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Review

Agroecology, scaling and interdisciplinarity

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Abstract

Based on a review of its history, its present structure and its objective in the future, agroecology is defined as an integrative discipline that includes elements from agronomy, ecology, sociology and economics. Agroecology's credentials as a separate scientific discipline were measured against the norms of science, defined by Robert King Merton (1973): communalism, universality, disinterestedness, originality and doubt. It is concluded that agroecology meets many of these norms and where it differs, it does so in a way that perhaps anticipates the manner and the direction in which the social position of science is changing.

Accepting agroecology as a separate scientific discipline, the two main issues with which it must contend were considered to be those of scaling and interdisciplinarity. Scaling is a problem because results of agroecological research are typically generated at small spatial scales whereas applications are frequently implemented in larger, administrative units. A framework to convey information from science to decision-makers was proposed and tested in a case study of farm energy use. Interdisciplinarity is a problem because researchers from different disciplines see the world from different viewpoints, use different language, work at different locations and use different criteria to evaluate one another's work. Progress in this area is likely to be slow and driven by the need to justify the value of science to society.

Keywords: Agroecology; Discipline; Food production systems; Hierarchy; Interdisciplinarity; Mertonian norms; Scale; Sustainability

1. Introduction

A major challenge facing the world is how a 21st century population of perhaps 9 billion people will feed themselves in a sustainable manner (Evans, 1998). During the 20th century, a doubled population was fed via the so-called Green Revolution, with its introduction of pesticides, synthetic fertilisers and new high-yielding cultivars. With the reduction in the proportion of hungering people from more than 50% of the total population after World War II to under 20% today (Grigg, 1993), the success of this revolution is indisputable. However, there are still malnourished people and the impacts of intensive agriculture on natural resource degradation and the environment may not be sustainable (Brown et al., 2000). The proposed role of agroecology is to facilitate the design and management of sustainable food production systems (Gliessman, 1998), and to investigate possible synergisms that can help alleviate the above problems (Altieri, 1980). However, agroecology has not fully matured as a scientific discipline. In this paper, the definition and scientific method of agroecology,

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its credentials as a scientific discipline and the challenges that face it are considered. The intention is to establish a general framework for the integration of information within agroecology, and for the communication of this information to the decision-makers targeted. Here, it is recognised that the rationale for agroecology is currently the need to develop sustainable systems of food production and this requires that knowledge must be effectively delivered to the people who are in a position to take appropriate action.

2. A history of agroecology

The term agroecology was in parallel proposed by German zoologists (Friederichs, 1930), and American crop physiologists (Hanson, 1939) as a synonym for the application of ecology within agriculture. At that time, ecologists had relatively narrow foci but with a trend towards a more integrative view of ecosystems. The early population ecology school of Henry Gleason investigated plant populations seen from the organism's perspective, thereby focusing on the hierarchical levels of the organism (Fig. 1). In contrast, the community ecology school of Frederic Clements viewed plant populations from the landscape perspective, thereby also including higher hierarchical levels than the organism (O'Neill et al., 1986). However, the true roots of agroecology probably lie in the school of process ecology as typified by Tansley (1935), whose worldview included both biotic entities and their environment (Fig. 1). It was from this school of process ecology that the agroecosystem concept emerged (Harper, 1974), and the foundations for modern agroecology were laid.

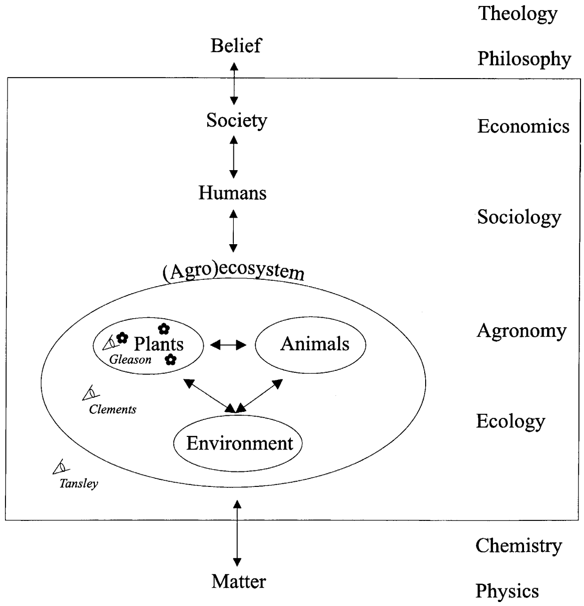

Fig. 1. The box symbolises the window of agroecology within food production systems. The viewpoints of the different schools of ecology are marked with eye signatures. The classical, scientific disciplines, where some are within the window of agroecology, are lined up in the right column, ordered in a hierarchy with the 'hard' disciplines at the bottom and the 'soft' disciplines at the top (Checkland, 1999).

2.1. "Hard" agroecology

According to Hecht (1995), the hard branch of agroecology (physical–analytical and natural science based) was initiated by works such as "Silent Spring" (Carson, 1964), "The Population Bomb" (Erlich, 1966), "Tragedy of the Commons" (Hardin, 1968) and "The Limits to Growth" (Meadows et al., 1972). The gloomy predictions of these and similar polemical writings have largely not come to pass, mainly because the speed of technological developments was underestimated. However, hard agroecology has shown that badly managed agriculture can lead to the degradation of agricultural land (Waldon et al., 1998), undesirable changes in semi-natural ecosystems (Lambert et al., 1990) and the depletion and pollution of natural resources (e.g. de Molenaar, 1990). Consequently, the focus of agricultural science has changed over the past 20–30 years from the maximisation of food and fibre production towards understanding the mechanisms linking costs (nutrient losses, loss of biodiversity and landscape degradation) to the benefits of agriculture (production, wealth generation and landscape maintenance). To understand these linkages required a combination of ecology, agronomy and economy (Reintjes et al., 1992) that may be considered "hard" agroecology. Such hard systems thinking, integrating various disciplines within natural sciences and economy, was significantly developed during the 1980s and 1990s, but remains the approach of an engineer or a classical economist (Checkland, 1999). This means that the resources entering and leaving agricultural systems are considered to be finite capital measured in physical or monetary units (Pearce, 1996). Furthermore, the position of the observer and scientist are thought of as external to the systems under study, which as we will see is not necessarily the case of soft agroecology.

2.2. "Soft" agroecology

There has been a debate whether hard system optimisation of agriculture alone could solve the problem of feeding an expanding world population. It is increasingly felt that this is not the case and that a much broader view of the structure, function and role of agroecosystems is called for (Conway, 1987). Such a vision addresses hard issues such as the follows of energy and matter through agroecosystems but also includes the role of human and society, and the empowerment of citizens for developing their own food systems, and thereby feeding themselves. The exploration of the interaction between these human activity system and the hard agroecosystem is here defined as soft agroecology. According to this soft system thinking (Checkland, 1999), the capital entering and leaving agricultural systems is not only measured in physical units but also includes cultural knowledge, human experiences, potentials for technological development, etc. In contrast to hard capital, this soft capital is flexible (Pearce, 1996) and can even to some degree substitute hard capital. For example, knowledge of traditional farming systems inherited from their forefathers may help future farmers to save physical inputs (Gliessman, 1990a). However, a major problem is that the disciplines of rural sociology and economics, which deal with this area of soft agroecology, tend to operate at higher hierarchical levels than the hard disciplines of agronomy and ecology. This means that the soft disciplines often work at the farm or the regional level, while the hard disciplines often work at the plot or the field level. Furthermore, some soft systems researchers work as accomplices to the farmer, both giving and receiving knowledge, unlike their hard systems colleagues who work as external observers to the system under study. This is a consequence of the inclusion of interactions between humans within the window of agroecology (Fig. 1). They argue that all people dealing with agricultural production systems, including scientists, are intimately and subjectively involved in the activities of the growing of food and that to study this process is to become a part of it (Longino, 1990).

2.3. Where is agroecology now?

Recognising that agroecology is still developing, a survey of the published literature was conducted to establish its current status. The survey was conducted by interrogating electronic databases (CAB, 2001; AGRICOLA, 2001; ISIS-SCI, 2001; SSCI, 2001; ECONLIT, 2001), reading literature reviews (Carls, 1988, 1989, 1990) and visiting The Agroecology Library, University of California, Santa Cruz. In agreement with Carroll et al. (1990), most references were related to natural sciences within the fields of agronomy and ecology (e.g. the work in Gliessman, 1990b). However, references were also found within the social sciences (e.g. Francis and King, 1997; Thomas and Kevan, 1993), economics (e.g. Allen, 1999; Rosset, 1996), or in combination of two or more areas (e.g. Edwards et al., 1993; Van Latesteijn, 1997). To quantify this distribution, the number of references to "agroecology" or "agro-ecology" (with a hyphen) in literature databases of natural sciences (ISIS-SCI, 2001), resulting in 94 references, social sciences (SSCI, 2001) and economics (ECONLIT, 2001) were compared. The majority (66%) of the references were only found in the natural science databases, with 13% only in social science database, and 5% only in economic literature. No references were in the databases from all three fields of science. The remaining references were found in two out of the three fields, with 2% in social and natural sciences, none in social sciences and economics, and 16% in a combination between natural sciences and economics (Fig. 2).

Compared to the total number of references in the searched databases, relatively few referred to agroecology. For example CAB (2001) refers to 1195 abstracts including the term agroecology out of the more than 2 million references in total. In comparison, more than 300,000 references referred to animal nutrition. Using the definition of agroecology stated in the next section, we could have redefined a number of additional and often earlier studies as agroecological, even though the authors chose not to describe them as such at the time. However, the point of the survey was not to determine what work was being done but rather

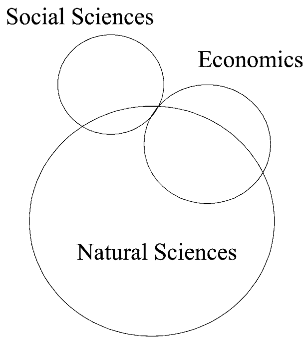

Fig. 2. The triangular composition of the subjects for agroecological studies. The area of the circles is proportional to the number of references found.

whether the scientists involved considered the studies to be agroecological.

2.4. A definition of agroecology

In this paper, agroecology is defined as “the study of the interactions between plants, animals, humans and the environment within agricultural systems”. Agroecology as a discipline therefore covers integrative studies within agronomy, ecology, sociology and economics (Fig. 1). Most authors acknowledge agroecology as a discipline of integration, but define it in other terms, for example as ‘the application of ecological science to design and management of sustainable agroecosystems’ (Gliessman, 1998). Thereby, the upper part of the window of agroecology in Fig. 1 is excluded. Clearly there is still not one, finally acknowledged definition of agroecology, indicating the ongoing development within the discipline.

The historical development of agroecology shows that it began originally as a part of crop physiology, agricultural zoology, and ecology but the term was adopted by a movement which wished to promote the development of sustainable agriculture through the integration of ideas and methods from other disciplines (Altieri, 1980). Now agroecology departments exist at a number of universities across the world but particularly in the USA and Europe. This implies that at least some people think that agroecology has made the transition from a proposition to a separate scientific discipline. In the next section, the case for considering agroecology as a separate scientific discipline is examined.

3. Agroecology as a separate, scientific discipline

3.1. A separate discipline

To be considered a separate discipline, agroecology must be distinguishable from existing disciplines. The argument is that agroecology is distinguished from its parental disciplines of agronomy, ecology and socio-economics by its integration between these disciplines and across scales. The agroecology-related studies found in the literature survey were characterised by an integrative approach, where information from single disciplines was collected and combined to solve problems at a higher scale. An additional indication that agroecology is a separate discipline is that the numbers of references to agroecology have increased in recent years, indicating that more scientists feel that their work lies sufficiently far from the existing scientific disciplines that an alternative term is necessary.

3.2. A scientific discipline

The assessment of agroecology as a scientific discipline was made using the norms of science as defined by the sociologist Robert King Merton (Merton, 1973). This approach was inspired by a recent attempt by the physicist John Ziman (Ziman, 2000) to define science in terms of what it is and what it means.

The first Mertonian norm of science is communalism, meaning that the outcomes of academic science are delivered to the public in the broadest sense, including other scientific colleagues and the wider public. Scientists differ in the weight they assign to the importance of these dissemination routes. These can vary from scientific papers in specialist journals to popular television programmes. Agroecology values communalism. It is probably the case that many agroecologists place as much emphasis on sharing results with society as with their scientific colleagues.

The second norm is that science should be universal and open to contributions from all, irrespective of race, gender, nationality, religion, etc. The only things that should wither, and be excluded from science, are ideas and theories not meeting with experimental verification or observation. Agroecologists would try to maintain the norm of universality in the Mertonian sense, as

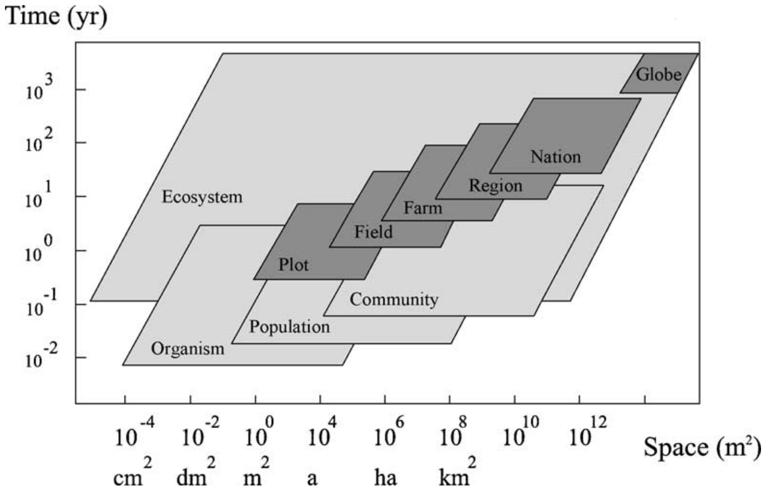

Fig. 3. Examples of the spatial and temporal scale for investigations of hierarchical levels within natural (light coloured), and agricultural systems (dark coloured) (after Rabbinge, 1997).

is evidenced by the papers refereed to in Section 2.3. However, universality in agroecology can often be very broad and may deliberately include other stakeholders, so that agroecology sometimes borders on being a socio-political movement. Agroecology faces a paradox when moving its focus to higher and thereby more aggregated levels of hierarchy (Figs. 1 and 3). At the highest hierarchical levels, local context can so swamp generality that research in, for example, rural sociology often ends as a series of case studies from which it is impossible to draw general conclusions.

Disinterestedness in the reporting of science is the third norm. Science reporting is unusual principally because of its impersonal manner, conveying an impression of non-prejudice and disinterestedness from the reported work. Thus, the impersonality and care taken in reporting science stems from the knowledge that results and conclusions are likely to be challenged by others. It is thus part of a scientist's duty to facilitate this examination in the interests of the wider scientific enterprise. With respect to disinterestedness, agroecology does not differ from any other scientific discipline. Thus, experiments are reported, models can be verified, and social and economic analyses are sometimes but not always repeatable. An important interaction between these norms is that the communalism of science acts as a control on science's disinterestedness (Ziman, 2000)—the value of an objective scientific observation or experiment assessed via the social process of peer review. Thus, science and agroecology are disinterested attempts to search for objective truths that are paradoxically mediated by socially constructed controls and evaluation processes.

Originality is the fourth norm. The tried and tested route to making an original scientific contribution, in the sense of a 'new' piece of knowledge, is to plough the furrow ever deeper. Thus, it is a rational scientific response to focus on ever more detail in the hope of developing a fragment of the scientific story for oneself. In supplement, agroecology's originality also stems from synthesis as well as from thinking outside the commonly accepted thesis of the existing knowledge base. Marching under the twin banners of synthesis and interdisciplinarity, agroecology, in line with disciplines like anthropology, psychology and sociology, is at odds with what is commonly termed 'basic', natural research with its clear defined boundaries for research, theoretical framework and sense of coherence. However, science is perhaps moving towards the agroecological model, where the constructed and the objective aspects of science are both recognised. For example, disciplines such as climatology and some aspects of geosciences appear to becoming more integrative and less reductionist. This trend is evident, for example, when the activities of humans are seen as within the system of study rather than external to it. An example would be the role that human activities play in land use change or as drivers of biogeochemical processes such as the global carbon and nitrogen cycles. Nowadays, these originally natural cycles cannot be studied and understood without understanding and integrating the human role. In this ‘post-academic’ science (Ziman, 2000) the cultural and social context of science as a process of knowledge creation is explicit.

Doubt is the restraint on originality in science and its application, via scepticism, is the fifth Mertonian norm. This enters in at least two stages in the scientific process. New ideas and theories are evaluated against a sceptical starting point—the null hypothesis. Having successfully cleared this obstacle, a new piece of scientific knowledge is then subjected to further doubt by anonymous referees who act on behalf of the scientific community. In agroecology, the first of these steps sometimes differs from the above scientific norm. Some agroecological studies do not start with a classical null hypothesis but include semi-quantitative surveys, rapid rural assessments and studies closely linked to agricultural development. These can be and are subjected to the second level of doubt. However, no method of collecting data should preclude the need for an explicit underlying hypothesis, question or assumption that is being tested.

In summary, agroecology meets many of the Mertonian norms of science and where it differs it does so in a way that perhaps anticipates the manner and the direction in which the social position of science is changing. Having concluded this, the next two sections consider two of the main issues that face agroecologists; scale and interdisciplinarity (Marceau, 1999).

4. Scale

The issue of scale means that there is a gap between the scale at which most agroecological information is currently generated and the scale at which most decisions concerning agricultural systems are made (Dalgaard, 2001). The results of agroecological studies, generated on the plot, field or farm level, cannot always readily be generalised to the regional, national or global level relevant for decision-makers. Because of this gap, the results are often misinterpreted or not used in the decision-making process (Lerland et al., 2000). Scaling issues have been addressed for many years in sciences such as physics (Crutchfield, 1994) or economics (Cropper and Oates, 1992). Until recently, there has been relatively little focus on methods to convey information between scales in the environmental sciences of ecology (Rastetter et al., 1992) or agronomy (Bierkens et al., 2000; Stein et al., 2001), although within theoretical ecology there are some references from the 1970s and 1980s (e.g. O’Neill et al., 1986). Consequently, agroecologists tend to use scaling procedures that are too simple (Grace et al., 1997) and that are poorly suited to global problems e.g. green house gas emissions (Flavin and Dunn, 1998). However, recent advances in scaling have responded to the need to translate environmental and socio-economic indicators from the scale of observation or collection to that of individual operator or national policy. This has led to several new statistical developments, and the application of geostatistics in particular (Riley, 2001).

4.1. Hierarchy and scale

Shown below are the classical examples of the hierarchy within natural (1) or agricultural systems (2, 3) (Odum, 1971), where the lower levels of organisation or complexity are to the left, and the higher levels to the right:

1. cell ↔ organism ↔ population ↔ community ↔ ecosystem ↔ landscape
2. plot ↔ field ↔ farm ↔ watershed ↔ region ↔ nation ↔ union ↔ globe
3. cell ↔ organ ↔ animal/plant ↔ herd/field ↔ farm ↔ region

These hierarchies represents levels of organisational complexity ranked by category or class, and are the basic structural units of the system investigated (Whyte et al., 1969). Often hierarchical levels are nested, so that high level units consist of lower level units (Fresco, 1995; Fig. 3). The boundary between hierarchical levels may be visible, such as the skin of an organism or the shoreline of a lake, or intangible in the case of for instance of populations and species. There are two dimensions of scale: spatial and temporal (Fig. 3). Consequently, the term scale relates to space and time period (e.g. a regional scale study of a 100 km^2 area in 4 years). In this paper, the colloquial definition of scale is used (Curan et al., 1997), meaning that large scale studies cover large areas and/or time spans and small scale studies the reverse.

4.2. Linear, non-linear and hierarchical scaling

Even though hierarchies and scales are connected, so that high level hierarchies are normally studied on larger temporal and spatial scales, they are not synonymous (Allen and Hoekstra, 1992; Fig. 3). The range over which a single level in a hierarchy can extend has consequences for describing the behaviour of higher hierarchical levels because there may be scale-dependent processes present within one or more levels of a hierarchy.

For example the total diesel fuel use F_{total} (l) can be calculated at the hierarchical level of the field (Eq. (1)), and aggregated to the farm level (Eq. (2)). In this very simplified example, derived from the Dalgaard et al. (2001) model, F_n is the average fuel use per ha on field n, A_n the field area in ha, and N is the number of fields on the farm.

$$F_{total} = F_n A_n \tag{1}$$

$$F_{total} = \sum_{n=1}^{N} F_n A_n \tag{2}$$

With a *linear scaling* procedure (also called simple scaling, Grace et al., 1997), F_n is constant, e.g. $F_n = 100\,\mathrm{l\,ha^{-1}}$ for all fields, and the fuel use is an identical, linear function of both field and farm area. With a *non-linear scaling* procedure, F_n is a non-linear function of the field area. For example, if $F_n = 103\,A_n – A_n{}^2$, when $A_n < 3$ ha, $F_n > 100\,\mathrm{l\,ha^{-1}}$, whereas if $A_n > 3$ ha, $F_n < 100\,\mathrm{l\,ha^{-1}}$. Such non-linearity, caused by a higher proportion of energy use for turning, pausing, etc. on small fields than on large fields (Nielsen and Sørensen, 1994), would be realistic for $A_n \in [0; 20]$ ha. A *hierarchical scaling* procedure also includes properties emerging when system boundaries are extended, for example from the field to the farm level. One example of such emerging factor is the non-field fuel use for transport between fields and the farm buildings, dependent on the distance to the fields D_n (km), and the load transported to each field (Dalgaard et al., 2001). The load is correlated to A_n, and therefore Eq. (2) for the farm level energy use could be extended to a hierarchical scaling procedure by including a term to describe non-field fuel use (Eq. (3)). The important point is that different scaling procedures are required within and between different levels in a hierarchy (Marshall et al., 1997).

$$F_{total} = \sum_{n=1}^{N} F_n A_n + D_n(1 + A_n) \tag{3}$$

Differences between the three scaling procedures are illustrated in Table 1, where fuel use are upscaled from the field to the farm level for a 4 ha small, and a 50 ha larger farm, using each of the three scaling procedures proposed. Clearly, the scaling procedures give different results, especially for the larger farm. When upscaling, it is therefore important to consider whether simple linear scaling may suffice or whether more complicated non-linear or hierarchical scaling procedures must be developed. In this case, the following framework of hierarchy and scale may be helpful.

Table 1
Example on the linear, non-linear and hierarchical scaling procedure, used to calculate the farm level fuel use F_{total} on a 4 ha small farm with $N = 2$ fields, and a larger 50 ha farm with $N = 3$ fields

	n	A_n (ha)	D_n (km)	F_{total} for different scaling procedures (l)		
				Linear	Non-linear	Hierarchical
Small farm	1	1	1	100	102	104
	2	3	1	300	300	302
Total		4		400	402	406
Average ($\mathrm{l\,ha^{-1}}$)				100	101	102
Large farm	1	20	2	2000	1660	1702
	2	10	1	1000	930	941
	3	20	10	2000	1660	1870
Total		50		5000	4250	4513
Average ($\mathrm{l\,ha^{-1}}$)				100	85	90

A_n is the area of field no. n; D_n is the distance to the field.

Table 2
General framework of hierarchy and scale with four criteria to support and evaluate the conveyance of information between science and a decision-maker

Criteria 1	Define the decision-maker and the problem and the scale at which the decision-maker needs information.
Criteria 2	Determine on which scales information regarding this problem is available and collect the relevant information.
Criteria 3	Create a hypothesis of how existing information, identified in criteria 2, can be transformed to the scale needed for decision-making, identified in criteria 1. First try with simple linear scaling procedures, and after having tested them in criteria 4, try more complicated, non-linear or hierarchical scaling procedures.
Criteria 4	Test the hypothesis of criteria 3 with independently sampled decision-maker scale information. If the hypothesis is rejected, try with a new hypothesis or seek new information, which can be transformed to the decision-maker scale.

4.3. Framework of hierarchy and scale—an example

To cross the barrier of scale, a general framework based upon the classical method of natural sciences, involving observation, hypothesis and test is proposed (Table 2). Within this framework, which here is posed for a simplified case that assumes one uniform decision-maker, specific linear, non-linear or hierarchical scaling functions may be explored and used to support decision-making (Bierkens et al., 2000).

In the following, an application of this simplified framework is illustrated with a simple example, with one group of decision-makers. However, in reality there are often many different actors, stakeholders and decision-makers in many hierarchies and scales, making application of the framework more complicated. In the present example, the criteria of the framework of hierarchy and scale are indicated with numbers in brackets. The targeted decision-makers were Danish politicians who after the Rio-Conference in 1992 demanded information on how agriculture could contribute to reduce the Danish energy use and greenhouse gas emissions by the promised 20%. Specifically, they wanted to know whether three different scenarios for conversion to organic farming might help to reduce the energy use (Bichel Committee, 1999). The time scale was a 12-year period (Danish Ministry of Environment and Energy, 1995), and the spatial scale was the 27,000 km^2 agricultural area of Denmark (criteria 1 in Table 2). As the existing figures on energy use were sampled on the field and animal housing level (criteria 2), the question was how to upscale these data to the national level. The simplest option would have been a linear scaling procedure, where the average energy uses for different field crops and livestock housings is multiplied with national crop and livestock figures (criteria 3). However, because of scale dependent non-linearities and significant emerging factors, a linear scaling procedure was too simple for the upscaling (criteria 4). For reasons discussed in section a non-linear scaling procedure (criteria 3) was also too simple to predict fuel use (criteria 4), and a hierarchical scaling procedure was needed (criteria 3). In this case, a two-step application of the hierarchy-scale framework was tested. Step one was from the field to the farm level and step two was the final national level generalisation.

4.3.1. Step one

Measurements revealed a 47% deficiency in farm level fuel use compared to field level literature values linearly upscaled to the farm level (Refsgaard et al., 1998), and extended sampling on the field and farm level was initiated (criteria 4). A new model for calculation of farm level fossil energy was made (Dalgaard et al., 2001) including fuel use as a function of the amount of inputs used, yield and the soil type on each field (criteria 3). Also, the above-mentioned emergent factors of fuel use for transport between fields and the farm and between the farm, fodder stocks and feedstuff businesses were included. Finally, the new model was verified (criteria 4) with samples of fuel use, F, and the $F_{observed}$–$F_{simulated}$ difference was found to be insignificant.

4.3.2. Step two

The derived model was used in the final national level generalisation of the fossil energy use in the primary Danish agricultural sector. A linear scaling procedure was used, where the estimated average energy use for each crop and animal type was multiplied by the areas of crops and the number of animals according to national agricultural statistics (criteria 3). The simulated and lineally upscaled energy use embedded in each of the accounted energy carriers was similar to the expected energy use according to national statistics, with a total difference of less than 3% (Dalgaard et al., 2002). In this case, it was concluded that the applied linear scaling procedure was sufficient for the step two generalisation (criteria 4).

5. Interdisciplinarity

Interdisciplinary means working across traditional disciplinary boundaries. For science in general, this can lead to creative breakthroughs, the identification of oversights, and provide more holistic solutions than work within single disciplines (Nissani, 1997). For agroecology, the specific issue is its continued growth from its roots in agriculture and ecology to include relevant aspects in sociology and economics. This development is desirable both because humans are an integral and important part of food producing systems and because it is necessary if decision-makers are to act on the basis of both ecological, social and economic principles (Wood, 1998).

Achieving interdisciplinarity will require the removal of the barriers to the flow of information between the disciplines relevant to agroecology. These barriers include mind set and communication, where science has developed into increasingly specialised disciplines, talking different languages and having different areas of interest. Ideally, one could call upon scientists with a more generalist background to assist in communication between specialists but institutional barriers within modern science mean there is no encouragement for such creatures to flourish. These barriers are both physical and organisational. The physical barrier is that scientists from the different disciplines that interact with agroecology are normally in different institutes or departments, often in different physical locations. With the developments in information technologies and infrastructures this barrier may be less than it once was but the lack of social interaction will continue to be an obstacle to collaboration. The organisational barrier relates to the way in which science reward researchers via the provision of resources and career advancement. This depends heavily on the publication of papers in peer-reviewed scientific journals. Here the researchers within agroecology are faced with new opportunities but also several problems. The challenge of scaling is encouraging the development of novel experimental methodologies, e.g. through the combined use of modelling, observational science and advanced statistical mapping procedures (Riley, 2001). However, for the more reductionist scientists, integration to higher hierarchical levels, e.g. from the field to the farm level, means fewer opportunities for controlled experiments, experiments of greater duration and more time spent communicating with scientists from other disciplines. The experiments are likely to provide results that are more difficult to generalise than is common for more reductionist disciplines. However, as discussed earlier, the norms and social position of science are changing as the presumption that science is sacrosanct withers and scientists increasingly have to argue their value to human endeavour. As agriculture is a mature science, compared to other disciplines such as biotechnology or microelectronics, agroecologists may find themselves in the forefront of this development.

6. Procedures and strategies to address agroecological questions at different scales

It is argued here that studies of how to cross the barriers of scaling and interdisciplinarity should be central issues for future agroecogical research projects. For soil sciences, Bouma (1997) drew similar conclusions and appealed for new methods to deal with the issues and proposed a seven-step procedure for research in sustainable management of agricultural soils (Bouma et al., 1998). This procedure was found useful to address agroecological questions (Wagenet, 1998) but problems were encountered in integrating socio-economic information and in the issues of hierarchy and scale (Dumanski et al., 1998). The framework presented here (Table 2) builds upon Bouma et al.'s (1998) procedure and corresponds to the application of the scientific method of natural sciences—observing, measuring and interpreting—stressed in the introduction to the agroecology book by Carroll et al. (1990). The difference is that the framework presented here was extended to distinguish between hierarchy and scale in the form of the defined linear, non-linear or hierarchical scaling procedures. In addition, the present framework included a test (criteria 4) in the defined scaling procedure and an iterative exploration of scaling functions that proceeds until the error does not exceed a sensible threshold value (Table 2). To develop such scaling functions, comprehensive decision-support systems have been developed (Bierkens et al., 2000) but to date only methods to answer hard agroecological questions have been included, while the integration of information from the soft agroecological ones is not included. The framework of hierarchy and scale presented here is similarly bound to hard agroecology but provides a hint at a starting point for interdisciplinary research projects. This would typically be a common problem of sustainability, investigated by both soft and hard researchers, corresponding to the criteria 1 problem in the framework. However, because the soft sciences do not produce pure quantitative results, it might not merely be a question of currency shifts—for example from the physical units of an agronomic study to the monetary units of an economical study (Squire and Gibson, 1998)—followed by the traditional scaling procedure of criteria 2–4. Instead, criteria 2–4 could be interpreted as a communicative process (Bawden, 1995), where statements regarding solutions to the common problem are compared at spatio-temporal scales of relevance for decisions.

One example where the results from soft and hard sciences differed, and interdisciplinary research would gain knowledge is illustrated in the recent debate concerning the possible benefits of introducing a "golden rice variety" (Schiermaier, 2001). In contrast to traditional varieties, the golden rice is genetically engineered to contain Vitamin A precursors, a deficiency of which causes blindness and other illnesses. One of the inventing plant scientists predicted the introduction of this new variety to solve the "unnecessary death and blindness of millions of poor every year" (Potrykus, 2001). However, nutritionists argue that Vitamin A can only be absorbed by the body if consumed with sufficient oils and fats, which is often lacking in many Third World diets, and social scientists argue that some of the Vitamin A problem is caused by the social status of eating hulled, white rice, with a low Vitamin A content, and that better nutrition could as easily have been achieved by campaigning for the consumption of existing, more wholesome varieties of brown paddy rice (Schnapp and Schiermaier, 2001). This example illustrates that the potential effect of feeding malnourished people with golden rice varieties differs when seen from the perspective of the uni-disciplinary perspective of the plant scientist than from a perspective that also includes nutritional and social knowledge. Estimating consequences of conversion to organic farming is another subject where both ecological (Dalgaard et al., 1998), economic (Hansen et al., 2001), and social driving forces (Trewavas, 2001) are relevant to include. This is because conversion to organic farming is driven both by the ecological potential of this system compared to conventional farming and by the socio-economic gains for farmers and the society.

A common feature of the problems encountered in the development of sustainable food production is the need for feedback mechanisms between the different research disciplines and between decision-makers and researchers. This is because the decisions to be made must take into account both the functioning of natural ecosystems and the response of humans acting either as individuals or as part of society. Consequently soft and hard science mechanisms interact with one another, and a dialectical approach (Levins and Lewontin, 1985), where both top-down and bottom-up viewpoints are valued, becomes fundamental for the iterative integration of information from multiple disciplines.

7. Conclusions and perspectives

The current driving force for agroecology is the need to facilitate the development of more sustainable agricultural systems. This emphasis on sustainability is drawing agroecology up from its roots in agronomy and ecology to include elements of both sociology and economics. This study found that agroecology can currently be defined as the study of interactions between plants, animals, humans and the environment within agricultural systems. One of its hallmarks is that it integrates between scientific disciplines and scales.

The first Green Revolution was achieved primarily through the development and application of technology. Whilst successful in terms of food production, serious questions have been raised concerning the impact of these agricultural practices on the health of the cultivated land (Oldeman et al., 1991). Conway (1997) argued that a second Green Revolution is required, which is even more productive than the first

Green Revolution and even more "green" in terms of conserving natural resources and the environment. In addition to the productive and environmental aspects, the social and economic dimensions of agricultural systems must therefore also be considered.

In recent years, significant progress has been made in understanding the issue of scaling and in the development of appropriate techniques. The barriers to interdisciplinarity are mainly cultural and political not technical, and lying deeply embedded in the way science has developed, these barriers present the major obstacle to the development of agroecology.

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References

AGRICOLA, 2001. AGRICultural OnLine Access (http://www.nalusda.gov/ag98/). The National Agricultural Library, US Department of Agriculture, Beltsville, MD, USA.

Allen, P., 1999. Reweaving the food security safety net: mediating entitlement and entrepreneurship. Agric. Human Values 16, 117–129.

Allen, T.F.H., Hoekstra, T.W., 1992. Toward a Unified Ecology. Columbia University Press, New York, ISBN 0-231-06919-7, 384 pp.

Altieri, M.A., 1980. Agroecology: The Science of Sustainable Agriculture, 2nd Edition, 1995. Westview Press, CO, USA, ISBN 0-8133-1764-9, 433 pp.

Bawden, R., 1995. Systemic Development: A Learning Approach to Change. Occasional Paper #1, Centre for Systemic Development, University of Western Sydney, Hawkesbury, 8 pp.

Bichel Committee, 1999. Rapport fra den Tværfaglige økologigruppe (Report from the Interdiciplinary Group on organic farming). Danish Environmental Protection Agency, Copenhagen, ISBN 87-7909-292-6, 98 pp.

Bierkens, M.F.P., Finke, P.A., de Willigen, P., 2000. Upscaling and downscaling methods for environmental research. Developments in Plant and Soil Sciences, vol. 88. Kluwer Academic Publishers, Dordrecht, ISBN 0-7923-6339-6, 190 pp.

Bouma, J., 1997. Soil environmental quality: a European perspective. J. Environ. Qual. 26, 26–31.

Bouma, J., Finke, P.A., Hoosbeek, M.R., Breeuwsma, A., 1998. Soil and water quality at different scales: concepts, challenges, conclusions and recommendations. Nutr. Cycling Agroecosys. 50, 5–11.

Brown, L., Flavin, C., Fench, H., 2000. State of the World 2000. W.W. Norton and Company, London, ISBN 0-393-04848-9, 263 pp.

CAB, 2001. Commonwealth Agricultural Bureaux. CAB International (http://www.cabi.org/), Wallingford, Oxford, UK.

Carls, J., 1988. Abstracts on Sustainable Agriculture, vol. 1. Deutches Zentrum für Entwicklungstechnologien, Braunsweig, Germany, 294 pp.

Carls, J., 1989. Abstracts on Sustainable Agriculture, vol. 2. Deutches Zentrum für Entwicklungstechnologien, Braunsweig, Germany, ISBN 3-528-02060-1, 372 pp.

Carls, J., 1990. Abstracts on Sustainable Agriculture, vol. 3. Deutches Zentrum für Entwicklungstechnologien, Braunsweig, Germany, ISBN 3-528-02062-8, 453 pp.

Carroll, C.R., Vandermeer, J.H., Rosset, P.M. (Eds.), 1990. Agroecology. Biological Resource Management Series. McGraw-Hill, New York, ISBN 0-07-052923-X, 641 pp.

Carson, R.L., 1964. Silent Spring. Houghton Miffin Company, Boston, USA, ISBN 0-395-68329-7.

Checkland, P., 1999. Systems Thinking, Systems Practice. Includes a 30-Year Retrospective. Wiley, Chichester, ISBN 0-471-98606-2, 330 pp.

Conway, G., 1997. The Doubly Green Revolution. Food for All in the Twenty-First Century. Cornell University Press, Ithaca, NY, ISBN 0-8014-8610-6, 335 pp.

Conway, G., 1987. The properties of agroecosystems. Agric. Syst. 24, 95–117.

Cropper, M.L., Oates, W.E., 1992. Environmental economics: a survey. J. Econ. Lit. XXX, 675–740.

Crutchfield, J.P., 1994. Is anything ever new? considering emergence. In: Cowan, G., Pines, D., Melzner, D. (Eds.), Complexity: Metaphors, Models, and Reality, SFI Series in the Sciences of Complexity, vol. XIX. Addison-Wesley, Redwood City, pp. 479–497.

Curan, P.J., Foody, G.M., van Gardingen, P.R., 1997. Scaling up. In: Gardingen, P.R., Foody, G.M., Curran, P.J. (Eds.), Scaling-up From Cell to Landscape. Seminar Series 63, Society for Experimantal Biology, Cambridge University Press, Cambridge, UK, ISBN 0-521-47109-5, pp. 1–6, 386 pp.

Dalgaard, T., 2001. Simulation and regional generalisation of agricultural resource use, Ph.D. Thesis. The Royal Veterinary and Agricultural University of Denmark, Copenhagen, ISBN 87-988287-3-8, 184 pp.

Dalgaard, T., Halberg, N., Porter, J., 2001. A model for fossil energy use in Danish agriculture used to compare organic and conventional farming. Agric. Ecosys. Environ. 87 (1), 51–65.

Dalgaard T., Halberg, N., Fenger J., 2002. Can organic farming help to reduce national energy consumption and emissions of greenhouse gasses in Denmark? In: van Lerland, E.C., Lansink, A.O. (Eds.), Economics of Sustainable Energy in Agriculture. Economy and Environment, vol. 24. Kluwer Academic Publishers, Dordrecht, The Netherlands, ISBN 1-4020-0785-X, pp. 191–204.

Dalgaard, T., Halberg, N., Kristensen, I.S., 1998. Can organic farming help to reduce N-losses? Experiences from Denmark. Nutr. Cycling Agroecosys. 52, 277–287.

Danish Ministry of Environment and Energy, 1995. Danmarks Energifremtider (Danish Energy Futures). The Danish Energy Agency, Copenhagen, 214 pp.

Dumanski, J., Pettapiece, W.W., McGregor, R.J., 1998. Relevance of scale dependent approaches for integrating biophysical and socio-economic information and development of agroecological factors. Nutr. Cycling Agroecosys. 50, 13–22.

ECONLIT, 2001. American Economic Association's Electronic Bibliography of Economic Literature (http://www.econlit.org), Pittsburgh, USA; J. Econ. Lit.

Edwards, C.A., Grove, T.L., Harwood, R.R., Pierce Colfer, C.J., 1993. The role of agroecology and integrated farming systems in agricultural sustainability. Agric. Ecosys. Environ. 46, 99–121.

Erlich, P.R., 1966. The population bomb. Buccaneer Books, New York, USA, 1997 (reprint), ISBN 1-568-49587-0.

Evans, L., 1998. Feeding the 10 Billion: Plants and Population Growth. Cambridge University Press, Cambridge, ISBN 0-521-64685-5.

Flavin, C., Dunn, S., 1998. Responding to the threat of climate change. In: Brown, L.R., Flavin, C.F., French, H. (Eds.), State of the World. W.W. Norton, New York, ISBN 0-393-31727-7, pp. 113–130.

Francis, C., King, J., 1997. Impact of personal values on agricultural research. Soc. Nat. Resour. 10 (3), 273–282.

Fresco, L.O., 1995. Agro-ecological knowledge at different scales. In: Bouma, J., Kuyvenhoven, A., Bouman, B.A.M., Luyten, J.C., Zandstra, H.G. (Eds.), Eco-regional Approaches for Sustainable Land Use and Food Production. Kluwer Academic Publishers, Dordrecht, ISBN 0-7923-3608-9, pp. 133–141.

Friederichs, K., 1930/1965. Die Grundfragen und Gesetzmässigkeiten der land- and forstwirtshaftlichen zoologie, Berlin. In: Tischler, W. (Ed.), Agrarökologie. Gustav Fischer Verlag, Jena, 499 pp.

Gliessman, S.R., 1998. Agroecology. Ecological Processes in Sustainable Agriculture. Ann Arbor Press, Chelsea, MI, ISBN 1-57504-043-3.

Gliessman, S.R., 1990a. Understanding the basis of sustainability for agriculture in the tropic: experiences in Latin America. Sustainable Agricultural Systems. Soil and Water Conservation Society, Ankeny, IA, USA, Chapter 22, pp. 378–390.

Gliessman, S.R., 1990b. Agroecology. Researching the Ecological Basis for Sustainable Agriculture. Springer, Berlin, ISBN 0-387-97028-2, 380 pp.

Grace, J., van Gardingen, P.R., Luan, J., 1997. Tackling large-scale problems by scaling up. In: Gardingen, P.R., Foody, G.M., Curran, P.J. (Eds.), Scaling-up From Cell to Landscape. Society for Experimental Biology. Seminar Series 63, Cambridge University Press, Cambridge, ISBN 0-521-47109-5, pp. 7–16, 386 pp.

Grigg, D., 1993. The World Food Problem, second ed. Blackwell, Oxford.

Hansen, B., Alrøe, H.F., Kristensen, E.S., 2001. Approaches to assess the environmental impact of organic farming with particular regard to Denmark. Agric. Ecosys. Environ. 83, 11–26.

Hanson, H.C., 1939. Ecology in agriculture. Ecology 20, 111–117.

Hardin, G., 1968. The tragedy of the commons. Science 162, 1243–1248.

Harper, J.L., 1974. Agric. Ecosyst. Agroecosyst. 1, 1–6.

Hecht, S., 1995. The evolution of agroecological thought. In: Altieri, M (Ed.), Agroecology: The Science of Sustainable Agriculture. Westview Press, CO, USA, ISBN 0-8133-1764-9, pp. 1–20, 433 pp.

ISIS-SCI, 2001. Science Citation Index Expanded (http://www.isinet.com). Institute for Scientific Information, Thomson Scientific, Philadelphia, PA, USA.

Lambert, J.D.H., Brubacher, D., Arnason, J.T., 1990. Nutrient mobility in a shifting cultivation system, Belize, Central America. In: Gliessman, S.R. (Ed.), Agroecology. Researching the Ecological Basis for Sustainable Agriculture. Springer, Berlin, ISBN 0-387-97028-2, pp. 122–129.

Lerland, E., van Lansink, A.O., Schmieman, E., 2000. In: Summary from the Conference: Sustainable Energy—New Challenges for Agriculture and Implications for Land Use. Wageningen, The Netherlands, 18–20 May 2000.

Levins R., Lewontin R., 1985. The Dialectical Biologist. Harvard University Press, Cambridge, MA, ISBN 0-674-20281-3.

Longino, E., 1990. Science as Social Knowledge. Princeton University Press, Princeton, NJ, USA, ISBN 0-691-02051-5, p. 262.

Marceau, D.J., 1999. The scale issue in social and natural sciences. Can. J. Remote Sens. 25:4, 347–356.

Marshall, B., Crawford, J.W., Porter, J.R., 1997. Variability and scaling: matching methods and phenomena. In: Gardingen, P.R., Foody, G.M., Curran, P.J. (Eds.), Scaling-up From Cell to Landscape. Seminar Series 63, Society for Experimental Biology, Cambridge University Press, Cambridge, ISBN 0-521-47109-5, pp. 253–272, 386 pp.

Meadows, D.H., Meadows, D.L., Randers, J., Behrens, W.W., 1972. The Limits to Growth: A Report for the Club of Rome's Project on the Predcament of Mankind. Earth Island Ltd., London.

Merton, R.K., 1973. The normative structure of science. In: Storer, N.W. (Ed.), The Sociology of Science: Theoretical and Empirical Investigations. University of Chicago Press, Chicago, pp. 267–278.

de Molenaar, J.G., 1990. The impact of agrohydrological management on water, nutrients, and fertilisers in the environment of The Netherlands. In: Gliessman, S.R. (Ed.), Agroecology. Researching the Ecological Basis for Sustainable Agriculture. Springer, Berlin, ISBN 0-387-97028-2, pp. 275–304.

Nielsen V., Sørensen K.G., 1994. Green fields. Operational Analysis and Model Simulations. Report 59, National Institute of Agricultural Engineering, Bygholm, ISBN 87-7471-040-0, 155 pp.

Nissani, M., 1997. Ten cheers for interdisciplinarity: the case for interdisciplinary knowledge and research. Social Sci. J. 34 (2), 201–216.

Odum, H.T., 1971. Fundamentals of Ecology, third ed. Saunders, Philadelphia, ISBN 0-7216-6941-7, 574 pp.

Oldeman, L.R. et al., 1991. World-Map of the Status of Human-Induced Soil Degradation. An Exlanatory Note, second ed. International Soil Reference and Information Centre and UN Environment Programme, Wageningen, The Netherlands and Nairobi.

O'Neill, R.V., DeAngelis, D.L., Waide, J.B., Allen, T.F.H., 1986. A hierarchical concept of ecosystems. Monogr. Popul. Biol. 23, 1–272.

Pearce, D., 1996. Measuring sustainable development. In: Nicolaisen, M. (Ed.), Four Lectures on Environmental Sciences. University of Copenhagen, Copenhagen, ISBN 87-87848-910.

Potrykus, I., 2001. In Vitro Cellular and Developmental Biology—Plants, vol. 37. MA, USA. p. 2; IAPTC&B J.

Rabbinge, R., 1997. Integrating policy and technical issues for international research on agriculture and the environment using systems approaches. In: Teng, P.S., Kropff, M.J. (Eds.), Applications of Systems Approaches at the Farm and Regional Levels, vol. 1. Kluwer Academic Publishers, Dordrecht, ISBN 0-7923-4285-2, pp. 249–262.

Rastetter, E.B., King, A.W., Cosby, B.J., Hornberger, G.M., O'Niell, V.R., 1992. Aggregating fine scale ecological knowledge to model coarse-scale attributes of ecosystems. Ecol. Appl. 2 (1), 55–70.

Reintjes, C., Haverkort, B., Waters-Bayer, A., 1992. Farming for the Future. Macmillan, London, ISBN 0-333-57011-1, 250 pp.

Refsgaard, K., Halberg, N., Kristensen, E.S., 1998. Energy utilization in crop and dairy production in organic and conventional livestock production systems. Agric. Syst. 57 (4), 599–630.

Riley, J., 2001. Preface: the indicator explosion: local needs and international challenges. Agric. Ecosys. Environ. 87 (2), 119–120.

Rosset, P.M., 1996. Input substitution. A Dangerous Trend in Sustainable Agriculture. Working Paper 4, Institute for Food and Development Policy, Oakland, CA, USA.

Schiermaier, Q., 2001. Designer rice to combat diet deficiences makes its debut. Nature 409, 551.

Schnapp, N., Schiermaier, Q., 2001. Critics claim 'sight-saving' rice is over-rated. Nature 410, 503.

SSCI, 2001. Social Sciences Citation Index. Institute for Scientific Information, Thomson Scientific, Philadelphia, PA, USA.

Squire, G.R., Gibson, G.J., 1998. Scaling-up and scaling-down: matching research with requirements in land management and policy. In: Gardingen, P.R., Foody, G.M., Curran, P.J. (Eds.), Scaling-up From Cell to Landscape. Seminar Series 63, Society for Experimental Biology, Cambridge University Press, Cambridge, ISBN 0-521-47109-5, pp. 17–34, 386 pp.

Stein, A., Riley, J., Halberg, N., 2001. Issues of scale for environmental indicators. Agric. Ecosys. Environ. 87 (2), 119–259.

Tansley, A., 1935. The use and abuse of vegetational concepts and terms. Ecology 16, 284–307.

Thomas, V.G., Kevan, P.G., 1993. Basic principles of agroecology and sustainable agriculture. J. Environ. Ethics 6 (1), 1–19.

Trewavas, A., 2001. Urban myths of organic farming. Nature 410, 409–410.

Van Latesteijn, H.C., 1997. Scenarios for land-use in Europe: agroecological options within socio-economic boundaries. In: Bouma, J., Kuyvenhoven, A., Bouman, B.A.M., Luyten, J.C., Zandstra, H.G. (Eds.), Eco-Regional Approaches for Sustainable Land Use and Food Production. Kluwer Academic Publishers, Dordrecht, ISBN 0-7923-3608-9, pp. 43–64.

Wagenet, R.J., 1998. Scale issues is agroecological research chains. Nutr. Cycling Agroecosys. 50, 23–34.

Waldon, H., Gliessman, S., Buchanan, M., 1998. Agroecosystem responses to organic and conventional management practices. Agric. Syst. 57 (1), 65–75.

Whyte, L.L., Wilson, A.G., Wilson, D., 1969. Hierarchical Structures. Elsevier, New York, ISBN 444-00069-0, 317 pp.

Wood, D., 1998. Ecological principles in agricultural policy: but which principles? Food Policy 23 (5), 371–381.

Ziman, J.M., 2000. Real Science: What It Is and What It Means. Cambridge University Press, Cambridge, 399 pp.