Review

Assessing farm innovations and responses to policies: A review of bio-economic farm models

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Abstract

Bio-economic farm models (BEFMs) are developed to enable assessment of policy changes and technological innovations, for specific categories of farming systems. A rapidly growing number of research projects is using these models and there is increasing interest for application. The paper critically reviews past publications and applications of BEFMs on their strengths and weaknesses in assessing technological innovation and policy changes for farmers and policy makers and highlights key issues that require more attention in the use and methodology of BEFMs. A BEFM is defined as a model that links formulations describing farmers’ resource management decisions to formulations that represent current and alternative production possibilities in terms of required inputs to achieve certain outputs, both yield and environmental effects. Mechanistic BEFMs are based on available theory and knowledge of farm processes and these were the focus of our study. Forty-eight applications of mechanistic BEFMs were reviewed as to their incorporation of farmer decision making and agricultural activities, comprehensiveness, model evaluation, and transferability. A clear description of end-use of the BEFM, agricultural activities, model equations and model evaluation are identified as good practices and a research agenda is proposed including the following issues: 1. development of a thorough and consistent procedure for model evaluation; 2. better understanding and modelling of farmer decision making and possible effects of the social milieu; 3. inclusion of several economic and environmental aspects of farming including multifunctionality and 4. development of a generic, modular and easily transferable BEFM.

Keywords: Agriculture; Agricultural systems; Farmer decision making; Mathematical programming; Multi-functional agriculture; Risk

Contents

1. Introducion ................................................................. 623
2. Methodology and use of BEFMs ........................................ 624
   2.1. A classification .................................................... 624
   2.2. Major types of application ........................................ 624
3. Farmer decision making ................................................ 627
   3.1. Profit maximization versus multiple criteria approaches .......... 627
   3.2. Risk .......................................................... 627
   3.3 Time .......................................................... 628
4. Agricultural activities .................................................. 629

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1. Introduction

Policy makers and farmers have an interest in making ex-ante assessments of the outcomes of their choices in terms of policy and farm plan (cf. Rossing et al., 1997; Zander and Kächele, 1999; Leeuvis, 1999; EC, 2005). This interest mainly concerns the assessment of socio-economic and environmental performance of farms as a result of innovations, and the assessment of socio-economic and environmental effects of policies on the major categories of farms. Mathematical models based on systems analysis are suited to explore and assess uncertain future states of systems. As expressed by Edwards-Jones and McGregor (1994) "the utility of a series of whole farm models for the European situation would be substantial, particularly in the ex-ante policy assessment and marketing of on-farm technology". Certainly, not only the European situation would benefit from assessments of agricultural innovations or agricultural and environmental policies.

For such assessments research has proposed the use of methods such as Bio-Economic Farm Models (BEFMs), multi-agent systems, environmental risk mapping, life cycle analysis, environmental impact assessment and agri-environmental indicators, which are each briefly reviewed in Payraudeau and Van der Werf (2005). A BEFM is defined as a model that links formulations describing farmers’ resource management decisions to formulations that describe current and alternative production possibilities in terms of required inputs to achieve certain outputs and associated externalities. The focus of this article is on BEFMs as they have some clear advantages with respect to the other methods reviewed by Payraudeau and Van der Werf (2005): (i) they are based on a constrained optimization procedure and thereby seem to match the reality of small farmers, striving, with limited resources, to improve their lot (Anderson et al., 1985); (ii) many activities, restrictions and new production techniques with sound technical specifications can be considered simultaneously (Wossink et al., 1992; Ten Berge et al., 2000; Weersink et al., 2004), including linkages between crop and livestock production (Antle and Capalbo, 2001); (iii) the effects of changing parameters, for example prices, can easily be assessed through sensitivity analysis (Wossink et al., 1992), and (iv) they can be used both for short term predictions and long term explorations (Van Ittersum et al., 1998). A BEFM permits the (ex-ante) assessment of technological innovations and policies over a range of different geographic and climatic circumstances. A rapidly growing number of research projects is using these models and there is increasing interest for application (Deybe and Flichman, 1991; Donaldson et al., 1995; Rossing et al., 1997; Louhichi et al., 1999; Vatn et al., 2003; Gibbons et al., 2005; Torkamani, 2005).

The presently available publications and applications of BEFMs can be subdivided in three broad classes based on their purpose: (i.) exploring the suitability of alternative farm configurations and technological innovations, i.e., assessing whether a technology will be viable financially and will have positive environmental effects, for example Abadi Ghadim (2000), usually focused at (groups of) farmers and extensionist; (ii.) predicting or forecasting the effects of changing policies on agriculture, focusing at policymakers or facilitating discussion between multiple groups of stakeholders, for example, Berentsen and Giesen (1994) and Bartolini et al. (2007), and (iii.) efforts to highlight methodological aspects of BEFMs and their improvement; for example Apland (1993), usually targeted at researchers.

Currently many descriptions and applications of BEFMs are being published (cf. Bartolini et al., 2007; Acs et al., in press; Onate et al., in press; Semaan et al., in press). A critical analysis of the methodological strengths and shortcomings of these BEFMs and their applications, as related to ex-ante assessment of farm innovation and policies for farmers, policy makers and other stakeholders is lacking. From such analysis, an overarching research agenda can be derived to help and guide efforts on the third class of purposes mentioned above, i.e., methodological improvement of BEFMs.

The objectives of this article are to critically review past publications and applications of BEFMs as to their strengths and weaknesses in assessing technological innovation and policy changes for farmers and policy makers.
and to highlight key issues that require more attention in the use of BEFMs. As a result, this article tries to draw up a research agenda and to identify good practices in the use of BEFMs. An in depth analysis of 48 model studies was carried out (see Table 1), which was supplemented with information from text books and methodological articles. These 48 model studies used 42 different models, as sometimes a model was used in subsequent studies. The review and examples focus on agriculture in industrialized countries, though many aspects will be equally valid for agriculture in developing countries.

In the next section, a classification of BEFMs and their use will be presented. In the subsequent Sections ‘Farmer decision making’, ‘Agricultural activities’ and ‘Comprehensiveness’ of BEFMs are discussed. We then analyse methods to evaluate quality of BEFMs. Finally, conclusions in the form of good practices and a research agenda are presented.

2. Methodology and use of BEFMs

2.1. A classification

For this article the term bio-economic farm model (BEFM) is proposed, but the literature uses a wide range of terms for the same type of models. Publications use terms such as ‘bio-economic’, ‘ecological-economic’ or ‘combining the environmental and economic,’ referring to the integration of economic and biophysical processes and models.

The distinction between on the one hand empirical and mechanistic BEFMs and on the other hand normative and positive approaches is proposed here to classify BEFMs. These distinctions between empirical versus mechanistic and normative versus positive are sometimes mentioned in publications (cf. Thornton and Herrero, 2001; Flichman and Jacquet, 2003; Calker et al., 2004), but poorly defined. Hereby we propose a set of definitions. Mechanistic BEFMs are built on a certain image the researcher has of the processes on farms occurring in reality (Pandey and Hardaker, 1995); in other words a mechanistic model is built on existing theory and knowledge (Austin et al., 1998). Mechanistic models are suitable both for extrapolations and long-term predictions, as these models can simulate system “behaviour outside the range of observed data in ways consistent with established scientific understanding” (Antle and Capalbo, 2001). Empirical models are constructed from the data that are incorporated in them, and try to find relationships in the observed data that are not known ex-ante (Austin et al., 1998). In empirical models prediction of future changes is mostly based on an extrapolation of historical time-series of observed past behaviour and a description of past agricultural technologies. Therefore, they cannot easily deal with specific alternative technological options or new constraints and polices (Ruben et al., 1998; Falconer and Hodge, 2000; Flichman and Jacquet, 2003). This article will further focus on mechanistic BEFMs.

BEFMs can be used according to a positive or a normative approach. Positive approaches try to model the actual behaviour of the farmer by describing farm responses and trying to understand them, while normative approaches try to find the optimal solutions and alternatives to the problem of resource management and allocation (Flichman and Jacquet, 2003). BEFMs based on a normative approach are setting a ‘norm’. The ‘norm’ describes what farmers ought to do in order to achieve a certain objective, for example optimise profits (Berntsen et al., 2003). Farmers often do not succeed or do not desire to manage the farm according to model outcomes (the norm) due to various reasons, such as imperfect information, risk aversion, management quality and skills (Wossink and Renkema, 1994; Falconer and Hodge, 2000; Calker et al., 2004).

Mechanistic farm models generally use mathematical programming or optimization models, which are often based on Linear programming (LP), see Table 1. Linear programming represents the farm as a linear combination of so-called ‘activities’. An activity is a coherent set of operations with corresponding inputs and outputs, resulting in e.g. the delivery of a marketable product, the restoration of soil fertility, or the production of feedstuffs for on-farm use (Ten Berge et al., 2000). An activity is characterised by a set of coefficients (technical coefficients or input–output coefficients) that express the activity’s contribution to the realisation of defined goals or objectives in modelling terms (Ten Berge et al., 2000). As inputs are limited resources, constraints to the activities are defined, which represent the minimum or maximum amount of a certain input or resource that can be used. This system of activities and constraints is then optimised for some objective function, reflecting a user-specified goal, for example profit. Standard mathematical formulations of different types of LP models can be found in Hazell and Norton (1986).

2.2. Major types of application

Often mechanistic BEFMs are used in a normative approach, for example Wossink et al. (1992), Ten Berge et al. (2000), Berntsen et al. (2003), Berentsen (2003) and Pacini (2003). Normative mechanistic approaches may be used in assessments of alternative farm configurations and technological innovations targeted at farmers, and explorations of the long term effects of policies, and technological innovations targeted at policy makers or groups of stakeholders. However, the predictive power of such models is restricted and hence their usefulness in policy assessment.

To assess technological innovations to their economic viability and environmental effects static BEFMs focusing on one or more technologies with exogenous input/output prices are often constructed, for example Abadi Ghadim (2000) and Benoit and Veysset (2003). A problem with mechanistic BEFMs is that when a technological innovation becomes available to the model, it is instantaneously used as it is a better option than existing technologies.
Table 1
Model studies included in this research

<table>
<thead>
<tr>
<th>Reference</th>
<th>Farm type(s)</th>
<th>Country</th>
<th>End use</th>
<th>Model type: name</th>
</tr>
</thead>
<tbody>
<tr>
<td>Abadi Ghadim (2000)</td>
<td>Arable</td>
<td>Australia</td>
<td>1</td>
<td>LP: MIDAS</td>
</tr>
<tr>
<td>Acs et al. (in press)</td>
<td>Arable</td>
<td>Netherlands</td>
<td>4</td>
<td>Dynamic LP</td>
</tr>
<tr>
<td>Annetts and Audsley (2002)</td>
<td>Arable</td>
<td>United Kingdom</td>
<td>2</td>
<td>MCDM</td>
</tr>
<tr>
<td>Apland (1993)</td>
<td>Arable</td>
<td>USA</td>
<td>1</td>
<td>LP (DDP and DSP)</td>
</tr>
<tr>
<td>Barbier and Bergeron (1999)</td>
<td>Mixed</td>
<td>Honduras</td>
<td>2</td>
<td>Dynamic recursive LP</td>
</tr>
<tr>
<td>Bartolini et al. (2007)</td>
<td>Arable</td>
<td>Italy</td>
<td>2</td>
<td>MCDM: MAUT</td>
</tr>
<tr>
<td>Benoit and Veysset (2003)</td>
<td>Livestock</td>
<td>France</td>
<td>1</td>
<td>Static LP: Opt/INRA</td>
</tr>
<tr>
<td>Berentsen (2003)a</td>
<td>Dairy</td>
<td>Netherlands</td>
<td>4</td>
<td>Static LP</td>
</tr>
<tr>
<td>Berentsen and Giesen (1994)b</td>
<td>Dairy</td>
<td>Netherlands</td>
<td>2</td>
<td>Static LP</td>
</tr>
<tr>
<td>Berentsen et al. (1998)c</td>
<td>Dairy</td>
<td>Netherlands</td>
<td>1</td>
<td>Static LP</td>
</tr>
<tr>
<td>Berger (2001)</td>
<td>Several</td>
<td>Chile</td>
<td>4</td>
<td>LP coupled to MAS</td>
</tr>
<tr>
<td>Bernts et al. (2003)</td>
<td>Mixed</td>
<td>Denmark</td>
<td>2</td>
<td>Static LP: FASSET</td>
</tr>
<tr>
<td>Beukes et al. (2002)</td>
<td>Livestock</td>
<td>South Africa</td>
<td>1</td>
<td>Dynamic LP</td>
</tr>
<tr>
<td>Bos (2000)</td>
<td>Livestock</td>
<td>Netherlands</td>
<td>1</td>
<td>MGLP</td>
</tr>
<tr>
<td>Cain et al. (in press)</td>
<td>Mixed and dairy</td>
<td>Pakistan</td>
<td>1</td>
<td>Normative LP</td>
</tr>
<tr>
<td>Calker et al. (2004)</td>
<td>Dairy</td>
<td>Netherlands</td>
<td>2</td>
<td>Static LP</td>
</tr>
<tr>
<td>De Buck et al. (1999)</td>
<td>Arable</td>
<td>Netherland</td>
<td>3</td>
<td>Normative LP</td>
</tr>
<tr>
<td>Deybe and Flichman (1991)</td>
<td>Arable</td>
<td>Argentina</td>
<td>2</td>
<td>LP</td>
</tr>
<tr>
<td>Dogliotti et al. (2005)d</td>
<td>Vegetable</td>
<td>Uruguay</td>
<td>1</td>
<td>MILP: farm images</td>
</tr>
<tr>
<td>Donaldson et al. (2003)d</td>
<td>Arable</td>
<td>England and France</td>
<td>2</td>
<td>dynamic recursive LP</td>
</tr>
<tr>
<td>Dorward (1999)</td>
<td>Subsistence</td>
<td>Malawi</td>
<td>3</td>
<td>LGP with DSP and SSP</td>
</tr>
<tr>
<td>Falconer and Hodge (2000)a</td>
<td>Arable</td>
<td>United Kingdom</td>
<td>2</td>
<td>Normative LP</td>
</tr>
<tr>
<td>Falconer and Hodge (2001)b</td>
<td>Arable</td>
<td>United Kingdom</td>
<td>2</td>
<td>Normative LP</td>
</tr>
<tr>
<td>Gibbons et al. (2005)</td>
<td>Arable</td>
<td>United Kingdom</td>
<td>4</td>
<td>LP: farm-adapt</td>
</tr>
<tr>
<td>Gutierrez-Aleman et al. (1986a) and Gutierrez-Aleman et al. (1986b)</td>
<td>Mixed</td>
<td>Brazil</td>
<td>1</td>
<td>LP</td>
</tr>
<tr>
<td>Jannot and Cairoi (1994)</td>
<td>Arable</td>
<td>France</td>
<td>1</td>
<td>Normative LP</td>
</tr>
<tr>
<td>Kruseman and Bade (1998)</td>
<td>Mixed</td>
<td>Mali</td>
<td>2</td>
<td>MGLP</td>
</tr>
<tr>
<td>Louhichi et al. (1999)</td>
<td>Mixed</td>
<td>Tunisia</td>
<td>2</td>
<td>dynamic non-linear mathematical programming model</td>
</tr>
<tr>
<td>Meyer-Aurich (2005)</td>
<td>Mixed</td>
<td>Germany</td>
<td>2</td>
<td>MCDM LP: MODAM</td>
</tr>
<tr>
<td>Morrison et al. (1986)a</td>
<td>Mixed</td>
<td>Australia</td>
<td>1</td>
<td>Normative LP: MIDAS</td>
</tr>
<tr>
<td>Ogletorpe (1995)c</td>
<td>Livestock</td>
<td>England</td>
<td>2</td>
<td>Static LP (MOTAD)</td>
</tr>
<tr>
<td>Ogletorpe and Sanderson (1999)d</td>
<td>Livestock</td>
<td>Scotland</td>
<td>2</td>
<td>Static LP (MOTAD)</td>
</tr>
<tr>
<td>Onate et al. (in press)</td>
<td>Arable</td>
<td>Spain</td>
<td>2</td>
<td>PMP</td>
</tr>
<tr>
<td>Pacini (2003)</td>
<td>Mixed</td>
<td>Italy</td>
<td>2</td>
<td>LP</td>
</tr>
<tr>
<td>Pfister et al. (2005)</td>
<td>Subsistence</td>
<td>Nicaragua</td>
<td>1</td>
<td>Dynamic mathematical programming model</td>
</tr>
<tr>
<td>Ramsden et al. (1999)</td>
<td>Dairy</td>
<td>United Kingdom</td>
<td>2</td>
<td>Static LP</td>
</tr>
<tr>
<td>Schilizzi and Boulier (1997)</td>
<td>Mixed</td>
<td>Mexico</td>
<td>3</td>
<td>MCDM</td>
</tr>
<tr>
<td>Semaan et al. (in press)</td>
<td>Arable</td>
<td>Italy</td>
<td>2</td>
<td>LP with risk</td>
</tr>
<tr>
<td>Ten Berge et al. (2000)</td>
<td>Several</td>
<td>Netherlands</td>
<td>2</td>
<td>MGLP</td>
</tr>
<tr>
<td>Vatin et al. (1997) and Vatn et al. (2003)</td>
<td>Arable</td>
<td>Norway</td>
<td>3</td>
<td>Dynamic LP: ECECMOD</td>
</tr>
<tr>
<td>Wallace and Moss (2002)</td>
<td>Livestock</td>
<td>Ireland</td>
<td>3</td>
<td>Dynamic Recursive LP and WGP</td>
</tr>
<tr>
<td>White et al. (2005)</td>
<td>Arable</td>
<td>Peru</td>
<td>3</td>
<td>LP</td>
</tr>
<tr>
<td>Wossink et al. (1992)a</td>
<td>Arable</td>
<td>Netherlands</td>
<td>4</td>
<td>Static LP</td>
</tr>
<tr>
<td>Wossink et al. (2001)a</td>
<td>Arable</td>
<td>Netherlands</td>
<td>4</td>
<td>Static LP: MIMOSA</td>
</tr>
<tr>
<td>Zander and Kächele (1999)</td>
<td>Several</td>
<td>Germany</td>
<td>4</td>
<td>MCDM LP: MODAM</td>
</tr>
</tbody>
</table>

a If authors wrote more than one article based on the same model, both articles were included as the research question was often different, which lead to different model structures and analysis.
b Different end uses are assisting farmer decision making (=1), policy assessment (=2), developing or improving methodologies (=3), both assisting farmer decision making and policy assessment (=4).
c DDP and DSP refer to discrete deterministic programming and discrete stochastic programming, where DSP has several time periods in one year and DDP has not. SSP is semi-sequential programming and a form of DSP.
d MILP is mixed integer linear programming.
e See Table 2.
(Wossink and Renkema, 1994). This problem of instantaneous adjustment goes well with the aims of a normative approach, like demonstrating farmers promising alternative set-ups, but less so with a positive approach aiming at predicting actual responses. To solve this problem of instantaneous adjustment, the process of diffusion of an innovation should be part of a positive mechanistic BEFM. To incorporate this, two aspects must be considered: on the one hand the nature of the innovation itself and on the other hand, the attitude of the farmers (Wossink and Renkema, 1994) (see Section 5.1).

A shortcoming identified by McCown (2001) in the use of mechanistic BEFMs in advising farmers, is that a gap exists between the normative, economically and technologically efficient advice given to farmers and the situation on the farm, in which the farmer finds himself. McCown (2001) proposes participatory approaches based on dialogue between farmers and researchers instead of design approaches to bridge this gap as, for example, done by Schilizzi and Boulier (1997).

It is possible to use mechanistic BEFMs in a positive approach (e.g. Deybe and Flichman, 1991; Vatn et al., 2003), for example through the use of Positive Mathematical Programming (PMP). Positive Mathematical Programming (Howitt, 1995) is a methodology that ensures that the model outcomes in the base run calibrate exactly on what is found in reality and that counters the tendency for overspecialization of LP models by adding quadratic cost terms to the objective function. Positive mechanistic approaches are more suitable for predictions of the effects of policy changes and technological innovations in the medium to short term. Strengths of BEFMs in policy assessment are that they have the potential to identify the possible trade-offs between economic and environmental objectives (Ruben et al., 1998) and that they include important aspects often disregarded in the policy making process, i.e., they follow a holistic approach and environmental effects at lower spatial scales (Pacini, 2003) and allow assessment of policies based on coercion (direct regulation or command and control, e.g. quotas, income support) or exchange (e.g. taxes, subsidies, cross-compliance policies, agri-environment schemes), but cannot handle policies based on persuasion, e.g. education and information (Falconer and Hodge, 2000).

Results of a BEFM can be presented in different ways, depending on the interest of policy makers, farmers or other stakeholders. Means of presentation of results (Fig. 1) are response multipliers (Kruseman and Bade, 1998), indicators (Pacini, 2003; Zander and Kächele, 1999), elasticities (Pannell, 1997; Falconer and Hodge, 2000), trade-off curves (Rossing et al., 1997; Zander and Kächele, 1999; Ten Berge et al., 2000; Weersink et al., 2003).
3. Farmer decision making

3.1. Profit maximization versus multiple criteria approaches

The objective function of the mechanistic BEFM states which goals the farmer wants to achieve and the activities selected simulate how the farmer could achieve these goals. The end use of the mechanistic BEFM has large implications for the complexity of the objective function used. A simple formulation can be used for showing a farmer the financial or environmental effects of a change in farm technology in a normative approach, while a more complex formulation is needed for showing policy makers the possible response of farms to policy changes or a group of stakeholders with differing objectives the land use to strive for, e.g. using utility functions or multiple criteria approaches.

Farmer decision making can be classified as operational, sequential and strategic decision making, with an increasing time horizon of the decision at stake (Bouma et al., 1999). Operational decisions are the day-by-day management decisions during the growing season (Bouma et al., 1999), such as deciding whether to mow a pasture or spray a crop depending on the weather forecast. Sequential or tactical decision making relates to decisions within a growing season and to the fact that decisions on crop choice and technology are of a sequential nature. For example, a farmer may decide to use relatively more inputs on his onions during the growing season than foreseen at the start of the growing season, if he notices during the growing season that onion prices are increasing. Strategic decision making has an impact on the structure of the farm over many years, such as the choice between conventional and organic farming and investment decisions.

In the 42 different models used in 48 model studies, farmer decision making was modelled in different ways in the objective function: 23 used a simple measure of profit (income, net revenue, etc.) maximization, 5 a measure of profit maximization minus some risk factor (e.g. risk as avoidance of income variability), 5 an objective function that maximized expected utility (e.g. by including long term goals or measuring utility by interviewing respondents) and 9 studies used an objective function based on different objectives (multi-criteria approaches). If a farmer is assumed to be a rational profit-maximiser, his production decisions are influenced mainly by the relative prices of inputs and products (Falconer and Hodge, 2000) and the production of products, on which the farmer is assumed to have perfect knowledge (McCown, 2001). As Dent et al. (1995) state “common sense suggests that not all farmers or farm households within any given farm type are similar, and it is becoming increasingly apparent that few individuals maximize financial gain”. In reality decisions of farmers are motivated by multiple, often conflict-
Table 2
An overview of some MCDM approaches used in BEFMs

<table>
<thead>
<tr>
<th>Methodology</th>
<th>Abbreviation</th>
<th>Reference</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Multiple goal linear programming</td>
<td>MGLP</td>
<td>Rossing et al. (1997), Zander and Kächele (1999), Ten Berge et al. (2000)</td>
<td>A number of optimization rounds, in each of which one goal is optimized, while the constraints on the other goals are increasingly tightened</td>
</tr>
<tr>
<td>Weighted goal programming</td>
<td>WGP</td>
<td>Ogletorpe (1995), Wallace and Moss (2002), Weersink et al. (2004)</td>
<td>For each of the goals targets are specified and the overall objective is to minimize deviations from those targets</td>
</tr>
<tr>
<td>Lexicographic goal programming</td>
<td>LGP</td>
<td>Dorward (1999)</td>
<td>A form of WGP, but instead of the weights being relative as in WGP the weights are absolute or pre-emptive</td>
</tr>
<tr>
<td>Modelling environmental effects as externalities</td>
<td>NOLP</td>
<td>Jeffrey et al. (1992)</td>
<td>One goal is maximized, other objectives are captured in indicator values resulting as joint outputs from agricultural production</td>
</tr>
<tr>
<td>Compromise programming</td>
<td>CP</td>
<td>Yu (1973), Zeleny (1973)</td>
<td>Solutions are produced that are not optimal with respect to any one objective, but instead are ‘nearly’ optimal for all objectives</td>
</tr>
<tr>
<td>Multi-attribute utility functions</td>
<td>MAUT</td>
<td>Keeney and Raiffa (1976)</td>
<td>Solution closest to the Ideal Point is sought: the Ideal Point is the optimum value of different objectives given the constraints of the model and the preference of the decision maker</td>
</tr>
<tr>
<td>Outranking</td>
<td></td>
<td>Strassert and Prato (2002)</td>
<td>Multi-attribute utility function is assumed for the decision maker or elicited from the decision maker, which is used to rank a set of finite alternative solutions</td>
</tr>
</tbody>
</table>

Non-embedded risk is often defined as income variance. Pannell et al. (2000) found that farmer welfare was only reduced to a small extent with a large reduction in income variance. Therefore, they argue that it is often not worthwhile to model non-embedded risk when assisting farmer decision making, as it is relatively less important in determining optimal farmer welfare than the correct representation of underlying biophysical relationships and the incorporation of tactical decision making. However, even if this is true in some conditions the agricultural activities and farm intensity selected by a model depend on whether or not non-embedded risk is incorporated (Ogletorpe, 1995; Pannell et al., 2000) as the model will select activities with a low variance in income, when non-embedded risk is avoided. We, therefore, think that in policy assessments it is useful to incorporate non-embedded risk if prices or yields do vary significantly. An example of an objective function to take account of non-embedded risk is (adapted from Freund, 1956):

\[
\text{Max } u = e - \phi \lambda
\]

with \( u \) as expected utility, \( e \) as expected income, \( \phi \) as a exogenously determined risk aversion coefficient indicating to what extent the farmer avoids non-embedded risk and \( \lambda \) as the variance of income according to states of nature. This variance of income is calculated on the basis of the deviation of the expected income for each state of nature, where each state of nature has different weather and price conditions. Effects of weather variation can also be investigated by running the BEFM with technical coefficients derived from non-average weather data e.g. by modelling good and bad years (Gutierrez-Aleman et al., 1986a), and assessing whether income can be maintained when extreme weather events occur (Gibbons et al., 2005). This indicates to what extent income and environmental effects are weather dependent.

Farm behaviour as related to embedded risk and sequential (often tactical) decision making depends on access to resource markets and opportunities the farmer has to adjust his decisions as information becomes available (Dorward and Parton, 1997). Thus, when using BEFMs for policy assessment and assisting farmer decision making, it may not be extremely relevant to model embedded risk in cases in which farmers have access to input markets for labour and short term capital (Deybe and Flichman, 1991) as these farmers will be able to maintain ‘ideal’ production activities by hiring in resources from outside the farm in case of unfavourable conditions occurring (Dorward, 1999). The construction and calculation of models incorporating embedded risk (stochastic programming models, Fig. 2, e.g. Apland (1993) and Dorward (1999)) are data and labour intensive as the size of a sequential decision problem increases rapidly (Hardaker et al., 1997), also termed curse of dimensionality (Bellman, 1957) so the extra effort and costs should be worthwhile (Dorward, 1999).

3.3. Time

Most BEFMs do not explicitly take account of time, i.e., they model a period with one time step. Dynamic models take account of time explicitly to capture some of the decision variables as functions of time (Blanco Fonseca and Flichman, 2002). A subdivision of dynamic models (Blanco Fonseca and Flichman, 2002) can be made in recursive models, intertemporal models and dynamic recursive models (Fig. 2). Recursive models are run over several periods;
for each period the starting values are the end values of the last period (Wallace and Moss, 2002). Optimization is carried out for each period separately. Inter-temporal models optimize an objective function over the whole time period and allow for inter-temporal trade-offs between the time periods. For example, an objective function maximizes farm income over the whole time period, while considering the relative preference for current income above future income through a discount rate and the inter-temporal allocation of resources through a set of constraints (Pandey and Hardaker, 1995). Dynamic recursive models optimize the whole period, while explicitly accounting for the inter-temporal allocation of resources through a set of constraints (Pandey and Hardaker, 1995). Dynamic recursive models optimise over the whole period, while explicitly accounting for the dynamic interactions across years by using for each year starting values as the end values of the previous year (Louhihchi et al., 1999). An example of a dynamic recursive model is used by Barbier and Bergeron (1999).

Stochastic programming models subdivide one year into several sub-periods (Fig. 2). They deal with information becoming available during the growing season and embedded risk (Section 3.2) by using a distribution of the values of technical coefficients at each time step. They can be said to be a type of dynamic model as they sub-divide one time step into several smaller time steps.

Out of 48 models studies considered, 37 used static models and 11 dynamic models. The static BEFMs ignore firstly the feedback on yields of adverse environmental effects (such as depletion of soil organic matter) on the longer term. However, static models can monitor what the environmental effects are of certain practices, for example with respect to soil organic matter (Dogliotti et al., 2005). Secondly, static BEFMs ignore the strategic decision making by farmers over many years, e.g., whether or not to build a new shed or incorporate a new enterprise in the farm system, and thirdly, they overlook the changing farm family objectives over time. Farm family objectives do change, as the farm family goes through a process of generation, maturation, decline and regeneration (Wossink and Renkema, 1994; Wallace and Moss, 2002).

Strategic decision making affects the farm system in the long term. According to several authors (Csaki, 1977; Hardaker et al., 1997; Wallace and Moss, 2002) it is of vital importance for the performance of the farm system that the farmer gets ‘big’ investment decisions right. Following Csaki (1977), investment depends on the availability of capital (dependent on the capital market and the capital position of the farm) and the need to invest. Once the investments are made, the increased fixed costs have to be paid and a farmer cannot easily move away from his investments. Only two model studies (Barbier and Bergeron, 1999; Wallace and Moss, 2002) incorporated strategic objectives into the objective function. Given the importance and relative absence of strategic decision making and investment in BEFMs, BEFMs could benefit from more attention to these aspects.

In conclusion, how to model farmer decision making, and whether or not to incorporate embedded or non-embedded risk and time depends first and foremost on the issues at stake (Weersink et al., 2004), as it can be a complicated task in terms of data requirements and model complexity. Our understanding of farm decision making is still limited, which is a hindrance in positive BEFMs more than in normative BEFMs. Incorporating non-embedded risk is justified when the interest is in the activities selected by the BEFMs rather than in the objective values only, while embedded risk needs to be incorporated when the farmer has poor access to resources and resource markets (labour, capital, inputs) to supplement his scarce resources during the season. If a large number of objectives, periods and risks are considered, BEFMs can become “bushy messes” (Hardaker et al., 1997), requiring large amounts of data and long solution time.

4. Agricultural activities

4.1. Activities to represent interactions between inputs

An agricultural activity consists of an enterprise, e.g. maize–wheat–potato rotation, sugar beet crop, dairy cows or beef cows, and a production technology describing the management of the activity (the inputs). An agricultural activity in BEFMs is described through the technical coefficients (TCs) or input–output coefficients. These technical coefficients are discrete estimates stating the amount of inputs needed to achieve certain outputs and the associated economic and environmental effects. Technical coefficient generators (TCGs) (Hengsdijk and van Ittersum, 2003) can then be defined as algorithms to translate data
information into coefficients that represent the input and output relationships for each discrete activity.

The biophysical and economic rules that determine the transformation of inputs into outputs for a given activity are generally non-linear (Ten Berge et al., 2000). These non-linearities and the non-linearity of the production functions should ideally be embedded in the technical coefficients by defining several agricultural activities. Each agricultural activity then represents a point on the non-linear production function. Through the use of technical coefficients synergy between inputs and outputs can be taken into account. Agricultural activities are constructed according to a Leontief production function (Leontief, 1986), in which inputs are used in fixed proportions, which is one of the core advantages of BEFMs compared to econometric methods using continuous production functions. Substitution between inputs is captured by formulating different agricultural activities in which different ratios of inputs are used (Hazell and Norton, 1986). Technical coefficients take account of the non-convexities of production and pollution as explained by Flichman and Jacquet (2003). Responses of a crop yield to a single input are usually concave, while responses of pollution to a single input are usually convex. However, if several inputs are considered jointly, yield and pollution curves may be, respectively, non-concave or non-convex (De Wit, 1992).

Current and alternative activities can be discriminated. Current activities are those being practiced on farms and can be derived from observed data or from experts with knowledge of the current situation. Alternative activities (alternatives in the remainder of this article) are not currently practised by specific farmers, but might be a suitable alternative for the future, often representing technological innovations or newly developed cropping or husbandry practices. These technical coefficients are usually generated and assessed using different sources of information, such as literature, census data, national statistics, farm management handbooks, expert knowledge, field trials and research farms. From the 48 model studies reviewed 13 did not mention their data sources for their technical coefficients.

Two approaches of estimating technical coefficients can be taken. The input-oriented approach implies that inputs serve as a basis for the calculation of outputs, which together form the technical coefficients. In the output-oriented approach, the production target (output) is set dependent on the most limiting growth factor and on the objectives of the agricultural activity and then the most efficient set of inputs to realize this target is defined (Van Ittersum and Rabbinge, 1997; Hengsdijk and van Ittersum, 2002). The latter method is particularly apt for alternatives.

4.2. Alternative activities

In assessment of technological innovations a ‘very’ large number of alternatives needs to be included, as this is the only way a BEFM can find the most promising alternative cropping and husbandry techniques from economic, social or environmental viewpoint (Hazell and Norton, 1986; Falconer and Hodge, 2000; Ten Berge et al., 2000; Hengsdijk and van Ittersum, 2002). This ‘very’ large number of alternatives represents the technological innovation (e.g. precision weeding) in combination with other management aspects (e.g. irrigation and fertilization) of the farm that might influence the uptake of this particular technological innovation. In policy assessment, the number of the alternatives can be relatively low; the alternatives defined should capture already identified promising techniques that are used by progressive farmers or broad categories of technologies that might be picked up due to the policy change. Alternatives must be feasible from a biophysical and technical point of view; whether or not they are socio-economically viable will be assessed in the BEFM (Hengsdijk and van Ittersum, 2002).

Immense numbers of activities can potentially be incorporated, for example over 100,000 crop rotations can be generated if potentially 15 crops can be grown on a certain farm. The number of activities is commonly reduced to a feasible number based on expert judgement. This dependence on expert judgement poses the risk of missing out on activities that experts could not think of, thus limiting the solution space and feeding arbitrariness (Dogliotti et al., 2003). This risk is also noted by Hengsdijk and van Ittersum (2002), who found that many land use studies hardly discuss or ignore completely the underlying concepts and data used for the description of activities, and choices concerning the type of activities that are considered are not made explicit. Of the 48 model studies reviewed 18 mentioned and described the alternatives included in their model, while 18 model studies included only currently used activities. Of the remaining 12 model studies it could not be derived from the publication whether also alternatives or only currently used activities were included. To counter this risk of missing out on promising activities, Dogliotti et al. (2003) developed a tool (ROTAT) to generate all possible activities, in this case crop rotations, and then reduce them to a feasible number of activities by the use of explicit filters. Generally speaking, alternatives should not be an arbitrarily selected set, but must be selected according to well-thought and explicit agronomic and socio-economic rules.

4.3. Level of analysis

Agricultural activities might be quantified or generated at different hierarchical levels, for example at crop, rotation, herd or livestock unit-level. Whether to model at the rotation/herd or individual crop/livestock unit level largely depends on how the model takes account of time. A potential advantage of offering rotations and herds instead of crops and animals as activities to a static BEFM is that non-linear temporal interactions across crops and management alternatives can be captured outside the linear programming frame (Dogliotti et al., 2003). Hence, the structure of the BEFM remains simpler as interactions
between crops and animal classes do not need to be modelled within the LP by adding rotational or herd constraints in the LP that restrict, for example, crops to be grown after other crops, or crops to grow in too high frequency within a rotation, or root crops to be grown too frequently. Static linear programming models can only capture temporal interactions by adding extra constraints with integer and binary variables. In a dynamic model, it is probably easier to model at rotation/herd level in terms of model complexity, but the model can also be constructed at the crop level. In the studies reviewed, modelling at crop and livestock unit level was more popular than modelling at rotation level: 24 out of the 48 were at crop and livestock unit level, while 14 were at herd and rotation level (in the other 10 model studies it is not explained at which level the activities are modelled). The models at crop level often ignored temporal interactions in the cropping system.

Interactions between plant and animal production, can be well captured within LP models (cf. Berentsen, 2003). A thorough discussion of the possibilities of modelling interactions between crops and livestock is provided by Thornton and Herrero (2001).

Next to temporal interactions and interactions between plant and animal enterprises, spatial interactions occur between adjacent agricultural fields or systems. Input–output relationships of agricultural systems could be defined as a function of output of soil and hydrological processes of adjacent agricultural fields or systems (Hengsdijk and van Ittersum, 2002). For example in the case of erosion or run off, there is an input into an adjacent agricultural or non-agricultural field or system. To simplify and study these spatial interactions, Vatn et al. (2003) introduce the concept of partitioning to include lateral interactions.

5. Comprehensiveness

Obviously, a farm is organised differently than science: in a farm the social, economic, agronomic, environmental and institutional aspects are fully integrated and dependent on each other. In science, these aspects are generally studied from different disciplinary perspectives. A BEFM that is weak in one of the disciplines is likely to lead to biased analyses. Constructing a BEFM thus requires integration in an inter/multi/trans-disciplinary set up. In principle, a strong point of BEFMs is that they allow such integration of disciplines. In this section, BEFMs are assessed on their ability to accurately model all the different aspects of the farming system. Three general aspects which we consider important in the construction of a comprehensive BEFM for policy and technology assessment will be further discussed in the next paragraphs: 1. social milieu; 2. environmental impacts; and 3. new functions of agriculture.

Table 3 provides a comprehensive overview and indicates which aspects of farming systems have been often incorporated through the activities or constraints in 48 model studies. The analysis shows that some aspects are more popular than others; for example aspects related to nitrogen are often incorporated, but generally far little attention is paid to pests and diseases, off- and non-farm income, soil fertility as a constraint, soil organic matter, landscape quality, and biodiversity and nature.

5.1. Social milieu

A farmer often does not decide independently on how to react to a policy and a potential technological innovation: he is influenced by his social milieu (Anderson et al., 1985). The utility of BEFM for policy assessment is limited by the lack of understanding of the dynamics of the farm household and of the impact of psychological and cultural values on farmer decision making (Dent et al., 1995), as no mechanistic BEFMs were found that incorporated the social milieu of the farmer. As Anderson et al. (1985) noted: “If farming systems research (FSR) is not ‘major-crop’ biased, the farmer of relevance in many cases will be a woman. Since the preferences of women are likely to be different from men, omission of the women’s viewpoint is likely to lead to misspecified models”. Presumably the most important factors of this social milieu
are the other members of the farm family (Edwards-Jones and McGregor, 1994; Dent et al., 1995; Ruben et al., 1998) and farm families living in the neighbourhood (Berg, 2001). Wossink et al. (1992) propose to distinguish different categories of family farms as to their financial and technical status. But not only the economic background of the farm families is important, also social parameters like attitudes, values, traditions, peer group pressure and culture should be considered (Dent, 1990).

Potentially suitable objective functions for the incorporation of the social milieu are an additive utility function, which adds up the utility functions of the individual household members or a constrained objective function which is constrained by certain basic goals other family members have and that are entered as constraints. The use of so-called farming styles (Van der Ploeg, 1994) to distinguish groups of farms with different strategies due to farm internal and external factors might be useful for application of BEFMs to different farm types.

5.2. Environmental impacts

Environmental impacts are a result of agricultural practices. This is also termed 'joint production' of agricultural outputs and environmental effects (Falconer and Hodge, 2001). Those environmental impacts should be incorporated, that have a clear relation to agricultural practices. Most often environmental effects are modelled through indicators. Effect-based indicators are indicators based on the results in terms of environmental effects, while means-based indicators are based on changes in agricultural practices that could lead to a better environmental performance (Payraudeau and Van der Werf, 2005). Effect-based indicators are preferred above means-based ones (Payraudeau and Van der Werf, 2005), because they characterise the environmental risk more directly and are easier to validate.

5.3. New functions of agriculture

New functions of agriculture, according to the European Union (EC, 1999), are preservation, management and enhancement of the rural landscape, protection of the environment and a contribution to the viability of rural areas. Some of these new functions can be modelled and quantified by including extra activities a farmer might incorporate on his farm, for example a recreation-activity, others can be modelled by quantifying the positive or negative externalities of activities, for example effects of cows on landscape quality. Quantification of the production of ‘rural landscape’ and ‘protection of the environment’ is far more difficult than the quantification of extra income from, for example, farm shops. Production of ‘rural landscape’ can be understood as maintenance of biodiversity and the provision of a pleasant landscape. Biodiversity can be measured with indicators, for example crop diversity indicator, livestock diversity indicator, herbaceous plant biodiversity indicator (Pacini, 2003), or indicators for wild plants, partridges or amphibians (Meyer-Aurich et al., 1998). These indicators, however, either focus only on the agro-biodiversity, or focus on the single species rather than on the complex interactions in food webs underlying biodiversity. It is also challenging to find indicators for the provision of a pleasant rural landscape as pleasantness of landscape is largely subjective. Potential indicators regarding landscape issues which might be further explored are presence, size and amount of landscape elements like field margins, hedges, pools, wetlands, etc. (Hendriks et al., 2000; Groot et al., 2007).

6. Evaluation of BEFMs

A challenge in the use of BEFMs is to ensure that its results can be trusted as sensible and reliable and that the model can be re-used. This section, therefore, discusses model evaluation and transferability of BEFMs.

6.1. Model evaluation

A broad definition of model evaluation is given by Jansen (1997): the major method of showing the reliability of a model for a purpose. The BEFM and its outcomes should closely match reality (Gutierrez-Aleman et al., 1986a). Of the 48 BEFMs reviewed 23 carried out some form of comparison with actual farming practices, of which 8 BEFMs fitted their simulated results to observed data by (automatically) adjusting model parameters as part of a calibration procedure. Only Thompson (1982), Schilizzi and Boulier (1997), Ramsden et al. (1999) and Vatn et al. (2003) describe the comparison between their model outcomes and actual farming practices quantitatively, while others only briefly mentioned the fit with observed data without discussing the quality of fit. The gap between model outcomes and actual farming practices (Wossink et al., 1992) gives an indication of the ability of the model to come close to reality (Thompson, 1982). This gap varied from 5% to 10% in land use at farm level and input coefficients at activity level for Thompson (1982), from 1% to 65% in land use at farm level and input coefficients at activity level for Vatn et al. (2003), from 15% to 40% in income for Schilizzi and Boulier (1997) and from 7% in total production at farm level to 40% in input–output coefficients at activity level for Ramsden et al. (1999). Model outcomes contain a number of different variables, so a model may match closely actual farming practices for one variable, while a large gap exists for other variables. The fact that only four references were found, which explicitly discuss their thorough model evaluation, demonstrates the urgent need for more work in this area.

Four reasons can cause the gap between model outcomes and actual farming practices (Wossink et al., 1992), i.e., poor specification of the objective function, missing dynamic aspects, poorly defined activities, and an incomplete model. This gap can be minimized by making
the model more specific and comprehensive and hence complex. Obviously, a trade-off between simplicity and greater accuracy exists (Thompson, 1982) (Fig. 3).

Even if the model is robust to changes in parameters, it still does not mean that the model structure itself is correct (Pannell, 1997). As part of model evaluation a model can be validated by introducing a new dataset and assessing whether the model can without changes in structure and parameters adequately reproduce the new observed values (Thomann and Muller, 1982). This new dataset could refer to a different year with a policy change or a technological innovation or to a similar farm in another region. Such a validation exercise was explicitly mentioned by only 5 out of the 48 model studies.

Sensitivity analysis of an LP model to parameter values represents a special case according to Rossing et al. (1997) and Makowski et al. (2001), as different technical coefficients may have little effect on the realisation of objectives, but leads to very different activities selected by the optimisation procedure. Eight model studies worked with sensitivity analysis.

6.2. Transferability

BEFMs in principle provide the ability to replicate assessments for a vast range of spatial conditions and farming practices. A BEFM that is easy to transfer between locations or farm types is called generic. Although some of the model studies claim that their model is easily transferrable, no evidence from the literature has been found trying to transfer one model between several locations and farm types. This could be due to on the one hand these models being very specific for a location or farm type or on the other hand modellers preferring to build their own model rather than re-using existing models. Data needs, size and structure of a BEFM can limit its transferability. A simple, small, easily manageable model with a clear structure is probably easier to transfer, but it requires time and effort to make a BEFM generic. The lack of generic BEFMs could limit the uptake of BEFM as a tool for assessments of policies and technological innovations on a larger scale outside the research domain, as the development and use of BEFMs remains a time and resources consuming exercise requiring specialist knowledge of researchers.

7. Good practices and research agenda

Bio-Economic Farm Models enable assessment of policy changes and technological innovations as claimed by a large number of studies, which carried out such an exercise. In previous sections, different aspects of BEFMs were explored, thereby drawing up a state-of-the-art in terms of strengths and shortcomings of present BEFMs. In this section, we identify some good practices in the use of BEFMs and draw up a research agenda for the coming years based on our assessment of methodological shortcomings or limitations.

The following good practices were identified based on the review of 48 model studies. First, authors should clearly state or discuss the end-use of their BEFM, i.e. policy assessment, assisting farmer decision making or methodology development, and link their end-use to the assumptions they are making in their modelling. The modelling purpose...
has strong implications on the details of the BEFM as argued in this paper.

Second, the definition of agricultural activities that form the input to the model should be explicit and documented in any publication, as the inputs determine the outputs of any model. Too many model studies do not mention sources of their data on technical coefficients, while many others did not explicitly discuss assumptions in formulating their current and/or alternative activities.

Third, model evaluation is a vital part of any application of a BEFM and should be explicitly and comprehensively presented in any BEFM publication, as it is the only way of conveying that the assumptions made during the modelling exercise are valid and acceptable. Few of the cited studies explicitly address model evaluation. As a result, the reader of these model studies cannot objectively judge the quality of the BEFM, and the discussion of the results loses grounding.

Fourth, all constraints incorporated in the model across the different scenarios should be explicitly mentioned and discussed. Given that it is very difficult and often not even accepted to provide all modelling details in the form of mathematical equations or LP tableaux in a scientific paper, the models together with their documentation should be made available for download.

Our review suggests several shortcomings in current research. As a first item on a research agenda, it would be essential to develop a consistent and widely accepted model evaluation procedure, comprising steps of checking the correspondence with observed values, calibration and validation. Secondly, it should be further investigated how strategic farmer decision making, including possible effects of the social milieu, can be more adequately represented in BEFMs, especially when targeting policy assessments.

As a third research challenge, in the previous Sections some suggestions were made of aspects that could be incorporated in a BEFM, which have so far only received limited attention, e.g. investment decisions, pests and diseases, biodiversity and landscape quality and temporal effects of soil fertility.

Finally, we suggest the development of an easily transferable BEFM with a generic and modular structure, as currently many BEFMs exist, amended to specific locations or purposes. Existing BEFMs are rarely re-used and the newly developed models and their applications do not add a lot of new features or approaches to the body of the literature. An easily transferable BEFM with a generic and modular structure could enable a group of researchers to work jointly on one model, extending it with new features and allowing re-use across data-sets, farm types and locations.

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