ANALYSIS

Technical coefficients for bio-economic farm household models: a meta-modelling approach with applications for Southern Mali

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Abstract

In recent years, different types of bio-economic models have been developed to support the analysis of the potential impact of agrarian policies on changes in land use, sustainable resource management and farmers’ welfare. Most bio-economic models rely on series of discrete input–output coefficients for current and improved cropping and livestock activities, whereas mathematical programming procedures are usually applied to analyse optimum allocative choice. Adequate procedures for the smooth integration of biophysical information into economic decision models are, however, not readily available. This article provides a new and comprehensive framework for the incorporation of technical input–output coefficients derived from agroecological simulation approaches into bio-economic farm household models. Therefore, continuous production functions are estimated for the production side of the farm household model, making use of meta-modelling principles. It is shown that meta-modelling offers considerable scope for improving the specification and behaviour of bio-economic farm household models. This procedure is applied in a farm household model developed for the analysis of farmers’ response to agrarian policies in Southern Mali. Results are presented for the behaviour of a typical household, focusing attention on the trade-offs between farm income and soil nutrient balances under free market conditions and with constraints on labour, capital and animal traction markets. The stability and robustness of the model is analysed through a simulation of the impact of higher input costs for land use and fertiliser applications. © 2001 Elsevier Science B.V. All rights reserved.

Keywords: Technical input–output coefficients; Farm household behavior; Land use; Crop growth; Production function; Bio-economic models; Meta modelling; Mali

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1. Introduction

Policy makers in developing countries ask for decision support systems that are able to assist them in the appraisal of the most likely farmers’ responses to different types of interventions. Decisions about public investment, market reform or institutional change have a decisive impact on rural incomes, land use and resource allocation that should be acknowledged before these are implemented. Therefore, analytical procedures are required that can support decision-making processes regarding agricultural policies (Sadoulet and de Janvry, 1995).

Policy makers and international donor organisations increasingly care about the implications of economic policies for the sustainability of the resource base (Munasinghe and Cruz, 1994). This implies that both welfare effects and changes in soil quality should be taken into account. In the short run, soil degradation can be considered as an externality, but in the long run technological change deserves major attention. In the latter case, the analysis should be broadened to include potentially feasible and sustainability-enhancing production technologies that are currently not yet applied.

Economic models for policy analysis mostly limit their attention to the historical evolution of land use patterns. Changes in production systems are thus exclusively addressed within the framework of currently applied technologies. Transition towards more sustainable production systems requires, however, insight into a wider range of potential technological options which can be derived from agroecological simulation models (van Keulen and Wolf, 1986; Rabbinge, 1990). These models provide a set of technically feasible input–output coefficients for crop and livestock activities for given soil and climate conditions (Rabbinge and van Ittersum, 1994).

Farmers’ decision-making regarding the adoption of new technologies can be analysed with bio-economic farm household models where production decisions are linked with preferences regarding consumption (Singh et al., 1986; Kuyvenhoven et al., 1998). Technological change towards more sustainable production options can take place if reallocation of production factors in time and space permits improvement of farmers’ welfare under given market and institutional conditions. These bio-economic models are used to analyse the impact of different types of economic incentives (i.e. price policies, market development, public investment) on farmers’ resource allocation decisions, as well as their implications for the natural resource base (in terms of changes in nutrient and organic matter balances).

Adequate procedures for linking technical input–output coefficients with bio-economic farm household models are not readily available. Econometric analyses are limited to current technologies and cannot be used for a simultaneous appraisal of welfare and sustainability effects of new technological options. When new and potential technologies have to be included, mathematical programming approaches are generally used (Barbier, 1994; Schipper, 1996; Deybe, 1998). The discrete nature of the whole range of technically-efficient input–output coefficients leads in practice to analytical problems related to the frequent occurrence of corner solutions (Hazell and Norton, 1986). Recent development in meta-modelling techniques (Kleijnen and van Groenendaal, 1992; Kleijnen and Sargent, 1997) provide a suitable alternative for the integration of technical input–output coefficients derived from agroecological simulation procedures into econometrically specified farm household models. We apply this meta-modelling approach for an analysis of agrarian policies to halt soil degradation in Southern Mali.

The remainder of this article is structured in the following way. In Section 2 the general structure of bio-economic farm household models is presented, taking into account both production and consumption decisions. Section 3 provides a review of different procedures for the specification of technical input–output coefficients for cropping and livestock activities. In Section 4 the basic principles of meta-modelling are outlined and applied for the estimation of production functions based on the parameters of agroecological simulation models. Section 5 reviews the behaviour and robustness of the bio-economic meta-model under different specifications. In Section 6, some final remarks are made regarding the usefulness and shortcomings of meta-modelling for the analysis of economic policies and technological change.
2. Bio-economic farm household models

Economic policies influence farmers’ welfare through the adjustment of relative prices that could lead to: (i) reallocation of land and labour resources; and (ii) changes in market engagement (i.e. net demand or supply). The simultaneous impact of policy instruments on resource allocation and market exchange asks for an integrated analysis that takes into account both production and consumption behaviour. Farm household models provide a useful framework for the appraisal of the responses of different types of farmers to policy measures, considering income and substitution effects (Singh et al., 1986). Moreover, these models can be extended to account for multiple objectives (i.e. profit maximisation, risk aversion, food security) and multi-period criteria (savings and investment).

Farm household models are particularly useful to assess trade-offs between income objectives and the quality of natural resources. Therefore, separate procedures are used to define: (i) technical production possibilities; and (ii) consumptive preferences. The production side of the models is specified in terms of technical input–output coefficients for different agricultural activities, including parameters that indicate the net balance for soil nutrient and organic matter content. This permits appreciation of the implications of changing prices and market conditions on (short-term) production volumes and (long-term) soil resources. The consumption side of the model includes farmers’ preferences regarding expenditures for food and non-food items (derived from household budget surveys) and preferences regarding leisure. Dynamic properties can be incorporated into the model through the specification of savings and investment preferences, permitting adjustments of the resource base in subsequent periods. Linking production and consumption behaviour into a single modelling framework enables an analysis of technical change induced by farm household preferences.

Bio-economic models have been developed at household, village, watershed and sector level (see Ruben et al., 1998 for a review) and are usually built from a number of separate modules that specify: (i) farm household resources and objectives; (ii) technological options and related sustainability indicators; and (iii) prices and market conditions. This modular framework makes the models suitable for use in different locations and permits the integration of information from different disciplines. For optimisation iterative or sequential mathematical programming procedures are used. Although this approach permits the integration of a wide number of different data sources within a single model, estimation procedures are highly complex and model outcomes are not always fully comprehensive. Therefore, efforts are made to control the size of bio-economic models and to adapt the model structure to the specific conditions that prevail in less-developed countries (Krusman, 1999).

Fig. 1 provides a schematic presentation of the structure of the bio-economic farm household and the optimisation procedures used to calculate changes in land use, income and soil nutrient balances due to changing production conditions (for a full mathematical description of the model: see Kruseman and Bade, 1998).1

Farm households optimise their utility derived from consumption expenditures, taking into account available resources (land, labour, capital) and market prices for production factors and products. This procedure results in the selection of technically feasible and economically efficient production activities from the set of potential technical coefficients for land use activities. The derived production structure includes the optimal allocation of available resources to land use activities that guarantee highest farm household welfare and/or lowest levels of natural resource degradation. Adjustments in land use and technology choice can be simulated under conditions of changing relative prices. Response multipliers indicate the percentage

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1 More advanced specifications of this model include separate modules for savings and investment behaviour, goal weighting procedures (i.e. relative importance attached to current consumption vis-a-vis changes in soil quality that influence future consumption), risk parameters and feedback mechanisms to account for the impact of changes in aggregate supply on market prices (Bade et al., 1997; Kruseman et al., 1997).
change in welfare or soil quality as a result of a discrete change in market conditions.

The bio-economic model used in this article has been developed for the analysis of soil degradation processes in the semi-arid area of Southern Mali. In this region, land degradation is particularly severe due to: (i) limited access and use of (in)organic fertilisers; and (ii) the expansion of extensive livestock activities beyond the carrying capacity of pastures (Berckmoes et al., 1990; Sissoko, 1998). Cultivated area of food crops has increased during the last decades, while revenues from cash crop production are used for purchasing more cattle. Consequently, fallow practices are strongly reduced and maintenance of soil fertility becomes dependent on the use of chemical fertilisers, animal manure, and the recycling of crop residues. Possibilities for intensification of farming systems are, however, constrained due to limited exchange on factor markets for labour, capital and animal traction. Therefore, major attention is given to the identification of economic incentives to farmers that permit them to improve the application of inputs (organic and inorganic fertilisers, manure) into more efficient production systems that satisfy both welfare and sustainability criteria.

Model simulations are made for a typical farm household in ‘Koutiala’ region of Southern Mali composed of 25 people (with 12 active people that supply 1800 labour days) that have the disposal of 18 ha of land with defined soil quality characteristics, three pairs of oxen and four ploughs. Production activities are defined as unique combinations of land use and production technologies that can be carried out on a given land unit to produce a certain level of output. The production side of the model includes a set of 1443 technical coefficients for cropping activities (maize, cotton, millet, sorghum, cowpea and groundnuts) and 96 technical coefficients for livestock activities (milk and meat production). The consumption side of the model is based on a cross-section budget survey regarding expenditures for cereals, meat, milk, vegetables and non-agricultural commodities. The latter information is used to estimate marginal utility of consumption for different expenditure categories, making use of a continuous farm household utility function. Expected prices for produced commodities and inputs (labour, traction, implements, fertilisers and manure) are derived from local surveys (Sissoko, 1998). Optimisation takes place for expected utility of consumption (corrected for nutrient losses) under given market conditions and defined resource constraints.
The behaviour of the bio-economic farm household model is strongly dependent on the specification of resource and market constraints. In Southern Mali, market imperfections prevail for labour, capital and animal traction. Labour and animal traction are limiting factors at the beginning of the cropping season when soil preparation must take place immediately after the first rainfall (Fafchamps, 1993). Access to capital for input purchase is constrained due to high risks associated with rainfed production and the scarcity of collateral for borrowing, leading to a generally low development of financial institutions. Moreover, within the framework of common property resources, land is non-tradable. Under these conditions, production and consumption decision, clearly depend on each other, and thus a recursive specification of the farm household model (based on non-separability) must be used (de Janvry et al., 1991). The existence of market failures also implies that intensification of agricultural production meets major difficulties since farmers must rely to a great extent on their internally available resources to improve factor productivity and soil nutrient balances (Corsi, 1994). Consequently, functional integration of cropping and livestock activities within the farm household becomes especially important.

3. Technical coefficients

Technical options for arable cropping and livestock production can be defined in terms of input–output coefficients. For current production activities, these coefficients can be derived from field surveys, taking into account also the timing of input applications, the active ingredients and the exact weight of both the harvest and the sub-products (crop residues, manure). Alternative methods for producing the same commodities can only be derived from field experiments or agroecological simulation procedures. These alternatives are based on better procedures to optimise biomass production through: (i) reduction of water or nutrient constraints; and (ii) control of crop losses, making use of improved input applications, crop residue management strategies, better timing of operations (soil preparation, weeding, grazing) and the implementation of soil erosion control measures. We estimated a whole range of input–output coefficients for these potential production activities that guarantee higher levels of input efficiency and lower levels of soil nutrient depletion.

The so-called generation of technical coefficients is based on different combinations of inputs that are converted into agricultural products (including sub-products) during the production season (divided into five periods). Alternative production technologies for arable cropping are defined by Hengsdijk et al. (1996) according to: (i) soil type (quality, texture, rooting depth); (ii) rainfall and water availability/distribution; (iii) reliance on animal traction for soil preparation; (iv) utilisation of crop residues (harvesting, grazing or ploughing); (v) frequency of fallow for soil recovery; (vi) use of soil and water conservation measures (simple or tied ridging); and (vii) anti-erosion measures (stone hedges). Similarly, livestock activities are specified with a stationary herd model, taking into account different animal production levels (milk, meat and traction). The requirements in terms of digestible organic matter are estimated according to the type of animal (age, production purpose) and the feed energy intake level. The quality and quantity of available animal feed depends on the type of pastures and the grazing strategy (permanent or seasonal grazing). These criteria applied to the defined cropping and livestock activities resulted in 6480 unique input–output coefficients that were subsequently reduced to a feasible set of 1443 technical coefficients for arable cropping and 96 for livestock activities.2

The procedures for estimating these alternative input–output coefficients are basically derived from agroecological simulation models. Technically feasible production levels are determined, taking into account the most limiting factor (i.e. water, nutrients or plant diseases). In the next

2 This reduction is based on technical criteria (soil types that are not adequate for some crops, certain crop residues that cannot be used for fodder) and economic criteria (relative prices rule out a number of input-output combinations).
step, different input requirements for these production levels are determined. Major attention is given to the interactions between soil characteristics and input efficiency (i.e. soil organic matter influencing nutrient availability; annual loss of organic matter due to decomposition that can be replenished by crop residues or manure) and the interactions between input use and soil management practices (conservation and anti-erosion practices influencing fertiliser and water efficiency; organic matter restoration through fallow practices). These ‘synergy effects’ are usually disregarded with direct estimates of production coefficients from empirical data (de Wit, 1992).

Finally, soil organic matter and nutrient balances can be determined, taking into account the supply of external inputs (inorganic fertilisers, manure, crop residues), the uptake by the plants, and losses forthcoming from leaching, denitrification and harvesting of products (Smaling and Fresco, 1993). The latter procedure enables us to combine within a single framework information on production levels, input requirements and sustainability implications. Therefore, these agroecological simulation procedures represent a highly useful approach to analyse trade-offs and/ or complementarities (i.e. potential win-win situations) between production and sustainability objectives. For this latter analysis, mathematical programming procedures are generally used (WRR, 1992; Barbier, 1994; Bade et al., 1997; Kuyvenhoven et al., 1998).

This approach for the quantification of alternative technical coefficients for alternative (more sustainable) activities is widely used in explorative land use studies. Rabbinge and van Latesteijn (1992) rely on estimations for potential production to identify different long-term options for land use in the European Union. In a similar vein, Bouman et al. (1999) present an analysis for improved land use in the Atlantic Zone of Costa Rica, based on separate agroecological models of alternative input–output coefficients for cropping activities (LUCTOR) and pasture and livestock activities (PASTOR). Similar models are available for Malang, Indonesia (van Rheenen, 1994), and for the fifth region of Mali (Veenenklaas et al., 1994). Breman and Sissoko (1998) analyse the technical feasibility of different technical options for agricultural intensification for the Soudano-Sahelien region, while Sissoko (1998) made use of these coefficients for the appraisal of suitable policy instruments that could enable the implementation of promising technological options in Koutiala region of Mali. These models have in common that scientific information on the interactions between soil characteristics, weather (i.e. temperature and rainfall) and crop phenotypes is combined to derive technically feasible coefficients for improved production systems that make a more efficient use of available inputs and produce less soil erosion and nutrient depletion.

The agroecological approach for identifying alternative technical coefficients obviously has a great number of advantages. The analytical procedures are based on a detailed understanding of how production conditions and farming practices influence yield levels. Moreover, interactions between cropping and livestock activities are explicitly addressed, taking into account the use of crop residues as fodder, the use of animal traction for field preparations, and the manure applications for the recovery of crop fields. Finally, the agroecological analysis provides a clear insight into the locally relevant limiting factors for increasing yields or reducing nutrient balances. This is an important starting point for subsequent discussions on suitable policy measures that could be helpful in improving agricultural production in a suitable manner.

A number of disadvantages of the input–output coefficients generated with agroecological simulation procedures should, however, also be acknowledged. In the first place, while major attention is devoted to soil–weather–crop interactions, other possibilities of input substitution (i.e. between labour and animal traction, or between pesticides and labour) are generally neglected. Secondly, given the output-oriented character of the agroecology framework, only technically optimum solutions can be simulated, while intermediate and near-optimum options are disregarded. This poses huge problems once economic criteria are included and second-best optima might appear to be the preferred outcome. This brings us to the third point of criticism related to the fre-
quent occurrence of corner solutions when agroe-
cological input–output coefficients are used
within mathematical programming procedures.
The limited stability and the lack of robustness of
these bio-economic models makes them less useful
for policy analysis since marginal effects can
hardly be registered. In order to overcome these
problems while maintaining the insights forth-
coming from agroecological simulation proce-
dures, meta-modelling techniques provide a useful
additional tool.

4. Meta-modelling

Meta-modelling is an analytical procedure that
has been developed to gain insight into the be-
behaviour of complex simulation models. The devel-
opment of meta-models can serve different
purposes (Kleijnen, 1987; Kleijnen and Sargent,
1997). In the first place, meta-modelling is meant
to simplify the outcomes of simulation models
with the objective of gaining better insight into
the critical relationships within the simulation
procedures. Secondly, meta-models are used for
the validation and verification of the robustness
of simulation models. Finally, meta-models are
often much smaller in size and can be used to
replace the original simulation model in subse-
quent analyses. The latter objective is especially
relevant for the purpose of this article, whereas we
are looking for possibilities to integrate informa-
tion derived from agroecological simulation mod-
els into an econometric model on farm household
behaviour. This implies that the set of agroe-
cological technical input–output coefficients from crop-
ning and livestock activities are analysed with
regression techniques to define continuous pro-
duction functions. This information is used again
within the bio-economic mathematical program-
ning model to analyse farm household allocative
choice.

Meta-modelling offers a great possibility to
overcome the mathematical programming limita-
tions intrinsic to bio-economic farm household
modelling that have been mentioned in the previ-
ous paragraph, providing adequate procedures to
capture large numbers of discrete input–output

data in one model. Meta-models often have the
form of a regression analysis of the input and
generated output data of simulation models or
mathematical programming models (Kleijnen,
1987). In Fig. 2 the basic steps of the meta-mod-
elling approach are shown. In brief, the (meta-)
regression model analyses the results of a (agroe-
cological) simulation model and prepares the
functional relationships that can be used again for
mathematical programming analysis.

Different applications of meta-modelling are
available from simulation models for the analysis
of global warming (van Ham et al., 1990) and
climate change (Kleijnen and Standridge, 1986).
Kleijnen and Sargent (1997) provide general
guidelines for the estimation of meta-models, in-
cluding a number of tests for the specification of
the adequacy of functional forms, the design of
experiments to detect most limiting factors, and
procedures to determine the validity of the meta-
model.

Meta-modelling offers clear advantages for the
processing of large data sets that are used again in
subsequent mathematical programming proce-
dures. Instead of discrete point data for technical
input–output coefficients, continuous production
functions are estimated that can be used consis-
tently for econometric analysis. These functions
still retain the synergetic properties (related to

![Fig. 2. Stepwise estimation of technical input–output coeffi-
cients.](image-url)
complementary input) that are fundamental to agroecological simulation models, but permit more insight into the available options for factor substitution in which economists are primarily interested. Moreover, an even wider range of input–output coefficients becomes available that enhances the stability of the model and prevents the occurrence of corner solutions. Finally, the estimated functions still include all points of technical efficiency but enable a more detailed analysis of marginal effects.

The performance of meta-models demonstrates in practice a number of problems related to the typical distribution of observations and error terms. Since most meta-models are derived from rather deterministic simulation procedures, problems with heteroscedasticity and serial correlation frequently appear. Therefore, Durbin–Watson statistics and the White test should be carefully analysed. The relative prediction error can be calculated, based on the percentage change in the forecasted value of the regression function when one observation is deleted. Other problems arise when joint output is considered in the meta-model (e.g. yields and nutrient balances). In this article we calculated the environmental implications of selected input–output coefficients by using again the original agroecological data. In principle, both yields and environmental effects could also be estimated simultaneously using two-stage least square (2SLS) procedures (Pindyck and Rubinfeld, 1991). Otherwise, parametric distance functions might offer a suitable alternative (Reinhard and Thijssen, 1998).

5. Results

To explore the potential of meta-modelling for bio-economic household modelling, the procedure is applied to the production side of a bio-economic farm household model for Kouiala region in Southern Mali (Kruseman and Bade, 1998). The original data for the meta-model consist of a series of discrete technical input–output coefficients for current and alternative (or potential) production activities. These coefficients stem in turn from the agroecological simulation model.

The meta-model can be optimised within a mathematical programming framework. Optimisation takes place for the farm household objective of consumption utility.

The meta-modelling approach is applied to this series of several hundreds of data points for all crop and livestock activity to derive continuous production functions for each activity, making use of the Battese (1996) procedure to account for zero input use. For arable cropping, we estimated the following Cobb–Douglas production function:

\[
\ln Y = \beta_0 + \beta_1 \ln(L) + \beta_2 \ln(T) + \beta_3 \ln(N)
+ \beta_4 \ln(P) + \beta_5 \ln(M) \quad (1)
\]

where \( Y \) represents the quantity of the different harvested crops (in monetary units), \( L \) and \( T \) are the total amounts of labour and traction (in working days); \( N \) and \( P \) are the amounts of active ingredients of nitrogen and phosphorous fertilisers applied to the crop (in kg/ha); and \( M \) is the amount of manure applied (in kg/ha). Table 1 shows the results of the production functions for cropping activities using the White correction for heteroscedasticity.

The results of the estimated functions are acceptable. All but a few signs for inputs are positive and those negative are not significant. The coefficients for labour are positive and significant, and especially in cotton and cowpea production the elasticity of labour is high. This is consistent with the scarcity of labour in the research area. The traction elasticities for cereals and cotton are estimated between 0.06 and 0.20, while for cowpea and groundnut these are estimated to be about 0.7. The (valid) coefficients for different types of fertilisers are lower than 0.3; for sorghum, cowpea and groundnut the fertiliser coefficients are, however, not significant. The negative coefficients for manure in millet and cowpea production are difficult to explain since it is common

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3 The Cobb-Douglas functional form is used for its relative simplicity and because it provided the best fit in the analysis. Other functional forms (translog, quadratic) produced a singular matrix. Given the synergy effects involved in agroecological simulation, a quadratic specification would have been preferred.
Table 1
Cobb–Douglas production functions for cropping activities (Coefficients and t-statistics using OLS regression)

<table>
<thead>
<tr>
<th></th>
<th>Maize</th>
<th>Cotton</th>
<th>Millet</th>
<th>Sorghum</th>
<th>Cowpea</th>
<th>Groundnut</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Coef.</td>
<td>t-stat</td>
<td>Coef.</td>
<td>t-stat</td>
<td>Coef.</td>
<td>t-stat</td>
</tr>
<tr>
<td>c</td>
<td>1.47***</td>
<td>5.72</td>
<td>-4.05***</td>
<td>-9.39</td>
<td>1.62***</td>
<td>3.95</td>
</tr>
<tr>
<td>Labour</td>
<td>0.97***</td>
<td>16.97</td>
<td>1.94***</td>
<td>20.61</td>
<td>0.86***</td>
<td>9.60</td>
</tr>
<tr>
<td>Traction</td>
<td>0.16***</td>
<td>8.67</td>
<td>0.13***</td>
<td>5.07</td>
<td>0.20***</td>
<td>7.59</td>
</tr>
<tr>
<td>N fertiliser</td>
<td>0.10***</td>
<td>5.35</td>
<td>0.09***</td>
<td>3.34</td>
<td>0.20***</td>
<td>7.74</td>
</tr>
<tr>
<td>P fertiliser</td>
<td>0.25***</td>
<td>14.24</td>
<td>0.09***</td>
<td>8.07</td>
<td>0.05</td>
<td>1.77</td>
</tr>
<tr>
<td>Manure</td>
<td>0.06***</td>
<td>8.58</td>
<td>0.07***</td>
<td>7.27</td>
<td>-0.02**</td>
<td>-1.39</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>N</th>
<th>309</th>
<th>192</th>
<th>273</th>
<th>309</th>
<th>192</th>
<th>168</th>
</tr>
</thead>
<tbody>
<tr>
<td>Adj. $R^2$</td>
<td>0.95</td>
<td>0.93</td>
<td>0.89</td>
<td>0.88</td>
<td>0.81</td>
<td>0.77</td>
</tr>
<tr>
<td>D-W*</td>
<td>1.23</td>
<td>1.07</td>
<td>0.73</td>
<td>0.77</td>
<td>0.91</td>
<td>0.82</td>
</tr>
<tr>
<td>RPE*</td>
<td>3.71</td>
<td>1.20</td>
<td>0.97</td>
<td>0.55</td>
<td>2.30</td>
<td>3.20</td>
</tr>
</tbody>
</table>

* *N* is the number of observations; D-W is the Durbin–Watson statistic; and RPE is the relative prediction error (in %)
* *P < 0.05.
** *P < 0.01.
*** *P < 0.001
understanding that additional manure should have a neutral or positive influence on crop yield. Apparently, input efficiency of nutrients derived from organic manure is rather limited compared to chemical fertilisers (Ruben and Lee, 2000). Moreover, part of the nutrients from organic manure may become immobilised into lower soil-layers. The production function for groundnut has the lowest $R^2$ and only two coefficients are significant. All functions for crop production have increasing returns to scale, as can be derived from the sum of the individual input elasticities. The Durbin–Watson statistics are relatively low, probably due to serial correlation related to the fixed soil-input relations in the agroecological simulation model.4

Livestock activities are defined for meat and milk production under different regimes of animal feeding. These feeding categories are related to the maintenance requirements and the needs for production, taking into account the feed source (pasture, crop residues, cotton cake) and quality (N-content and digestible organic matter) of different feed types. We used the following linear specification for the production function of livestock:

$$\ln Y = \beta_0 + \beta_1 (q1) + \beta_2 (q2) \ldots \ldots \beta_{10} (q10)$$

where $q1$...$q10$ represent feed sources available during the wet and dry season that correspond to different levels of energy intake and digestible organic matter. In Table 2 the results for the functions for meat and milk production are shown.

The coefficients in Table 2 are all positive and most of them are significant at the 99% level, except for the constants. The negative constant can be explained by the fact that cattle needs feed for maintenance, which does not contribute directly to production. Only above a certain level of food intake do cattle start producing milk and meat. The variables $q1$ and $q2$ in the equation of meat could be estimated together, as the Wald test indicates that they were not significantly different

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Table 2
Linear production functions for meat and milk production*

<table>
<thead>
<tr>
<th></th>
<th>Milk Coef.</th>
<th>t-stat</th>
<th>Meat Coef.</th>
<th>t-stat</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$-1346***$</td>
<td>166</td>
<td>$-516***$</td>
<td>$-7.16$</td>
</tr>
<tr>
<td>q1</td>
<td>$0.99***$</td>
<td>0.20</td>
<td>$0.54***$</td>
<td>6.85</td>
</tr>
<tr>
<td>q2</td>
<td>$1.16***$</td>
<td>0.19</td>
<td></td>
<td></td>
</tr>
<tr>
<td>q3</td>
<td>$1.26***$</td>
<td>0.18</td>
<td>$0.56***$</td>
<td>7.46</td>
</tr>
<tr>
<td>q4</td>
<td>$1.38***$</td>
<td>0.17</td>
<td>$0.46***$</td>
<td>5.26</td>
</tr>
<tr>
<td>q5</td>
<td>$1.54***$</td>
<td>0.16</td>
<td>$0.49***$</td>
<td>6.24</td>
</tr>
<tr>
<td>q6</td>
<td>$1.69***$</td>
<td>0.15</td>
<td>$0.52***$</td>
<td>7.24</td>
</tr>
<tr>
<td>q7</td>
<td>$1.80***$</td>
<td>0.14</td>
<td>$0.56***$</td>
<td>8.34</td>
</tr>
<tr>
<td>q8</td>
<td>$1.93***$</td>
<td>0.13</td>
<td>$0.60***$</td>
<td>9.37</td>
</tr>
<tr>
<td>q9</td>
<td>$2.10***$</td>
<td>0.13</td>
<td>$0.63***$</td>
<td>10.1</td>
</tr>
<tr>
<td>q10</td>
<td>$2.40***$</td>
<td>0.13</td>
<td>$0.69***$</td>
<td>11.0</td>
</tr>
</tbody>
</table>

Adjusted $R^2$ 0.92 0.70
Durbin–Watson Stat. 0.17 0.19
Number of observations 96 96

* $q1$...$q10$ are food categories of different qualities. In the function for meat $q1$ and $q2$ are estimated together. *** $P<0.001$.

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4 Attempts were made to include a dummy for different soil types to reduce serial correlation, but this did not improve the D-W statistics.
Table 3
Land use pattern, input use and farm household profit and investment under the assumption of perfect markets and with different market constraints*  

<table>
<thead>
<tr>
<th>Missing markets</th>
<th>Land use (ha)</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Maize</td>
<td>Sorghum</td>
</tr>
<tr>
<td>None (base run)</td>
<td>3.6</td>
<td>0</td>
</tr>
<tr>
<td>Labour</td>
<td>3.6</td>
<td>0</td>
</tr>
<tr>
<td>Capital</td>
<td>2.8</td>
<td>0</td>
</tr>
<tr>
<td>Traction</td>
<td>3.6</td>
<td>0</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Profit (*10^3)</th>
<th>Investment (*10^3)</th>
<th>Labour (days)</th>
<th>Traction (days)</th>
</tr>
</thead>
<tbody>
<tr>
<td>None (base run)</td>
<td>2047</td>
<td>834</td>
<td>3410</td>
</tr>
<tr>
<td>Labour</td>
<td>1629</td>
<td>634</td>
<td>1800</td>
</tr>
<tr>
<td>Capital</td>
<td>1750</td>
<td>600</td>
<td>2282</td>
</tr>
<tr>
<td>Traction</td>
<td>2042</td>
<td>849</td>
<td>3500</td>
</tr>
</tbody>
</table>

* All crops in hectares, meat and milk in kg; profit and investment in Fcfa.

from each other. The adjusted $R^2$ value is very high which indicates a good fit. However, the Durbin–Watson statistics indicate that in these functions positive serial correlation occurs.

The estimated functions for crop and animal production are incorporated into a non-linear bio-economic farm household model (Bade et al., 1997; Kruseman and Bade, 1998) which is optimised for the objective of expected utility of consumption, given the availability of resources (land, labour, traction):

$$\max EU = \sum (u \cdot C \mid (Y^* - p_c E))$$

$$\text{s.t. } Y^* = p_I I + p_C C + p_L L$$

where $C$ represents a vector of consumption goods, $Y^*$ represents income derived from production, $I$ represents the different inputs, $L$ is labour force, and $p$ are their respective prices. The vector $E$ includes environmental externalities (e.g. nutrient losses) valued against their replacement costs. For optimisation the standard Gams software is used. When market constraints are effective, this implies that only resources available at the farm household can be used. In the base run, households can fully rely on purchased inputs as long as their budget permits. After optimising the household model, soil nutrient and organic matter balances are calculated for the selected technical coefficients as major indicators for the sustainability and resilience of the system (Hengsdijk et al., 1996).

The household model is first optimised under the assumption of perfect markets, allowing for separability and thus sequential optimisation (Singh et al., 1986). This base run of the model is used as a reference point. Subsequently, constraints are imposed on the labour, capital and animal traction market by limiting the use of these inputs to the quantities owned by households. The model specifications with different market imperfections are optimised in a non-separable way, which means that the production and consumption part are estimated simultaneously (Delforce, 1994). In Table 3, the model outcomes under the assumptions of perfect and missing markets are presented.

Table 3 demonstrates that missing markets diminish the production of crops and meat considerably. The labour market constraint causes a shift from millet production towards less labour-intensive fallow and cowpea activities, while the area for maize production is maintained. Consequently, less crop residues are available for meat

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5 In this model different nutrient loss and supply processes are quantified and — in combination with production levels and input use — soil nutrient balances are estimated.
production. The market constraint for capital causes a shift from maize and millet production to less input-intensive cowpea production and fallow, occasioning a similar decline of crop residues for meat production. With a restriction on the market for animal traction the original land use pattern is maintained, but production activities become far more labour- and input-intensive.

The introduction of market imperfections reduces the level of profit due to changes in the land use pattern and/or shifts in production technologies. Missing markets for labour and capital clearly reduce their factor intensity in the production process. Apparently, animal traction and labour can be used as substitutes: with a missing labour market the use of animal traction rises sharply, while the use of labour increases when constraints for animal traction are imposed. In principle, when different market imperfections coincide, possibilities for factor substitution will further decrease.

The utility levels for the four different model specifications behave consistently. With market imperfections utility decreases compared to the situation with perfect markets. Table 4 shows the results for the consumption side of the model.

Consumption of all categories of goods is lower when market constraints are taken into consideration. The shift from meat consumption towards cereals if per capita income falls is consistent with consumer demand theory where meat is normally considered as a luxury good. Consequently, a decrease in income will cause a more than proportional fall in meat consumption. Cereals are considered to be basic requirements for food security and therefore cereal consumption does not decrease as much as meat consumption.

The implications of market imperfections for the soil quality under different production systems can be reviewed through the calculation of nutrient balances. Whereas differences in nutrient balances between various cropping activities are large, the deviations between the model specifications are relatively small. This can be explained by the fact that the yields per hectare and fertiliser use per hectare differ only slightly between the models with market imperfections. Consequently, nutrient balances are relatively stable as well. The influence of labour and capital market imperfections is most pronounced in the increase of fallow. In this case, market imperfections have a general ‘positive’ effect on sustainability, though at the expense of a decreasing farm household income. Table 5 shows soil nutrient balances under different market conditions:

For policy purposes, we are interested in analysing the effects of higher factor prices (result from structural adjustment programmes) on input use and farm household profit. Table 6 shows the effects of price increases for N-fertiliser and animal traction in order to review the responsiveness of the bio-economic farm household model. A 10% increase of N-fertiliser results in small de-

### Table 4
Consumption of different goods as percentage of total per capita income

<table>
<thead>
<tr>
<th>Missing market</th>
<th>Cereals</th>
<th>Meat</th>
<th>Milk</th>
<th>Legumes</th>
<th>Others</th>
<th>Utility</th>
</tr>
</thead>
<tbody>
<tr>
<td>None (base run)</td>
<td>27.0</td>
<td>2.5</td>
<td>2.3</td>
<td>0.8</td>
<td>67.4</td>
<td>715</td>
</tr>
<tr>
<td>Labour</td>
<td>28.7</td>
<td>2.3</td>
<td>2.2</td>
<td>0.8</td>
<td>65.4</td>
<td>528</td>
</tr>
<tr>
<td>Capital</td>
<td>33.0</td>
<td>2.3</td>
<td>2.2</td>
<td>0.8</td>
<td>65.5</td>
<td>593</td>
</tr>
<tr>
<td>Traction</td>
<td>27.0</td>
<td>2.5</td>
<td>2.3</td>
<td>0.8</td>
<td>67.5</td>
<td>714</td>
</tr>
</tbody>
</table>

The implications of market imperfections for the soil quality under different production systems can be reviewed through the calculation of nutrient balances. Whereas differences in nutrient balances between various cropping activities are large, the deviations between the model specifications are relatively small. This can be explained by the fact that the yields per hectare and fertiliser use per hectare differ only slightly between the models with market imperfections. Consequently, nutrient balances are relatively stable as well. The influence of labour and capital market imperfections is most pronounced in the increase of fallow. In this case, market imperfections have a general ‘positive’ effect on sustainability, though at the expense of a decreasing farm household income. Table 5 shows soil nutrient balances under different market conditions:

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### Table 5
Nutrient balances in optimal solutions (kg/ha)*

<table>
<thead>
<tr>
<th>Missing market</th>
<th>N-balance</th>
<th>P-balance</th>
<th>C-balance</th>
</tr>
</thead>
<tbody>
<tr>
<td>None (base run)</td>
<td>−27</td>
<td>−4.1</td>
<td>−1752</td>
</tr>
<tr>
<td>Labour</td>
<td>−24</td>
<td>−3.8</td>
<td>−1400</td>
</tr>
<tr>
<td>Capital</td>
<td>−22</td>
<td>−3.4</td>
<td>−1401</td>
</tr>
<tr>
<td>Traction</td>
<td>−26</td>
<td>−3.7</td>
<td>−1743</td>
</tr>
</tbody>
</table>

* N is nitrogen, P is phosphorous and C is the organic matter balance.
Table 6
Implications of a 10% increase of N-fertiliser price and animal traction

<table>
<thead>
<tr>
<th>Indicator</th>
<th>Nitrogen</th>
<th>Animal traction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Profit</td>
<td>-0.19</td>
<td>-0.34</td>
</tr>
<tr>
<td>Animal traction</td>
<td>-4.5</td>
<td>-5.7</td>
</tr>
<tr>
<td>Nitrogen</td>
<td>-0.8</td>
<td>-0.5</td>
</tr>
<tr>
<td>Phosphorous</td>
<td>2.0</td>
<td></td>
</tr>
<tr>
<td>Manure</td>
<td>2.2</td>
<td></td>
</tr>
</tbody>
</table>

*Figures give percentage change in indicator values compared to the base run.

6. Discussion and conclusions

Limited availability of large and consistent data sets necessary for the empirical simulation of technical input–output coefficients for bio-economic models is one of the major bottlenecks in policy analysis. Decision-support systems for policy makers should be able to address issues related to the implications of technological change for farmers’ welfare and sustainable resource management, and could be helpful to identify feasible policy instruments to induce farmers towards the adoption of these technologies. Therefore, behavioural aspects of farmers’ choice and available options for technological change must be combined within a single and consistent modelling framework.

In this paper we applied a meta-modelling approach for the production side of a bio-economic farm household simulation model in order to generate continuous production functions on the basis of discrete production data that can be derived from agroecological simulation results. These data are linked to a bio-economic mathematical programming model that takes into account both production behaviour (technological choice) and consumption preferences in a recursive manner.

The basic farm household model in which these production functions for cropping and livestock activities are incorporated shows a consistent behaviour. When no market constraints are considered (i.e. assuming separability between production and consumption), the household relies strongly on market exchange for labour and animal traction. The introduction of market constraints for labour, capital and animal traction in the model (i.e. assuming non-separability) leads to substantial changes in land use and production technologies in favour of less-intensive cropping and feeding activities, and consequently also a lower profit. This implies in turn a sacrifice in terms of household consumption and welfare.

The use of meta-models to replace a series of discrete input-output data in a farm household model is a promising concept. Meta-modelling offers the possibility to improve the operational use of farm household models since the large

increases in N-fertiliser use for crop production, while the input of phosphorous and manure slightly increases. The substantially higher fertiliser price results only in a very small decrease of profit. Similarly, a 10% increase in the price of animal traction results only in a minor decrease of profit, even when the use of animal traction is reduced by almost 6%. This is due to the fact that labour can be used to a certain extent as a substitute for animal traction. It can be concluded that these increases in factor prices have a major impact on technology choice, but do not modify substantially the land use pattern (i.e. distribution of activities over the available farmland) nor the produced quantity of each production activity. The non-linear farm household model thus gives results of a rather robust nature, in the sense that small discrete parameter changes lead to marginal adjustments in resource use and objective values.

These simulated response multipliers derived from the bio-economic meta-model are well below the results calculated with mathematical programming procedures (as reported in Kruseman and Bade, 1998). This can be explained by the fact that the non-linear nature of the meta-modelling specification gives rise to smaller adjustments in line with the marginality principle. Mathematical programming tends to overestimate farm household responses due to the discrete nature of technical input–output options. Meta-modelling results indicate that farmers exhibit usually rather modest response reactions to changes in economic policies.
numbers of (actual and potential) production possibilities are condensed into a limited number of continuous production functions. Moreover, these production functions enable the appraisal of production activities that are both technically and economically efficient. Traditional shortcomings of agroecological simulation procedures related to the neglect of factor substitution can be overcome within this framework, while fundamental insights into the synergetic relations amongst different inputs as well as between cropping and livestock activities are retained.

Some critical notes could be made regarding this approach. Firstly, a meta-model is essentially ‘a model of a model’ and therefore important basic specifications can be lost. This implies that the functional forms used to estimate the meta-model are of crucial importance. Secondly, the possibilities to evaluate the robustness of meta-models are still rather limited. It is good practice to rely on different time-series of input–output data that can be used for: (i) the estimation of calibration of the meta-model; and (ii) the validation of the meta-model vis-à-vis the results derived with the original simulation model, permitting a comparison of the outcomes of the simulation model and the meta-model. The model we used for Southern Mali did not permit such a procedure due to the absence of data, and therefore we relied on the relative prediction error as a measure for the robustness of the meta-model. Finally, while bio-economic models are built to analyse changes in farm household welfare and adjustment in agroecological nutrient and soil organic matter balances, the environmental implications of selected input–output coefficients were calculated by using the original agroecological data. In principle, parametric distance functions could be used to analyse both effects simultaneously.

It can be concluded that the presented meta-modelling approach provides a useful tool to explore the characteristics of the discrete technical input–output coefficients that are subsequently incorporated into the framework of a dynamic and continuous bio-economic farm household model. These procedures enable improvement of the specification and the robustness of meta-mod-


