Multi-scale analysis and modelling of natural resource management options

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Abstract: Problems related to natural resource management (NRM) are typically complex and require integration of information across several scales and disciplines. Operational concepts to support such integration are scarce. Systems analysis and modelling can be helpful but the complexity of environmental systems also requires application of appropriate upscaling methods. Simultaneous assessment and modelling of system behaviour at several levels of organisation poses particular problems. Here, we provide an introductory overview on the critical issues related to multi-scale analysis and modelling of NRM. We describe the problems related to NRM within the context of systems thinking and hierarchy theory. Methods of upscaling commonly used in natural sciences are presented and discussed for application to NRM. The use of indicators is considered as alternative where systems understanding is less developed. The need for involving stakeholders in integrated assessments is stressed. We conclude that systems understanding required to support sustainable NRM is fragmented but that available knowledge can be utilised through integrated assessment modelling of sustainability indicators developed in close interaction with stakeholders. Advancement in multi-scale analysis and modelling will require (i) a problem driven approach; (ii) appropriate upscaling methods to reduce complexity of composite models; (iii) proper methods of stakeholder involvement; and (iv) software solutions to support flexible development of composite models;

Keywords: Complex systems, Impact assessment, Sustainability indicators, Stakeholders

1. INTRODUCTION

The complex problems of natural resource management (NRM) require integration of information across several scales and disciplines. Despite the enormous amount of literature that stresses the need for appropriate upscaling and integration, operational concepts to support such integration are rather scarce. Systems analysis and modelling is a possible approach to understand and assess complex relationships (Campbell and Sayer, 2003). However, the number of processes and the degree of added organisational information increase as the range of spatial and temporal scales is extended and models become too complex to approximate systems reality. The ambition to assess system behaviour simultaneously at several levels of organization is particularly challenging.

In this paper we provide an introductory overview of the critical issues related to multi-scale analysis and modelling of NRM. Problems are approached following the concepts of systems thinking and hierarchy theory. We attempt to clarify to what extent available up- and downscaling methods and the system concept as a whole can be used to support analysis and modelling of NRM options.

2. MODELLING ACROSS SCALES AND LEVELS OF ORGANISATION

2.1 System thinking, complexity and hierarchical structures

Systems theory assumes that no matter how complex or diverse the world is, it will always be possible to identify different types of organization in it and these can be described by principles, which are independent from the specific issue subject to investigation. NRM problems are often characterized as complex but the notion of complexity is vague. The simplest definition of a complex system refers to the whole that is more than the mere sum of its parts implying that understanding of the components of a system is not sufficient to understand its overall behaviour. Hierarchy theory offers a concept for the investigation of systems that operate on several spatio-temporal scales (Weston and Ruth, 1997). It is a branch of general systems theory and has emerged as part of a movement towards a general science of complexity. It focuses on levels of organization and issues of scale and the perspective of the observer of the system plays an important role. An example for hierarchical systems is the biological organisation as commonly used in ecology and environmental sciences with levels such as organism, population, community, ecosystem etc. (Fig. 1).

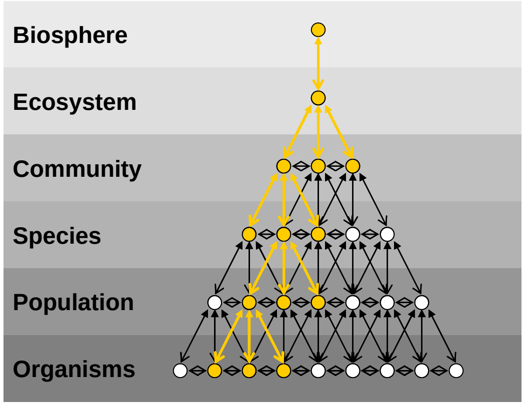

Figure 1. Schematic representation of a hierarchical system with fully (white circles) or partially (orange circles) nested sub-systems. Proper scaling (e.g. development of summary models) may reduce the nested detail.

Hierarchical systems have an organisational structure that refers to the shape of a pyramid, with each row of objects linked to objects directly below (Fig. 1). Thus, at a given level of resolution, a system is composed of interacting objects/components (i.e., lower-level entities or sub-systems) and is itself a component/object (or sub-system)) of a larger system (i.e., a higher level entity). In fact, such nested systems are commonly called holarchic systems with holons representing the objects/components of the system. To analyse such systems it is not always required to account for their full complexity; concentration on objects/components that are of particular importance for the behaviour of the system may suffice.

Scale issues are of critical importance when describing processes. The system level (i.e. the level of interest with respect to behavioural changes) is simulated considering lower (or higher) level processes and relationships. From a modelling perspective it generally suffices to move more than two levels down in the hierarchy in search for a mechanistic understanding of the system’s responses. Proper scaling may reduce complexity (Parker et al., 2002); only important relationships appear at the higher hierarchical levels and thus reduce the complexity of components and simplify the analysis and interpretation of results.

2.2 Changes in space, time and system functioning

There is some confusion about terms such as scale, and level, as well as scaling, projection, aggregation and integration, which are often used interchangeably. While scale refers to physical dimensions (most commonly space and time) of observed entities and phenomena (meaning that dimensions and units of measurement can be assigned), the term level refers to *level* of organization in a hierarchically organised system (O'Neill and King, 1998) such as the biological organisation. Changes in scale are usually continuous, e.g. changes in space or time. In contrast, changes in level are discrete, e.g. from community to ecosystem. However, moving up the organizational hierarchy from one level to the next usually implies that relevant spatial and temporal scales also change (Fig. 2).

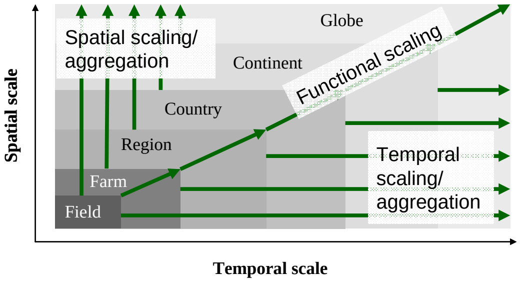

Figure 2. Schematic representation of scales and levels of organization. Field, farm, region etc. are different levels of organisation and changes from one level to the next are discrete. Changes in temporal and spatial scale are continuous. Moving between levels implies that scale will also change.

Scaling involves a change in the spatial and temporal resolution of a model to be consistent with the data available to derive it (Rastetter et al., 2003). For instance, a plant productivity model based on the concept of radiation use efficiency (RUE) may have originally been developed for field level applications at a daily time scale. Any application at larger spatial or temporal scales will require that RUE needs to be scaled to the new level of application. In addition, other processes may become important such as heterogeneity in farm management or technology development which will require not only scaling but reformulation of the model. In other words, when moving far enough across scale, the dominant process(es) will change (O'Neill and King, 1998). Such level related changes in model content and structure are considered here as functional scaling.

In the absence of sufficient understanding of higher level systems as relevant for NRM, lower level models are applied repeatedly across space and time without changing its scale. This we call projection (Rastetter et al., 2003). The term aggregation refers more specifically to the sum, count or average of the underlying detail and is commonly used in association with spatial and temporal scaling. Integration is closer related to abstraction (from reductionisms) and may better be associated with functional scaling (Fig. 1). It implies that (functional) relationships that determine systems behaviour at one level are not consistent across levels of organisation.

2.3 Methods of upscaling in natural sciences

Different methods have been employed in natural sciences to estimate systems responses across scales or levels, (Fig. 3). The simplest approach is the extrapolation of results obtained at a detailed level up to a higher level (Fig. 3a). More advanced attempts use some form of aggregation of the underlying detail to project the results from one level to the next level(s) (Figs. 3b, c). Such approaches may aggregate either the model input or the simulated output data. Aggregation of input data results in simulation errors if process responses to input variables are non-linear - as is true for most environmental systems (Rastetter et al., 1992). However, many scaling attempts are based on this method and have to be judged critically. To account for such non-linearity, multi-site simulations within a region and aggregation of output data (or projection) is more appropriate, but is often restricted by lack of data availability and number of simulation runs.

Some approaches have tried to couple models from different levels of organization ranging from e.g. leaf to ecosystem (Anderson et al., 2003), (Fig. 3d). Again, the input data and model parameters requirements are high and their availability often limited for application across multiple regions. To overcome the problem of ineffective modelling detail, data requirements and/or simulation runs, important relationships may be calculated from lower-level model simulations (Fig. 3e). The derived parameters can be used as inputs for higher-level models. For instance, yield response functions have been developed for climate change impact assessment studies (Rosenzweig et al., 1999; Iglesias et al., 2000; Parry et al., 2004). Such pre-derived relationships have the advantage of reducing the simulation time but do not enable consideration of complex interactions and feedback mechanisms.

Finally, instead of data or parameter aggregation, models might be aggregated (or rather integrated) into higher level models (Giller et al., 2006), (Fig. 3f). Structure and detail of the integrated, the summary model at the higher level(s) will depend on the objectives of the model, the understanding of the system under investigation and the skills of the modeller. To avoid unnecessary detail the importance of components or processes that determine the higher-level systems behaviour must be understood and eventually modelled in adequate and consistent detail. Several techniques by which lower-level relationships can be scaled-up have been developed (Rastetter et al., 1992).

The methodology that will finally be implemented depends on the research question, the behaviour of the system, the understanding of this behaviour (including the underlying processes, mechanisms and their interactions), and the availability of data.

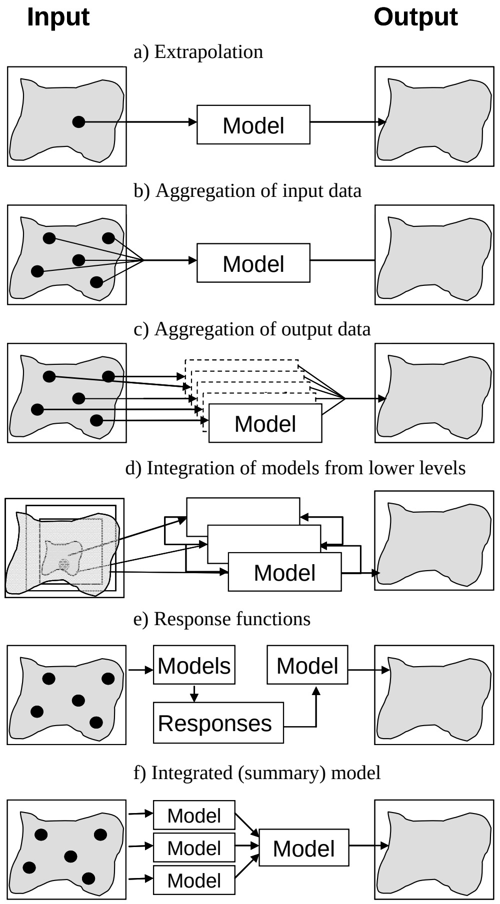

Figure 3. Approaches used to scale (up) ecosystem productivity from field to higher levels. See text for further explanation.

2.4 Multi-scale modelling

The approaches described above refer to situations where information is transferred across levels of organization to explain behavioural changes at a given system level. However, in NRM there is interest in behavioural changes that occur simultaneously at several levels of organization. For instance impacts of changes in agricultural policy on sustainability and sustainable development must include assessment of responses at field, farm and regional or even higher levels. While farmers may be interested in plot yields and farm performance, other stakeholders, such as regional planners and policy makers may have an interest in understanding associated impacts on watersheds, landscapes or contributions to greenhouse gas emissions and climate change (Laborte et al., forthcoming). In such cases several relevant system levels can be identified and may require modelling in some detail resulting in rather complex composite model. Particularly challenging is the linking of models with different spatial and temporal detail. Nested simulation (see Fig. 3d) is presently the most common approach but resulting composite models are typically complex with high demands for input and computation time.

3. LINKING DISCIPLINES IN INTEGRATED SYSTEMS

3.1 Multiple hierarchies and the role of indicators

Natural systems are strongly affected by human activity. In agriculture, which comprises about 38% of all global land area (FAO, 2000), NRM also depends on economic and social conditions which need to be considered in assessing NRM options. Consequently, various perspectives become important representing different aspects of the system (such as biophysical, social, economic, political etc.). For each aspect one or more (depending on the issue) hierarchical systems can be identified (Fig. 4a). Most critical is that these different aspects represent different conceptual paradigms and that their various levels do not necessarily match in time and space. For instance, ecosystems do not follow administrative or cultural boundaries and the dynamics of biological and socio-economic systems may differ. Such disjunct and overlapping hierarchies need to be considered. Moreover, terms are defined and used differently in the different domains. For instance, productivity, yield and supply are terms that are used across disciplines but with a different meaning. Linking models from the different domains requires matching of the spatial and temporal detail of the models and of the definitions of transferred variables.

The ultimate goal of NRM is to improve system sustainability and sustainable development at large, but the concept of sustainability is elusive. From a systems perspective, a system is sustainable if it exists and can persist its existence in the future. However, understanding and modelling of NRM systems is far from complete. Alternatively, indicators may provide approximate information about the state of the system and its response to impact. From these indicators conclusions can be derived about its dynamics towards sustainability and sustainable development. The selection of indicators is critical as that is guided by assumptions on the definition of sustainability and sustainable development. As presently a multitude of definitions is available, the number of indicator frameworks to support indicator selection is also large.

Importantly, modelling can support derivation of indicators from level- and domain-related understanding of processes and relationships (Fig. 4b), thus avoiding application of inadequate (dis)aggregation procedures for indicators that often fail to represent level-specific mechanisms which determine indicator responses to impact.

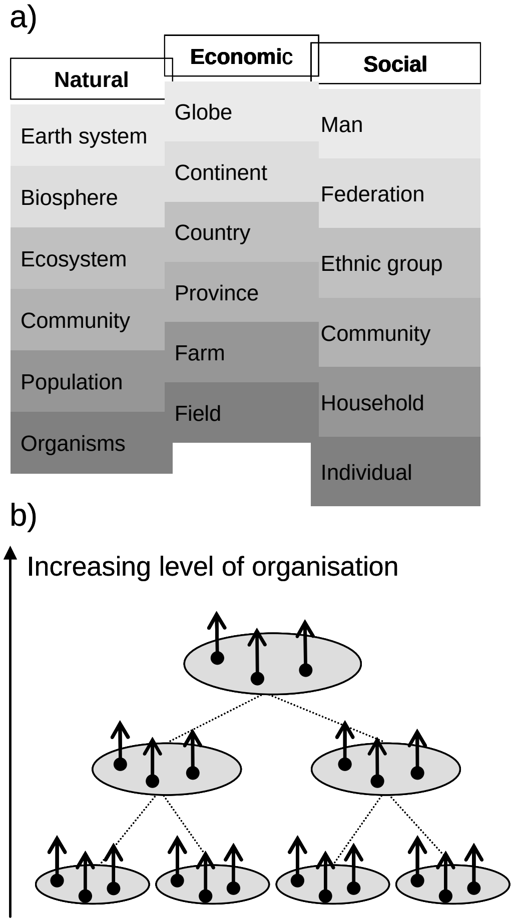

Figure 4. a) Integrated system with multiple hierarchies and b) level and system specific development of indicators (symbolised by vertical bars).

3.2 Integrated assessment and the role of stakeholders

Integrated assessment and modelling (IAM) has been suggested as a support to the management of complex environmental systems. It is a way of systems thinking; a way to balance the different aspects (biophysical, institutional, social and economic) of the system (Harris, 2002). Importantly, IAM has been defined as “an interdisciplinary and participatory process combining, interpreting and communicating knowledge from diverse scientific disciplines to allow a better understanding of complex phenomena" (Rothman and Robinson, 1997). Thus, in IAM the process of understanding and management of environmental systems is considered a joint activity between scientist and (all) relevant stakeholders. In this respect, IAM is responsive to (groups of) stakeholders (Parker et al., 2002) and modelling is not seen as a purely scientific activity that provides prescriptions for decision makers but as a participatory approach with strong emphasis on communication. Systems analysis can be conducted as a multi-stakeholder participatory process (Campbell et al., 2001).

The involvement of stakeholders is particularly crucial for the specification of indicators (López-Ridaura, 2005). As the identified indicators represent the understanding of sustainability and sustainable development, stakeholder involvement for indicator selection will ultimately determine the perception of these terms. Consequently, the considered stakeholders should represent the levels of organisation, and disciplines found important from the perspective of systems analysis to ensure sufficient integration for the NRM problem to be addressed.

3.3 A framework for integrated assessment and modelling

Few efforts have been made to develop modelling frameworks for integrated assessment and modelling (Laborte et al., forthcoming).

A recent attempt which follows up on the conceptual ideas presented above is the computerised integrated framework SEAMLESS-IF presently developed in an EU funded integrated project (van Ittersum et al., 2006). The framework aims to assess, *ex-ante*, agricultural and environmental policies across a range of scales, from field-farm to region, EU25 and globe. It has the following specific features and capabilities: (i) a multi-perspective set of economic, social and environmental indicators of the sustainability and multifunctionality of systems, policies and innovations in agriculture and agroforestry, derived through so-called indicator frameworks facilitating interactive and systematic selection of indicators with users and stakeholders; (ii) quantitative models and tools and databases for integrated evaluation of agricultural systems at multiple scales and for varying time horizons; and (iii) a software architecture, SeamFrame, that allows reusability of model and database components and knowledge, also ensuring transparency of models and procedures developed. An example of the domains for which models are available in an initial version of the framework is presented in Figure 5. The model composite considers different scaling methods such as nested modelling (Fig. 3d), the use of response functions (Fig. 3e) and summary models (Fig. 3f) and approaches to project from multiple simulations within a region (Fig. 3c).

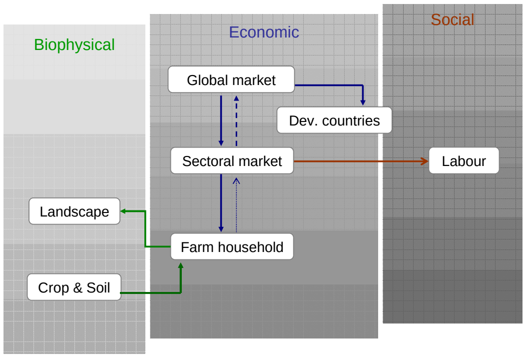

Figure 5. Domains representing different system aspects and levels of organisation for integrated assessment of policy changes on agricultural sustainability for which models will be integrated and linked within the modelling framework SEAMLESS-IF. For detailed description see van Ittersum et al. (2006).

4. CONCLUSIONS

Systems understanding required to support NRM is fragmented. However, available knowledge can be made available through integrated assessment modelling to assess sustainability indicators developed in close interaction with stakeholders. Advancement in multi-scale analysis and modelling will require:

- problem driven approaches; the problem will define which disciplines and scales or levels of organisation and associated models should be considered;
- scaling approaches to reduce complexity of composite models;
- proper methods and ways of involving stakeholders; and
- software solutions to support flexible development of composite models.

The selection of models and stakeholders should adequately represent the complexity of levels and disciplines relevant for the specific problem.

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