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Integrative modelling approaches for analysis of impact of multifunctional agriculture: A review for France, Germany and The Netherlands

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Abstract

This paper reviews integrative modelling approaches which were developed to analyze the impact of multifunctional agriculture, or which may be used as such. The approaches are integrative in combining multiple goals of agriculture, and confronting these with current or potential performance of agricultural land-use systems at different spatial scales. The paper focuses on France, Germany and The Netherlands, countries with a track record in quantitative systems modelling, to identify convergence of concepts and technologies applicable to assessment of multifunctional agriculture and to establish shortcomings through analysis and comparison of 15 integrative modelling cases. An analytical framework for comparison is applied, based on a conceptual model of goal-oriented evaluation of agriculture. Results demonstrate unexpectedly large differences between countries in the number of integrative models; the nature of agro-ecological or bio-economic relations used, and target audience. Common elements were a focus on methodology development rather than answering questions of specific clients, limited attention for model evaluation and impact analysis, and an imbalanced attention for economic and abiotic environmental indicators at the expense of biotic, landscape and social indicators. None of the approaches specifically addressed multifunctionality of agriculture. In the discussion we argue that to be relevant research efforts aimed at supporting policy development for multifunctional agriculture cannot concentrate on filling gaps in knowledge and technology alone, but need to concern the process of utilization of knowledge as well.

Keywords: Multifunctional agriculture; Integrative models; Goal-oriented approaches; Heuristics; Optimization; Simulation; Agro-ecology

1. Introduction

The notion of multifunctionality of agriculture emerged in the policy arena when it was referred to in the Agenda 21 documents of the Rio Earth Summit of 1992, ‘‘particularly with regard to food security and sustainable development’’ (UNCED, 1992). In 1998 the Organisation for Economic Co-operation and Development (OECD) expanded upon the concept in its Declaration of Agricultural Ministers Committee, stating that agriculture is multifunctional when it has one or several functions in addition to its primary role of producing food and fibre. Specific reference was made to contributions to landscape, environmental benefits and contributions to socio-economic viability of rural areas. In its framework for analysis of multifunctionality OECD interpreted the notion in a descriptive rather than a normative economic sense, by defining multifunctionality as a set of interlinked outputs from a production activity, where some outputs are commodities or private goods that can be marketed, and others are non-commodities or public goods (OECD, 2001). This concept of joint production which is basic to the economic interpretation of multifunctionality is explained in an early ground-breaking paper

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by Vatn (2000). A normative economic interpretation of the notion was adopted by the European Union and used in its Agenda 2000 agricultural reform, by recognizing and encouraging the range of services provided by farmers and advocating a multi-sectoral and integrated approach to the rural economy. The notion was used by the EU and others in the WTO negotiations on agricultural trade liberalization, where it was seen by the major exporting countries of the Cairns Group in particular as an excuse to continue market protection. Despite the political controversies over the economic interpretation of the notion, many organizations used and developed the term to point to the goods that are provided by agriculture without being sold in the marketplace (e.g. FAO, 1999; Boody et al., 2005).

In a number of European countries the notion of multifunctional agriculture has become embedded in legislation; in others it is used in relation with notions such as sustainable development or rural development (Kröger and Knickel, 2005). From a scientific viewpoint, multifunctional agriculture can be perceived as a concept to understand and analyze the role of agriculture in society. Also in this domain, different conceptualizations occur. In addition to OECD's market economic interpretation, conceptualizations have emerged which emphasize the spatial planning nature, the role of the farmer and the role of public regulation (Van der Ploeg, personal communication April 2005). The full variation and impact of these conceptualizations was recently described by Le Cotty et al. (2005). A basic problem in many conceptualizations is their partial nature, originating from a disciplinary viewpoint, which obscures assessment of synergies between functions of agriculture.

The policy issue at stake when discussing multifunctionality of agriculture is that the public goods provided by agriculture do not accrue automatically as inevitable outcomes of any type of farming, but vary widely based on farming practices, farm size, farm location and interactions between these variables. This leads to questions on policy incentives and regulations, their relation to multifunctional goals of society, and the way in which the outcomes of policies are affected by the locality-specific aspects of farming. These questions play a role during policy design and the associated negotiation process, as well as during monitoring and evaluation of implemented policies. During policy design, alternative policy options are assessed in terms of their contribution to goal achievement, and trade-offs between goals become topics of negotiation. During this phase investigation of a wide array of potential policies is desirable to avoid the debate becoming locked in on narrow visions. During the phase of monitoring and evaluation, predictions are needed of the degree of goal achievement over the policy planning horizon given the current state of the object of the policy.

Both during policy design and during monitoring and evaluation, indicators may be used to simplify, to quantify and to communicate consequences of actions. These indicators may be based on direct measurements as part of monitoring schemes or policy assessments. Because the scale at which information can be collected differs from the scale at which conclusions are needed, scaling up or other types of transformation of information usually occur in indicators (Dumanski et al., 1998; Dalgaard et al., 2003). During both policy design and policy evaluation, quantification of effects may be useful to evaluate consequences of alternative options. Models that integrate disciplinary knowledge enable such quantitative assessment of alternatives and have been developed and used in scientific research for some 10–15 years. An early application in agriculture was described by De Wit et al. (1988).

This paper reviews integrative modelling approaches and associated indicators which have been developed by application-oriented research to analyze the impact of multifunctional agriculture, or which may be used as such. Agro-forestry and urban planning approaches are omitted. The review is geographically restricted to agricultural research from France, Germany and The Netherlands. In view of the relative novelty of the notion of multifunctionality in agriculture and research and the long tradition of model- and indicator-based approaches in the three countries this pragmatic selection of countries, based mainly on available research capacity was considered adequate to offer a perspective of approaches that are or may be pertinent for evaluation of multifunctional agriculture without attempting to be exhaustive.

This paper does not address indicator systems as such, as reviews have appeared recently (Wascher, 2000; Roedenbeck, 2004; Halberg et al., 2005; Payreaudau and van der Werf, 2005). Instead, indicators are discussed as part of integrative modelling approaches in which land-use decisions by local actors are mimicked and evaluated using indicators. Section 2 describes the analytical framework that was developed to analyze and compare the various integrative modelling approaches, and outlines the sources of information used. Results are presented in Section 3, starting with a description of the policy context for multifunctional agriculture in France, Germany and The Netherlands, as this shapes the application-oriented research efforts. The discussion in Section 4 assesses the state of the art of integrative modelling approaches in terms of their contribution to the analysis of impact of multifunctional agriculture. It compares the results for the three countries and proposes an agenda for research and development.

2. Methodology

2.1. Conceptual framework

2.1.1. Goal-oriented versus means-oriented approaches

The role of model-based approaches for evaluation of multifunctionality of agriculture was analyzed from a goal-oriented perspective (e.g. De Wit et al., 1988; Von

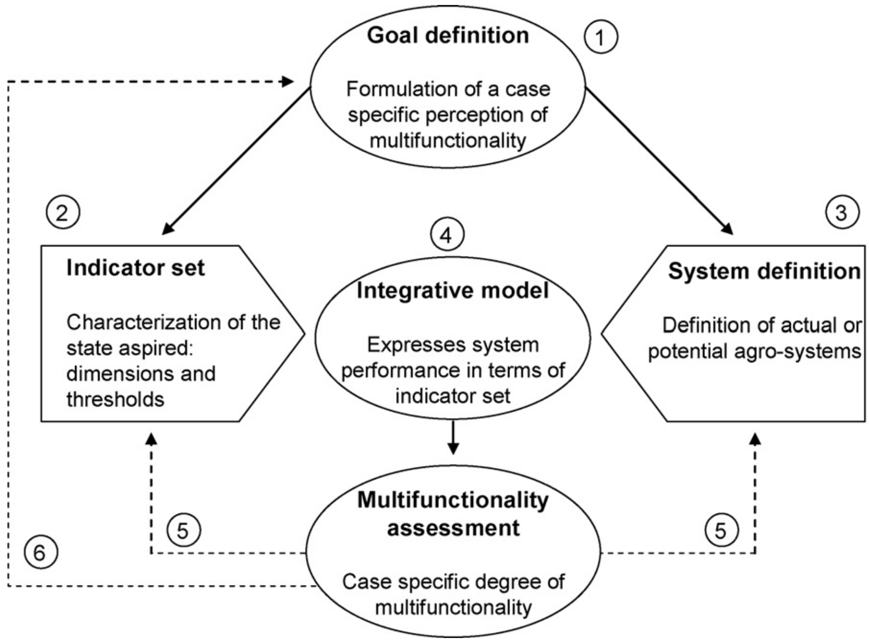

Fig. 1. Model-based assessment of multifunctionality of agriculture: components and their interrelations. Solid arrows indicate functional relations, hatched arrows indicate learning loops. For explanation of numbers see text.

Wirén-Lehr, 2001). In this perspective, multifunctionality assessment is based on comparison of the state of a system to a set of explicit goals (Fig. 1, item 1), which are made operational through a set of indicators. The alternative to the goal-oriented perspective is the means-oriented perspective that bases the assessment on direct evaluation of discrete agricultural measures and instruments at field and farm level. This perspective focuses on presence and quality of means that are a priori labelled as sustainable, e.g. crop rotation, supervised pesticide application schemes or use of natural enemies for plant protection, mixed crop-livestock systems. Several authors have commented that goal-oriented approaches outrank means-oriented approaches due to their ability to evaluate the contribution to sustainability of the means employed in a case- and site-specific way (Von Wirén-Lehr, 2001; Halberg et al., 2005; Payreaudau and van der Werf, 2005).

In a goal-oriented perspective goal definition is the first and essential step, and introduces a strong case-specific element. Three broad categories of goals have been proposed to cover all relevant aspects of multifunctionality; economic, environmental and social goals (e.g. OECD, 2001). When specified in more detail, the goals determine the characteristics of systems that matter, implying that other characteristics do not matter, thus representing a major normative element. Goals may be formulated at different spatial and temporal scales and at different organization levels.

2.1.2. Indicator sets

Goals are translated into indicators (Fig. 1, item 2) to arrive at measurable, calculable or communicable quantities. Again, a normative element enters the assessment, since limited knowledge of system functioning does not allow formulation of truly systemic indicators. Instead, actors such as farmers, policy makers or scientists propose indicators, resulting in a more or less subjective selection with limited transferability. Indicators may represent the actual quantity of interest or may represent proxies. An example of the latter is the nitrogen surplus which may be used as a proxy for pollution of the ground water at 2 m depth with nitrate (see e.g. Brouwer and Crabtree, 1999). A special set of economic proxy indicators tries to express the monetary equivalent of consumer demand for system outputs that are not valued through markets (*cf*. Madureira et al., 2007). Once monetary values are assigned to system outputs ‘cost-effective’ policies may be formulated. Such economic valuation approaches are based on empirical, statistical techniques, which measure an individual’s ‘willingness to pay’ for benefits or ‘willingness to accept’ losses. Because results are strongly linked to the measurement procedure, each procedure can be considered a separate proxy. These economic valuation approaches met with considerable interest in North America and Australia, but later disappeared from Australian policy making and, in Europe, have not been taken up outside the research domain to date (Navrud and Pruckner, 1997; Baarsma, 2000; Madureira et al., 2007). As part of our framework for assessment of multifunctionality of agriculture we consider economic valuation as one of the methods to measure economic performance of the system.

2.1.3. System definition

Goals have an effect on the definition of the systems that are assessed (Fig. 1, item 3), as the goals implicitly or explicitly express pertinent spatial and temporal scales and organization levels. For example, the goal of meadow-bird conservation requires a regional approach including multiple farms and multiple fields commensurate with the species' home ranges. Global carbon sequestration goals cannot be evaluated with a system description consisting of individual fields, unless appropriate ways to summarize information at intermediate levels are invoked. To evaluate the goal of social cohesion in rural areas, the system description should include social components in addition to biophysical components, while evaluation of the provision of clean water by certain farm types does not require the inclusion of a major social component in the system definition. As a last example, evaluation of the demand for multifunctionality of agriculture is usually not relevant at the field scale, and requires confrontation with supply at the farm or regional scales. Systems may describe reality as it can be perceived, but may also constitute potential realities. The latter are particularly relevant when the assessment procedure is not so much geared to the current situation but aims to explore alternative future systems.

2.1.4. Integrative models

Integrative models (Fig. 1, item 4) constitute the means to express the performance of the formulated systems in terms of the defined indicator set. The adjective 'integrative' here refers to the integration of goals in one model. These models may comprise qualitative sub-models such as rules of thumb or expert systems as well as quantitative models of different levels of complexity ranging from statistical or census data to statistical descriptive relations and mechanistic simulation models. The output of the model represents the multifunctionality assessment of the case under consideration. The output may constitute the end point of the multifunctionality assessment. In view of the rather ill-defined nature of the notion and its role in negotiations among actors, however, it is more likely that results feed back to the definitions of indicator set or system, thus contributing to emergence of more refined specific descriptions of multifunctionality as part of a learning cycle. The output may even feed back to the goal definition, thus affecting the definition of multifunctionality at a more fundamental level (Fig. 1, items 5 and 6).

2.1.5. Analytical framework for model comparison

The goal-oriented perspective of model-based multifunctionality assessment was used to create an analytical framework for comparison of integrative modelling approaches using information on published studies (Table 1). The aim of the framework is to demonstrate patterns among approaches in the different countries, to shed more light on items which are addressed similarly, and issues which are underexposed. The framework was developed empirically, expanding the elements of Fig. 1 and adding categories of information that demonstrate details on techniques, model quality and research investment. Eight major categories of information are distinguished. The 'General description' (category 1) includes a brief description of the purpose of the model or model family, as a reminder to the reader. In 'Major objectives of modelling' (category 2) two types of objectives are distinguished, methodology development and answering questions of specific 'clients'. The two objectives may occur together. Nevertheless, when the prime objective is to answer questions of specific clients, their questions and the way

Table 1
Analytical framework for integrated models

Categories
1. General description
2. Major objectives of modelling
Methodology development
Answering questions of specific 'clients'
Ex ante evaluation
Ex post evaluation
3. Intended user groups
Policy makers
Farmers
Citizens
Consumers
Scientists
4. Integrated modelling tools
Optimization, simulation, database, GIS
5. Model evaluation
Testing: whole model, components
Method: expert assessment, quantitative methods
Impact assessment
6. Investment and continuity
Number of projects
Years in use
R&D expenses (person years)
Ongoing work: updating of databases, component development projects, empirical testing
7. System definition
Spatial scale addressed: highest–lowest
Intermediate spatial scales
Temporal scales: largest–smallest
Time horizon
Objects describing the system
Type of result
8. Categories of multifunctionality indicators and method of quantification
Environmental
Number of indicators
Abiotic: nutrients, pesticides, erosion, water, climate
Biotic: individual plant species, floristic categories, individual animal species, faunistic categories
Landscape: structure and spatial cohesion, biodiversity index
Economic
Number of indicators
Costs, gross margins, full costing, utility, investments, liquidity, rate of return on factors, other (specify)
Social
Number of indicators
Labour, other (specify)

that research has addressed them should be in the focus of a report or paper. In papers or studies with a focus on methodology, the techniques and tools receive relatively high levels of attention, and answering an applied question is dealt with as an illustration of the methodology. Two types of scope of modelling were distinguished to provide extra information on the type of specific questions that are addressed by the integrative model: ex ante evaluation and ex post evaluation. Focus in the first type is on demonstrating options for development in the future. The second type addresses the past and assesses the consequences of strategies or policies. Both types of scope may be exhibited by the same integrative model, but they have different implications for the definition of the system (e.g. the objects describing the system). Ex post analyses generally require no simulation of human decision making, while in ex ante analyses farmer responses to policies always need to be addressed.

Category 3 in Table 1, 'Intended user groups', describes which users have actually been involved in studies, as expressed in reports or papers. Category 4, 'Integrative modelling tools', refers to the techniques used: the type of optimization approach (if any), and it specifies the use of simulation, databases and/or GIS. Category 5, 'Model evaluation', distinguishes testing of the performance of the model as a whole, and testing of performance of components. Both may be done by asking experts about plausibility of results, or by comparison with independent quantitative data. Category 6, 'Investment and continuity', aims to provide information on the size of the work and the degree of operational availability of the tools.

The 'System definition' (Category 7) is given in terms of the spatial and temporal scales, the manner of scaling up, the objects that characterize the system and the type of results aimed for. In dealing with space, phenomena that are described at a small scale are combined ('scaled-up') to explain or predict phenomena at the (larger) scale of interest. We characterized studies by the smallest spatial scale used, and by the scale of interest, i.e. the largest scale. In addition intermediate scales are included that describe how scaling up is performed. For instance, some studies use the farm scale as an explicit intermediate scale between field and region, whereas others aggregate information from field to regional scale directly.

In dealing with time, studies are classified based on their smallest and largest units of time. The largest unit of time represents the temporal scale of interest. Differences between smallest and largest temporal scale reveal the nature of representation of systems. Where differences are absent, behaviour of system components is described by relations fitted through data that are obtained at the system level. This is typical for descriptive, regression-based relations. Differences of one or two orders of magnitude are typical of more or less mechanistic approaches, where behaviour of system components is explained based on description of behaviour of system processes.

Another aspect of time is the time horizon of a study, which we related to the assumptions on institutional constraints. In a number of studies, options are explored which will only be possible if institutional settings change as compared to the current situation. These studies address the long-term future. Other studies start from current institutional settings, and address the short term. The latter is always the case for ex post evaluations.

A final aspect of time is whether a dynamic approach is adopted in which the model calculates time trajectories as part of its results or whether a static approach is used in which the assumption usually is made that dynamic processes have equilibrated. To allow such an assumption, a combination of dynamic modelling to find the equilibrium values of component processes such as soil organic matter, demand and supply or distribution of wildlife in a landscape, and static optimization of the full problem may be used.

The objects that characterize the system are those variables that capture the essential components of the system. If the system model were a regression model, these would be called the independent variables, if it were a simulation model these would be called state variables, and in linear programming context they are known as decision variables or activities. The section on type of results reveals the relation between model variables and purpose of modelling. How are the objects in the model presented, e.g. as trade-off curves, as scenarios, as maps.

Category 8 on 'Multifunctionality indicators and method of quantification' contains information on environmental, economic and social indicators in the system model, and its output. Two types of information are provided: the origin of the data, and the type of transformation applied. The origin of the data may be statistical data, i.e. regional or sectoral averages (e.g. average yields, average labour requirement, average demand for a function), locally specific information obtained from surveys or experiments, or expert assessment. The type of transformation describes the method used in calculating or deriving the indicator. We distinguish rule based systems (which in some cases use fuzzy relations to describe uncertainty), regression models, and dynamic simulation models which may be more or less complex. Sometimes, the transformation is so simple that it may be omitted. An example is found in many economic indicators. For instance 'costs' is a simple summation of component costs. In these cases only the origin of the data is described, i.e. local surveys or general statistical databases.

2.2. Data collection

A survey of the literature on integrative modelling approaches in agriculture was performed for three countries: France, Germany and The Netherlands. Sources of literature included peer-reviewed journals, 'grey' literature in reports often in local language, and websites of policy and research institutes. Sources were identified by searching library resources, the internet and by accessing the research networks of the authors. Studies that dealt with a combination of an economic indicator and a single abiotic environmental indicator were omitted to avoid becoming overwhelmed by studies focusing on economics of changing nitrogen or pesticide input.

The direction of development of model-based approaches and indicators in the three countries were expected to be affected by national policies regarding agriculture and land-use. Main trends in policies with an impact on multifunctionality of agriculture were derived from reviews performed as part of the Multagri project (www.multagri.net, visited September 2005).

3. Results

3.1. Multifunctionality as a concept in policy and research

Multifunctionality of agriculture appeared in French agricultural policy as part of the ''Loi d'Orientation Agricole'' (Agricultural Orientation Law) that was passed in 1999 after a period of increasing concerns about environmental problems caused by agriculture (Hervieu, 2002). The law asserts the multifunctional character of agriculture, postulating that this activity realizes economic, social and environmental functions. It introduced a new policy tool, the ''Contrat Territorial d'Exploitation'' (Rural Farming Contract), in 2003 modified to ''Contrat d'Agriculture Durable'' (Sustainable Agriculture Contract) by which farmers enter in a contract with the state to create added value, by quality improvement of products, by farm diversification and by creating and maintaining jobs among other ways, and to contribute to improved land management from biotic and abiotic viewpoints. This reorientation stimulated research into characterization and evaluation of multifunctionality, particularly to support the accountability of farmers holding a Rural Farming Contract. As a result, emphasis in research has been on development of indicators and indicator sets that enable ex post evaluation.

In Germany, multifunctionality of agriculture became an essential element of rural development policy in 2001. Following the appointment of a 'green' Federal Minister of Consumer Protection, Food, and Agriculture in 2001, a more consumer-oriented agricultural policy was introduced (BMVEL, 2005). The objective of the so-called ''turnabout in agriculture'' is the introduction of new agricultural practices in order to guarantee food security, environmental conservation, and financial survival of farm enterprises. Policy instruments concentrate on regulation of land-use practices and on economic incentives, mostly in the frame of the EU Common Agricultural Policy (CAP) second pillar measures. Regulation of land-use practices takes so-called ''good agricultural practices'' (GAP) as the reference, as defined in the ''Bundesnaturschutzgesetz'' (Nature Conservation Law), the ''Bundesbodenschutzgesetz'' (Soil Protection Law) and regulations at federal and state level referring to, e.g. fertilizer application rates and crop protection. The definition of ''good agricultural practice'' provides targets and guidelines for what the society considers a sustainable agricultural land-use with the aim of shaping the relation between agriculture, nature conservation and landscape planning. Additionally, incentive policy measures such as the agri-environmental programmes are increasingly conceived as means to ensure and remunerate the production of non-commodities such as the protection of abiotic and biotic natural resources and the maintenance of infrastructures and attractive locations in rural areas. Hence, agricultural policy is clearly addressing a multifunctional agriculture, although it is not referred to as such. In recent years, the concept of multifunctional agriculture or multifunctionality of land-use became part of a number of national research projects.

In The Netherlands, multifunctionality of agriculture appears as one of the development options in the public debate on land-use in rural areas. In agricultural policy, however, sustainable development, rather than multifunctionality has been adopted as the central notion, and multifunctional land-use is more prominent a term than multifunctionality of agriculture. Definition and measurement of sustainable development is through indicators in the domains of people, planet and profit (e.g. Serageldin et al., 1994). ''Participation'' is often added as the fourth ''p'' of sustainable development, referring to the political and institutional climate which stimulates or deters contributions and commitment of citizens to public processes. The Minister of Agriculture has acknowledged that indicators in the people domain are the least developed and development of an operational set of indicators for monitoring of policy goals has been commissioned. Ex post monitoring of policies is performed by several governmental planning agencies who report yearly on development of indicators. Scenario studies which extrapolate trends up to 30 years into the future and define consequences of alternative policy choices are published bi-annually. In the scenario studies for biotic and abiotic environmental developments, scientific progress in thematic fields is integrated in a standardized integrative modelling framework called Nature Planner which provides a bridge between information supply and demand and is developed and maintained with ear-marked research funds. Scenarios for economic development of agriculture are planned to be generated by similar standardized modelling frameworks.

3.2. Aims, user groups, techniques and continuity (categories 1–6, Table 1)

A total of 15 integrative model-based approaches were identified (Table 2). Some of these comprised ''schools of thought'', and included several studies in which similar approaches were used. Others represented efforts in which a single approach appeared to have been developed across

Table 2
Integrated model-based approaches used in the comparative study

Id	Country	Approach name	Brief description	References
F-M	France	Multi-agent simulation approaches	Interactive simulation of land-use dynamics with agent-based models	Bommel and Lardon (2000), Etienne and Le Page (2002), and Becu et al. (2004)
F-O	France	Opt'INRA	Farm economic optimization by linear programming under environmental constraints for crop and suckler cow systems	Veysset et al. (2005)
F-P	France	POLEN	Analysis of impact of CAP in several European regions based on linear programming with risk aversion	Flichman (1997)
F-S	France	SIMBA	Environmental-economic evaluation of banana-based cropping systems	Tixier (2004)
G-K	Germany	Kraichgau	Farm optimization by linear programming and spatially explicit ecological evaluation tools	Dabbert et al. (1999) and Hermann et al. (2003)
G-Mo	Germany	MODAM	Farm optimization by linear programming and fuzzy tools for ecological evaluation of crop production	Zander and Kächele (1999), Kächele and Dabbert (2002), Zander (2003), and Sattler and Zander (2004)
G-Mu	Germany	MULBO	Optimization of landscape functions using multiple goal linear programming per gridcell	Meyer (2002) and Meyer and Grabaum (2003)
G-P	Germany	Pro-Land	Spatially explicit maximization of land rent per spatial decision unit using different ecological models (SWAT, ANIMO, ProF and GEPARD)	Möller et al. (1999), Weber et al. (2001), and Weinmann et al. (2005)
G-R	Germany	RAUMIS	Policy evaluation by aggregation of regional farm models	FAL (1996)
N-C	Netherlands	CLUE	Prediction of land-use change based on regression analysis of driving forces	Veldkamp and Fresco (1996) and Veldkamp and Verburg (2004)
N-F	Netherlands	Farm scale bio-economic approaches	Farm optimization by linear programming and ecological evaluation tools	Wossink (1993), Berendsen and Giesen (1995), Van de Ven (1996), Rossing et al. (1997a), Wossink et al. (1999), Van Wenum (2002), De Koeijer (2002), Bos (2002), Dogliotti et al. (2003, 2004, 2005, 2006), Berendsen and Tiessink (2003), Pacini et al. (2003), Pacini et al. (2004a,b), and Van Calker et al. (2004)
N-L	Netherlands	Landscape IMAGES	Spatially explicit multiple goal and multiple scale optimization using mixed optimization models	Rossing et al. (2003) and Groot et al. (2007)
N-N	Netherlands	Nature Planner	Assessment of the state of nature and environment for Dutch government	Oostermeijer and van Swaay (1998), De Heer et al. (2000), Schouwenberg et al. (2000), Van der Hoek et al. (2000), Reijnen et al. (2001), Verboom et al. (2001), Bakkenes et al. (2002), and Wamelink et al. (2003)
N-R	Netherlands	Regional Production Ecology approaches	Regional optimization of economic and environmental objectives using linear programming	De Wit et al. (1988), Rabbinge and van Latesteijn (1992), Van Keulen et al. (1998), Bouman et al. (1999), Schipper et al. (2001), Van Ittersum et al. (2004), and Lu et al. (2004)
N-T	Netherlands	Trade-off Analysis model	Prediction of aggregated farmer behaviour under environmental constraints using simulation	Stoorvogel et al. (2004)

different studies. The general aim in the studies was assessment of consequences of alternative land-use at farm or regional scales. With the exception of two approaches, RAUMIS and Nature Planner, all approaches aimed at methodology development (category 2 of Table 1; Table 3). RAUMIS and Nature Planner were both developed to meet a demand for policy support and are currently routinely used in policy evaluation and development. Recent reports on the CLUE approach (Veldkamp and Verburg, 2004) indicate that this approach moved from methodology development to application in local policy development. Many studies described specific questions of 'clients' as part of the objectives and used real-world cases as illustration for the methodology. Since impact evaluation was usually absent (see below), it was unclear to which degree the clients' needs were met. Most approaches aimed at ex ante evaluation and discussion support. In a number of cases, underlying biophysical models were also used for ex post evaluation.

Among the groups of intended users of information generated by the approaches (category 3 of Table 1; Table 3), policy makers and scientists were mentioned most frequently. Farmers were addressed by a number of approaches from France and The Netherlands, citizens appeared as users of multi-agent simulation approaches, Nature Planner, CLUE and an application of farm-based models to flower bulb production (Rossing et al., 1997a), and none of the approaches referred to consumers as intended users.

Optimization approaches dominated, but what-if scenario analyses, dynamic simulation and heuristic methods were

Table 3
Major objectives of the integrated model-based approaches, intended users and estimated investment up to 2005

	F-M	F-O	F-P	F-S	G-K	G-Mo	G-Mu	G-P	G-R	N-C	N-F	N-L	N-N	N-R	N-T
2. Major objectives of modelling															
Methodology development (M)	M	M	M	M	M	M	M	M		M	M	M		M	M
Answering clients' questions (A)	A	A	A			A	A		A	A	A	A	A	A	
Ex ante evaluation (Ea)	Ea	Ea	Ea	Ea	Ea	Ea	Ea	Ea	Ea	Ea	Ea	Ea	Ea	Ea	
Ex post evaluation (Ep)					Ep	Ep			Ep				Ep		
3. Intended user groups															
Policy makers (Po)	Po	Po	Po		Po	Po	Po	Po	Po	Po	Po	Po	Po	Po	Po
Farmers (Fa)	Fa	Fa		Fa		(Fa)	(Fa)				Fa	Fa			Fa
Citizens (Ci)	Ci									Ci	Ci		Ci	(Ci)	
Scientists (Sc)	Sc	Sc	Sc	Sc	Sc	Sc	Sc	Sc		Sc	Sc	Sc		Sc	Sc
4. Integrated modelling tools															
Optimization[a], simulation (S), database (D), GIS (G)	S, D	L, S D	L, S D	S, D	P, S D, G	L, S D, G	L, S D, G	L, S D, G	L, D G	H, S D, G	L, S D, G	H, S D, G	S, D G	L, S D, G	S, D G
5. Model evaluation															
Full model (F), components (C)	F:e	F:e,q	F:e	F:e	F:e	F:e	F:e	F:e,q	F:e	F:e,q	F:e	F:e	F:e	F:e	
Expert assessment (e), quantification (q)	C:e,q	C:e,q	C:e,q	C:e,q	C:e,q	C:e	C:e	C:e	C:e	C:e,q	C:e,q	C:e,q	C:e,q	C:e,q	C:e
Impact assessment (yes/no)	Yes	No	No	No	No	No	No	No	No	No	Yes	No	No	No	No
6. Investment and continuity															
Inception year	2001	2000	1995	2004	1995	1998	1994	1998	1993	1997	1992	2003	1998	1988	2002
Application (number of projects)	3	4	>1	2	1	5	9	2	>10	>10	>10	1	>10	>10	1
R&D expenses (person years)	>5	4	>5	5	3–4	>10	>10	6	>10	>10	>10	6	>10	>10	>5
Ongoing work: updating of databases (D), component development (C), empirical testing (T)	D, C, T	D, C, T	D, C, T	D, C, T	–	D, C, T	D, C, T	D, C, T	D, C, T	D, C, T	–	D, C, T	D, C, T	–	D, C, T

For identifiers at the top of the columns see Table 2. Numbers in the first column refer to the categories in the analytical framework in Table 1. Entries between parentheses indicate use in some of the studies only.
[a] L: linear programming; P: positive quadratic programming; H: heuristics.

Table 4
System definition of integrated model-based approaches based on the characteristics in Table 1: spatial and temporal scales, time horizon, system objects and type of results

Id	Spatial scales			Temporal scales		Time horizon[a]	System objects	Results
	Highest	Lowest	Intermediate	Largest	Smallest			
F-M	>25,000 ha	1 ha	Farm	50 years	1 week	m	Categories of actors, farms, forests, plots, herds, individual animal and plant species	Land-use dynamics maps
F-O	Farm	Field	–	1 year	1 year	s–l	Land-use activities: cropping systems, animal production systems	Gross margin and abiotic performance
F-P	10^3 to 10^4 ha	Field	Farm	25 years	1 year	s	Land-use activities: cropping systems	Land-use, economic and abiotic performance
F-S	Field	Field	–	250 weeks	1 day	s–l	Land-use activities: cropping systems	Crops, economic and abiotic performance
G-K	Region	Field	Farm	1 year	1 year	s–l	Land-use activities: cropping systems, animal production systems	Land-use scenarios
G-Mo	Region	Field	Farm	1 year	1 year	s–l	Land-use activities: cropping systems, animal production systems	Trade-offs, land-use scenarios
G-Mu	Landscape/region	Landscape element	–	1 year	1 year	s–l	Land-use activities: forest, grassland, arable, urban, cropping systems	Land-use scenario maps with functional assessment
G-P	Province	25 m × 25 m	–	1 year	1 year	s–l	Land-use activities: cropping systems, animal production systems, natural elements	Land-use scenarios; economic key indicators
G-R	Country	NUTs-3	Regional farm	1 year	1 year	s–l	Land-use activities: cropping systems, animal production systems	Land-use scenarios
N-C	Eco-region	9.25 km × 9.25 km	37 km × 37 km	1 year	1 year	s	Current agricultural land-use and land management	Trade-offs, land-use maps, hot spots for development
N-F	Farm	Field	–	2–100 years[b]	1 day	s–l	Land-use activities: cropping and grazing systems, animal production systems, natural elements, set aside	Trade-offs, land-use scenarios
N-L	Landscape (5 km × 5 km)	Field, landscape element	Farm	2–100 years[b]	1 day	s–l	Land-use activities: cropping and grazing systems, animal production systems, natural elements	Pareto-frontiers, land-use scenarios, land-use maps
N-N	Country	250 m × 250 m	–	100 years	1 day	s–l	Current land-use (nature, agriculture, urban areas, infrastructure)	Land-use scenarios
N-R	NUTs 1	1 ha	Crop rotation	50–100 years[b]	1 day	s–l	Land-use activities: cropping systems, animal production systems, agro-forestry systems	Trade-offs, land-use scenarios
N-T	50 km^2	0.5 ha	Farm	5 crop cycles	1 day	s	Current and past agricultural land-use and its drivers	Trade-offs

For identifiers in the first column see Table 2.
[a] s = short term; l = long term.
[b] 2–10 years for rotations; 50–100 years for soil organic matter dynamics.

also represented. In most cases GIS and databases were among the technical tools (category 4 of Table 1; Table 3). Evaluation (category 5 of Table 1; Table 3) of the plausibility of whole model predictions with experts was common; testing with empirical data and quantitative methods was rare. Testing of model components appeared to rely on expert assessment. Despite the technical feasibility of testing of components with empirical data, in a number of cases this was not done or only partly so, meanwhile referring to disciplinary experts to justify the use of model components. Expert assessment of model quality appeared more often in the German approaches than in those reported from France and The Netherlands. Impact assessment was reported by only few authors (Rossing et al., 1997a; Barreteau, 2003; Barreteau et al., 2003; Schuler and Kächele, 2003; Sterk et al., 2005).

Information on investment and continuity (category 6 of Table 1; Table 3) suggested that in a number of cases approaches were maintained and further developed beyond the initial investment. Compared to the other two countries France started to develop integrative models more recently, i.e. 2000 versus early 1990s. This may be caused by a primary focus on the development of environmental indicators for ex-post analysis, stimulated by the Rural Farming Contract, and the associated emphasis on assessment of the current situation rather than on evaluation of alternatives.

3.3. System definition (category 7 of Table 1)

The approaches covered a wide range of spatial scales (Table 4). Approximately half of the models started at the scale of one or a few hectares, denoted as field or landscape element which was taken as the smallest homogeneous unit. By scaling up results were obtained at the scale of farms (50 to few hundred hectares) or even regions. Approaches that took larger areas as starting points, sometimes defined by administrative borders, aimed at results at regional, country, watershed or eco-regional scales. Often intermediate scales were defined at which information from the more detailed scales was collated before further scaling up. Such stratification resulted in crop rotations, farms, farm types or region farms, or aggregated map units which allowed further scaling up to the largest spatial scale. In some approaches large differences between smallest and largest spatial scale were overcome without intermediate re-scaling by ignoring the farm level and using computing power, e.g. Nature Planner, Pro-Land and Mulbo. While these approaches enable rapid analyses at regional level, the consequence of ignoring the farm as decision making unit, is that questions such as farm level investments or farm type related subsidies cannot be analyzed appropriately.

Differences between smallest and largest temporal scale occurred for most of the approaches originating in The Netherlands, for Pro-Land and for the family of multi-agent models, indicating that in these approaches explanatory components were included. All approaches appeared to model at least part of the system by descriptive relations including statistical analyses at a single level of integration and expert knowledge.

Time horizons of the approaches appeared to combine short and long term. Only POLEN, TOA and CLUE concentrated on the short term. These approaches used descriptive relations of response of human actors to external factors as a key element for calculating outputs. The statistical and econometric relations were based on empirical data, and therefore could not be used for extrapolations over long time horizons. In the other cases, scenario approaches in combination with biophysically and ecologically based component models appeared to enable considerable flexibility in time horizons.

Objects in the approaches which characterized the systems under study were in all cases land-use types, i.e. a particular type of land-use defined in varying degrees of details but usually including a listing of inputs and outputs (after FAO, 1976). All studies included agricultural land-use types involving animal husbandry and/or cropping systems. Some studies included forestry and ‘natural elements’ (Pro-Land, Mulbo, Nature Planner, models from the Regional Multiple Goal Explorations family, Landscape IMAGES, Multi-agent simulation), urban and infrastructural land-use types (Mulbo, Nature Planner and CLUE). The multi-agent simulation approach was the only approach that included individuals as objects: human actors such as farmers, foresters and conservationists, individual plant and animal species. In some studies the defined land-use types all occurred in reality (Nature Planner, CLUE, TOA), while other studies included a mixture of current and potential or alternative land-use types which were created by the scientists in a design-oriented approach.

Output in most approaches was described as land-use types associated with specific goal achievement often represented in maps and as trade-offs between goals. Two models included the factor time, the multi-agent approach and TOA, both demonstrating land-use dynamics associated with different management strategies.

3.4. Multifunctionality indicators (category 8 of Table 1)

The number of environmental and economic indicators exceeded the number of social indicators in all approaches (Table 5). Among the environmental indicators, indicators of the abiotic environment were more abundant than biotic and landscape indicators.

To quantify indicators a range of methods was found, ranging from direct use of (survey or statistical) data, expert assessment and simple calculations to various modelling techniques such as regression, (fuzzy) rule-based methods and more or less complex simulation models.

For the abiotic indicators, detailed methods based on mechanistic simulation appeared to be commonly used for

Table 5
Categories of multifunctionality indicators and method of quantification of integrated model-based approaches identified in Table 1

	F-M	F-O	F-P	F-S	G-K	G-Mo	G-Mu	G-P	G-R	N-C	N-F	N-L	N-N	N-R	N-T
Environmental indicators															
Number of indicators	6	1	2	3	3	10	13	8	3	0	>10	4	>10	>10	1
Abiotic													sim		
Plant nutrients		si	si	si, ru	si, ru	fru	ru	si	exp		si, re	re		si, re	si
Pesticides				si, ru				si	exp		st, su, exp			st, su, exp	si
Erosion				ru	si	fru	si	si	exp		si			exp	
Water			si			fru	re	si			si		sim	si	si
Climate															
Biotic															
Individual plant species	si											re	si		
Botanical categories	si					fru					re		re		
Individual animal species	si					fru	ru	si				re	si		
Faunistic categories	exp					fru		si					re		
Landscape															
Spatial cohesion							ru	ru				si	ru	exp	
Biodiversity indices	exp				ru	fru	ru	ru			re		stat		
Economic Indicators															
Number of indicators	3	3	3	1	1	1	4	>10	4	1	>10	1	1	>10	1
Costs	stat	stat	stat		stat	stat	stat	stat	stat		stat, exp, su	stat	stat, exp	stat, exp, su	
Gross margins		stat	stat	stat	stat	stat	stat	stat	stat		stat, exp, su	stat		stat, exp, su	
Full costing		stat	stat		stat	stat			stat		su				
Utility			calc					su	stat						
Investment	stat								stat		su, stat				
Liquidity									stat						
Rate of return on factors	stat				stat				stat						
Other (specify)			risk				[a]			[b]				[c]	[d]
Social indicators															
Number of indicators	2	1	1	0	1	1	4	1	1	0	2	2	2	5	0
Labour	stat	stat	stat		stat	stat		stat	stat		exp, su	stat		stat	
Other (specify)	[e]						[f]				[g]	[h]	[i]	[j]	
Total number of indicators	11	5	6	4	5	12	20	>10	8	1	>10	7	>10	>10	2

Abbreviations: calc = simple summation; exp = expert assessment; (f)ru = (fuzzy) rule-based; re = regression model; si = simulation model; stat = statistical data; su = survey or experimental data.

[a] Land accessibility, soil productivity, land price, development cost.
[b] Land-use: crops, pasture, other.
[c] Land productivity; resource use efficiency.
[d] Net return.
[e] Intensity of social networks.
[f] Landscape visibility, recreation, traffic noisiness, housing environment.
[g] Skilled/unskilled labour.
[h] Landscape perception.
[i] Landscape perception; recreation demand and supply.
[j] Regional employment; dietary requirements; skilled/unskilled labour.

plant nutrients, water and in some cases pesticides. Erosion and pesticides were frequently quantified using simple simulations, survey and statistical data, or expert opinion. We did not encounter studies with indicators referring to carbon sequestration or other aspects of climate change.

In the few cases where they were part of approaches, biotic indicators were calculated using expert opinion in combination with fuzzy logic (MODAM, Zander and Kächele, 1999; Sattler and Zander, 2004), using formal biodiversity indices such as Braun-Blanquet (Pacini et al., 2004a,b) or based on empirical data (Nature Planner, Landscape IMAGES). In the Nature Planner more advanced ecological knowledge, captured in simulation models was mobilized to calculate occurrence of individual plant and animal species. Landscape indicators addressed both structure and biodiversity using rule-based methods and regression models to arrive at an index value.

Economic indicators were part of each of the reviewed integrative approaches. Some approaches used one indicator such as net return (TOA) or costs (CLUE). Most approaches evaluated several alternative indicators. Less commonly used indicators included utility (RAUMIS), investment, return on investment (in money or some other production factor) or family income above a social minimum (Farm

IMAGES; Dogliotti et al. (2005)). Economic valuation of non-market benefits was never used as an indicator of cost effectiveness. Instead, trade-off curves between monetary and non-monetary indicators were used in nearly all studies.

Labour input was the most frequently used social indicator, and often the only one. Other indicators that were used in the reviewed studies included landscape perception indicators, noisiness, recreational demand and supply, dietary requirements, regional employment, quality of labour and intensity of social networks.

4. Discussion

In this paper integrative modelling approaches from France, Germany and The Netherlands were reviewed and compared based on an analytical framework (Table 1), with the aim of establishing their potential and shortcomings for analyzing and predicting the impact of multifunctional agriculture. This section addresses commonalities and differences in approaches among the three countries, and assesses the state of the art in model-based impact assessment of multifunctional agriculture, to end with a research and development agenda linked to expected developments in land-use in Europe.

4.1. Country comparison

In each of the three countries, methodology development appeared as the major objective for modelling. Methodology development addressed all elements of the conceptual goal-oriented framework in Fig. 1, including elicitation and definition of goals, derivation of appropriate indicator sets, system definition in space and time, scientific and software engineering aspects of building integrative models, and representation, validation and impact of the multifunctionality assessment. Static approaches dominated dynamic approaches; application was more in ex ante than in ex post assessment; maps and trade-off curves were common outputs; and evaluation of the impact of the studies on stakeholders was rare.

Typical differences existed among the results for the three countries. Integrated model-based assessment to date appeared to have received less attention in France than in the other two countries, despite a considerable amount of scientific effort to develop indicator sets such as INDIGO (e.g. Girardin et al., 2000) and IDEA (Vilain, 2000; Briquel et al., 2001). A possible explanation is the focus on ex post evaluation of farming systems performance required by the Agricultural Orientation Law, in combination with less tradition in design-oriented (i.e. ex ante) approaches at the farm and regional scales (Rossing et al., 1997b). Different from the other two countries, France appeared to be developing the field of multi agent modelling linked to GIS to support negotiation processes at the regional level (Barreteau, 2003; Barreteau et al., 2003; Becu et al., 2004). Results for Germany revealed a more frequent intention of policy support than in the other countries where farmers and citizens also appeared as stated stakeholders. A second typical feature was the extensive use of rule-based expert systems in Germany, which contrasted to the statistical and process-based approaches in France and The Netherlands. The advantage of rule-based systems lies in the relatively rapid operationalization of existing information and its relatively low data requirements. Its disadvantage is the limited transportability due to missing insights in causal relations. For The Netherlands, the review demonstrated a relatively large number of studies at both the farm and the regional scales, originating both from biophysical and micro-economic research groups. Although this suggested that development reached a certain level of maturity, the expected consolidation into a limited number of standards so far only occurred in the case of the Nature Planner.

4.2. Towards analysis of multifunctionality

None of the approaches specifically targeted assessment of multifunctionality of agriculture, despite conducive policy environments in France and Germany. Several shortcomings will have to be overcome to enable such assessment. We will structure their discussion using the numbered items in Fig. 1.

In terms of goals and their indicators (items 1 and 2, Fig. 1), all studies lacked depth of representation of social goals of multifunctionality in the public debate. Apart from number of hours or quality of labour input, no other social aspects were addressed systematically across studies. This lack of attention may be primarily due to difficulties in defining social goals by society itself and only secondarily to making them operational in a quantitative modelling context. Fundamental questions on the role of agriculture and agricultural land-use for citizens other than provision of food and fibre are at stake. Here, disciplines from social and natural sciences have a role to play by jointly investigating needs of society and elucidating potential provision by agriculture (Mattison and Norris, 2005). Clarification of needs and opportunities will result in new goals, which in turn will affect system definition and indicators sets used to measure system performance. Thus, the societal definition of multifunctionality will determine the way integrative models will need to appear.

Among the environmental and economic goals, biotic and landscape goals were the least represented, while most studies addressed one or more abiotic and economic goals. In contrast to the lack of attention for social goals, the lack of attention for biotic and landscape goals cannot be attributed to poor articulation by society, as witnessed by policy documents at the EU level such as Habitat 2000, and a wealth of national policy documents and implementation schemes. In a review the European Environmental Agency listed several hundred proposed and partly implemented biodiversity indicators (European Environmental Agency, 2004). Rather than lack of articulation by society, lack of knowledge on the interaction between agricultural practices and species occurrence or survival at the field and regional level appears to hamper integrative studies with biotic and landscape goals (Tscharntke et al., 2005). With much of the ecological research concentrating on natural habitats, the relevance of ecosystem service management on agricultural fields and in agro-landscapes is ignored or oversimplified. In addition to disciplinary (conservation) ecological research aimed at better understanding of species traits in agricultural landscapes (see review by Grashof-Bokdam and van Langevelde, 2004), interdisciplinary approaches are called for which provide information on agricultural land-use management and its consequences for species and ecological communities prevalence and survival.

System definition (item 3, Fig. 1) is strongly determined by the purpose of a study. When goals will change to include social and biotic aspects, this will have important consequences for the way models conceptualize reality. For most of the abiotic and economic goals currently pursued, spatial relations are irrelevant and scaling up or down is relatively simple. Many social goals, however, are related to spatial arrangements in rural areas, since spatial arrangements affect, e.g. aesthetic value or ease of access from urban centres. Similarly, biotic goals depend on spatial relations because they are affected by, e.g. connectivity of habitats, links between natural and agricultural land, or time-space sequences of suitable foraging areas. Most of the reviewed models did not consider space or only did so in a simple fashion, and combinations of time and space were only found in the multi-agent models. Consideration of social and biotic goals will require new methodological developments in spatially explicit modelling.

Integrated models (item 4, Fig. 1) that constitute standards to which a range of researchers contribute are rare. Nature Planner and RAUMIS appear to have such status in their specific domains; Nature Planner in relation to Dutch ecological goals and RAUMIS in relation to German economic issues. Both were closely associated with policy support which provided a financial commitment for continuity. Most other approaches had their basis in research projects. Nevertheless, considerable time investment appeared to have gone into some models, indicating that a number of research groups have reached a point where the dynamics of a young field of science can be replaced by consolidation efforts. In the wider European Research Area this trend can also be observed in a number of large software-development oriented modelling efforts.

Quality control of integrative models is an issue that requires attention. Quality control not only refers to technical integrity but also pertains to the justification for the representation of various system components. Evaluation of agro-ecological relations was lacking in a number of reviewed models, both for quantitative models and for decision rules. While during 'immature stages' of development of new methodology it may be acceptable to illustrate approaches with 'artificial' examples, now that the field seems to have developed to 'adolescence' renewed attention will have to be given to establishing validity domains in model components by reference to empirical data and to uncertainty in model results as a whole.

Learning loops (items 5 and 6, Fig. 1) involving the confrontation of stakeholders with modelling results were seldom reported. Such impact assessment may cause learning effects at two levels. It may show whether there is a shared view among the stakeholders of the conceptualization of the problem, reflected in the system definition and the indicator set (item 5, Fig. 1). At a more fundamental level, it may result in reviewing and redefining of the goals that stakeholders set out with to assess multifunctionality (item 6, Fig. 1). This more fundamental learning effect is seen as essential in effective negotiation processes but also in iterative policy evaluation and redesign, since it enables communication on the drivers of choice (e.g. Leeuwis, 2000; Raiffa et al., 2002). Our review revealed only few publications dealing with impact assessment of integrative models (Rossing et al., 1997a; Barreteau, 2003; Barreteau et al., 2003; Schuler and Kächele, 2003; Sterk et al., 2005). This may be due to scientific culture in the natural science disciplines in which such impact assessments are considered outside the disciplinary scope. Nevertheless, in view of the poor application of modelling approaches to formulation and evaluation of EU policy related to multifunctionality (Kröger and Knickel, 2005) there appears to be an urgent need to understand why impact is low. A broad review of agricultural decision support systems (McCown, 2002) suggests that attention for learning support based on credible albeit simple representation of critical system components and a sense of shared ownership of the modelling tools contribute importantly to impact. This effect may be stronger when timely strategic information is provided that gives a comparative advantage. The successful uptake of Nature Planner and RAUMIS by policy makers may be explained from this perspective. Timeliness is not a trivial issue: in our experience studies often come up with solutions for problems of yesterday due to the time needed to update data and to rewrite models to new questions. A final point related to model impact is attention for communication of modelling results, including appropriate visualization. Visualizations using GIS were reported to be highly effective, particularly in more complex land-use optimization approaches (Barreteau, 2003; Barreteau et al., 2003).

4.3. A research agenda for model-supported policy development and evaluation

Important changes in international agricultural policies which are to be expected in view of the current trade liberalization paradigm will have their impact on land-use policies in Europe. Transformation of agricultural land-use from one predominantly aimed at production to one in which other goals may play a role presents a challenge for synthesis-oriented research because the questions that emerge cannot be answered by mono- or multidisciplinary approaches but require more intensive forms of interdisciplinary collaboration (Boody et al., 2005; Mattison and Norris, 2005; Vereijken, 2002). In such interdisciplinary collaboration different disciplines agree, at least generally, on a common description of the problems under review; they then proceed to process certain aspects of the whole problem on a relatively independent basis and, for the most part, using their customary disciplinary theories and methods. The results, however, are viewed in the context of results from other disciplines, thus becoming subject to reflection and modification.

The drawing up of a research agenda for policy support on multifunctional agriculture is affected by the insight that multiple societal perspectives exist on the goals of such forms of agriculture, making the notion of multifunctionality both the object and the outcome of discussion and negotiation in society. Research efforts aimed at supporting policy development therefore cannot concentrate on filling gaps in knowledge and technology alone, but need to be concerned with the process of utilization of knowledge as well to be relevant.

Knowledge gaps identified in this review concern indicator systems, scaling issues and data availability. Indicator systems described in this paper generally demonstrate a lack of balance, with strong emphasis on economic and abiotic environmental indicators. Definition of relevant social indicators is a major task for both the societal debate and for scientific research. In Germany and in The Netherlands initiatives of governments were identified that aimed to initiate such debate. Here, experiences from forestry (Slee, 2007) may be useful as a starting point. Biotic indicators appear to focus on conservation outside agricultural areas rather than address interactions between agricultural land-use and key ecological variables such as quality and connectivity of potential habitats on or associated with agricultural land (Tscharntke et al., 2005; Grashof-Bokdam and van Langevelde, 2004). Moreover, much of the knowledge captured in the models we reviewed appeared to have a basis in expertise rather than empirical data or understanding of underlying processes. Overcoming the disciplinary separation between landscape ecology and production ecology is needed to arrive at a modern form of agro-ecology which concerns mutual relations between agricultural land-use and the non-production areas in agro-landscapes.

From the country review spatial scaling appears as an issue requiring further work to accommodate the farm, the main decision making unit, as part of scaling up from field to region. For all dimensions of the problem (economic, environmental, social) upscaling to landscape scale is required for the evaluation of the generated designs. This implies that a gap should be bridged (Dalgaard et al., 2003) since for bio-physical processes related to agro-ecology, most data and process knowledge is available at smaller scales (field and lower). The scales of interest of policy makers, however, are administrative units such as farms and higher, and methods for upscaling to these hierarchical levels without losing integrity of data have received limited attention (Dumanski et al., 1998). The methods for upscaling should be selected such that the presence of scale-dependent processes resulting in emergent properties at higher levels of aggregation can be accounted for (Dalgaard et al., 2003). The review also showed that relatively little work has addressed the European scale, or the scale of large or medium-sized regions such as NUTs-1 and NUTs-2. Computing power and easy access to computing tools in combination with stratification of sources of variability and appropriate simplification of the description of processes is needed to enable spatial extrapolation of knowledge.

Timeliness of results from the integrative models reviewed in this paper would benefit greatly from European data standards on economic and environmental quantities. Data from Farm Accountancy Data Networks (FADN) prepared in a way that allows quick and easy transfer to a diversity of modelling approaches would make results more reproducible among integrative approaches and enhance validation opportunities. Currently, projects at national and EU-levels are repeating the same procedures over and over again: extraction of FADN data to construct typical farms, collecting data on current and alternative production processes, collecting and combining GIS data from different sources for the purpose of agro-ecological zoning and relating these different data to allow regionalization of modelling results for farm types. These time consuming processes could be organized more efficiently if national and European organizations would joint their efforts and provide standardized data interfaces for models.

Farm Accountancy Data Networks monitor abiotic environmental as well as economic quantities, but these data networks are weak in biotic, landscape and social quantities. Extending monitoring networks to include new indicators as well as new actors such as inhabitants and part-time users of rural areas will enrich analysis of the current situation and better enable exploration of future options for multifunctional agriculture (Knickel and Renting, 2000).

To put knowledge in the negotiation context that appears to be characteristic for multifunctional agriculture, research needs to better understand the negotiation process and the negotiators (e.g. Pannell, 2004). Where researchers view models as excellent aids for their own understanding of complex systems, the same models may be irrelevant for actors because of their complexity, lack of comprehensiveness or transactions costs involved in accepting a model in a negotiation process. Promising developments in visualization techniques and in optimization approaches that present acceptable rather than 'optimal' solutions to stimulate discussion of alternatives have resulted in multi-agent approaches and multi-criteria genetic algorithms combined with GIS. In terms of social processes, still much has to be learned about how models that are useful for informing scientists can also be made useful to policy makers. Case-based research on successes and failures and in-depth monitoring of policy development and evaluation processes may provide novel insights. Given the lack of analytical progress in understanding of negotiation and social learning processes in agriculture, new transdisciplinary concepts may be needed to integrate contributions from social and natural sciences.

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