Functional Roles of Information in Ecosystems – a Theoretical Approach

M. Knoflacher

Austrian Research Centers, Seibersdorf

Abstract: Information is a common phenomena in the biotic parts of ecosystems. Additional to the intraspecific long term transformation of information by the genetic code, intra- and interspecific relations are determined by information. A wide spectrum of chemical and physical conditions is used as carrier for information. The high variety of information propagation is processed in different ways by organisms. Simple deterministic processing of information are at one end of the potential range, high complex and non linear processing the other end. In comparison to the food webs in ecosystem, the investment of energy in transmission or perception of information is relatively low. However, information is of high relevance for interactions among organisms. Highly evident is the role of information in intraspecific interactions of social organisms. Despite this fact is well documented and supported by several theories, it is still an open question how far emergent characteristics of ecosystems are caused by relations of information. Answers for this question are of high relevance for our understanding of ecosystems functions, and in particular for the functional relevance of biodiversity in ecosystems. It can be demonstrated on a theoretical basis, that information has different functions in ecosystems. Basically, in heterogeneous environments it is an essential precondition for the allocation of resources. For this reason, a high variability of information qualities has to be expected. Because this explanation is not sufficient for multi species systems, the functional relevance of information processes has to be considered. With this extended view it is possible to show the relevance of information for the fitness of organisms. In this analysis, the effects for specific species have to be distinguished from effects for the systems.

Keywords: *Information; Ecological Functions; Complexity; Self-Organization, Self-Structurization*

1. INTRODUCTION

Information is interpreted in different ways, depending on the scientific disciplines. For the application in the ecological context, the definitions of Ebeling et al. (1998) are essential. Structural information (I_S) is each nonrandom spatial or temporal structure or relation of entities. Functional information (I_F) is the algorithm for decoding of structural information. Pragmatic information (I_P) is the effective information for the receiver.

The relativity of the definitions supports its application in ecology. Additionally, it delivers a first hint about the characteristics of information in ecosystems: information in ecosystems is contextual to the actual state of a receiver, and not standardized over ecosystems except of the genetic code. This information saves the ability of organism for reproduction, and self organization. The genetic code is also a main player in the evolution (Ridley 1993). Whereas the functional role of the genetic code is discussed intensively (Kauffman, 1993), the relevance of non – genetic information in ecosystems is dominantly investigated in the physiological or ethological context (Krebs and Davies, 1981; Walther, 1984; Schlee, 1986; Alcock, 1993; Madigan et al., 2003). More explicitly considered is the functional relevance of information in investigations of social structures of species (Rubenstein and Wrangham, 1986; Bourke and Franks, 1995). A very comprehensive presentation of the theoretical background and functional relevance of information in animals can be found in Bradbury and Vehrenkamp (1998). However, the mainstream of ecosystem research and theoretical interpretation of ecosystems is focused on the exchange of energy and matter with only a marginal consideration of information (Jørgensen, 1992).

A main cause for the under-representation of information in ecosystem research is probably the methodical problem for observation of information relationships in empirical investigations. This argument is based on the fact, that information theory is discussed longer than fifty years till now (Shannon and Weaver, 1948), but mainly in the context of cybernetics.

In this paper the principal functions of information in ecosystems are analyzed from a theoretical point of view.

2. INFORMATION IN COMPARISON TO OTHER FUNCTIONAL RELATIONS IN ECOSYSTEMS

2.1. Basic characteristics of information in ecosystems

Information is basically dependent on the existence of a transmitter as a source of information, and a receiver for the reception of information. The functional relation between transmitter and receiver depends on the existence of a channel for the transmission of information (Reza, 1994). Information can be transmitted in ecosystems from abiotic and biotic components if the definition of Ebeling et al. (1998) is used. But only some organisms (Lerdau, 2002) are able to receive information, if technical receivers are understood as parts of the anthropogenic system. It can be concluded, that in ecosystems the functional information (I_F) is a real subset of structural information (I_S):

$$I_F \subset I_S \tag{1}$$

The relationship between pragmatic information (I_P), and functional information depends on the physiological characteristics of organisms. But it can be concluded that pragmatic information is a subset of functional information:

$$I_P \subseteq I_F \tag{2}$$

Under consideration of competition among organism, it can be beneficial for an organism to detect a new subset of structural information. The criteria for a benefit will be discussed subsequently.

2.2. Comparison to other functional relations

Basic functional relations in abiotic and biotic parts of ecosystems are flows of energy and material. The quantitative dimensions of this flows are unequally distributed over ecological partial systems (Knoflacher, 2002). The phenomena of self-structurization (Ebeling et al., 1998) can occur in all stages of combined energetic and material flows (Kauffman, 1993). Both flows are therefore contributing to the development of structural information.

The existence of organisms depends on the availability of energy and material. No life can exist without this preconditions. But one of the big challenges for organism is the unequal distribution of energy and of particular substances in space and time (Shorrocks and Swingland, 1990, Tuomisto et al., 2003). Organism can solve this task with different strategies. The strategy of a species is successful, if the expenditure of energy (E_{ex}) does not exceed the harvested energy (E_{ha}):

$$E_{ex} \leq E_{ha} \tag{3}$$

This criterion can be accomplished energetically by a reduced investment of energy for the exploration of resources. Resources can be explored without information only by random strategies, with sufficiently high numbers of trials. Examples for random strategies in ecosystems are the distribution of seeds for plants or eggs in some aquatic organisms. Because of the high number of trials, necessarily the energetic investment for each trial should be very low. Otherwise the strategy would not be successful.

The success of nonrandom strategies depends on several preconditions. One precondition can be a regular cycle, and spatial constant occurrence of resources. Organism has to be simply synchronized to the resource cycles in such cases. However, the evolution of the synchronization depends on the application of random strategies. An other precondition are structural gradients, closely related to the occurrence of resources. The number of trials can be reduced essentially if a species can decode this information. This benefit can be taken into action if the organism is also mobile, and can arrive earlier at the resource than competitors. On the other hand it has to be considered, that mobility is energy consuming (Swingland and Greenwood, 1983). This is different to the effort for decoding of information, which needs only a very low input of energy (Kunsch, 1997). The use of information is therefore beneficial, if the expenditure of energy for a random walk (W_r) is higher than for an oriented walk (W_o):

$$E_{ex}(W_r) > E_{ex}(W_o) \tag{4}$$

For both cases the same amount of harvested energy is assumed.

The same interdependency between information decoding and mobility is valid if species are potential preys. Mobile organism can escape by investing energy. In this context, the definition of mobility has to be extended also to sessile organisms which are able actively to escape by retraction into protected parts of their environment. But this strategy can only be successful if potential predators are identified timely, and the escape reduces the risk to become captured. The ability for the decoding of information is an essential precondition for both functions.

A first conclusion from these findings in the interspecific context is, that information does not substitute energetic or material relationships. But information can be beneficial for mobile organism, because it reduces the probability of energy losses. This findings are also complementary to theoretical findings for the intraspecific value of information (Bradbury and Vehrenkamp, 1998).

If the reception of information is beneficial, so it is the question how far is this also valid for the transmission of information? Any transmission of information increases for the transmitter the probability to become detected by other organisms. The valuation of this changed conditions depends on the consequences of the detection for the transmitter. This can be expressed by the relations between the energetic expenditures for the case of detection (E_{ex} (T_{d1})), and the case for non–detection (E_{ex} (T_{d0})). A transmission of information is only beneficial if the subsequent imbalance is valid:

$$E_{ex}\left(T_{d1}\right) \leq E_{ex}\left(T_{d0}\right) \qquad (5)$$

In ecosystems this imbalance is realized in different ways. For immobile organisms the detection can be beneficial for pollination or dispersal of seeds (Denno and McClure, 1983). For mobile organisms the detection can be beneficial for mating or for the defense of territories (Bradbury and Vehrenkamp, 1998). The benefit of warning information, like chemical signals of warning coloration, is independent of mobility. Information exchange is an essential precondition for interactive parent – offspring relations, and mutual interactions.

If the imbalance can not be satisfied, it is beneficial for organisms to apply defensive strategies. This can be realized in different ways. One strategy is camouflaging for the reduction of the detection risk. An other strategy is necessary, if only the detection by certain organisms should be avoided. In that case the validity of the imbalance can be achieved by a specific encoding of the emitted information. Hence the transmitted information should by interpretable only by organisms with beneficial effects. Other organisms must not be excluded totally, but the risk for adverse effects should not violate the imbalance.

3. STRUCTURAL EFFECTS OF INFORMATION IN ECOSYSTEMS

3.1. Influence on the order of systems

Relations between organisms becomes less random if at least one organism uses information in the interplay, because information can only be obtained from non-random structures (Reza, 1994). Relevant for the transmission of information are only the nonrandom parts of the whole messages. Hence, the transmission of information increases the order within a system. This phenomena is defined as self-organization by Ebeling et al. (1998), in difference to the above mentioned processes of self-structurization.

For ecosystems it can be hypothesized that the relevance of information for the harvesting of energy increases along food chains from primary producers to top consumers. In other words, consumers at a higher trophic level have to process more information in order to achieve one unit of consumable energy than consumers at lower trophic levels. Theoretically the higher trophic levels in ecosystems should be more self-structured than lower trophic levels.

Effects of specialization for information processing have to be considered in difference to this general hypothesis. Consumers can be specialized for particular organisms, or have a wide spectrum of potential food. In the first case consumers are successful because of a specialized, but narrow spectrum of actively processed information. Essential framework conditions for the success are a sufficient pool of potential prey, and the absence of a more successful competitor. In the second case organisms must be able to decode a wide spectrum of potential information. Their flexibility, and spectrum for processing different information must be higher than in specialized organisms. But omnivorous organisms can survive under different environmental conditions, and they can also adapt to changing environmental conditions. Specialized organisms are more sensitive for changing environmental conditions, although their relations to the environment have a higher degree of order.

Emergent effects of information relations are organized subsets of organic entities. Such subsets can be defined by the intensity of information exchange, and by quality characteristics of the information. The bandwidth of the emergent phenomena spans from interactions of cells in organisms to temporary mating interactions in animals (Alberts et al., 1986; Rubenstein and Wrangham, 1986). Of high interest in ecological systems is the socialization of species, which is based on the, in comparison to other individuals, intensified exchange of information among the group members. Social living is not automatically more beneficial than solitary life. Like other strategies it can only evolve, if positive effects are outweighing negative effects (Alcock, 1993).

The organization, and the exchange of information in social animals varies from genetically differentiated to relatively equal organized groups. Genetically differentiated groups are well known from social insects. The integration of a single individual into the information exchange of the social group depends strongly on the specialization of the specific individual. However, the social group can process relatively complex information. In social groups of mammals, each individual is potentially able to process the whole information. Specialization of individuals is dependent on the predominant actual contextual situation, but it can change over the time (Alcock, 1993).

3.2. Influence on the stability of ecosystems

Theoretically it could be expected, that the exchange of information in ecosystems will increase their stability. Necessary preconditions for that effect are feedback loops with a high efficiency in the identification, and compensation of unstable system conditions. Such feedback loops can not be expected for whole ecosystems, because the potential ability for processing information increases with the decrease of available energy for organisms. The theoretical assumption may be valid for local ecosystems with stable framework conditions. But there is no evidence, that an increase in the diversity of organisms, as simple indicator for information relations, provides a continuous increase of stability. From empirical data it can be derived, that the stability of the biotic parts of ecosystems increases only till an optimum number of species. With an further increase of species number, a decrease of the stability can be observed (Begon et al., 1991).

However, it has to be considered that the network characteristics of food webs are different from network characteristics of information networks (Milo et al., 2002). One should therefore be careful in the application of analogies between species diversity, and intensities of information interactions. This raises the question, how far the fitness of information processing organisms is improved in dynamic environments? A crucial challenge for organisms is the limited amount of endogenous accumulated amount of energy, which limits the temporal and spatial range of search for food. The answer for this question can be based on formula (4), under consideration of the temporal dimension:

$$\int E_{ex}(W_r;t)dt \geq \int E_{ex}(W_o;t)dt \quad (6)$$

The answer depends on external, and internal conditions of the considered organisms. External conditions are concerning changes on the resource distribution characteristics. A benefit for oriented walk has to be expected, if the distribution characteristics of the resources can be better mastered by information processing than by random search within the given limits of endogenous energy. The benefit can only be realized, if the organism is also able to adapt his information processing fast enough to the new environmental conditions. This challenge can be solved with different strategies.

In social insects, the environmental conditions are regularly controlled by random walks of a big number of organisms. But the information about the actual state of the environment is transferred by information to other members of the society. This causes finally a oriented walk for the exploitation of the identified resources.

Small groups or singular organisms can not expect such support in random search. Their success in resource exploitation under changing environmental conditions can be improved, if they are able to recognize new information. This requires awareness for unknown information, and the ability for an integration of the new information into the existing experience. In other words, information processing can be helpful for adaptation, if new information can be perceived by the organism, and if the new information is not completely different from previous information.

3.3. Orientation of information relations in ecosystems

Orientation along food chains

From the preceding analyses it can be derived, that information relations along of food chains can be characterized by a competition in encoding and decoding. The dominant interest for a potential prey is the defense against a detection by a predator. Strategies are camouflaging, active misinformation, or encrypting of unavoidable information. A potential predator is on the other hand interested on an easy detection of prey, and on information about its particular condition. The success of each counterparts depends not only on the applied tactics, but also on the actual environmental conditions. In the terms of Ebeling et al. (1998) is the emitted information of a prey

(I_{Ef}) part of the structural information (I_{Sp}) for the predator:

$$I_{Ef} \subseteq I_{Sp} \tag{7}$$

In cases of camouflaging, the signal characteristic of the emitted information from the potential prey is very similar to the signal characteristic of the general structural information. In cases of encrypting, the information can be detected but not decoded by the potential predator. In cases of active misinformation, the potential predator can detect and decode the information. But the derived pragmatic information is wrong in relation to the actual status of the potential prey.

Orientation across food chains

Information relations across food chains, or horizontal relations, are common at all consumer levels. Normally the same code is used by the transmitter and the receiver. The intensity of information expression can substitute the physical interactions between the involved individuals. Information relations across food chains are indirectly influencing the access of individuals to potentially available resources. This effect is dependent on the consequences of information exchange for real activities of animals, and on the population density. As stated above, animals can use the information for a defense of their territory or they can co-operate in the exploitation of a resource. Both strategies are producing different effects in combination with changing population densities.

However, the predominant orientation of information relations across food chains (Alcock, 1993; Bradbury and Vehrenkamp, 1998) is an indicator for adaptive effects of information relations in ecosystems because of following reasons. Changes in the spatial distribution of the resources are better detectable by horizontal relations. This is of crucial importance for the detection of spatial and temporal discontinuous resources, like big animals. The real effects for the consumer are depending on their specific strategy, and social organization. Horizontal information relations are also contributing to energy saving in organisms, if they are substitutes for physical interactions. In particular this is valid for the protection of territories against invaders by chemical or acoustic information.

4. CONCLUSIONS

In discussions about the functional role of information in ecosystems, it is essential to differentiate clearly the different ecological effects of transmitting and receiving of information. The effects of information transmission are relatively similar for mobile and sessile organisms. For the reception of information only benefits for mobile organisms could be found. Mobility and the reception are probably essential functional twins for surviving in heterogeneous environments.

Expectations for stabilizing effects of information relations in ecosystems could not be accomplished. However, information relations may improve the potentials for adaptation in changing environments because of their functional characteristics, and their predominant orientation in relation to food chains.

Socialization in animals can be interpreted as emergent effect of information relations. The realization of this is strongly dependent on the balance between benefits and adverse effects.

Information relations can substitute the expenditure of energy in some cases. But information can never substitute the dependencies of organisms on energy and substances. But information causes new, and only particularly understood quality characteristics in ecosystems.

5. REFERENCES

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