International Congress on Environmental Modelling and Software

3rd International Congress on Environmental Modelling and Software - Burlington, Vermont, USA - July 2006

Jul 1st, 12:00 AM

A GIS-based Framework To Model Farm And Landscape Scale Indicators For Sustainable Rural Development

C. Kjeldsen

Tommy Dalgaard

P. K. Bøcher

A GIS-based Framework To Model Farm And Landscape Scale Indicators For Sustainable Rural Development

C. Kjeldsen, T. Dalgaard, P. K. Bøcher

Danish Institute of Agricultural Sciences, Department of Agroecology, Tjele, Denmark

Chris.Kjeldsen@agrsci.dk; Tommy.Dalgaard@agrsci.dk; Peder.Bocher@agrsci.dk

Abstract: Facilitation of sustainable rural development has a high priority on the European Union policy agenda and extensive research on this subject has been started. This paper presents results from the strategic EU research project MEA-scope (www.MEA-scope.org), and the development of a GIS-based framework to model farm and landscape scale indicators for rural sustainability. Problems in scaling information between the farm- and the landscape levels in particular are addressed. Both aggregation and disaggregation techniques are needed to convey information between the two levels. This is demonstrated in a case study of (1) landscape level aggregation of farm level information, from statistics and from farming simulation models, and (2) disaggregation of landscape level features such as soil, climate and land use types, for farm level modelling. This interaction between farm- and landscape level information sources gives the opportunity for integrated modelling of farm level indicators (e.g. nutrient balances, energy use, farmers age, employment etc.) and landscape level indicators (e.g. groundwater supply, corridors between habitats and population density). The framework developed gives valuable inputs to the discussion of which indicators are valid at farm and landscape level, respectively, and whether they have different interpretations at different scales. Whether the demonstrated aggregation and disaggregation techniques are sufficient in terms of the inclusion of linear, non-linear or other emergent effects of scale, is discussed.

Keywords: multifunctionality; downscaling; upscaling; emergence; GIS

1. INTRODUCTION

The concept of multifunctionality has gained an increasing use as a new paradigm for agricultural and rural development in the European Union in recent years [FAO, 2000, OECD, 2001, van Huylenbroeck & Durand, 2003]. The use of the concept stems from the recognition that rural space is not just a productive space, but also a consumptive space, where non-commodity as well as commodity outputs are produced and consumed [Durand & van Huylenbroeck, 2003]. Some would argue that agriculture has always been multifunctional, but what is new in this context is that an increasing public demand for non-commodity outputs can be identified. This creates a tension between the continued externalisation of non-commodity outputs, which can be attributed to the ongoing modernisation of agriculture, and the public demand [Belletti, et al., 2003]. The particularly challenging aspect of the concept is the wide range of economic, social and environmental functions that should be considered relevant for sustainable rural development. Adding further to this complex task, these functions can be analysed and evaluated at a wide range of analytical scales, ranging from global level to the level of individual farms or rural residents. The development of an analytical framework to investigate multifunctionality issues should thus include the utilisation of techniques for addressing issues at the appropriate level of inquiry i.e. a scaling framework. This paper presents an example of such a framework for handling the multidimensional, multilevel character of multifunctionality.

2. ELEMENTS OF THE APPROACH

2. 1 The MEA-scope framework

The five main objectives for the MEA-scope project include to provide: (1) further conceptual development of the multifunctionality concept, (2) development of quantitative tool for assessment of the multifunctionality impacts of Common European Agricultural Policy (CAP) reform scenarios, (3) answers to policy-relevant questions for implementation of the multifunctionality concept, (4) a demonstration of the operability of an integrated assessment framework and (5) scientific knowledge on specific questions regarding multifunctionality of agriculture, particularly with respect to spatial scale and regional differences [MEA-scope, 2004]. In this paper, we will focus on the issue of spatial scale and its significance on analysing multifunctionality of agriculture. The development of a quantitative tool which can assess impacts of CAP reform scenarios forms the centrepiece of the MEA-scope approach. The MEA-scope approach uses two main analytical scales, landscape level and farm level (Figure 1).

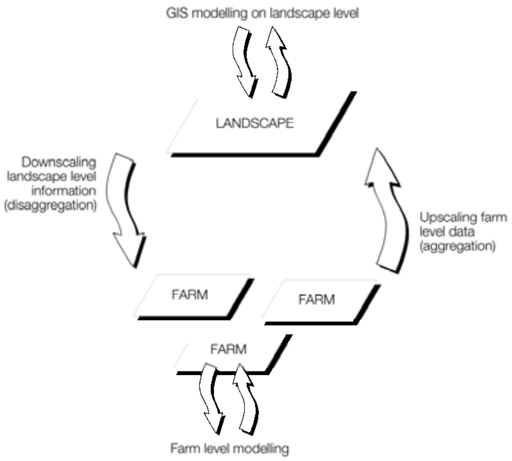

Figure 1: *The MEA-scope modelling framework*

Effects of CAP reform options, and in particular second-pillar options (support for rural development initiatives), are being modelled on farm level by a number of simulation models. These models are driven by higher-level data such as elevation data, farm economic statistics, soil texture and climate data. The output of the models is in turn being upscaled to landscape level and used as indicators for possible future states of the landscape following implementation of policy scenarios. This forecasting scenario approach to exploring pan-European policy options is common to related scenario studies [van Latesteijn, 1999, WRR, 1992], but differs in the sense that the modelling is carried out on a much more detailed scale, down to the level of individual farms. MEA-scope should thus be able to deliver results which are much more sensitive to contextual factors than studies operating on a much coarser scale.

2. 2 Case areas

In order to reflect regional differences, seven different case areas within the European Union were studied. The case areas exhibit significant differences in terms of farming and landscape structure.

Figure 2: *Case areas of MEA-scope*

Also in terms of institutional settings, the case areas also exhibit great heterogenity. However, a common feature in all case areas is the presence of significant beef production which is a farming style deemed particularly relevant as a target for second-pillar policies and the delivery of non-commodity outputs [Piorr, et al., 2005].

2.3 Farm level simulation models

Impacts on farm level are being modelled through the utilisation of three simulation models, each of them describing different aspects of the farm operation. Structural development of the farms is simulated using the agent-based model AgriPoliS, which utilises a stochastic modelling approach [Happe, et al., 2004]. The model simulates how farmers, as individual agents, respond to production opportunities in relation to their given context (age, initial farm type and size) with regards to the purchase, rental or sale of property. Farmer decisions concerning land use and management are simulated using the linear optimisation model MODAM [Zander, 2003], based on the structural context supplied by AgriPoliS. The flow of nutrients within the farming system and losses to the environment are being simulated using the whole farm model FASSET [Berntsen, et al., 2003], using the management data simulated by MODAM.

2.4 Indicators

The simulation models yield abundant data on the development of the individual farms. More than 100 indicators have been identified as relevant to to the project [Waarts, 2005]. The indicators can be divided into three thematic groups, respectively economic, social and environmental indicators.

Table 1: *Types of indicators in MEA-scope*

Type of indicator	Subtypes
Economic	Costs, Income, rural entrepreneurial activities
Social	Cultural heritage, non-farming activities, social infrastructure, consumer interests
Environ-mental	Biotic and abiotic environmental quality, biodiversity and habitats, landscape and land use

Most of the indicators are generated at farm level by the model simulations, whereas landscape level indicators must be modelled in GIS. Their development is not modelled dynamically but can be analysed in relation to the development of the agricultural space within the case areas.

3. ANALYTICAL ISSUES

3.1 Issues of scale

In landscapes as in other complex ecological systems, phenomena occur on very different scales of space, time and organisation [Levin, 1992, Levin & Pacala, 1997]. There is no single natural scale at which inquiry should be performed; any system shows patterns at a range of scales. The description of a system thus depends on the perspective chosen, and it is essential to understand not only how patterns and dynamics vary with scale, but also how patterns at one scale are connected with processes operating at other scales. In a modelling framework as the one proposed for MEA-scope, conveyance between scales is essential. This is also true in a policy perspective, since many policy issues are formulated at a coarser scale than research operates [van Latesteijn, 1999]. The MEA-scope modelling framework involves both upscaling and downscaling of information between the farm and the landscape level (Figure 1). It is therefore important to question how this scaling might influence the indicator results (Table 1). Here, we will focus on analytical methods to analyse downscaling and upscaling issues through examples of the important factors to consider when scaling in either direction (sections 4.2 and 4.3). In both of the cases, we will use examples from the Danish case area.

3.2 The Modifiable Areal Unit Problem

One well-known problem when transferring spatial data between different analytical levels, and in particular when aggregating data, is known in the geographical and statistical literature as the *Modifiable Areal Unit Problem* (MAUP) [Openshaw, 1984]. The MAUP consists of two closely related aspects: (1) *the scale problem* and (2) *the zoning problem* [Jelinski & Wu, 1996]. The scale problem refers to the problem that arises when data are averaged in an aggregation process, causing important variability within data to be lost. The other aspect refers to the zoning of spatial units used for data collection, where the geometry of sampling units can influence subsequent modelling results. Different approaches have been proposed to overcome these problems. Some approaches, such as the basic entity approach [Fotheringham & Wong, 1991] or the optimal zoning approach [Openshaw, 1984] aim to overcome the MAUP by optimising the data sampling procedure. But these approaches can be difficult to implement, since they hinge on the possibility of defining basic ecological entities or optimal sampling zones, which in practice are highly contextual concepts depending on what the objectives behind a given study is [Fotheringham & Wong, 1991]. Instead of these basically context-independent approaches, a sensitivity approach has been proposed [Jelinski & Wu, 1996], which seeks to address the questions of which variables are sensitive to scale varitions and to what degree, and thus make the conclusions from such studies both scale- and zoning system specific. However, there remains the practical issue that a complete sensitivity analysis for a project like MEA-scope would be very time-consuming, given the number of scales and variables involved. We will try to demonstrate the problem, using two different versions of soil texture data as an example.

3.3 A scaling framework

Based on the concepts of hierarchy and scale [Allen & Hoekstra, 1992], we distinguish between three basic types of scaling: 1) linear scaling, 2) non-linear scaling, and 3) hierarchical scaling [Dalgaard, et al., 2003]. The differences between these types are illustrated in Figure 3, showing two different pathways for the aggregation of farm level data and the modelling of landscape level indicator results. In the dotted pathway, models are applied before aggregation and averaging of the results; in the solid pathway data are aggregated and averaged before modelling. In section 4.3 such two pathways are exemplified via the modelling of either all farms in a landscape separately, or the modelling of one average farm representing the whole landscape. If there is no significant difference between the results of the two pathways, the properties scale linearly. If the result derived from the dotted pathway differs significantly from that of the solid pathway, the properties scale non-linearly because the model includes a number of non-linear functions, so the sum of disaggregated model results differs from those based on aggregated, averaged data [Marshall, et al., 1998]. In some cases, it is not possible to model the landscape level indicator results required via linear or non-linear scaling of farm level data. This is because processes that operate above the farm scale modify the outcomes and in this situation a hierarchical scaling procedure is needed that includes emerging factors in addition to linear or non-linear scaling functions. However, it should be added that a close inspection is necessary to determine whether the observed non-linearity or emergence is caused by MAUP effects or emergent factors, since the former applies in both cases.

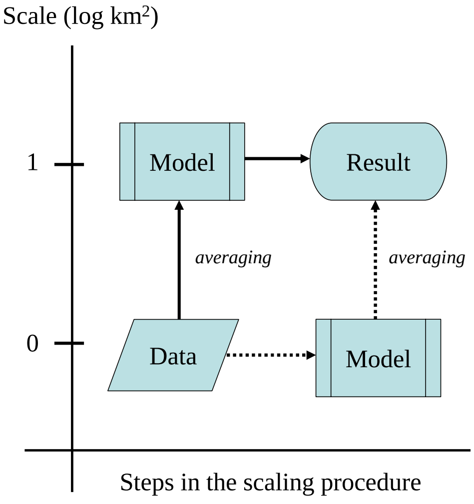

Figure 3: *Two different pathways for data and model result aggregation (based on [Bierkens, et al., 2000, Dalgaard, 2001, Marshall, et al., 1998]*

The following four criteria can be used in order to evaluate proper handling of scaling issues in relation to the modelling of indicators: (1) Identify the indicators needed and the scale where it is relevant to present the indicator results. (2) Determine at which scales data in relation to this indicator is available and collect relevant data. (3) Create a hypothesis of how this data can be transformed to indicator results at the relevant scale, either using linear, non-linear or hierarchical scaling procedures. (4) Test the hypothesis of criteria 3, with independently data sampled on the scale where indicator results are required according to criteria 1. Iteratively improve the criteria 3 hypothesis until you find a satisfactory scaling function to address the problem identified [Dalgaard, et al., 2003].

4. RESULTS AND EXAMPLES

4.1 Downscaling from landscape level

In MEA-scope, two levels of resolution in soil texture data are used as input data to the farm level simulation models. The first map is based the soil database of the European Commission Joint Research Centre [ECJRC, 2004] (figure 4).

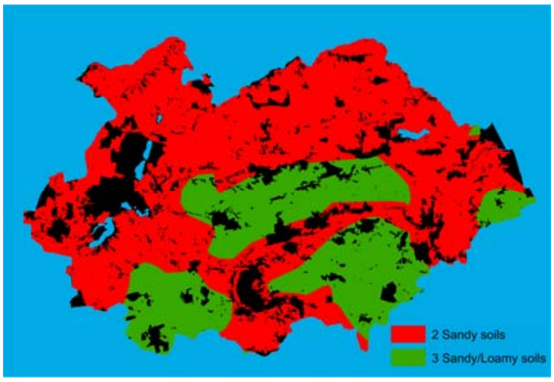

Figure 4: *Soil texture in ECJRC soil map*

The areas in black are cities, forests and other areas where soil texture could not be determined. The other map (figure 5) is on a much finer scale and is based on the Danish soil classification [DJF, 2005]. These two maps can be viewed as two separate sampling scales on landscape level and as such are well-suited for illustrating the MAUP. The difference between the two maps can be expressed as the combined effect of both the scale and the zoning problem, since both the level of resolution and the geometry of the spatial units differ (table 2). These pre-modelling comparisons (without comparing effects on model output) give sufficient indication that there is indeed a MAUP to account for in the MEA-scope context, and that strategies for coping with it must be implemented within the framework of the project.

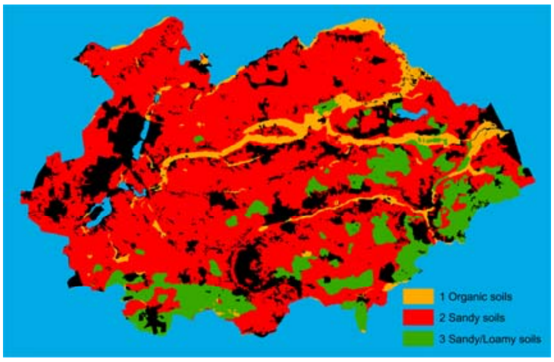

Figure 5: *Danish soil map 1:50000*

Table 2: *Distribution of soil classes, % of area*

Map	Organic soils, %	Sandy soils, %	Sandy-loamy soils, %
ECJRC	0	69	31
DK	8	77	15

4.2 Upscaling from farm level

The nitrogen (N) surplus is an important indicator for agricultural nitrates pollution of water resources [Dalgaard, et al., 2002] and will be used in the following case study of upscaling from farm to landscape level. In the MEA-scope project, N-surplus is a relevant indicator for the effect of agriculture on the landscape level environmental quality (criteria 1 of the scaling evaluation presented in section 3.3). However, N-surplus is calculated on the farm level (criteria 2), and procedures to upscale from farm to landscape level are needed. A first hypothesis (criteria 3) of how to scale N-surpluses from farm to landscape level would be a linear scaling procedure, where landscape level N-surplus is modelled from averaged farm data. However, such scaling procedure might be too simple, and the implementation of a non-linear scaling procedure is necessary. This is illustrated in Figure 6, presenting N-surplus as a function of livestock density. If we assume the average landscape level livestock unit (LSU) density for the landscape is 1.5 LSU/ha (the solid arrow in figure 6, corresponding to the solid pathway in Figure 3), the corresponding N-surplus is around 180 kg/ha. However, in reality there is a great variability in the livestock densities of farms. Therefore, following the dotted pathway of figure 3, where the N-surplus of each farm is estimated separately before aggregation and averaging, would lead to a different result. For example, two equally sized farms with 0.5 LSU/ha and 2.5 LSU/ha would lead to an estimated N-surplus of around 100 kg/ha and 300 kg/ha, respectively (the dotted arrows in Figure 5), and a resulting average N-surplus of 150 kg/ha.

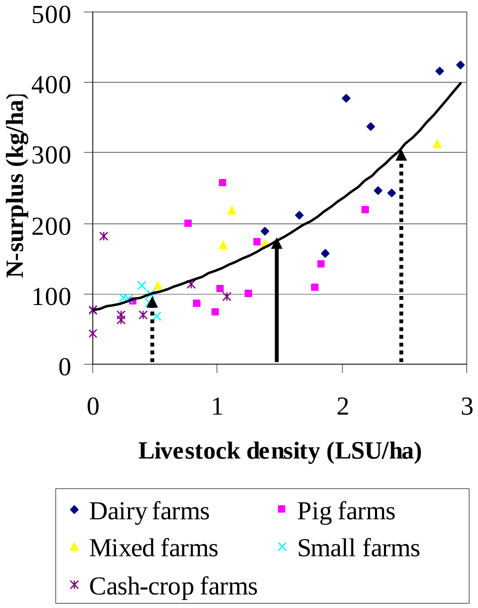

Figure 6: *N-surplus from 41 farms within the Danish case area [Dalgaard, et al., 2002]*

In conclusion, implementation of non-linear scaling procedures is important for the estimation of indicators for N-losses, and should be implemented within the MEA-scope modelling framework. In addition, hierarchical scaling factors like emerging effects of shelter belts and other landscape structures outside the agricultural fields might be important, but is not included in the present case study.

5. OUTLOOK

The overall conclusion to the present study is that scale definitely matters in relation to the MEA-scope framework. Approaches for dealing with the MAUP as well as performing linear, non-linear and hierarchical scaling processes must be an integrated part of the research framework. The further development of such a framework will be of invaluable importance to guiding inquiry into what indicators are valid at which scale when analysing the complex interactions between farming, landscape and rural development.

6. REFERENCES

Allen, T. F. H. & Hoekstra, T. W., *Toward a unified ecology*, Columbia University Press, 1992.

Belletti, G., Brunori, G., Marescotti, A. & Rossi, A., *Multifunctionality and rural development: a multilevel approach*, van Huylenbroeck, G. & Durand, G., Multifunctional Agriculture: A New Paradigm for European Agriculture and Rural Development, Ashgate, Aldershot, UK, 2003: 55-80

Berntsen, J., Petersen, B. M., Jacobsen, B. H., Olesen, J. E. & Hutchings, N. J., Evaluating nitrogen taxation scenarios using the dynamic whole farm simulation model FASSET, *Agricultural Systems 76*(3), 817-839, 2003

Bierkens, M. F. P., Finke, P. A. & de Willingen, P., *Upscaling and downscaling methods for environmental research*, Kluwer Academic Publishers, Dordrecht, NL, 2000.

Dalgaard, T., *Simulation and generalisation of agricultural resource use*, Ph.D., Danish Institute of Agricultural Sciences, Tjele, 2001

Dalgaard, T., Heidmann, T. & Mogensen, L., Potential N-losses in three scenarios for conversion to organic farming in a local area of Denmark, *European Journal of Agronomy 16*(3), 207-217, 2002

Dalgaard, T., Hutchings, N. J. & Porter, J. R., Agroecology, scaling and interdisciplinarity, *Agriculture, Ecosystems & Environment 100*(1), 39-51, 2003

DJF, *Den danske jordklassificering [The Danish soil classification]*, Danish Institute of Agricultural Sciences, Tjele, DK, 2005

Durand, G. & van Huylenbroeck, G., *Multifunctionality and rural development: a general framework*, van Huylenbroeck, G. & Durand, G., Multifunctional Agriculture: A New Paradigm for European Agriculture and Rural Development, Ashgate, Aldershot, UK, 2003: 1-16

ECJRC, *The European Soil Database, Version 1.0*, The European Commision Joint Research Centre, 2004

FAO, *Twenty Second Regional Conference for Europe: Multifunctional Character of Agriculture and Land*, FAO, Porto, Portugal, 2000.

Fotheringham, A. S. & Wong, D. W. S., The modifiable areal unit problem in multivariate statistical analysis, *Environment and Planning A 23*(7), 1025-1044, 1991

Happe, K., Balmann, A. & Kellermann, K., *The agricultural policy simulator (AgriPoliS) - an agent-based model to study structural change in agriculture (version 1)*, IAMO - Institute of Agricultural Development in Central and Eastern Europe, 2004.

Jelinski, D. E. & Wu, J., The modifiable areal unit problem and implications for landscape ecology, *Landscape Ecology 11*(3), 129-140, 1996

Levin, S. A., The problem of pattern and scale in ecology, *Ecology 73*(6), 1943-1967, 1992

Levin, S. A. & Pacala, S. W., *Theories of simplification and scaling of spatially distributed processes*, Tilman, D. & Kareiva, P., Spatial Ecology: the role of space in population dynamics and interspecific interactions, Princeton University Press, Princeton, New Jersey, 1997: 271-295

Marshall, B., Crawford, J. W. & Porter, J. R., *Variability and scaling: matching methods and phenomena*, Gardingen, P. R., Foody, G. M. & Curran, P. J., Scaling-up from cell to landscape, Cambridge University Press, Cambridge, UK, 1998: 253-272

MEA-scope, *The objectives of MEA-scope*, MEA-scope website www.mea-scope.org, 2004.

OECD, *Multifunctionality: towards an analytical framework*, OECD, Paris, 2001.

Openshaw, S., *The modifiable areal unit problem*, GeoBooks, Norwich, UK, 1984.

Piorr, A., Uthes, S., Müller, K., Sattler, C. & Happe, K., *Design of a MEA-compatible multifunctionality concept*, Centre for Agricultural Landscape and Land Use Research (ZALF), Müncheberg, Germany, 2005.

van Huylenbroeck, G. & Durand, G., *Multifunctional agriculture: A new paradigm for European agriculture and rural development*, Ashgate, Aldershot, 2003.

van Latesteijn, H. C., *Land use in Europe - a methodology for policy-oriented future studies*, Sdu Uitgevers, The Hague, 1999.

WRR, *Ground for choices - Four perspectives for the rural areas in the European Community*, WRR - Netherlands Scientific Council for Government Policy, The Hague, 1992.

Waarts, Y., *Indicators for the quantification of multifunctionality impacts*, European Centre for Nature Conservation, Tilburg, The Netherlands, 2005.

Zander, P., *Agricultural land use and conservation options: a modelling approach*, Ph.D. dissertation, Wageningen Agricultural University., Wageningen, Holland, 2003