clear that such zones had had ecological functions such as purifying water. When considering the planet Earth from a truly ecological angle it is clear that all the components of the terrestrial system have a specific function, and that it can be fatal to consider the existence of some of them as useless. Helmfrid concludes that neither a purely ecological nor a purely anthropocentric perspective is sufficient, but that both are necessary.

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3 The research underlying this section was prepared by Chr. Aschan-Leygonie in the context of the ARCHAEOMEDES research programme which S.E. van der Leeuw co-ordinated from 1992 to 2000. It is included in extenso as chapter 2 in vol. 4 of the ARCHAEOMEDES I final report to DG XII of the European Commission (1994), and has been summarised in the synthesis of that research (ARCHAEOMEDES 1998).

The Brundtland report itself also illustrates the ambiguity of the term 'sustainability' The commission presented a wide-ranging inventory of global environmental and economic problems and placed them in the context of the politics of development. Its major conclusions are that global environmental problems have arisen from unbalanced development, leading on one hand to over-exploitation linked to poverty in large parts of the developing world and on the other to wasteful development in the developed world. Its main recommendation is that the protection of the environment and sustainable development should become an integral part of any directives for governmental and international organisations, as well as for larger private institutions. But clearly, the role of subjectivity in the interpretation of the 'sustainability' as a concept makes it difficult to verify if this recommendation is followed or not, and in particular to understand how it may be made operational.

Among the sceptical reactions a certain number consider the concept of sustainable development as useful, but do not agree with the use that is made of it in the Brundtland report. Others proclaim that the notion is fundamentally contradictory and consequently useless. Daly (1990) and Trainer (1990) for example, reject the amalgam between 'sustainable development' and 'sustainable growth' made by the commission, according to whom growth is an integral part of development. In economy the notion of sustainable development is generally considered equivalent to economic growth. Pearce (1987) supports this idea, as for him:

> "Sustainable economic development involves maximising the net benefits of economic development, subject to maintaining the services and quality of natural resources over time."

This point of view is criticised by Daly (1990), particularly because of the underlying meaning of the words 'growth' and 'development'. The criticisms are based on the absence of growth in the global ecosystem, on which the economic system depends.

To grow is 'to increase naturally in size by the addition of material through assimilation or accretion'. To develop is 'to expand or realise potentialities of; bring gradually to a fuller, greater or better state'. In short, growth is quantitative increase in physical scale, while development is qualitative improvement or unfolding of potentialities. An economy can grow without developing, or develop without growing, or do both or neither. Since the human economy is a subsystem of a finite global ecosystem that does not grow, even though it does develop, it is clear that growth of the economy cannot be sustainable over long periods of time. The term sustainable growth should be rejected as an oxymoron.

This well-founded opposition has provoked some adaptation of definitions, for example in the terminology of the United Nations. Initially, their use of the term 'development' was related to the notion of growth, but subsequently it was modified so as to mean integrated development, and later endogenous development. Presently, the word development implies sustainable development for the UN, but there are signs that its significance may change again, this time towards 'people-centred' development (Mayor 1992). Such a totally anthropocentric definition may cause vocal opposition.

Another important criticism of the Brundtland report concerns its succinct analysis of the factors responsible for the present global crisis, and the distinction it apparently makes between an ecological and a socio-economic crisis. According to Helmfrid (1992) the crisis is not due to insufficient development in the developing countries and too much development in the industrial countries, as the report states, but to inappropriate development almost everywhere.

Finally, a number of authors raise critical points concerning the notion of ‘need’, which is only defined in terms of present-day needs by the Brundtland commission. Redclift (1992) summarises the criticisms by stressing that the needs of human society evolve with its development.

After these considerations on sustainable development, what is there to say about the concept of sustainability? What significance can we accord this word? There seems to be general, if often implicit, agreement on understanding sustainability in the literal sense of the word: the persistence of a system (an aim often defined as desirable — but without mentioning for whom it is desirable) during a period which is generally considered as infinite. But there is no agreement on what is supposed to last. The phenomena that are worth sustaining depend on the disciplinary angle from which the problem is approached. Ecologists generally emphasise the need to sustain natural resources, or stay within the carrying capacity of an area. Many economists, however, underline the idea that the stocks of resources (natural, human, capital etc.) should be constant. But one could also argue that the quality of life should be sustained even if this implies consumption of non-renewable natural resources. Used singly, sustainability is not a satisfactory concept, and highlights the weak points of the concept of sustainable development.

Reactions to the original definitions of sustainable development have also occasioned a number of re-formulations. The one proposed by Costanza (1991) seems particularly interesting, as it takes into account the range of rhythms of the components of a system. He argues that different temporalities are a fundamental characteristic of the functioning of all systems and that they must be investigated in order to understand the complex relations between human society and its environment. According to Costanza, sustainability refers to a particular state of the dynamic relationship between human economic systems and (larger but normally slower) ecological systems. Such systems are said to be ‘sustainable’ when (1) human life can continue indefinitely, (2) human individuals can flourish, (3) human cultures can develop, and (4) effects of human activities remain within bounds, so as not to destroy the diversity, complexity, and function of the natural life support system.

Costanza stresses that ecological and economic aims are not necessarily in conflict, and that one must aspire towards a development which balances the two. However, in spite of the fact that the definition is better, the difficulties of arriving at such a development persist, largely due to the global character of the questions raised. Moving towards such a situation would require restructuring international politics so as to search for an equitable arrangement between developing and industrial countries, as well as finding a basis for agreement on the dimensions of sustainable development (ecological, social, economical etc.). The noble ambition of those proclaiming a sustainable development seems difficult to realise, and is a long term project which necessarily implies a general change in prevailing attitudes at all levels of most societies: the individual and the governmental level, as well as all levels in-between. Murdoch (1992) and Redclift (1987) present some of the difficulties that are inherent in ‘imposing’ such a global transformation.

## Resilience

The concept of *resilience* originally comes from physics, where it is defined as a value that characterises a material's resistance to shock. Subsequently it was adopted by ecologists, initially in the same sense as in physics. Thus, applied to ecosystems, resilience defines their capacity to resist a perturbation or to return to equilibrium after having been subjected to a shock. In this context, resilience expresses the notion of a system's stability around a point of equilibrium.

In 1973, Holling proposes a new significance for the term. It is no longer based on the traditional homeostatic systems approach, because it supposes the presence of a certain number of 'basins of attraction' or 'domains of equilibrium' rather than a single, fixed, equilibrium:

> "[Resilience is] the capacity of a system to absorb and utilise or even benefit from perturbations and changes that attain it, and so to persist without a qualitative change in the system's structure."

Thus a perturbation of considerable magnitude is necessary to trigger a qualitative change in a highly resilient system. In this definition, Holling distinguishes very clearly between stability and resilience; the first indicating a system's capacity to return to equilibrium, and the second the fact that the system does not lose its internal structure in a period of perturbation. A system can be highly resilient and yet fluctuate widely, i.e. have low stability. A resilient system is able to incorporate changes in its way of functioning without changing qualitatively. It keeps the properties that characterise it before, during, and after perturbation.

Another essential distinction between this perspective and the homeostatic systems approach concerns the way in which uncertainties and risks are taken into account in a system. Traditionally, human societies have searched for means to reduce uncertainties and risks by increasing control of the physical environment in particular. For example, we generally choose to protect ourselves from secular events (for example by constructing dikes against flooding), and we justify this with reference to medium-term risks, while we prefer to consider the occurrence of millenary events as uncertainties which are too difficult to take into account. Those responsible have preferred to ignore such uncertainties, because they are incalculable, and to turn their attention instead to the risks that can be estimated, in particular to those that occur frequently. But from the point of view argued here, rare occurrences and the uncertainties they imply are considered impossible to ignore or control. It is thus necessary to take them into account as an integral part of the system, while of course at the same time attempting to reduce their negative effects.

Thus there are two — closely related — aspects of 'resilience' which we must consider. The first concerns the behaviour of a system, due to the structure of its attributes and the interactions between them, due to voluntary management or depending both on the inherent characteristics of the system and on human effort. The other aspect concerns the perception of perturbations and change, and notably of unexpected or even unforeseeable future events.

## A 'Complex Systems' perspective on socio-natural dynamics

According to Holling (1986), only two conditions have to be met if we are to apply the concept to systems other than ecosystems: such systems need to be describable in dynamic terms, and they must have more than one potential state of equilibrium. These two requirements are met by most open systems, those that we propose to analyse among them. We therefore feel free to reason from case to case, though we are well aware that it must not be done without precautions.

Accepting these conditions requires a major change in the way we view social systems. Whereas the natural and life sciences view most interactions between different entities in terms of the exchange of matter, energy and (to a lesser extent, notably in ecology) information, the social sciences do not do so. For them, people, institutions, beliefs and other descriptive categories are also the main terms in which they formulate explanations.

In order to be able to integrate humans and other living species, as well as various material processes, in one and the same paradigm, we propose to apply the 'Complex Systems' approach to socio-natural dynamics. Although that perspective has not yet been widely used by the community dealing with the evolution of socio-natural relations, it seems to us to have considerable potential to bring the disciplines concerned together in a useful way (*cf.* McGlade and van der Leeuw, 1997). We base this claim on the fact that the 'complexity perspective' as a paradigm has shown itself to be capable of:

- Conceptualising problems in both natural and social dynamics in languages *independent of specific disciplines*; concepts used for genetic networks (Kaufman 1993), for example, may be even more appropriate to networks of economic exchange in small-scale societies (Kohler *et al.* 2000);
- Conceptualising the interaction between phenomena at different spatio-temporal scales by viewing large, stable, phenomena as the result of unstable interactions between smaller entities;
- Reformulating natural dynamics from an irreversible temporal perspective by introducing the notion that similar causes can have different results, and different causes similar results. A typical strategy is to characterise the various possible outcomes of a set of interacting processes in terms of their probabilities in the space of the parameters examined, and in terms of their stability under perturbation (Skyrms 1996);
- Inviting us to rethink issues of cause and effect in the social sciences, in which a common research tactic has been the evaluation of causal hypotheses with statistical analysis of data on system behaviour. However, in the non-linear dynamics that are apparently so pervasive in nature, the effect of a change in a state variable depends to a very great extent on the state of the entire system at that moment (Wagner 1999);
- Describing in one approach both continuity and change, tradition and innovation, by relating the one to the other and thus moving away from our traditional emphasis on stability and our focus on investigating change. This is seen, for example, in the emphasis on the trajectories of systems in Complex Systems approaches.

In practice, this entails a shift of perspective on the social dynamics involved. The social sciences have thus far predominantly opted for a descriptive paradigm in terms of individuals, social entities and institutions and the changes they undergo, rather than the kind of dynamic paradigm that forms the backbone of the natural and life sciences. The latter conceives of most processes in terms of flows of energy, matter and information that interact by means of different (positive and negative) feedback loops of varying duration and amplitude.

This is not the place to present the direction in which we propose to move in any detail, but a brief outline is necessary to understand what follows. To develop a 'Complex Systems' perspective on social systems we must take as our point of departure that the apparent stability and integrity of institutions and other social phenomena is not inherent. Rather, it is an illusion created by the choice of a *scale of observation that is much shorter* than the time over which the dynamic concerned plays itself out. In other words, phenomena are seemingly stable only when observed over time-scales that are of the order of $\delta\tau$ relative to the dynamics involved.

The next step is to assert that all phenomena are essentially nothing but interactions between feedback loops and delays. In effect, although this may sound rather a drastic statement, it only reformulates old philosophical principles which necessarily underlie any truly dynamic perspective: 'παντα ρει, ουδεν μενει'[4] or 'from dust to dust'. All processes we observe as humans are the result a set of interacting (positive and negative) feedback loops which occur at different rates and with different time delays between them. Such processes are in turn manifestations of differences in the spatio–temporal location of emergence and decay, which generate flows between them. Were it not for the differences in process rates and in the size and nature of the time-delays, all processes would be instantaneous and immediate, and therefore unobservable (as is the case with physical processes at 0º K.).

The above is based on what is essentially a 'field' approach to interactions which is not unlike (but much more general than) the field theory of electromagnetic processes. Institutions are from this perspective 'flow structures' – essentially temporary manifestations of the movement of matter, energy and information[5].

The former two flow symmetrically, are conserved, and are interchangeable (matter can be transformed into energy and energy at least theoretically into matter), but information acts differently, and the sense in which we use it needs some further explanation. Any observable creative process is 'the simultaneous substantiation of form and information of substance', and information is the organisation of matter and energy generated by the dynamics involved. As such, information is an abstract aspect that only has a presence in our minds, independent of the material and/or energetic substrate in which it may be expressed. It concerns only the organisation of the phenomena. The processes by which information is generated are what we usually call perception and cognition, and are heavily influenced by our individual and collective

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[4] The famous phrase of the Greek philosopher Thales of Miletus in the 6th century BC: "All is movement, nothing is stable"

[5] There are two concepts of 'structure' in social science. The traditional concept refers to *actual* relations between actors and groups that change slowly in terms of the normal frame of reference of social observers. More recently, Levi-Strauss has redefined them as groups or activity sets or roles *defined by some intersection of symbolic sets*. In our opinion, the second definition subsumes the first, as all actual relations that are significant in a culture derive their meaning from the symbolic sets to which they refer. These sets, in turn, owe their existence to the flow of information through the society concerned. Hence the term 'flow structures'.

histories and cultures.

This perspective should enable us to describe and investigate all processes, structures and events in the same manner – whether in the social, the natural, the socio-natural or any other realm – as different manifestations of (combinations of) flows, and of the interactions between such flows. The flows connect 'sources' (points of emergence) and 'sinks' (locations of decay) in time and space. All dynamics we observe can then be conceived of as resulting from a set of *interacting cybernetic relationships* and described in terms of *stocks and flows,* linked by (positive and negative) *feedback loops* with *different rates* and *different time delays* between them. The organisation of socio-natural systems is then described in terms of such concepts as:

- The potentials between which flows occur;
- The rates at which flows change;
- The spatio-temporal scale(s) at which flows manifest themselves;
- The strength of the links between flows;
- The boundary conditions of the flows.

Such descriptions are not fundamentally different from those that are used for purely ecological dynamics by, for example, Allen & Hoekstra (1992).

## A model of a dynamic socio-natural system

Next, we must briefly devote some attention to three essential questions that, together, present us with an outline of the perspective we propose, even though it is necessarily sketchy and basic at the present time:

- How do we conceive of the drivers of such a socio-natural system?
- How do we imagine the (dynamic) structure of such a system?
- How do we model the generic behaviour of such a system?

In this section, we will try to shed some light on all three of these aspects of the proposed approach.

### *How do we conceive of the dynamics that drive a socio-natural system?*

Of course, we can choose to define the system's drivers at a range of different levels, beginning with the solar energy that is essential to all of life. At the level we are most interested in, one could say that there are four categories of drivers:

- Those driving the processes of the geo-sphere;
- Those driving the bio-sphere (all species except human beings);
- Those driving (both physical and social) human dynamics;
- Those driving the interaction between human beings and the remainder of their environment.

From our perspective, the last of these categories is the most interesting, as their inclusion is what distinguishes 'socio-natural' systems from interacting 'natural' and 'social' systems. Every interaction between human beings and their environment is, of course, mediated by human perception, cognition and action. It follows that the dynamics we need to consider here are those which shape and relate these three domains. In designing a conceptual model of these, we have made a number of assumptions.

The first of these concerns the relationship between the environment and the knowledge that we accumulate about it. It follows from Luhman's work (1985, see above) that that relationship is one of asymmetric resonance between what happens in our environment and what we 'make of it'. The reason seems to be that the categories and theories cognised by human beings are under-determined by their observations (Atlan 1992). As a result, the dynamics of our cognitive processes over-determine both our observations and the categories and theories on which we base our actions.

The second assumption concerns the nature of these cognitive dynamics. Kahnemann, Slovic, Tversky (e.g. 1982) have shed considerable light on this topic by studying decision-making under conditions of uncertainty. Their conclusion is that these dynamics are driven by the asymmetry of the relationship between a phenomenon and its context. When a context is compared with, or related to, a phenomenon, similarities are stressed, but when a phenomenon is related to its context, differences are emphasised[6]. The relationship between our society and its environment can of course be observed either from the perspective of the society or from that of the environment[7]. It is our assumption that the interaction between these two perspectives drives the cognitive side of the socio-natural relationship. Moreover, in our culture the balance between these perspectives is presently such that the dangers of nature are systematically over-emphasised and the dangers of human intervention under-estimated, leading to ever more human intervention in the environment.

Our last assumption concerns such human intervention. Whereas perception and cognition transform objects in the real world, which have an infinite number of unknown properties, into symbols and ideas characterised by a very limited number of known properties, human action does the reverse. Each human intervention introduces many new, unknown, properties in the natural environment, enhancing the environment's unpredictability. Not only that, it does so in a non-random manner which leads to long-term difficulties. Human intervention in the environment will occur most often with respect to those risks that are most frequently observed. It thus has the perverse effect of reducing the number of known high-frequency risks while

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6 We experience this difference, for example, with respect to our cognition of the past and the future. In practising history, the present is compared to the past, and similarities between the two are emphasised. This leads us to look to the past for the origins of present-day phenomena. In dealing with the future the reverse happens, the future is compared to the present. As a result, differences between the two are accentuated, and the future is seen in terms of uncertainties and risks.

7 This is the case in French, which distinguishes between *'le milieu'* et *'l'environnement'*. The former perspective defines society as 'that what is in the middle of the (natural) environment'. The *'environnement'* perspective, on the other hand, refers to nature as 'that what surrounds society'. The *'milieu'* perspective compares society to nature, and emphasises the strength and unity of nature, while according mankind a passive role, adapting to nature. The '*environnement'* perspective, on the other hand, views mankind as 'strong' and 'active', and nature as 'manageable'.

introducing a mixture of new risks of all frequencies. Over the long term, socio-natural co-evolution will therefore introduce its own environmental time-bombs. Environmentalists call this the ‘Law of unintended consequences’.

*How do we imagine the (dynamic) structure of such a system?*

If we now turn to the structure of dynamic socio-natural systems, we must of course remind the reader first of all that what is ‘structural’ about certain dynamics is simply that they persist over longer timeframes. Often, this is because such dynamics are slower, but that is not necessarily so.

The structure of our dynamic socio-natural systems consists of its persistent ‘ways of doing things’, whether these are shared ideas such as customs, norms and the like, or commercial, legal or other institutions. For simplicity’s sake, in what follows, they will all be called ‘institutions’. Viewing institutions as ‘information flow structures’ is based on the idea that all institutions process information, and that in doing so they create and maintain themselves dynamically. As information is not subject to the principle of conservation, flows of information create and maintain shared meaning, understanding and expectations. These shared properties distinguish institutions from each other, as they do social groups, cultures etc., but they also create the coherence and the (dynamic) structure of the society and the institutions that compose it. One could argue that (raw) data are transformed into information by relating them to meanings, by contextualising them. Although the process of contextualisation may occur individually, the meanings involved have been negotiated among members of a society. Such shared meanings are here termed ‘institutions’. One could therefore imagine the dynamic process which links data, information, meanings and members of a society together in the dynamic structuring of information flows. The information that flows through society creates institutions (channels of shared meaning) which link actors, and the meanings shared by the actors in turn transform data into information. But as information is generally carried by a substrate, the channels thus created are also the channels through which matter and energy pass in order to guarantee the physical survival of the people who compose the society.

*How do we model the generic behaviour of a socio-natural system?*

We conceive of the co-evolution between a group of human beings and their environment as *non-directional* and *open-ended*, in the same way as (neo-) Darwinism conceives of evolution as open-ended: the *trajectory of the evolution is determined step by step,* depending on the circumstances of the moment. At each moment in time, there are (from an external vantage point) a *number of potential attractors or* basins of attraction towards which the socio-natural system might evolve, and a number of *trajectories* which might lead towards them. Which one the system eventually evolves towards depends among other things on whether or not:

- These attractors are perceived and cognised by the members of the society;
- These attractors are within reach (technologically, socially) in the time available to the society before it disintegrates or reaches another basin of attraction;
- The investment needed to reach the attractors seems warranted;

- The relations between the actors involved favour (or inhibit) the society in its evolution in that direction, etc.

It is not possible to predict for how long any trajectory might be followed. Initiating it will immediately change the context of the system's dynamics, and thus generate new basins of attraction and potential trajectories. *At any moment,* all levels of a society are involved in making *choices between various basins of attraction.* The *intervals* at which a system changes trajectory are determined by the effectiveness of the society's interface with the environment. As soon as that decreases, pressure builds up to improve the group's adaptive mechanisms.

## Resilience in dynamic socio-natural systems

The longer a trajectory has been followed, the more pressure for change builds up in the natural dynamics of the system, and the less easy it is to change it from within the human component. The *resilience* of a socio-natural system is dependent on the *degree of adequacy* of human interaction with the environment. This is expressed in figures 1,2 and 3, which relate the temporal dimension of change in the environmental and in the social dynamics to the resilience of the total socio-natural system.

The resilience is represented by the vertical distance between the curves of the 'social' and of the 'environmental' dynamics. If that distance is short, the resilience of the co-evolutionary system is higher than when that distance is larger. Whereas in figure 1 the system very rapidly loses its resilience, the situations represented in figs. 2 and 3 maintain the resilience of the system much longer.

The next question to ask is, of course: "what determines this 'degree of adequacy' of the human interaction with the environment?" An initial, preliminary, answer is that such adequacy is dependent on the respective changes in the rates of change of the different dynamics involved:

- *Changes in the rate of change of* (those parts of) *the dynamics of the natural system* which interface with human societies. These changes are primarily dependent on the effects of human action, but may also be triggered or accelerated by inherent natural dynamics.
- The *potential rate of change* of the *human information-processing* system. If the biological rate of information processing among human beings is assumed constant, this *potential rate of change* is in turn dependent on, among other things:
  - The *form* in which information is transferred and processed;
  - The *length and structure of the trajectories* along which it is passed.

We will look into these aspects in the next section.

## What influences the resilience of a socio-natural system?

Among the many factors that influence the resilience of socio-natural systems, we wish to highlight several different groups. The *first* of these groups, which in effect concerns all kinds of systems, involves:

***Figure 1:*** *The relation between an independent, incrementally changing, environmental dynamic and a cyclically changing cognitive dynamic with an invariant clock speed. The resilience of the relationship is inversely proportional to the vertical distance between the two curves. In this case, the system rapidly loses all resilience because the information-processing system does not adapt itself to the changes in the environmental dynamic.*

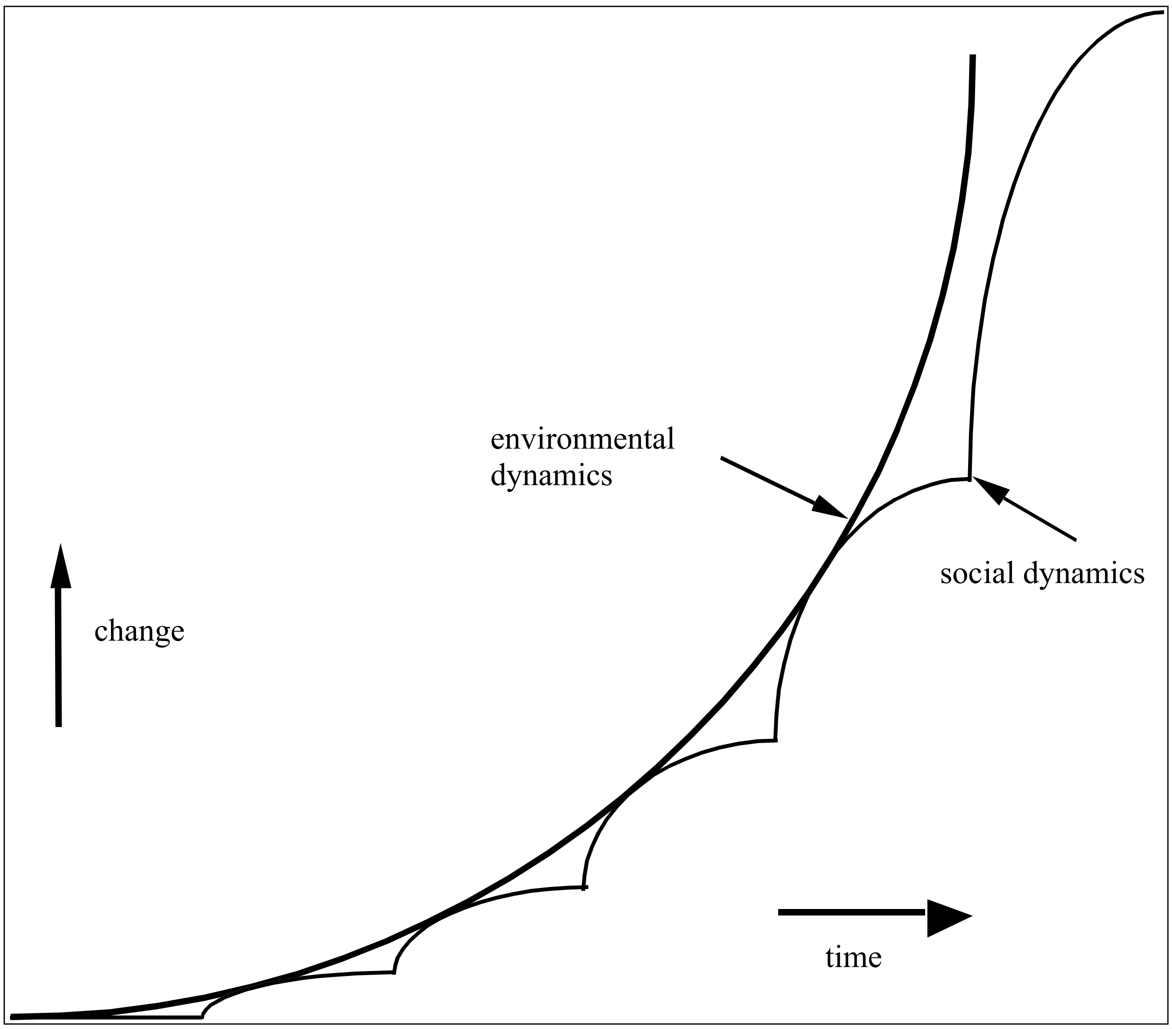


***Figure 2:*** *In this graph, we have assumed that the extent of the changes in the environment increases regularly with each cycle. The resilience is, again, inversely proportional to the vertical distance at any point in time. That distance still goes to infinity and resilience to zero, but after a larger number of time-steps because the changes in the information-processing system increase with each cycle of that system.*

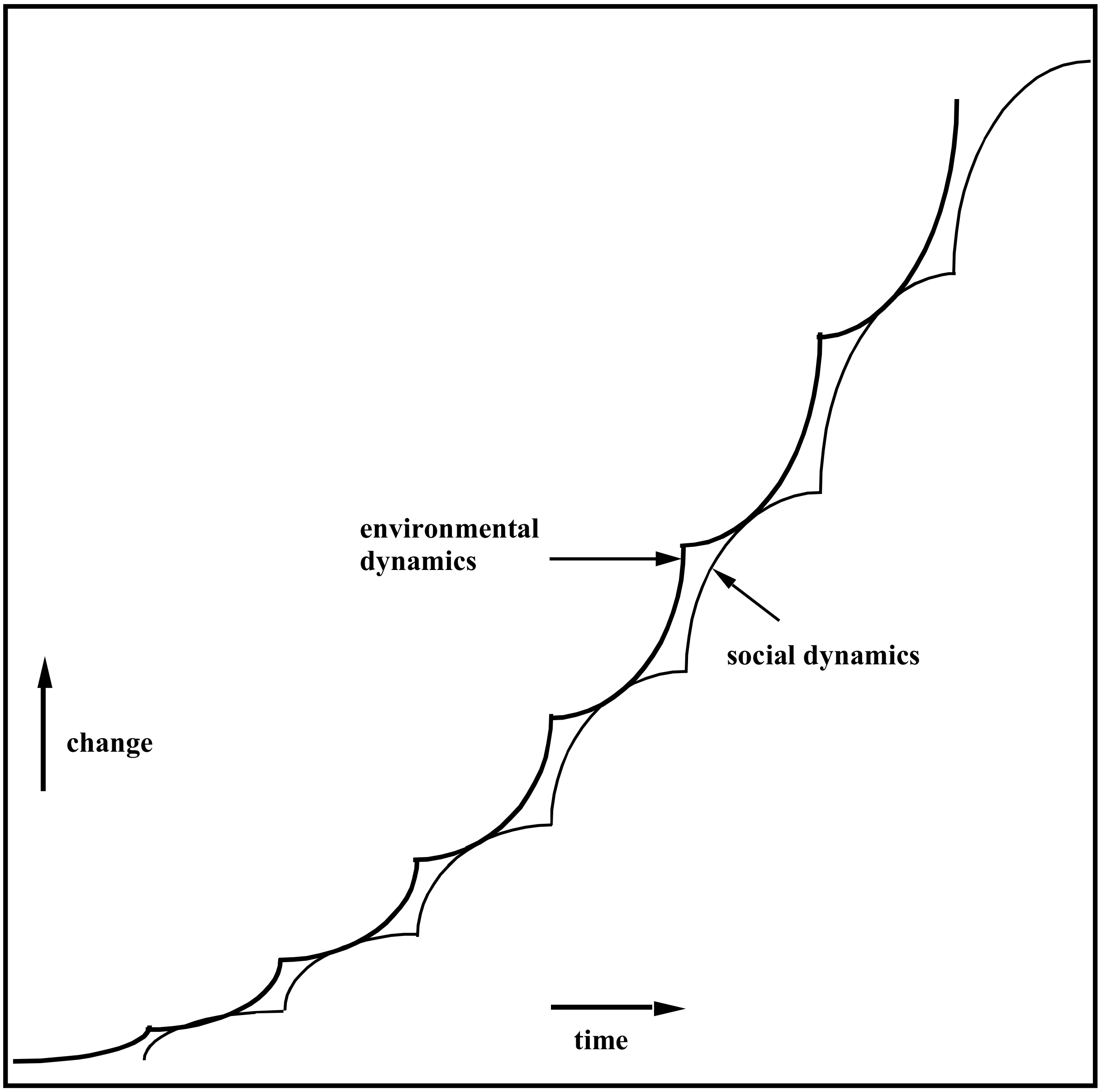
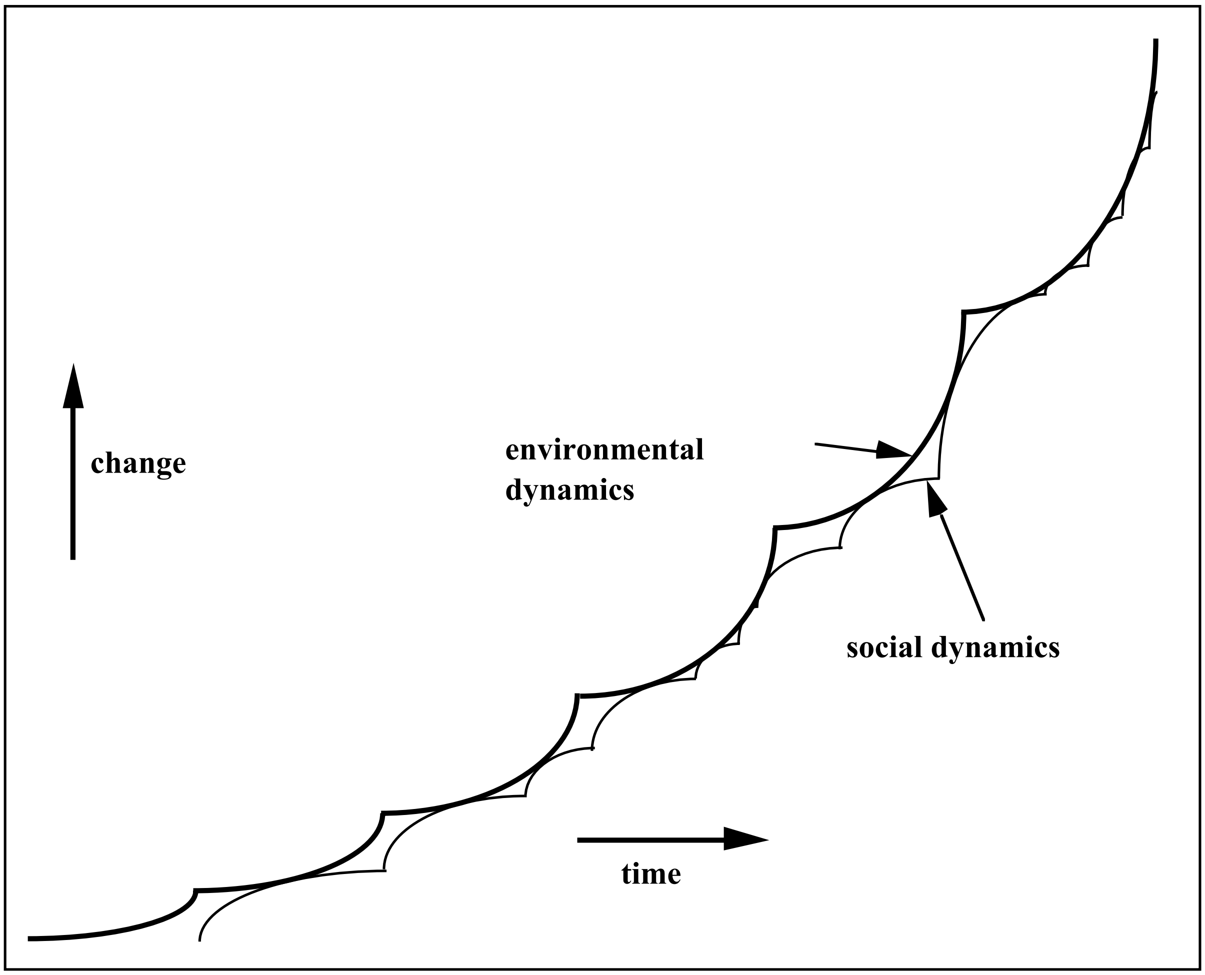


***Figure 3:*** *Resilience can be further improved by adapting the speed and frequency of change in social dynamics to the rate of environmental change. Very complex curves will result from this process, which reflect highly complex interactions, but which allow resilience to remain sufficient for a long time.*



- The *origin and place of impact* of a disturbance. Internal perturbations have very different consequences from external ones. The exact consequences depend on where in the system the disturbance occurs, *c.q.* where an external disturbance actually impacts on the system.
- The *speed* at which a perturbation occurs. Rapid shocks trigger rapid reactions, and may therefore under certain circumstances enhance resilience, as opposed to slow perturbations that delay the initiation of reactions. However, in other circumstances, the extra time available to effectuate changes may well 'save' a system that would have been destroyed under the impact of a rapid shock.
- The *duration* of the disturbance. Most disturbances set in motion a whole series of reactions in a system (Slobodkin & Rapoport 1974). Some of these are more rapid and superficial, while others are slower to emerge and imply more profound changes. In such cases, the duration of the perturbation will determine which of these 'defensive' reactions effectively neutralises the perturbation, and what therefore its consequences are for the system concerned.
- The *relative importance* (size) of the perturbation. Any shock causes excess entropy ('chaos') in the system (Prigogine 1978). The relative amount of such excess entropy determines whether it can be absorbed easily, or requires adaptations costly in energy and/or time.

The *second* group of factors influencing the resilience of a (socio-natural) system concerns the structure of information processing. In most human societies, information processing combines (in different ways) three different kinds of dynamic structures with very different characteristics, depending on how information is shared among the networks concerned. The relevant structural characteristics of the system include, notably, the persistence of different knowledge bases in the system, the speed with which information spreads, the extent to which different entities in the system can co-operate in reacting to disturbances, and the flexibility of the system.

As it is in the present context not possible to deal with the dynamics in detail, table 2 is intended to provide the reader with some insight into the kinds of differences we are concerned with. The list is evidently far from complete, and describes qualitatively and in relative terms what are essentially quantitative properties of the different information-processing systems. A more complete insight in how the structure of the information-processing dynamics affects its performance is available in cybernetics and the study of: organisations (*e;g.* Pattee 1973, Simon 1981), and more recently in information science (e.g. Huberman 1988, 1997 *et al.*).

A *third* group of factors relates to the functioning of the elements in the information-processing system. Whatever its dynamic structure, the proper functioning of a system requires that each and every actor in it plays the role (s)he should play. Yet, in many systems, the fact that different actors are part of dynamics at different scales and in different configurations potentially causes all sorts of problems which, under stress, may lead to system malfunctions (Rappaport 1972; Flannery 1972). Among the most frequent of these problems are:

- *Cybernetic problems* that occur when the feedback of information to regulatory mechanisms about the states of systemic variables and their effect on operations is faulty;
- *Temporal aberrations* that concern excessive or insufficient time-lags in feedback or other distribution of information among the parts of the system concerned;
- *Over- (or under-) response* that occurs when the response of one or more of the parts of the system concerned is incommensurate with the circumstances;

| |
|---|
| **Egalitarian information processing** |
| • is based on equal control of information |
| • there are limits to the size of the group involved |
| • all participants concerned know each other |
| • their contacts so frequent that all information passes to all members |
| • there is thus an homogeneous information pool: everyone in the group acts on complete information |
| • the information flows do not follow particular channels; there is no control over them |
| • there are no major delays in spreading information; the system reacts rapidly to stress |
| • egalitarian information processing is very efficient |
| • egalitarian information processing systems are very resilient |
| **Hierarchical information processing** |
| • there is differential control over information: some control information durably |
| • the groups involved are too large for all participants to know each other |
| • the channels of communication are hierarchically structured |
| • for many actors, who depend on singe channels, checking information is difficult |
| • some individuals act on complete information, others do not |
| • information sharing is asymmetrical, |
| • there is an heterogeneous information pool , but few are aware of it |
| • hierarchical information processing accommodates large groups |
| • hierarchical information processing is efficient |
| • hierarchical systems remain stable with large fluctuations in numbers and information load |
| • once established, certain nodes fall into disuse, so that adaptedness increases, resilience decreases |
| • efficiency is very dependent on structure of hierarchy: (a)symmetry affects performance |
| **Distributed information processing** |
| • In distributed information processing systems, there is no structured control of information |
| • the group is too large to deliberately reach all members; multiple channels; |
| • the actors share a heterogeneous information pool |
| • everyone acts entirely on partial information; |
| • the dynamics accommodate large groups |
| • distributed systems are less efficient than hierarchical systems |
| • distributed systems tends to instability with time ('it's so crowded nobody goes there') |
| • they remain adaptable |
| • such systems improve with specialisation or compartmentalisation |

***Table 2:*** *Properties of different dynamic information-processing structures*

- *Over-segregation or over-centralisation* concern the organisation of the dynamic system as a whole. Are there too many, or not enough, semi-independent actors to deal with all the tasks necessary to the correct functioning of the system? What is the 'information-processing distance' between them? If the actors are too distant, or if they are insufficiently far removed from one another, this may respectively lead to uncoordinated behaviour or interference.
- *Hyper-coherence* refers to the degree of dependency upon one another of the different actors or other entities in a system;
- *Mal-distribution of organisation* occurs when parts of a dynamic system are not sufficiently organised to function appropriately in the whole of the organisation. When, for example, the

top of a hierarchy is very efficient and effective, while the efficiency and effectiveness of parts of the lower levels are not commensurate;

- *Usurpation* occurs when subsets of entities come to control the entities themselves to an incommensurate extent, so that behaviour in response to certain circumstances comes to dominate overall behaviour, and the proper balance between different dynamics is lost.

In actual fact, the precise factors determining resilience in individual situations are in part historically determined, and therefore unique. The three groups of factors just mentioned as contributing to the overall resilience of a system do, of course, not cover all aspects of resilience, nor are they presented in an exhaustive manner. They have been summarised to present the reader with a set of concepts that may facilitate thinking about factors underlying resilience in particular cases.

## A case-study: the Comtat

We will end this contribution with an illustrative case[8]. It concerns a small area in France, the Comtat plain, around a few smallish towns such as Carpentras and Cavaillon in the Rhone valley. Its suitability for the present purpose derives from two factors:

- It is easy to isolate, as it has a specific economy (horticulture, principally of early specialty fruit) and spatial organisation, and strong internal interaction..
- It underwent two successive socio-environmental crises, one in the 1860's and one about a century later, in which the resilience of the area was tested — with very different results.

We will try and gain some insight in the nature of resilience by contrasting the resilient response of the region to a crisis between the 1860's and the 1890's with its lack of resilience in the crisis of the last twenty years (1980-2000). In doing so, we will in particular focus on two questions: "What are the consequences of the system's spatial structure, and its components, for the system's complexity?" and "What effects did its organisation and its complexity have on its resilience?"

### *The 19th century (c. 1860-1890)*

Many of the perturbations that affected the Comtat in the middle of the 19th century may be considered unexpected events. Amongst such atypical shocks, there is for example the discovery of a chemical dye that totally replaced madder, one of the main agricultural products of the area at the time. Another event that forced the system towards a reorientation of its agriculture was the *phylloxera* epidemic that heavily damaged the vineyards. To these one may add another rapid transformation, the construction of the railway between Paris, Lyon and Marseille, which changed the relative geo-graphical position of the Comtat and opened other markets to its products.

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8 This case study was carried out by Chr. Aschan-Leygonie in the context of the ARCHAEOMEDES research programme which S.E. van der Leeuw co-ordinated from 1992 to 2000. It is included in extenso as chapter 8 in vol. 5(1) of the ARCHAEOMEDES II final report to DG XII of the European Commission (1999).

Amongst the gradually introduced perturbations one may count the growing imports of wheat which followed the progressive opening of the national borders; they clearly had a negative effect on cereal production in the region. In a similar way the imports of silk from Asia (together with a disease affecting the silkworm) destroyed silkworm breeding which was an important source of income in the Comtat at the time. Towards the end of the 19th century the Comtat system shows signs of overcoming the crisis, even though its direct effects can be observed for a much longer period.

Before the region's farmers finally adopted a substitute for the cultivation of silk, madder and wine, there were long discussions at all levels — from the individual farmers to the agents in the regional and national agricultural networks — about the most promising direction to take for agriculture. The choice was not in any way a foregone conclusion. The final choice, arboriculture and market gardening, owes much to the fact that these activities had been exercised in and around Cavaillon since the Middle Ages, albeit on a small scale. The know-how necessary for developing the new activities was thus locally available in a tried and trusted form. That experience seems to have been essential for the survival of the regional system and the success of the ensuing adaptation. In other words a different, potentially successful, basin of attraction had been cognised by the population. Its existence facilitated a rapid response to the crisis once it emerged.

The more traditional agricultural production in the Comtat was not irrigated. Nevertheless, the region was at the time covered by a great number of irrigation canals, but more because of the needs for a general water supply in the region than because of the agricultural demands. This inherited irrigation network constituted another particularly important element in the resilience of the system in the 1860's. Without it, conversion to arboriculture and market gardening would have been hindered, or even blocked, by the need to raise capital for such an irrigation network, not to speak of creating it at a time when only manual labour was available for such activities. The development of speculative cash-crop agriculture naturally had a great impact on the extension and the improvement of this network, which now covers very large parts of the region. But if the core of that system had been absent when conversion to horticulture started, that conversion would in all probability, never have been crowned with success.

Fragmentation of land holdings is a structural feature of the local inheritance system, which is based on an equal division of the parents' properties between their sons. In the region, small farming units with small fields, owned by the exploiting farmer and run by him with the help of his family, may, according to George (1935), be traced back to at least the 15th century. Fragmentation was accentuated in the beginning of the 19th century, when the regional population exploded, and was dominant when the region was affected by the perturbations of the middle of the 19$^{th}$ century. It further increased in importance between 1861 and 1988. At the time of the first crisis, these small, owner-operated farms proved to be particularly resilient. They were well adapted to the new crops and methods, which the owner could rapidly introduce without making major organisational changes or investments.

The crisis in agriculture initially triggered a rural exodus, which to a certain extent facilitated a regrouping of smaller farming units into larger ones. But this trend was rapidly reversed under the impact of the development of the 'new agriculture'. The net effect of the intensification of land use was an even greater fragmentation of land ownership. As early as the 1860's, large properties were divided into small plots and sold, generating important financial benefits for the owners. The only domains that were maintained as large units were the ones that are very distant from the core areas of the system, the towns around which the new, speculative cash-crop agriculture developed in the first place. One important consequence of this specialisation in market gardening is thus a perpetuation, and to a certain extent an accentuation, of a land ownership pattern consisting of small properties owned by the farmers themselves.

The same type of feedback applies to the fact that the 'new agriculture' needed a large workforce, mainly daily and seasonal labourers. The farmers' families were generally too small to provide sufficient manpower (Mesliand, 1989). Thus, the fact that both silkworm breeding and madder cultivation had always required much external manpower facilitated the system's adaptation in the 1860's. The demand for labour attracted immigrants from nearby regions and countries (Italy in particular) which, after a certain time, often acquired a plot of land, and thus contributed to the success of the Comtat system around the end of the 19th century

All the above features have proved important in facilitating the development of orchards and market gardening. During the second half of the 19th century, the structures inherited from the past contribute in a significant manner to the system's ability to integrate a number of very strong perturbations. The new functions that are generated as a response to these perturbations induce a readjustment of most of the structures concerned. It is important to underline that these readjustments do not significantly modify the system's macro-geographical properties and that the most fundamental changes concern on one hand the kinds of crops grown, and on the other the emergence of more specialised markets.

However, in our opinion, none of the above structural characteristics of the system would, singly or in combination, have been sufficient to ensure its resilience. Even with all these advantages, the crisis would easily have broken the back of the local system were it not for two decisive factors: *time and space*.

We have seen that some of the dynamics triggering the crisis were rapid (chemical dye, *phylloxera*, silkworm epidemic, railroad) whereas others were actually quite slow (increased competition, wheat and silk imports). However, on balance, the population perceived the disturbance as a crisis, and rapid action was taken. As the resilience of a system depends on *adequate and timely adaptation* to changing circumstances, it is our contention that the perceived urgency of the situation, and the fact that measures were immediately taken, was crucial in ensuring the survival of the Comtat's exploitation system.

The other important condition for a system's survival is that the system's spatial structure is more or less adapted to its new mode of functioning, or that it is adaptable to it within a reasonable temporal delay. In the 1860's to 1890's, this was the case in the Comtat. When the crisis occurred, the region had recently acquired a good infrastructure around the market towns that form its core, such as Avignon, Cavaillon, Châteaurenard and Carpentras. On the one hand, the towns were eminently accessible to people, goods and ideas from outside the region. Avignon is located on a crossing of the Rhône, while Cavaillon is situated on the Durance. Both are linked to the national railway system. Such access facilities promoted contact with the rest of France, and the introduction of new ideas from elsewhere, but they also ensured rapid transportation of produce to the wider markets (Lyon, Paris, etc.). The region's spatial structure thus helped resolve the crisis, but by incorporating the area more directly into the dynamics of the wider outside world, it also laid the foundations for the next difficult episode, in the twentieth century (see below).

On the other hand, good connections existed between the market towns and the surrounding villages, integrating the region into a close-knit core-periphery structure. This was of crucial importance during the perturbed period, as the dense road network facilitated the regional movement of goods, people and information to those parts of the region that needed them to adapt. Firstly, the roads allowed the farmers to quickly bring the vegetables and fruits to the local market. At the same time, the road system facilitated travel from the towns to the countryside for the labourers that the farmers badly needed to be able to intensify their agriculture. And finally, the frequent movement of people over these roads, in both directions, facilitated the spread of information, notably among farmers who went to the daily or weekly markets. As a result, the different actors could rapidly devise adequate responses, based on sufficient, and sufficiently recent, information to be successful. Altogether, then, the dense urban network and the well-developed transportation system in the region played an essential role in the successful adaptation of the Comtat in the late 19$^{th}$ century. In return, the towns largely profited from the new agricultural dynamic. Durbiano (1997) shows that the population increase in a great number of villages and towns at the end of the 19$^{th}$ century is a direct consequence of agricultural intensification. Today, agricultural activity is still influencing the urban dynamics, even though its role is slowly declining.

In summary, during the second half of the 19th century the structures inherited from the past contributed in a significant manner to the system’s ability to integrate a number of very strong perturbations. The new functions that were generated as a response to these perturbations induced a readjustment of most of the structures concerned. But it is important to underline that these readjustments did not significantly modify the system’s macro-geographical properties and that the most fundamental change concerned the type of crop on one hand, and the emergence of more specialised markets on the other. It should also be underlined that the areas immediately around the towns played an essential role in the systems resilience during this period.

### *The 20$^{th}$ century (c. 1970-1990): advantages have become disadvantages*

In the 20th century, the difficulties emerged at a more leisurely pace than was the case in the 19$^{th}$ century. The ensuing crisis was in some ways also more profound, as it touched the system’s whole architecture, whereas in the 19th century it was essentially limited to the agricultural production subsystem. The problems were initially triggered by dynamics at a higher level of organisation. Among these, changes in trading conditions due to the creation and enlargement of the European Union, and the emergence of more competitive vegetable and fruit production areas in Europe, loom large. The initial impact, therefore, was contextual rather than local, changing the external conditions rather than the ones in the area itself. But the problems were compounded by the fact that the current trend towards growing integration of economic activities on a planetary scale decreased the autonomy of local or regional systems significantly, making them more vulnerable to perturbations.

As opposed to the positive influence of the existing structures in the 19th century on the system’s resilience, the current process of adaptation is highly constrained by the structures inherited from history. In the middle of the 19th century, if not very flexible, the spatial structure of the area is very well adapted to the functional changes brought about by the 'new agriculture'.

Today, the structure of the Comtat not only appears rigid, because of the strong interactions that link its various components, but it also seems poorly adapted to the functional changes necessary for the system's survival. The organisation of agriculture, the traditional irrigation network, the principal avenues of commercialisation of agricultural products, and even the core – periphery dynamics areas seem to be hindering the adaptive process. A great number of authors highlight the general inadequacy of the existing structure of agriculture in the face of the recent economical changes (Béthemont, 1972; Menessier, 1985; Santoyo, 1989; Durbiano, 1990; Berenguer, 1990; Derioz et al., 1994).

One of the impediments to the system's resilience in the 20th century is the small size of the farming units that was an advantage a century earlier. Indeed, in the newly developing areas of fruit and vegetable production in Europe, the average size of the individual farms is generally greater than that in the Comtat. In an environment that is increasingly price-competitive, the difficulties are compounded by some of the other traditional features inherent in small family owned and operated farms. The low level of capitalisation and the limited advantages of scale, for example, reduce the possibility of modernisation through the acquisition of new equipment. It is therefore not certain that modernisation is a good choice. Production based on quality instead of quantity, for example, would be more adapted to the specific features of the Comtat production system, and would thus have a better chance to prove resilient.

The inherited irrigation network also hinders the adaptation of the system. Gravity irrigation has perpetuated the very small size of the landholdings, as these are necessarily laid out around the canals. It is also much less efficient than other irrigation systems (drip irrigation, for example). Excessive dispersion of the land belonging to individual farms hinders re–allotment. Other elements of the infrastructure, such as rural paths and windbreaks, constrain the form and size of the parcels. Altogether, therefore, the agrarian morphology is rather rigid. As some of the recent production areas with which the Comtat is in competition, such as the Etang de Berre, consist of landholdings that are not only larger but also less dispersed, it is not surprising that some Comtat farmers currently try to group different farming units together. This would increase the possibility to invest and modernise the farms. But this tendency is hampered by a number of farmers who wish to preserve the old system (Béthemont 1972) because it has served them well. In this context, we should not forget that the existing agrarian structure is a result of a long evolution that did, in the 1960's, achieve a high degree of perfection and success.

In the 1970's, the commercial organisation of the region's agricultural production around the local markets is not able to deal with the economic changes that are occurring. Since that time, transformations have notably affected the trade in agricultural products all over Europe. It now relies more heavily on supermarkets and hypermarkets. This has also affected the mode of production and the approach to marketing. As a result, the international agricultural system is now geared to centralised commercial trading. But that in turn requires an efficient regional commercial organisation. In the Comtat, the evolution towards such a system is hampered by the survival of the traditional commercial channels. In terms of distance, time and real costs, commercialisation via the local market is uneconomic compared to most other forms of commercialisation. But in spite of a progressive decline in their numbers, the proportion of producers and traders that frequent the local markets is still predominant. Their reluctance to change the commercial channels seems due to the inertia of the inherited structure, itself a relic of the historically important spatial interactions between farmers and market towns. It fundamentally affects the system's capacity to deal with perturbations due to the recent transformations at the national and European level. Insufficiency of the system's commercial channels is the result, which weakens the role of the towns in the agricultural dynamics of the Comtat. The market towns, which for so long federated the different components of the system, are progressively losing their role as driving forces, and that in turn affects the core of the system's dynamics.

We have previously stated that the growing importance of the market towns in the dynamics of the spatial system since about the 1950's was linked to an increased concentration of the traders and transporters in the three core areas. This evolution certainly reinforced the system's dynamics. But, surprisingly enough, this trend has recently inverted itself. The central role played by the core areas in the dynamics of the Comtat system has significantly decreased. This expresses to a certain extent the weight of the inherited structure in the core areas of the Comtat themselves. This weakening of the integrating role of the cores seems to accompany a decrease in the system's resilience. One example of this hypothesis is provided by the development of modern greenhouses since the 1960's, which is a good indicator of the recent dynamics in the core and fringe areas of the system.

The greenhouses, in their modern plastic form, were first introduced and developed in the core areas, especially around Châteaurenard. Recent observations show that the advance of the greenhouses is particularly significant in the new production areas, such as the area north of the Etang de Berre, where traditional market gardening has not left any impression in the form of an inherited structure. Moreover, a study in the Vaucluse (Ministère de l'Agriculture et de la Forêt, 1990) shows that intensive greenhouse agriculture has greater success in sectors where traditional market gardening was little or not developed than in communes with traditional vegetable production. As a consequence, the core areas of the system, highly specialised in fruit and market gardening, often appear less dynamic than the communes situated in the fringe areas of the Comtat.

Thus, the weight of inherited structures appears a fundamental factor in explaining the differences in the recent dynamics. This example illustrates that the difficulties facing the transformation and modernisation of agriculture are greater in sectors that have an important tradition of market gardening. It must be underlined that the difficulties in the core areas do not only result from traditional habits, but also from the weight of the spatial and agrarian infrastructure that is greater in the areas which specialised early.

On the whole, many of the inherited spatial structures hinder the contemporary adaptation process. This process, in turn, accentuates the incompatibility between the spatial structures within the system and their interactions on the one hand, and the system's overall functioning on the other. Currently, the Comtat system is thus subject to a dynamic that is to a great extent based upon positive feedback loops that seem to drive the system away from a balanced state. The recent dynamic is mainly the result of the different actors' difficulties in coming to grips with the changes in the system's underlying dynamics. The spatial as well as the agrarian infrastructure became a handicap as early as the 1960's, but there was no general awareness, at that time of the gap between the structure and the actual functioning of the system. According to Durbiano (1997), the Comtat farmers had confidence in structures that had been successful for a long time. As a result, the system's actors perceived the internal structural crisis that had been triggered by the perturbations for a considerable time as a series of conjunctural crises. The gap between the spatial structures and the functioning of the system was concealed by a false interpretation of the nature of the crisis.

It is important to underline that the relationship between the spatial structures and the dynamics in the Comtat system has reversed over time. Whereas the core areas, the agricultural markets, the small farming units run by families, etc., had a positive influence on the resilience of the area in the middle of the 19th century, today they are an impediment to the system's adaptability. On the other hand, during the last century, the perturbations did not generate an inadequacy in the relationships between the different components of the system. As a matter of fact, the system did not only adapt, it actively used the inherited structures to absorb the perturbation, and managed to improve its functioning because of them. Today's growing commercial competition, on the other hand, has provoked a dysfunctioning within the spatial system of the Comtat. The traditions characterising the core areas and the inherited structures seem to inhibit the system's adaptation. Thus, there is a risk that they may contribute to the system's destruction. Indeed, the capacity of the spatial infrastructure to evolve weighs significantly on the system's dynamics and may accelerate its decay. This threat to the system's survival is to a large extent due to a dis–equilibrium between the spatial organisation and the modernisation of agriculture, which is in turn the result of differences in the rhythms with which the subsystems change. The evolution of the spatial structures appears slower than that of the human activities, so that an inadequacy between the two leads the system towards a less and less sustainable dynamic.

All in all, the inherited spatial structure and the concomitant interactions may influence a system's resilience in different ways, either by facilitating adaptation to the conditions introduced by the perturbations, or by impeding the necessary re-adjustments. It is thus impossible to draw any conclusions when it comes to the link between inherited structure and a system's dynamics. Nevertheless, it is possible to affirm that a fundamental condition for the incorporation of a perturbation in the system's functioning is the compatibility between the two.

## *Conclusion*

On the one hand the spatial structure and the interactions within it do affect the capacity of a system to be resilient in a significant way. The intense and rather rigid interactions that link the main components in the Comtat system today are blocking its potential adaptation to a new situation brought by changes on a higher level of organisation. On the other hand, the complexity of the system, inherent in its many different temporalities and its internal diversification is also a fundamental feature of system dynamics affected by a perturbation. Currently, the principal risks to the survival of the system are in our opinion the following:

- Growing agricultural specialisation recently observed in the Comtat, is generally considered as negative for a system's resilience. Heavy specialisation leads most certainly to more success against competition, but it also increases the system's vulnerability to perturbations, even weak ones, and decreases its adaptability because a narrower range of adaptive possibilities is inherent in a low level of diversification.
- A second potential problem is closely linked to growing specialisation. The intensification of production has definite detrimental effects on the environment. As an example we can quote the recent increase in the nitrates in the water table of Carpentras, which is directly linked with agricultural intensification (Bellon et al. 1997)

- The decline of the agricultural markets due to changing commercial patterns constitutes a serious risk for the survival of the system. Almost certainly, the regional spatial system would not be able to survive the disappearance of the markets, as its fundamental geographical macroscopic properties would then be completely modified. We have seen that these markets and the urban network have for a long time been the important driving forces in the system. Presently, their interactions are slowly changing. The privileged relationships observed between the rural and the urban activities are slowly becoming less and less frequent. Urban development in the Comtat does no longer depend on the area's agricultural dynamics, but is highly influenced by the hegemony of Avignon, the main urban centre.
- The decreasing autonomy of regional and local systems is closely linked to this last problem. The change in the level at which the commercialisation of the products is organised, and the development of international trading are according to us a serious threat to the regional coherence and dynamics.

**Where do we go from here?**

First, this paper has briefly outlined the case for a re-conceptualisation of environmental problems as socio-natural problems, and the need to devise a way to conceive of these dynamics as generated by flows of matter, energy and information. In doing so, it has emphasised the need to focus on the resilience of socio-natural systems rather than on their sustainability. Next, it has pointed to the fact that the resilience of most modern socio-natural systems is dependent on the adaptability of human societies, which in turn resides in their information-processing capacity. Thirdly, the paper has presented and briefly discussed some of the different aspects of human information-processing systems. And finally, it has presented a case-study which outlines some of the structural and historical conditions determining resilience by comparing the ways in which one and the same region responded to two successive crises, in the 19$^{th}$ and in the 20$^{th}$ century respectively.

In writing this paper and in co-ordinating the work of the team that has developed this approach, it has become clear that we are only beginning to understand the scope and nature of the job that lies ahead. But at the same time, we have become convinced that the work is urgent, as most of our present-day 'environmental' problems are due to the arbitrary separation in our minds between the 'natural' and the 'cultural'. To conclude this paper, we would therefore like to outline some of the tasks ahead in order to stimulate discussion and, where possible, wider collaboration on these issues. The following tasks seem particularly immediate in this context:

- To shape a truly transdisciplinary research community that is able to cover a wide range of subjects, from the purely social to the purely physico-chemical, at all scales of observation (from the modern world-system to molecular biology).
- To develop a general, co-evolutionary framework which conceives of socio-natural dynamics in complex systems terms. This includes assembling a conceptual toolkit which enables us to conceive of such mixed socio-natural systems as dynamic, complex 'flow structure' systems, both in qualitative and in quantitative terms, and testing this toolkit out on a number of case-studies. But it extends to developing the correct epistemology and philosophy of research, defining the scope of the research objects concerned, etc.
- To develop a better understanding of the interface between people and their environment. This

includes the dynamics of the perceptual/conceptual domain, as well as those of the evolution of techniques, the maintenance of traditions and the introduction of new inventions. But we should also look at the nature of human impact on the environment, and the unintended consequences that it entails. Such research should, moreover, link the roles of individuals to those of groups of various kinds, from the family up to the whole society, and must thus conceive of information processing as being in part distributed, in part localised.

- To develop modelling techniques that enable us to study the dynamic interactions between all three of the principal domains concerned: people, ideas and things. Such models should facilitate the study of the three, partially independent, dynamic sets of rules that govern them, as well as the interactions between these rule-sets. In particular, this means developing agent-based models in which the interaction between the agents and their resources is mediated by the cognitive logic that the agents develop in interacting with their environment.

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