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A review on farm household modelling with a focus on climate change adaptation and mitigation

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Abstract

This study systematically reviewed the literature to evaluate how suitable existing farm and farm household models are to study aspects of food security in relation to climate change adaptation, risk management and mitigation. We systematically scanned approximately 16,000 research articles covering more than a 1000 models. We found 126 models that met the criteria for subsequent detailed analysis. Although many models use climate as an input, few were used to study climate change adaptation or mitigation at farm level. Promising mixtures of methodologies include mathematical programming for farm level decision-making, dynamic simulation for the production components and agent based modelling for the spread of information and technologies between farmers. There is a need for more explicit farm level analyses with a focus on adaptation, vulnerability and risk. In general terms, this systematic review concludes that there are enough techniques for integrated assessments of farm systems in relation to climate change, adaptation and mitigation, but they have not yet been combined in a way that is meaningful to farm level decision makers.

Keywords

Review; farm model; household model; climate change; adaptation; mitigation;

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Contents

Introduction

Insight in farm functioning is important from an agricultural, social and from an environmental perspective. Farms and agricultural households naturally play a key role in food production and land use management, but their management decisions also play an important role around issues related to water use, pollution (Vatn et al. 2006), soil nutrient depletion, erosion, eutrophication of water bodies, and on an even larger scale the global emissions of greenhouse gasses as carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O). Global change is expected to have significant effects on management strategies of farmers. Insights in the capacity of farmers to adapt and identifying adaptation options are important to be able to estimate the consequences of internal and external changes on farmer's livelihoods, their land use and consequential effects on the environment. Such an integrated assessment (one definition is given by Rotmans and Asselt (1996), page 327: 'an integrated and participatory process of combining, interpreting and communicating knowledge from diverse scientific disciplines to allow a better understanding of complex phenomena') of agricultural changes caused by climate change is a challenging task and modelling is seen as an essential tool to be able to make ex-ante assessments of possible changes.

An essential step in the integrated assessment of agricultural driven land use changes is the modelling of consequences of farmers or land users decision-making on processes at smaller and larger integration levels (Figure 1). Management decisions made at the household level have effects on the individual sub-components of the household-level system, and can have aggregated effects at village, regional, watershed and landscape (national, global, market) levels. However, simulating decision-making at farm and household levels is a major challenge. Farm systems across the world are highly complex and diverse, and therefore tools that address their behaviour are similarly diverse. A range of different techniques and approaches to simulate farm systems is available. Each approach has its pros and cons, and there is no consensus on the best way forward for using this diversity of approaches to address critical questions of

food security under the conditions of a growing human population and a changing climate. Furthermore, few models really take into account in a balanced way the dynamic interactions between the social, production and environmental components of the farming system (Argent 2004), and models from different disciplines in general have a different representation of data, space and time (Janssen et al. 2011, Ewert et al. 2011). The detail of the description of the farm and its environment varies largely with the aims of the projects and background of the model developers. Several reviews have been written on the quantitative tools used to analyse and predict the behaviour of farm systems. However, these reviews often focused on certain techniques and were not comprehensive (McCown et al. 2009, Le Gal et al. 2011, Thornton and Herrero 2001, Janssen and van Ittersum 2007). None of these reviews focused on climate change and adaptation as a specific model application area. Models can help researchers to understand how farming households adapt to potential climate change. This area is still under-explored, and there is a need to evaluate how suitable existing farm household models are to study climate change adaptation and mitigation. This study has reviewed household and farm models world-wide, including models that address problems of both the developed and developing world.

The specific goals of this review are:

1. To present a comprehensive overview of farm and household level models and to analyse trends in the use of modelling techniques in publications in peer reviewed scientific journals.
2. To analyse how (combinations of) different approaches and techniques are used or can be used to study adaptation of farm systems to changes in the biophysical and socio-economic environment. Special attention has been given to how models can deal with adaptation to potential changes in climate.
3. To identify models and modelling techniques that can be further developed to improve their representation of adaptation of farm households in response to environmental change.

Methods

In this study we reviewed models which focused on the farm and household level. The literature was approached through a systematic review of peer reviewed publications. In this review, the farm was defined as the agricultural production system, consisting of a combination of cropping and livestock components that use labour, land, equipment, knowledge and capital resources over time and space to produce goods - which are consumed by the household members or marketed- and ecosystem services (Le Gal et al. 2011). Fisheries and aquaculture components are sometimes integrated with crop and/or livestock components in a farm, and sometimes they represent the unique components of the farm. A household was defined as a family-based co-residential unit that takes care of resource management and the primary needs of its members. A household is considered to be composed of individuals that do not necessarily live together in the same house but that share the majority of the household resources and daily activities (Rudie 1995).The household level includes not only farming activities but also off-farm activities that can bring in food and cash, and require labour. Management of a farm can be conceived, for the purposes of analysis, of taking place at different interconnected time scales: strategic (several years), tactical (seasonal), and operational (daily/weekly) (Le Gal et al. 2011).

Organising the literature through a systematic review

The literature review was carried out using the search engine SCOPUS (http://www.scopus.com/home.url), which covers the highest number of agronomy journals of the internationally available search engines. A matrix was formulated using key search words. The search words were separated into target concepts and application domain concepts (Table 1). Later on, the search was further refined using a list of modelling techniques to capture the variety of models applied to agriculture, fisheries and aquaculture, and natural resources management. This search resulted in 16,000

articles. The EndNote database of references will be made available as on-line supplementary material on the CCAFS website for download by interested users.

The articles corresponding to each combination of target and domain terms went through initial scanning to select those publications dealing with model development or model application. At this step 2,500 papers were selected. All selected publications were imported into a literature database (EndNote; www.endnote.com; Thomson Reuters). After this step, each of the papers was read in detail, and the model evaluated on a series of attributes. We only kept studies that included explicitly the farm or farm-household level, and excluded those focusing on farm component levels or landscape, regional or global levels without taking into account processes at the farm or household level. At this step 450 papers were still considered in the study. The models presented or used in these studies were evaluated on whether they included climate as a direct or indirect variable, and in the end 126 models were characterised in detail.

Characterising models according to their attributes

For all farm or farm household models information was recorded on:

i) modelling techniques used in the study;

ii) whether the study was an application of an existing model, or was using a newly developed model;

iii) the general characteristics of the model (Table 2); and

iv) the key attributes characterising the application possibilities of the model used / developed in the study.

The model characteristics on which information was recorded were i) model name ; year of publication; application level (crop, field, livestock, fish pond, tree lots, farm, grassland, landscape, watershed, basin,

region); ii) whether the model is dynamic (and in which aspects it is dynamic); iii) whether farm-level decision-making is included, and if yes, which type of technique is used; iv) which external factors are included; v) temporal resolution; vi) spatial resolution; and vii) system internal feedbacks included.

A set of key attributes (see Table 2) was defined to characterise the application possibilities of the models of interest for farm household research, and specifically for climate adaptation and mitigation research. Attribute 'Profit' is of general interest, attributes 'Food self-sufficiency' and 'Food security' are especially of interest in subsistence farming. Attributes 'Climate variability and change', 'Risk', 'Mitigation' and 'Adaptation' are of interest in relation to climate related research. Each selected model was evaluated on whether it can be used for assessing the behaviour of farm households for each of these attributes. Vulnerability (although not in Table 2, it is a term that will be used in this study) and adaptation are often defined in different ways in the literature. Here we define vulnerability as the susceptibility of a system to a hazard (Gallopin 2006). For a farm or household, vulnerability can be assessed using different indicators, for example the period of food shortages, food security, or bankruptcy, and therefore we did not include it as a separate attribute. Hazards are defined as threats to a system, comprised of perturbations and stresses. Perturbations are major spikes in pressure (e.g. extreme rainfall or drought events) beyond the normal range of variability in which the system operates. These normally originate outside of the system (Turner et al. 2003). Stress often comes from within the system and is defined as a continuous or slowly increasing pressure (e.g., soil degradation), commonly within the range of normal variability (Gallopin 2006). The adaptive capacity is defined as 'the system's ability to adjust to a disturbance, moderate potential damage, take advantage of opportunities, and cope with the consequences of a transformation that occurs' and an adaptation is 'the system's restructuring after its responses' (Turner et al. 2003, page 8075). In farm and household system research, focusing on systems where the structure is determined by human management, we understand adaptation as the change in farm management or livelihood strategy implemented by the households as a consequence of internal or external system changes. The widely used definition of resilience is that of Walker et al. (2004), first

page: ‘the capacity of a system to absorb disturbance and reorganise while undergoing change so as to still retain essentially the same function, structure, identity, and feedbacks’. Clearly this is a conservative definition which makes sense for ecological systems, but for farm household systems a high resilience can also mean that a farm household is not able to benefit from the opportunities an outside change brings (see for example the definition of ‘adaptation’ above).

Modelling techniques

We classified modelling techniques into three major categories: dynamic simulation, mathematical programming (MP), and multi-agent models (Table 3). This is a very simple categorisation, and many models actually use combinations of these techniques. We grouped the models according to the most important technique that is listed in the description of the models, and only made a separate class called ‘MP models together with simulation models'.

The first category is (dynamic) simulation models. These models make use of ordinary or partial differential equations or difference equations to calculate the behaviour of systems in space and time (Leffelaar 1999). This category represents a wide and large group of models that can simulate the behaviour of a system in time and space. Typically they represent decision-making through parameter settings or what-if rules in the model, a type of approach we will call ‘rule-based’ decision-making in this review.

The second category is optimisation models, which in their simple form are systems of equations aimed at characterising farm-level activities in relation to farm production, investment, marketing, etc. These types of models are based on the specification of behavioural assumptions (e.g. profit maximisation). Programming models (e.g. linear or multiple goal linear programming models) can be used to solve for optimal resource allocations subject to constraints. (Non-) Linear programming (LP) represents the farm

as a (non-) linear combination of so-called ‘activities’. An activity is a coherent set of operations with corresponding inputs and outputs. An activity is characterised by a set of (technical) coefficients that quantify the relationships between activities and certain defined goals or objectives (Ten Berge et al. 2000). As inputs are limited resources, constraints (i.e. minimum and maximum values) to the activities are defined. This system of activities is optimised within the limits of the constraints for a user-specified goal, such as profit. Standard mathematical formulations of different types of optimisation models can be found in (Hazell and Norton 1986).

The third category is multi-agent modelling techniques, i.e. modelling approaches in which families, farmers or household members are represented as an individual entity (agents) explicitly taking into account interactions between these entities. Often in terms of modelling technique, they make use of the same approaches as dynamic simulation models, but whereas those models typically focus on one household or an average representation of a population of households, agent based models represent multiple instances of individual households in their models, together with their interactions.

In this review we have excluded empirical models (econometric and statistical), which by their nature have a limited application domain, and in general cannot be used for adaptation studies under climate change. Econometric models (e.g. structural econometric models) that were used in simulation or mathematical programming models at farm or household level were included. Dynamic simulation models (e.g. crop, soil, livestock models) which focused on the component level have been excluded too.

The term ‘bio-economic model’ is widely used in the literature for models that integrate biophysical and economic components (Janssen and van Ittersum 2007), where the latter are becoming relevant especially in the decision component of the models (Brown 2000). However, the level of integration can vary widely: some bio-economic models are ‘biological process models’ to which an economic component has been added, for example the SAVANNA model (Coughenour 1993, Thornton, Galvin and Boone 2003), the DAFOSYM model (Harrigan, Rotz and Black 1994) and the NUTMON model (Hengsdijk, Meijerink

and Mosugu 2005). Other bio-economic models are economic optimisation models, in which modelled decisions are related to biological resources used as production. An example is the Mali Bio-Economic Farm household model (Ruben and Van Ruijven 2001) which models farm households with different resource endowments in a multi-objective optimisation framework and uses simulated biological processes as technical coefficients. Other integrated bio-economic models include the socio-economic features of the economic optimisation models on the one hand, and the process simulation features of the primary biological process models on the other. An example is the Vihiga Integrated Farm household model (Shepherd and Soule 1998) which, even when it does not incorporate an optimisation component, is able to assess both economic and biological sustainability of farm households with different resource endowments under different environmental, technical and policy scenarios. The term bio-economic model can be used for such a diverse set of models that is it no longer distinctive, and therefore we avoided using the term in this study.

Results

Overview of the systematic review

The systematic review included almost 16,000 peer-reviewed articles. The highest numbers of publications within farm/household research are focused on crops (28%), soils (26%) and water (28%) (Table 3). There are fewer publications focusing on livestock (11%), ecosystems (6%), and fisheries and aquaculture (2%). In terms of application domains, the focus in research is clearly on productivity (21%) and production (26%) of farm systems, and emissions and environmental pollution (26%). Adaptation studies in the context of farm and farm household research only represent 3% of the articles. Studies focusing on smallholders and farm households represent only 3% of the total.

The number of publications in which farm or household level models are used is increasing substantially over time (Figure 2A). The number of peer reviewed publications presenting new models is increasing as well, but more slowly. This shows that in recent years relatively more studies are applications of existing models rather than newly developed models. Also the number of publications in which combinations of modelling techniques are used is increasing substantially over time (Figure 2A). The differences in the re-use of models using different techniques are smaller than expected (Figure 2B). Previous studies stressed that re-use of models using mathematical programming approaches is a major challenge for the future (e.g. Janssen and van Ittersum 2007). Although re-use of these models is less frequent than that of simulation models, substantial re-use is occurring and roughly between 20 and 50% of the publications using mathematical programming as a technique present a model application rather than a newly developed model. For simulation models, about 30 – 60% of the studies present model applications. Over time, there is a trend that relatively more studies present model applications although large variability is visible from year to year. Especially the results of the years before 2000 should be taken with some care because the numbers of publications per year are relatively small and therefore individual studies have large effects on the results of Figure 2B. Typical differences are visible between the modelling techniques

in terms of their attributes (Table 4 and 5). We selected 2,528 articles for further reading. Of those articles, only 480 were selected for detailed evaluation because they explicitly included the farm or household level. That is, only 3% of the articles that resulted from the use of search words were initially scanned. Of the 480 selected studies, 54% used optimisation modelling techniques, 51% dynamic simulation, 7% were agent-based models, and 21% used a combination of modelling techniques. In the following sections we summarise the interesting features found in the models that can be useful for adaptation and mitigation studies.

Of the 480 selected studies we selected 126 models (presented in 160 papers) which are working at farm or household level, and that were of potential interest for our study. The full list of attributes of these models is presented in Tables S1, S2, S3 and S4 in the supplementary material. We also present in Tables 4 and 5 a summary of these tables: which models have dealt and can potentially deal with an attribute, with the models grouped per technique: MP, MP in combination with simulation models, (dynamic) simulation models, and agent based models.

Attributes of the MP models

In the detailed analyses a total of 24 MP models were assessed (Table 4A and 5A). These models included static linear programming models and only five dynamic or recursive MP models (Cittadini et al. 2008, Shively 2000, Louhichi, Alary and Grimaud 2004, Nicholson et al. 1994, Hansen and Krause 1989). Five models performed multiple goal or multiple criteria analyses (Rossing et al. 1997, Senthilkumar et al. 2011, Val-Arreola, Kebreab and France 2006, Dake, Mackay and Manderson 2005). These stand-alone MP models are quite restricted in the way they handle climate variability and climate change, as any change in production or prices should be directly incorporated into the technical coefficients the models use. Two studies take market and/or climate risk explicitly into account. One study focuses on the optimal trade-off between average gross margin and variations in gross margin

caused by environmental fluctuations (Dake et al. 2005). The other study represents climate variability through defining nine explicit season types, with different rainfall conditions and amounts, and analyse the consequences for optimal management, and for the robustness of the estimates of optimal management (Kingwell, Pannell and Robinson 1993). In all models adaptation to climate change or changes in market conditions can be simulated through changes in crop, grass, livestock or fish production coefficients and through changes in prices, but with the restriction that the models assume that the farmer is optimizing his or her behaviour for a specific goal, normally maximizing profit. The changes in production coefficients can be based on experimental work, or based on dynamic modelling analyses, which brings us to the next group of models.

Attributes of the MP models that are combined with simulation models

Thirty-six MP models which were combined with simulation models were analysed (Tables 4B and 5B). A wide range of modelling approaches was used for the simulation models, whereas for the MP techniques most models used optimisation through linear programming. Also used were Multiple Goal LP, dynamic or recursive LP (Popp et al. 2009), non-linear optimisation (García-Vila and Fereres 2011, Grove and Oosthuizen 2010), mixed integer optimisation (Dogliotti, Van Ittersum and Rossing 2005, Gibbons, Ramsden and Blake 2006), nested optimisation (Roetter et al. 2007), stochastic MP (Moghaddam and DePuy 2011) and evolutionary search algorithms followed by constrained programming (Ramilan et al. 2011).

Food security was only analysed by one model, IMPACT-HROM (Zingore et al. 2009, Waithaka et al. 2006), food self-sufficiency by two (Zingore et al. 2009, Waithaka et al. 2006, Thornton et al. 2004). Several models could potentially analyse food self-sufficiency but in the studies evaluated modellers did not focus on this attribute (Berntsen et al. 2003, Holman et al. 2005, Roetter et al. 2007, Moriondo et al.

2010, Ngambeki, Deuson and Preckel 1992, Keil et al. 2009, Herrero et al. 1999, Hatch et al. 1999, Moore, Robertson and Routley 2011).

Basically all models incorporate effects of climate variability on production, but detailed risk analyses on effects of climate variability and change on farm level production and economic welfare are scarce. Grove and Oosthuizen (2010) analysed drought risk on a farm by assessing gross margin as a function of a risk aversion factor, which can differ between farmers. In their study, (Holman et al. 2005) optimised an objective that was the weighted value of gross margin and a risk indicator, although unfortunately the latter was not specified in the paper. Several studies analyse the consequences of different market and/or climate conditions for management and system behaviour (García-Vila and Fereres 2011, Quintero, Wunder and Estrada 2009, Moghaddam and DePuy 2011, Messina, Hansen and Hall 1999, Donnelly et al. 2002, Thomas et al. 2010, Keil et al. 2009, Thornton et al. 2004), and others apply sensitivity analyses to assess the robustness of the optimised strategies (Amir, Puech and Granier 1991, Amir, Puech and Granier 1993). What was lacking in the studies analysed were stochastic input and output analyses, in which rainfall and other factors are entered as a probability density function and outcomes and probabilities of outcomes are quantified as well as distributions rather than average single values.

With regard to adaptation, MP techniques are widely used to assess this. MP models are used to quantify change in optimal management due to changes in the biophysical and socio-economic environment for an individual farmer (an average farm or of a specific farm types) and sometimes for a region (e.g. (Roetter et al. 2007)), and the biophysical consequences of these changes in management through the simulation models (García-Vila and Fereres 2011, Quintero et al. 2009, Moghaddam and DePuy 2011, Messina et al. 1999, Donnelly et al. 2002, Thomas et al. 2010, Keil et al. 2009, Thornton et al. 2004).

Attributes of the simulation models

The 52 simulation models found in the systematic review differ in calculation interval, and thereby the temporal resolution with which they estimate variables (Table 4C and 5C, Table S1): GAMEDE (Vayssières et al. 2009), APS-FARM (Rodriguez et al. 2011a), IFSM (Rotz et al. 2011) are daily time step models, needing daily meteorological input, whereas the models of (Bontkes and Van Keulen 2003), NUANCES-FARMSIM (van Wijk et al. 2009a) and the model of (Luckert et al. 2000) use seasonal or annual time-steps. This difference in time-step also represents a difference in the strategy of model development. The detailed time-step farm models are representative for a large group of models with integrated crop-pasture-livestock systems: GrazeIn (Delagarde et al. 2011a, Delagarde et al. 2011b, Faverdin et al. 2011), UDDER (Chapman et al. 2008a, Chapman et al. 2008b, Chapman, Kenny and Lane 2011), WFM (Beukes et al. 2005, Beukes et al. 2008, Beukes et al. 2010), SEPATOU (Cros et al. 2001, Cros et al. 2003), CEEOT-LP (Gassman et al. 2006, Gassman et al. 2010) and GRAZPLAN (Donnelly et al. 2002) are just a few examples. Often these models were originally operating at component level (e.g. crop, soil and cattle (Keating et al. 2003, Parton et al. 1987, Rotz et al. 1999)), but in the last 15 – 20 years were expanded to encompass farm-level processes and interactions. The other group of simpler models were developed using a top-down approach, i.e. starting at farm level and then representing the component processes as simply as possible (e.g. (Bontkes and Van Keulen 2003, van Wijk et al. 2009a, Shepherd and Soule 1998). These models were developed for applications in data poor environments such as many developing countries. In spite of the lower temporal resolution and the simplicity with which processes are represented, this sort of model can be used to test climate adaptation strategies as long as the simulation models include climate variability to estimate production. This is the case for example for SCUAF (Tamubula and Sinden 2000), NUANCES-FARMSIM (van Wijk et al. 2009a), Savanna-PHEWS (Thornton et al. 2003, Boone et al. 2006), the model of (Bell, Lemos and Scavia 2010), the model of (Bontkes and Van Keulen 2003), and the model of (Pfister et al. 2005), all applied in data scarce environments.

All 52 simulation models selected in this review are driven by rule-based management either implemented through rules or through model parameter settings. Scenario analyses are possible by

changing the settings of the management rules, which allows adaptation studies of many sorts. Traditionally, effects of market or environmental changes are assessed through scenario analyses, so-called 'what-if' analyses. In these scenarios, responses of farmers are incorporated as the scenario to be analysed. Management rules can be related to climate, for example season types which trigger a management plan described by farmers (Kingwell, Pannell and Robinson 1993). Data needs are in general large for the daily time-step models. Not only for the drivers, but also for farm management: timing of decisions, flows of organic material, and decisions with regard to buying, storing and selling of produce. This is the case for models such as GAMEDE (Vayssières et al. 2009) and APS-FARM (Rodriguez et al. 2011a). If this information is available, the dynamic farm models are useful tools to study short-term risk and effects of climate variability on farm production, but as mentioned before, within the given 'what-if' decision-making options of the analyses. The only model with a distinct approach is the TOA model (Claessens, Stoorvogel and Antle 2010, Stoorvogel, Antle and Crissman 2004) in which econometric analyses are used to generate trade-off curves between different objectives. The shape and position of these trade-off curves change if prices and climate change, and thereby allow analyses of adaptive behaviour of farmers.

Not all dynamic models include internal feedbacks between system components and use climate data as a driver. Crop models mostly include feedbacks in the description of soil carbon dynamics (e.g. SCUAF, Savanna-PHEWS, NUANCES, DSSAT models in (Hansen, Knapp and Jones 1997, Hansen et al. 2009) APSIM in APS-FARM, FASSET, DairyMod, SEPATOU, IFSM). The inclusion of soil feedback allows the impact of management strategies in soil emissions to be studied, as far as these are explicitly described. Most dynamic farm models include climate variables such as air temperature and rainfall. Exceptions are the models of (Nousiainen et al. 2011, Sulistyawati, Noble and Roderick 2005, Tichit et al. 2004, Villalba et al. 2010, Pardo, Riravololona and Munier-Jolain 2010, Eriksson, Elmquist and Nybrant 2005, Cabrera, Hildebrand and Jones 2005, Savoie et al. 1985). Climate affects crop and grassland production, and indirectly livestock production. This is described in all models that use climate variables, and in some models to assess climatic risk such as in the application of APSIM by (Hansen et al. 2009),

in the application of COTFLEX by (Helms et al. 1990) to study the effectiveness of crop insurances, and in the modelling study of (Clark et al. 2010) to analyse risk due to extreme climate on shrimp production.

Sixty percent of the selected simulation models included evaluations of economic performance. The description of the economics of the farm varies largely across models: from simple cash balances (Sulistyawati et al. 2005, Thornton et al. 2003, Tittonell et al. 2007) or partial budgets (Villalba et al. 2010), to profitability of the whole farm enterprise (Bell et al. 2010, Gassman et al. 2006, Hansen et al. 1997). There is clearly no consensus on which indicators of economic performance are most relevant for evaluating the welfare of target agronomic households. Few models estimate household food self-sufficiency and/or food security, and this happened exclusively in model applications in the developing world, where food production is closely linked to home consumption. To estimate food self-sufficiency or food security requires the household to be explicitly described in the model so that energy or protein requirements can be calculated on the basis of gender and age classes. Examples of models which included food self-sufficiency estimations are Savanna-PHEWS, NUANCES, NUTMON (although it is a static model), and the models of (Bontkes and Van Keulen 2003, Cabrera et al. 2005, Luckert et al. 2000, Pfister et al. 2005, and Shepherd and Soule 1998). Food security was assessed only with the models of Bontkes and Van Keulen (2003) and Shepherd and Soule (1998), although none of them included food storages in their estimations.

Climatic risk can be studied with most models that include climate effects on production; important to include here are the distribution of exogenous climate shocks and the frequency of severe events rather than changes in the mean. However, there is large variability in the way these effects are described in the selected models. Models that use annual climate data use one or more variables (modifiers) that affect crop or grassland production (e.g. (Hahn et al. 2005, Luckert et al. 2000), or annual or seasonal rainfall that has an effect on water availability, which translates into crop yields (Bontkes and Van Keulen 2003, van Wijk et al. 2009a). Daily time-step crop models using daily meteorological data can simulate crop

stress or failure (e.g. APS-FARM, DSSAT, FASSET), although these processes are very difficult to parameterise and the simulations of these events remain largely uncertain.

To evaluate mitigation options, models should describe at least emissions of CO_2, CH_4, nitrous oxides, leaching of N and P, and water use efficiency. Of the models evaluated, few include these features. GAMEDE can simulate N and CO_2 emissions. The model of Eriksson et al. (2005) calculates a Life Cycle Analysis (LCA) for the evaluated management options. DYNAMOF (Howden, White and Bowman 1996) estimates methane and nitrous oxides emissions. FASSET (Hutchings et al. 2007), ISFM (Rotz et al. 2011) and DairyMod (Johnson et al. 2008) estimate full GHG emissions of dairy and pig systems.

Attributes of the agent-based models

The 14 agent-based models analysed in this study (Tables 4D and 5D, Table S1) differ widely in their description of component processes, and the detail with which climate is taken into account. Most models work on a yearly time-step but a few have included detailed production models with a daily time-step (for example PALM (Matthews and Pilbeam 2005b), and some versions of MPMAS (Schreinemachers and Berger 2011)). In all cases decision-making takes place on a seasonal or yearly basis, thereby focusing on tactical and strategic decision-making. Detailed climate risk analyses in which drought periods and delays in the onset of the rainy seasons occur are not possible with most agent-based models at the moment because of this yearly time-step, unless transfer functions or adapted crop production values are used that can incorporate these climate effects. Decision-making in agent-based models is mostly rule based, although two models used optimisation through linear programming (Schreinemachers and Berger 2011, Shively and Coxhead 2004). Five agent-based models are spatially explicit (Valbuena et al. 2010, Castella, Trung and Boissau 2005, Heckbert 2011, Manson and Evans 2007, Schreinemachers and Berger 2011). All models include a module to calculate the economic performance of the farm, either net income or gross margin, and this is an important variable in the subsequent decision-making rules of the models. Many of the agent-based models have been explicitly developed for developing countries, and therefore

many models also calculate food self-sufficiency, whereas the PALM model also calculates food security (although without taking into account food storage) (Matthews and Pilbeam 2005b). Although explicit climate or market risk analyses have not been performed with these models up to now, most of the models can be used for this. The MPMAS model (Schreinemachers and Berger 2011) is explicitly taking uncertainty in climate and market prices into account. The model gives simulated outputs together with minimum and maximum ranges when taking into account uncertainty. Adaptation can in all models occur inherently in the model due to the decision rules: if climate or market conditions change this will affect farm production and farm income, and thereby also the outcomes of the decision model of the individual agents. Another option is to change the decisions rules if climate changes or market conditions change. The outcomes of the two models using optimisation techniques (Schreinemachers and Berger 2011, Shively and Coxhead 2004) can change due to adaptation because changes in climate and prices will lead to other optimal management decisions in the optimisation model. Also it is an option to change the coefficients and constraints of the optimisation models due to changes in the biophysical and socio-economic environment if there is a clear need for this when describing the system under change.

Recent developments

Major developments are taking place especially in the implementation of decision-making in the models. First, approaches are being developed to make the constraints and options within the optimisation models more flexible, and thereby giving the system the possibility to develop over time, depending on internal or external conditions. An example of this is the MPMAS model (Schreinemachers and Berger 2006, Schreinemachers, Berger and Aune 2007, Berger and Schreinemachers 2006, Berger, Schreinemachers and Woelcke 2006) in which the agent-based model takes care of the development of constraints and options over time and space. For example, the multi-agent model is used to simulate the spreading of knowledge in the farmer community, and with new knowledge new management options become available in the decision module. This increased flexibility of the optimisation models can be especially

relevant when dealing with adaption options under climate change. In MPMAS, the mathematical programming model is in principle rather small and simple, but therefore also easy to manipulate.

The other development in mathematical programming is actually contrary to this simple and flexible approach. Several new models have been developed in which large databases of technical coefficients feed the mathematical programming models (e.g. van Ittersum et al. 2008, Ponsioen et al. 2006, Herrero et al. 2007, González-Estrada et al. 2008). The coefficients in these databases can either be based on values from the literature, interviews or estimates from detailed model simulations. These databases give flexibility on the one hand: any type of data can be represented and thereby linked to the optimisation model so that many aspects of the farming system can be studied. On the other hand, the size and complexity of the database can also limit the flexibility of the household optimisation model, as a strict structure needs to be maintained, and the coefficients and strategic choices within the model are static. Furthermore, the flexibility is related to scope (more enterprises or regions can be simulated) rather than to flexibility in decision rules or adaptation strategies. Data availability can also be an issue, although this is a common problem for many modelling approaches. Therefore, in response to problems with data availability encountered while applying their own modelling approaches, researchers have developed so-called minimum data approaches to perform farm-level analyses (e.g. Stoorvogel et al. 2004, Claessens et al. 2010, Antle et al. 2010, Antle and Valdivia 2006).

New models, so-called ‘biodecision models’, are currently being developed to simulate decision-making of the farmers or households themselves, and then combined with biophysical models to assess the consequences of these simulated changes. An example of this is the ‘IRRIGATE’ model (Merot and Bergez 2010, Merot et al. 2008, Leenhardt et al. 2004). When dealing with a limited number of options this approach seems powerful, and it can link up easily to information given by farmers on their decision-making.

From a technical perspective, it is clear that newly developed models and re-vamped existing models make use of new developments within information technology. The coupling of simulation models to mathematical programming models or of different component models was already possible in the 1990s (e.g. Stoorvogel 1995), but increasingly complex interactions are implemented in farm models through object oriented programming and open – MI (Modeling Interface; Janssen et al. 2011, Power et al. 2011, Schreinemachers and Berger 2011, Martin et al. 2011). This allows the dynamic coupling of models on time intervals that were not possible previously and thereby also interventions by decision-making on much smaller time scales. This can give more flexibility in terms of the set of decision-making options that can be tested in relation to mitigation and adaptation, but it can also lead to increased data demands.

Discussion

Different modelling techniques can deal with different aspects related to the consequences of global change for farm households (Table 4 and 5): combining different techniques into a single modelling framework seems therefore a logical choice and is actually taking place in many new farm-level modelling studies (Figure 2). Combining Mathematical Programming (MP) and dynamic simulation models already goes back to the 1990s, but in recent years also MP, dynamic simulation and agent-based approaches are being combined (e.g. (Schreinemachers and Berger 2011), and this seems a promising approach. Dynamic simulation models are especially powerful tools for quantifying environmental consequences of different farm management options. Potential effects of climate change on production (e.g. Hansen et al. 2009, Helms et al. 1990, and Clark et al. 2010), long term effects on soil processes (Tamubula and Sinden 2000, van Wijk et al. 2009, Thornton et al. 2003, and Boone et al. 2006), quantification of mitigation options and effects of these (Eriksson et al. 2005, Howden et al. 1996, Hutchings et al. 2007, Rotz et al. 2011, and Johnson et al. 2008) are typical analyses that can be performed with such models. In general, decision-making is rule based, which can lead to limited flexibility in terms of representing adaptation by farmers. New approaches which through elaborate semantic 'if … then …' rules seem more flexible than the traditional approach for representing management decisions through different parameter settings (Merot and Bergez 2010, Merot et al. 2008, Leenhardt et al. 2004). When dealing with a limited number of options these decision models seem powerful, and can link up easily to information given by farmers on their decision-making processes.

Agent based models are by their nature strong in the quantification of consequences of variations across different households and higher scale feedbacks such as local price formation and landscape level processes. As with simulation models, decision-making is generally rule based (with exceptions, such as Schreinemachers and Berger 2011) which can, similar to simulation models, lead to limited flexibility in terms of representing adaptation by farmers. In combination with detailed biophysical models (e.g.

Matthews and Pilbeam 2005b, Schreinemachers and Berger 2011) consequences of climate change for agricultural production and greenhouse gas emissions can be evaluated.

Mathematical Programming (MP) techniques seem to be the most powerful approach to represent farm-level decision-making: they are grounded in economic theory and are the only technique that can deal with the many options available to the model 'farmer' to make a decision (Janssen and van Ittersum 2007). In combination with dynamic simulation models and agent based models, consequences of climate change for production and greenhouse gas emissions can be evaluated and fed back into the optimisation program to affect decision-making, although this assumes that "real" decision-making objectives can be appropriately encoded in model objectives.

Representing decision-making to study adaptation

In their most simple form, MP models are systems of equations characterising farm-level activities in relation to farm production, investment, marketing, etc. These types of models specify behavioural assumptions (e.g. profit maximisation) and can be used to solve for optimal resource allocations subject to constraints. Optimisation models have the advantage that they generally produce the results that best achieve the specified objective (e.g. profit maximisation, or cost minimisation) given specified constraints. Another advantage is that they allow for analysis of technologies at both intensive and extensive margins. Optimisation models are less data intensive in comparison to other approaches (e.g. econometrics or simulation). However, two major weaknesses of these models are that they do not explicitly capture the interaction between the agents in the model, and they do not fully take into account the spatial dimension of agricultural activities (Berger 2001). For more details see Hajkowicz, Collins and Cattaneo (2009), Zander and Kächele (1999), and Antle and Capalbo (2001).

Optimisation models are most useful when a very specific (often, single-variable) objective function and explicit constraints can be specified—they are less useful for determining what the objective function ought to be. Moreover, it is debatable whether optimisation is a good behavioral assumption for humans; optimisation models can be best thought of in most settings as “normative benchmarks” (i.e., “What’s the best that can be done?” rather than “How are people likely to respond in this situation?”). In part, this has to do with the information that is assumed to be available to decision makers.

The application of mathematical programming (MP) techniques to farm decision-making dates back at least to the 1950s, when linear programming (LP) techniques were applied to farm planning problems including the determination of optimal livestock feeding strategies given feed costs and livestock nutrient requirements (see e.g., Heady and Candler 1958, Waugh 1951). Linear programming methods in themselves continue to be of relevance to farm-level decision-making, while technique development has allowed for increased capabilities of LP models to handle complexities such as risk and dynamic changes (e.g., Valderrama and Engle 2002, Louhichi et al. 2004). In other LP-based models (e.g., Berger 2001, Schreinemachers and Berger 2011), spatial multi-agent programming techniques have been used to explicitly capture the social and spatial interactions of heterogeneous farm-households by linking economic sub-models and bio-physical models to spatial (Geographic Information Systems, GIS) data. Berger (2001) concludes that such GIS-based integrated multi-agent models are likely to be important tools for policy analysis and natural resource management in the near future.

In general, there has been considerable progress in the development and application of mathematical programming models for decision-making in agricultural and related activities, including the use of non-linear and mixed-integer techniques, the application of risk programming techniques and the development of goal programming methods (Cabrini et al. 2004, Wui and Engle 2004, Tauer 1983, Val-Arreola et al. 2006). For example, quadratic programming models (QPM) have been used that incorporate risk analysis by defining risk distributions or distribution of parameters to assess risk. Goal programming (GP) models allow for incorporating different decision-making goals into a single model. Multiple goals or objectives

are optimised simultaneously by giving prioritising weights. Other models integrate multiple goal linear programming models with econometric methods (Kuyvenhoven, Ruben and Kruseman 1998).

Econometric models rely almost entirely on the availability of numerical data. These usually represent only a small subset of the information that might be useful for the development of modeling tools, which could also include perceptions, personal interviews, and focus groups. Econometric methods have issues with out-of-sample prediction if the moments of future outcomes (mean, variance, skewness, kurtosis) differ from the past—which is likely to be the case with climate change. Antle, Capalbo and Crissman (1994) developed a conceptual and empirical framework that integrates bio-physical and economic relationships at a disaggregated level and then statistically aggregates to a level that is relevant for policymakers and that can be used for welfare and (ex-ante and ex-post) policy analysis. This approach follows the logical sequence of how macro-level policy affects farmers' decisions, the impacts of which are seen at the micro-level, and then these impacts are aggregated back to the units in which policymakers need to work. One disadvantage of these models is that generally they are data intensive and costly to implement. As a way to deal with the complexity of these types of models, Antle and Valdivia (2006) developed a minimum data approach based on a statistical model to characterise farms and population of farms. The model was applied to ecosystem services analyses. More recently, following the same minimum data concept, the TOA-MD model (Tradeoff Analysis for Multi-Dimensional Impact Assessment model) was developed.

Despite recent progress made in modeling decision-making, models in general seem to give limited attention to the importance of non-agricultural activities (whether off-farm employment or 'on-farm non-agricultural activities'), although it might prove one of the more robust strategies of adaptation. There is evidence from some regions already that having a family member working in the city is good for overall 'farm' household welfare and models should be developed that can analyse these kind of situations.

Focus level: farm and household level

A relevant issue is the extent to which farm and household level models can address adaptation strategies, if the aggregated responses of a larger set of households determines outcomes such as prices and nutrient flows. A single household model would assume values for exogenous drivers, but a key question is what the values of the drivers will be, and this often depends on aggregated behavioural responses of many households. That is, ‘best’ behaviour for an individual household will often depend on the behaviour of some collection of other households. This is typically addressed by multi-agent models, which was one of the main reasons to include them in this review. Also other studies used approaches to study the interactions between individual farm and household level behaviour and feedbacks from higher scales, mainly through prices (e.g. Bontkes and Van Keulen 2003; Roetter et al. 2007). In general, these studies seem to indicate that feedbacks from higher scale levels through prices are not that strong, and that policy interventions such as subsidies and price formation at larger regional (e.g. around big cities in developing countries), national and international scales play a more important role. Furthermore, the formulation of these price feedbacks in models is highly uncertain. However, it remains an interesting topic to study further through scenario analyses to quantify under which conditions it can be a key factor to take into account when analysing possible household level responses to, and the effects of, climate change.

Dealing with uncertainty, risk and vulnerability

Representation of risk, vulnerability and resilience of farm households is relatively poor in current farm level models, although econometric models have a long history of dealing with risk and uncertainty. With the advance of computer power, model outcomes can be represented not only as single model outcomes but as ranges of model outcomes and, even better, probability distributions (e.g. (Akponikpe et al. 2010, Rufino et al. 2009, Schreinemachers and Berger 2011). Surprisingly, there are only a few MP model applications at farm or household level in which risk has been taken into account explicitly in the objective function (e.g. Dake et al. 2005, Kingwell et al. 1993). In recent studies, the process, parameter

and measurement of uncertainty of soil carbon have been taken into account in the simulation of continental soil carbon stocks (Ogle et al. 2010), and similar approaches could be used to assess risk (probabilities of specific outcomes) and uncertainty (lack of information, whether about soil carbon or possible distributions of rainfall) in farm system analyses. An overall setup of such an analysis could look like the one presented in Figure 3, whereas probability density functions are used for all uncertain information on the input side, which in multiple model runs will lead to the estimation of the probability density functions of important output variables. In risk analyses, thresholds can be determined for the key output variables and, in combination with the probability density functions. the chances of exceeding those thresholds can be computed. Key output variables can be the management options of interest or the production or economic performance of the farming system. Obtaining results in such an analysis will give more robust information about farm household strategies, and will take into account the still uncertain predictions of potential climate change and uncertain knowledge about the system. Although there is a risk that the researcher will be drowned in uncertainty, and no conclusive recommendations can be made based on such a model analysis, it can identify the key areas in which progress is needed to be able to give reliable recommendations.

A key input needed for analysing appropriate risks related to climate variables is daily meteorological variables. To analyse effects of droughts on crop and grassland production, heat stress on crops and livestock and flooding on production, daily timestep simulation models are needed on which to base risk analyses. These risk quantifications can be used subsequently as input for MP models or farm level simulation models. Results of the review clearly show that attributes such as ‘food security’ and related to this ‘vulnerability‘ are still rarely addressed by farm household models. These attributes are not easy to model, as they require knowledge of the buffering capacity of many aspects of the farming system. However, progress is urgently needed in these areas of research and this is where dynamic or recursive optimisation models can play an important role. Dynamic optimisation could be combined with simple dynamic simulation models to quantify changes in important state variables such as food stored, cash,

number and state of livestock and soil fertility indicators such as organic matter content of crop fields. With proper representation of uncertainties and variability this could lead to a flexible framework where information from lower integration levels (for example, risk profiles of crop production under current and changing climates) forms input for farm level analyses of risk profiles for food security and economic performance. For the development of such a framework, consisting of a set of models working at different integration levels, there will be a need to strongly link the socio-economic characterisation of farming systems to the modelling approaches in place, and to develop long-term field monitoring programs. There is a lack of data in which farms are followed for a long period of time and in which characterisation has taken place at key moments when strategic choices were made by farmers. An example of this is the expansion of maize in sub-Saharan Africa, replacing sorghum and millet in many regions including southern Zimbabwe. However, this expansion is badly recorded and mapped out and the main drivers for this remarkable change are not well known. As this expansion will also have major consequences for the drought risk of food production in these regions, this is an example of a problem in which modelling, production and socio-economic characterisation should go hand in hand.

Limitations to combining models and modelling techniques

No generic approach to the coupling of models exists (Janssen et al., 2011). Existing models describing the different aspects of the farm system can be coupled dynamically, and interactions between the modules can be described explicitly. Approaches to such dynamic model integration and software coupling fall into two classes. First, embedded coupling is an approach in which all model components are incorporated into the same source code (Schreinemachers and Berger 2011). For integrated assessments of farm systems in which many different model components or models need to be connected, this practice is usually impractical. The run-time software coupling is preferable, which works through external driving programs which steer the individual component models. This is typically the approach

taken in large integrated international projects which work across a range of spatial and temporal scales and where models are integrated into model chains. European examples of these projects are ATEAM (Rounsevell et al. 2005), EURURALIS (Van Meijl et al. 2006), SENSOR (Helming, Pérez-Soba and Tabbush 2008) and SEAMLESS (van Ittersum et al. 2008). A separate technique is the so-called 'loose' coupling. In this approach model output of one set of models is the basis for the input of the next set of models, but this step of information exchange is not automated. Filtering, aggregation or any other data manipulation can take place before information is passed on from one model to the next. The term 'loose coupling' comes out of information technology, where it is used if a dependent class contains a pointer only to an interface, not to a concrete class with predefined characteristics (if the latter occurs the connection is called 'strong coupling').

Several recent papers (e.g. Janssen et al. 2011, Martin et al. 2011) stress the possibilities given by new information technology developments for the coupling of models, but do not point out that several drawbacks exist to this type of extensive model coupling. These relate to model complexity and data availability. Model behaviour in complex frameworks becomes more and more difficult to control as the risk increases that models will exceed their range of validity when they are applied at higher or lower levels. Furthermore, component models developed with a focus on component-level processes might not have the required focus to analyse systems at higher integration levels. Actually incorporation of detailed models into higher scale analyses might harm the robustness of model outcomes at larger scales if uncertainties of model descriptions are not properly taken into account. Furthermore, some of these model frameworks go contrary to insights gained from hierarchy theory (Pattee 1973). In general, for complex systems that can be organised into hierarchical levels (i.e. separate levels with different characteristic rates of processes such as behavioural frequencies, relaxation time, cycle time, or response time), there is no need to define more than two hierarchical levels. For a given study that is focused on a particular level, constraints from higher levels can be expressed as constants, boundary conditions, or driving functions, whereas the rapid dynamics at levels lower than one level down only manifest themselves as averages or

equilibria (Wu and David 2002). As already noted, occasional exceptions to this general rule exist, and certain nonlinear effects can penetrate through several levels above or below (Wu and David 2002).

In particular, the extensive need for data for large coupled models can be a constraint for applications. Here we have to make a distinction between data needs for model exogenous data (external drivers such as weather, market prices, size and setup of the farm and household) and model endogenous data representing model parameters (e.g. parameters characterizing processes determining crop growth, soil dynamics, weights in decision-making calculations, and so on). In general, driver data can be collected quite easily but model endogenous data are less easy to collect. Roughly, one can say that the larger the model, the needier it is in terms of model endogenous data. For the biophysical part of the model one could use standard parameterizations for soils, crops and livestock breeds as a starting point, without worrying too much about model robustness, but it clear from large scale model testing that non-calibrated models have low model performance (e.g. Affholder et al. 2012). By coupling component models which were originally developed with a focus on analysing and understanding a single component, data demands for characterisation of each of these components can be high. For example, if a crop – soil model is incorporated in a MP model which is embedded into a multi-agent system, data are needed for each of the components: biophysical and socio-economic inputs and parameters. As multi-agent systems generally work across a landscape or a region, it means the crop model needs input from across that region (different soil, hydrological and climatic conditions) and also needs crop parameters that reflect the crops and the crop varieties used in that region. Single location studies can be performed successfully with this type of framework, but it is hard to see how detailed approaches can simply be extrapolated to other situations without resulting in loss of robustness.

When looking at problems related to model complexity and data availability, even when ignoring problems related to continued model maintenance, it seems preferable that models are not combined in large integrated model frameworks, but that ‘loose’ coupling approaches are used. In these approaches a set of models is used to analyse systems from different perspectives and information is passed on not

automatically but through researcher action after filtering (e.g. Antle et al. 2010). Such a setup gives researchers much more flexibility to work on different aspects of the system and keeps the information technology load of a framework to a minimum. To limit data needs, other approaches to model coupling can be used. These basically try to simplify the outputs of component models into meaningful relationships (the transfer function approach), simplified models (so-called meta-models) or simple coefficients which can be used for analyses at higher integration levels. The latter is a standard approach in mathematical programming in which detailed process-oriented models provide the technical coefficients for the optimisation model (e.g. SEAMLESS). However it is clear that model coupling and use of coupled models still demands extensive knowledge of models and modelling in general. Actual fulfilment of a statement such as ‘The linked models can now easily be used for integrated assessments of policy changes, technological innovations and societal and biophysical changes’ (Janssen et al. 2011) still lies in the future, and it can be doubted whether it will ever be achieved.

Conclusion / recommendations: The way forward

There is a wide range of modelling techniques available to study different aspects of farm/household level research in relation to climate change and adaptation. However, there are no comprehensive modelling studies to date that address adaptation, vulnerability and risk at the household level. In general, it can be said that the techniques for integrated assessments of farm households in relation to climate change, adaptation and mitigation are there, but that they are scattered: they have not yet been combined in a meaningful manner. The terms adaptation and vulnerability are well defined in literature but still need specific and wide-spread implementation in farm systems research and definition at a scale that is relevant to the (farm-level) decision maker. Key will be that applications define well what they mean by ‘farm scale’. Many studies state that they are including the farm level, but actually the decision-making at farm level in terms of land use is not taken into account explicitly.

Recent developments show that new modelling frameworks attempt to combine the strengths of different modelling techniques (e.g. Schreinemachers and Berger 2011), and this seems a promising approach. To keep model complexity manageable it is preferable that models are not combined in large model frameworks, but that 'loose' coupling approaches are used, in which systems are analysed from different perspectives where information is passed on not automatically but through researcher interaction after filtering or processing. Integrated analyses can be performed without developing large integrative frameworks, which are difficult to maintain over time and difficult to apply outside of the region for which they are developed. Flexible and open approaches need to be developed to make use of existing tools so that in the end a sort of 'bookshelf' of models is available to the research community. Thus, depending on the research focus, a different combination of models can be taken off this 'bookshelf', can be applied and knowledge can be gained from the interactions between these models. Key for this is model documentation and open sourcing of models and model codes. Results of the review clearly show that attributes such as 'food security' and 'vulnerability' are still rarely addressed by farm household models. These attributes are not easy to model, as they require knowledge of the buffering capacity of many aspects of the farming system. However, progress is urgently needed in these areas of research, and this is where dynamic or recursive optimisation models can play an important role. Dynamic optimisation could be combined with simple dynamic simulation models to quantify changes in important state variables such as food stored, cash, number and state of livestock and appropriate soil fertility indicators. With proper representation of uncertainties and variability this could lead to a flexible framework where information from lower integration levels (for example, risk profiles of crop production under current and changing climate) forms input for farm level analyses of risk profiles for food security and economic performance. Despite recent progress made in modeling decision-making, models generally seem to give limited attention to the importance of non-agricultural activities, although it might prove one of the more robust strategies of adaptation. Models should be improved so that the effects of these changes can be quantified. The appropriate incorporation of model and input uncertainty is important for climate related applications (e.g. Figure 3) and has only been done in a few studies. Approaches to deal with uncertainty

are available in literature so they can be applied (e.g. Ogle et al. 2010, Vrugt et al. 2008, Fox et al. 2009). Agent based models and MP approaches working on different integration levels (e.g. farm level and regional level) can be used to study important feedbacks on price formation and price variations, thereby increasing the robustness of the assessment of possible adaptation options by taking into account the aggregated behavioural responses of many households.

References

Affholder, F., P. Tittonell, M. Corbeels, S. Roux, N. Motisi, P. Tixier & J. Wery (2012) Ad Hoc Modeling in Agronomy: What Have We Learned in the Last 15 Years? Agronomy Journal, 104, 735-748.

Akponikpe, P. B. I., B. Gerard, K. Michels & C. Bielders (2010) Use of the APSIM model in long term simulation to support decision making regarding nitrogen management for pearl millet in the Sahel. *European Journal of Agronomy,* 32**,** 144-154.

Amir, I., J. Puech & J. Granier (1991) ISFARM: An integrated system for farm management: Part I-Methodology. *Agricultural Systems,* 35**,** 455-469.

Amir, I., J. Puech & J. Granier (1993) ISFARM-An integrated system for farm management: Applicability. *Agricultural Systems,* 41**,** 23-39.

Anderson, D. P. (1993) Alternative grazing fee formula impacts on representative public land ranches. *Journal of Range Management,* 46**,** 548-554.

Anderson, D. P., J. W. Richardson, R. D. Knutson, J. C. Namken, T. R. Harris, W. O. Champney, T. R. MacDiarmid & A. B. Marshall (1993) Alternative grazing fee formula impacts on representative public land ranches. *Journal of Range Management,* 46**,** 548-554.

Andrieu, N., M. Bonhomme, M. Duru & C. Poix (2007a) FDMS, Farmland Diversity and forage production unit Management Simulator. *Computers and Electronics in Agriculture,* 59**,** 86-89.

Andrieu, N., C. Poix, E. Josien & M. Duru (2007b) Simulation of forage management strategies considering farm-level land diversity: Example of dairy farms in the Auvergne. *Computers and Electronics in Agriculture,* 55**,** 36-48.

Antle, J. M. & S. M. Capalbo (2001) Econometric-process models for integrated assessment of agricultural production systems. *American Journal of Agricultural Economics,* 83**,** 389-401.

Antle, J. M., S. M. Capalbo & C. C. Crissman (1994) Econometric production models with endogenouse input timing - an application to Ecuadorian potato production. *Journal of Agricultural and Resource Economics,* 19**,** 1-18.

Antle, J. M., B. Diagana, J. J. Stoorvogel & R. O. Valdivia (2010) Minimum-data analysis of ecosystem service supply in semi-subsistence agricultural systems. *Australian Journal of Agricultural and Resource Economics,* 54**,** 601-617.

Antle, J. M. & R. O. Valdivia (2006) Modelling the supply of ecosystem services agriculture, a minimum-data approach. *Australian Journal of Agricultural and Resource Economics,* 50**,** 1-15.

Argent, R. M. (2004) An overview of model integration for environmental applications: components, frameworks and semantics. *Environmental Modelling and Software,* 19.

Balderama, O. F. 2009. Development of decision support system for sustainable crop and water management in rainfed areas in the Philippines. 405-411.

Balderama, O. F. (2010) Development of a decision support system for small reservoir irrigation systems in rainfed and drought prone areas. *Water Science and Technology,* 61**,** 2779-2785.

Bell, A. R., M. C. Lemos & D. Scavia (2010) Cattle, clean water, and climate change: Policy choices for the Brazilian agricultural frontier. *Environmental Science and Technology,* 44**,** 8377-8384.

Berger, T. (2001) Agent-based spatial models applied to agriculture: A simulation tool for technology diffusion, resource use changes and policy analysis. *Agricultural Economics,* 25**,** 245-260.

Berger, T. & P. Schreinemachers (2006) Creating agents and landscapes for multiagent systems from random samples. *Ecology and Society* 11**,** Art. 19.

Berger, T., P. Schreinemachers & J. Woelcke (2006) Multi-agent simulation for the targeting of development policies in less-favored areas. *Agricultural Systems,* 88**,** 28-43.

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

Beukes, P. C., P. Gregorini, A. J. Romera, G. Levy & G. C. Waghorn (2010) Improving production efficiency as a strategy to mitigate greenhouse gas emissions on pastoral dairy farms in New Zealand. *Agriculture, Ecosystems and Environment,* 136**,** 358-365.

Beukes, P. C., C. C. Palliser, K. A. Macdonald, J. A. S. Lancaster, G. Levy, B. S. Thorrold & M. E. Wastney (2008) Evaluation of a whole-farm model for pasture-based dairy systems. *Journal of Dairy Science,* 91**,** 2353-2360.

Beukes, P. C., B. S. Thorrold, M. E. Wastney, C. C. Palliser, K. A. Macdonald, K. P. Bright, J. A. S. Lancaster, C. A. J. Palmer & M. J. Auldist (2005) Modelling the bi-peak lactation curves of summer calvers in New Zealand dairy farm systems. *Australian Journal of Experimental Agriculture,* 45**,** 643-649.

Blazy, J. M., P. Tixier, A. Thomas, H. Ozier-Lafontaine, F. Salmon & J. Wery (2010) BANAD: A farm model for ex ante assessment of agro-ecological innovations and its application to banana farms in Guadeloupe. *Agricultural Systems,* 103**,** 221-232.

Boissau, S., H. L. Anh & J. C. Castella (2004) The SAMBA role play game in northern Vietnam: An innovative approach to participatory natural resource management. *Mountain Research and Development,* 24**,** 101-105.

Bontkes, T. S. & H. Van Keulen (2003) Modelling the dynamics of agricultural development at farm and regional level. *Agricultural Systems,* 76**,** 379-396.

Boone, R. B., K. A. Galvin, P. K. Thornton, D. M. Swift & M. B. Coughenour (2006) Cultivation and conservation in Ngorongoro Conservation Area, Tanzania. *Human Ecology,* 34**,** 809-828.

Borges Jr, J. C. F., P. A. Ferreira, C. L. T. Andrade & B. Hedden-Dunkhorst (2008) Computational modeling for irrigated agriculture planning. Part I: General description and linear programming. *Engenharia Agricola,* 28**,** 471-482.

Bousquet, F., J. C. Castella, G. Trebuil, C. Barnaud, S. Boissau & S. P. Kam (2007) Using multi-agent systems in a companion modelling approach for agro-ecosystem management in South-east Asia. *Outlook on Agriculture,* 36**,** 57-62.

Brennan, L. E., S. N. Lisson, P. L. Poulton, P. S. Carberry, K. L. Bristow & S. Khan (2008) A farm-scale, bio-economic model for assessing investments in recycled water for irrigation. *Australian Journal of Agricultural Research,* 59**,** 1035-1048.

Brown, D. R. 2000. A Review of Bio-Economic Models. In *Cornell African Food Security and Natural Resource Management*

(CAFSNRM) Program. Cornell University.

Brown, P. D., T. A. Cochrane & T. D. Krom (2010) Optimal on-farm irrigation scheduling with a seasonal water limit using simulated annealing. *Agricultural Water Management,* 97**,** 892-900.

Cabrera, V. E., P. E. Hildebrand & J. W. Jones (2005) Modelling the effect of household composition on the welfare of limited-resource farmers in Coastal Cañete, Peru. *Agricultural Systems,* 86**,** 207-222.

Cabrini, S., B. Stark, H. Önal, S. Irwin, D. Good & J. Martines-Filho (2004) Efficiency analysis of agricultural market advisory services: A nonlinear mixed-integer programming approach. *Manufacturing & Service Operations Management,* 4**,** 237 - 252.

Carvallo, H. O., E. A. Holzapfel, M. A. Lopez & M. A. Mariño (1998) Irrigated cropping optimization. *Journal of Irrigation and Drainage Engineering,* 124**,** 67-71.

Castella, J. C., T. N. Trung & S. Boissau (2005) Participatory simulation of land-use changes in the northern mountains of Vietnam: The combined use of an agent-based model, a role-playing game, and a geographic information system. *Ecology and Society,* 10.

Chapman, D. F., S. N. Kenny, D. Beca & I. R. Johnson (2008a) Pasture and forage crop options for non-irrigated dairy farms in southern Australia. 1. Physical production and economic performance. *Agricultural Systems,* 97**,** 108-125.

Chapman, D. F., S. N. Kenny, D. Beca & I. R. Johnson (2008b) Pasture and forage crop options for non-irrigated dairy farms in southern Australia. 2. Interannual variation in forage supply, and business risk. *Agricultural Systems,* 97**,** 126-138.

Chapman, D. F., S. N. Kenny, D. Beca & I. R. Johnson (2008c) Pasture and forage crop systems for non-irrigated dairy farms in southern Australia. 1. Physical production and economic performance. *Agricultural Systems,* 97**,** 108-125.

Chapman, D. F., S. N. Kenny & N. Lane (2011) Pasture and forage crop systems for non-irrigated dairy farms in southern Australia: 3. Estimated economic value of additional home-grown feed. *Agricultural Systems,* 104**,** 589-599.

Cittadini, E. D., M. T. M. H. Lubbers, N. de Ridder, H. van Keulen & G. D. H. Claassen (2008) Exploring options for farm-level strategic and tactical decision-making in fruit production systems of South Patagonia, Argentina. *Agricultural Systems,* 98**,** 189-198.

Claessens, L., J. Stoorvogel & J. Antle (2010) Exploring the impacts of field interactions on an integrated assessment of terraced crop systems in the Peruvian Andes. *Journal of Land Use Science,* 5**,** 259-275.

Clark, J. L., R. N. Weldon, C. M. Adams & F. F. Wirth (2010) Risk assessment of a shrimp aquaculture investment in Florida. *Aquaculture Economics and Management,* 14**,** 332-357.

Coughenour, M. B. 1993. *Savanna—A Spatial Ecosystem Model. Model Description and User Guide*. NREL, Colorado State University, Fort Collins, CO.

Cros, M. J., M. Duru, F. Garcia & R. Martin-Clouaire (2001) Simulating rotational grazing management. *Environment International,* 27**,** 139-145.

Cros, M. J., M. Duru, F. Garcia & R. Martin-Clouaire (2003) A biophysical dairy farm model to evaluate rotational grazing management strategies. *Agronomie,* 23**,** 105-122.

Dake, C. K. G., A. D. Mackay & A. K. Manderson. 2005. Optimal trade-offs between financial and environmental risks in pastoral farming. 2421-2427.

Del Prado, A., T. Misselbrook, D. Chadwick, A. Hopkins, R. J. Dewhurst, P. Davison, A. Butler, J. Schröder & D. Scholefield (2011) SIMSDAIRY: A modelling framework to identify sustainable dairy farms in the UK. Framework description and test for organic systems and N fertiliser optimisation. *Science of the Total Environment,* 409**,** 3993-4009.

Delagarde, R., P. Faverdin, C. Baratte & J. L. Peyraud (2011a) GrazeIn: A model of herbage intake and milk production for grazing dairy cows. 2. Prediction of intake under rotational and continuously stocked grazing management. *Grass and Forage Science,* 66**,** 45-60.

Delagarde, R., H. Valk, C. S. Mayne, A. J. Rook, A. Gonzalez-Rodriguez, C. Baratte, P. Faverdin & J. L. Peyraud (2011b) GrazeIn: a model of herbage intake and milk production for grazing dairy cows. 3. Simulations and external validation of the model. *Grass and Forage Science,* 66**,** 61-77.

Dinar, A. (1994) Impact of energy cost and water resource availability on agriculture and ground water quality in California. *Resource and Energy Economics,* 16**,** 47-66.

Dinar, A., M. P. Aillery & M. R. Moore (1993) A dynamic model of soil salinity and drainage generation in irrigated agriculture: a framework for policy analysis. *Water Resources Research,* 29**,** 1527-1537.

Dogliotti, S., M. K. Van Ittersum & W. A. H. Rossing (2005) A method for exploring sustainable development options at farm scale: A case study for vegetable farms in South Uruguay. *Agricultural Systems,* 86**,** 29-51.

Donnelly, J. R., M. Freer, L. Salmon, A. D. Moore, R. J. Simpson, H. Dove & T. P. Bolger (2002) Evolution of the GRAZPLAN decision support tools and adoption by the grazing industry in temperate Australia. *Agricultural Systems,* 74**,** 115-139.

Dueri, S., P. L. Calanca & J. Fuhrer (2007) Climate change affects farm nitrogen loss - A Swiss case study with a dynamic farm model. *Agricultural Systems,* 93**,** 191-214.

Engle, C. R. (1997) Optimal resource allocation by fish farmers in Rwanda. *Journal of Applied Aquaculture,* 7**,** 1-17.

Eriksson, I. S., H. Elmquist & T. Nybrant (2005) SALSA: A simulation tool to assess ecological sustainability of agricultural production. *Ambio,* 34**,** 388-392.

Ewert, F., M. K. van Ittersum, T. Heckelei, O. Therond, I. Bezlepkina & E. Andersen (2011) Scale changes and model linking methods for integrated assessment of agri-environmental systems. *Agriculture Ecosystems & Environment,* 142**,** 6-17.

Faverdin, P., C. Baratte, R. Delagarde & J. L. Peyraud (2011) GrazeIn: a model of herbage intake and milk production for grazing dairy cows. 1. Prediction of intake capacity, voluntary intake and milk production during lactation. *Grass and Forage Science,* 66**,** 29-44.

Fox, A., M. Williams, A. D. Richardson, D. Cameron, J. H. Gove, T. Quaife, D. Ricciuto, M. Reichstein, E. Tomelleri, C. M. Trudinger & M. T. Van Wijk (2009) The REFLEX project: Comparing different algorithms and implementations for the inversion of a terrestrial ecosystem model against eddy covariance data. *Agricultural and Forest Meteorology,* 149**,** 1597-1615.

Gallopin, G. C. (2006) Linkages between vulnerability, resilience, and adaptive capacity. *Global Environmental Change,* 16**,** 293-303.

García-Vila, M. & E. Fereres Combining the simulation crop model AquaCrop with an economic model for the optimization of irrigation management at farm level. *European Journal of Agronomy,* 36**,** 21-31.

García-Vila, M. & E. Fereres (2011) Combining the simulation crop model AquaCrop with an economic model for the optimization of irrigation management at farm level. *European Journal of Agronomy,* 36**,** 21-31.

Gassman, P. W., E. Osei, A. Saleh, J. Rodecap, S. Norvell & J. Williams (2006) Alternative practices for sediment and nutrient loss control on livestock farms in northeast Iowa. *Agriculture, Ecosystems and Environment,* 117**,** 135-144.

Gassman, P. W., J. R. Williams, X. Wang, A. Saleh, E. Osei, L. M. Hauck, R. C. Izaurralde & J. D. Flowers (2010) The Agricultural Policy/Environmental eXtender (APEX) model: An emerging tool for landscape and watershed environmental analyses. *Transactions of the ASABE,* 53**,** 711-740.

Gibbons, J. M., S. J. Ramsden & A. Blake (2006) Modelling uncertainty in greenhouse gas emissions from UK agriculture at the farm level. *Agriculture, Ecosystems and Environment,* 112**,** 347-355.

Giller, K. E., P. Tittonell, M. C. Rufino, M. T. van Wijk, S. Zingore, P. Mapfumo, S. Adjei-Nsiah, M. Herrero, R. Chikowo, M. Corbeels, E. C. Rowe, F. Baijukya, A. Mwijage, J. Smith, E. Yeboah, W. J. van der Burg, O. M. Sanogo, M. Misiko, N. de Ridder, S. Karanja, C. Kaizzi, J. K'Ungu, M. Mwale, D. Nwaga, C. Pacini & B. Vanlauwe (2011) Communicating complexity: Integrated assessment of trade-offs concerning soil fertility management within African farming systems to support innovation and development. *Agricultural Systems,* 104**,** 191-203.

González-Estrada, E., L. C. Rodriguez, V. K. Walen, J. B. Naab, J. Koo, J. W. Jones, M. Herrero & P. K. Thornton (2008) Carbon sequestration and farm income in West Africa: Identifying best management practices for smallholder agricultural systems in northern Ghana. *Ecological Economics,* 67**,** 492-502.

Greiner, R. (1997) Optimal farm management responses to emerging soil salinisation in a dryland catchment in Eastern Australia. *Land Degradation and Development,* 8**,** 281-303.

Grove, B. & L. K. Oosthuizen (2010) Stochastic efficiency analysis of deficit irrigation with standard risk aversion. *Agricultural Water Management,* 97**,** 792-800.

Hahn, B. D., F. D. Richardson, M. T. Hoffman, R. Roberts, S. W. Todd & P. J. Carrick (2005) A simulation model of long-term climate, livestock and vegetation interactions on communal rangelands in the semi-arid Succulent Karoo, Namaqualand, South Africa. *Ecological Modelling,* 183**,** 211-230.

Hajkowicz, S., K. Collins & A. Cattaneo (2009) Review of agri-environment indexes and stewardship payments. *Environmental Management,* 43**,** 221-236.

Hansen, B. R. & M. A. Krause (1989) Impact of agronomic and economic factors on farm profitability. *Agricultural Systems,* 30**,** 369-390.

Hansen, J. W., E. B. Knapp & J. W. Jones (1997) Determinants of sustainability of a Colombian hillside farm. *Experimental Agriculture,* 33**,** 425-448.

Hansen, J. W., A. Mishra, K. P. C. Rao, M. Indeje & R. K. Ngugi (2009) Potential value of GCM-based seasonal rainfall forecasts for maize management in semi-arid Kenya. *Agricultural Systems,* 101**,** 80-90.

Happe, K., N. J. Hutchings, T. Dalgaard & K. Kellerman (2011) Modelling the interactions between regional farming structure, nitrogen losses and environmental regulation. *Agricultural Systems,* 104**,** 281-291.

Harrigan, T. M., W. G. Bickert & C. A. Rotz (1996) Simulation of dairy manure management and cropping systems. *Applied Engineering in Agriculture,* 12**,** 563-574.

Harrigan, T. M., C. A. Rotz & J. R. Black (1994) Comparison of large round bale storage and feeding systems on dairy farms. *Applied Engineering in Agriculture,* 10**,** 479-491.

Hatch, U., S. Jagtap, J. Jones & M. Lamb (1999) Potential effects of climate change on agricultural water use in the southeast U.S. *Journal of the American Water Resources Association,* 35**,** 1551-1561.

Hazell, P. B. R. & R. D. Norton. 1986. *Mathematical Programming for Economic Analysis in Agriculture*. Macmillan Publishing Company, New York.

Heady, E. & W. Candler. 1958. *Linear programming methods*. Iowa State University Press, Ames.

Heckbert, S. (2011) Agent-based modelling of emissions trading for coastal landscapes in transition. *Journal of Land Use Science,* 6**,** 137-150.

Helming, K., M. Pérez-Soba & P. Tabbush. 2008. *Sustainability Impact Assessment of Land Use Changes*. Springer Publishing.

Helms, G. L., J. W. Richardson, M. J. Cochran & M. E. Rister (1990) A farm level expert simulation system to aid farmers in selecting among crop insurance strategies. *Computers and Electronics in Agriculture,* 4**,** 169-190.

Hengsdijk, H., G. W. Meijerink & M. E. Mosugu (2005) Modeling the effect of three soil and water conservation practices in Tigray, Ethiopia. *Agriculture, Ecosystems and Environment,* 105**,** 29-40.

Herrero, M., R. H. Fawcett & J. B. Dent (1999) Bio-economic evaluation of dairy farm management scenarios using integrated simulation and multiple-criteria models. *Agricultural Systems,* 62**,** 169-188.

Herrero, M., E. González-Estrada, P. K. Thornton, C. Quiros, M. M. Waithaka, R. Ruiz & G. Hoogenboom (2007) IMPACT: generic household databases and diagnostics tools for integrated crop/livestock systems analysis. *Agricultural Systems,* 92.

Hervé, D., D. Genin & J. Migueis (2002) A modelling approach for analysis of agro pastoral activity at the one-farm level. *Agricultural Systems,* 71**,** 187-206.

Holman, I. P., M. D. A. Rounsevell, S. Shackley, P. A. Harrison, R. J. Nicholls, P. M. Berry & E. Audsley (2005) A regional, multi-sectoral and integrated assessment of the impacts of climate and socio-economic change in the UK: Part I. Methodology. *Climatic Change,* 71**,** 9-41.

Holtz, G. & C. Pahl-Wostl (2011) An agent-based model of groundwater over-exploitation in the Upper Guadiana, Spain. *Regional Environmental Change***,** 1-27.

Howden, S. M., D. H. White & P. J. Bowman (1996) Managing sheep grazing systems in southern Australia to minimise greenhouse gas emissions: Adaptation of an existing simulation model. *Ecological Modelling,* 86**,** 201-206.

Hutchings, N. J., J. E. Olesen, B. M. Petersen & J. Berntsen (2007) Modelling spatial heterogeneity in grazed grassland and its effects on nitrogen cycling and greenhouse gas emissions. *Agriculture, Ecosystems and Environment,* 121**,** 153-163.

Jackson, T. M., M. A. Hanjra, S. Khan & M. M. Hafeez (2011) Building a climate resilient farm: A risk based approach for understanding water, energy and emissions in irrigated agriculture. *Agricultural Systems,* 104**,** 729-745.

Jalvingh, A. W., A. A. Dijkhuizen & J. A. Van Arendonk (1994) Optimizing the herd calving pattern with linear programming and dynamic probabilistic simulation. *Journal of Dairy Science,* 77**,** 1719-1730.

Jalvingh, A. W., J. A. M. van Arendonk, A. A. Dijkhuizen & J. A. Renkema (1993) Dynamic probabilistic simulation of dairy herd management practices. II. Comparison of strategies in order to change a herd's calving pattern. *Livestock Production Science,* 37**,** 133-152.

Janssen, S., I. N. Athanasiadis, I. Bezlepkina, R. Knapen, H. T. Li, I. P. Dominguez, A. E. Rizzoli & M. K. van Ittersum (2011) Linking models for assessing agricultural land use change. *Computers and Electronics in Agriculture,* 76**,** 148-160.

Janssen, S. & M. K. van Ittersum (2007) Assessing farm innovations and responses to policies: A review of bio-economic farm models. *Agricultural Systems,* 94**,** 622-636.

Jogo, W. & R. Hassan (2010) Balancing the use of wetlands for economic well-being and ecological security: The case of the Limpopo wetland in southern Africa. *Ecological Economics,* 69**,** 1569-1579.

Johnson, I. R., D. F. Chapman, V. O. Snow, R. J. Eckard, A. J. Parsons, M. G. Lambert & B. R. Cullen (2008) DairyMod and EcoMod: Biophysical pasture-simulation models for Australia and New Zealand. *Australian Journal of Experimental Agriculture,* 48**,** 621-631.

Jouven, M. & R. Baumont (2008) Simulating grassland utilization in beef suckler systems to investigate the trade-offs between production and floristic diversity. *Agricultural Systems,* 96**,** 260-272.

Kaya, B., P. E. Hildebrand & P. K. R. Nair (2000) Modeling changes in farming systems with the adoption of improved fallows in southern Mali. *Agricultural Systems,* 66**,** 51-68.

Keating, B. A., P. S. Carberry, G. L. Hammer, M. E. Probert, M. J. Robertson, D. Holzworth, N. I. Huth, J. N. G. Hargreaves, H. Meinke, Z. Hochman, G. McLean, K. Verburg, V. Snow, J. P. Dimes, M. Silburn, E. Wang, S. Brown, K. L. Bristow, S. Asseng, S. Chapman, R. L. McCown, D. M. Freebairn & C. J. Smith (2003) An overview of APSIM, a model designed for farming systems simulation. *European Journal of Agronomy,* 18**,** 267-288.

Keil, A., N. Teufel, D. Gunawan & C. Leemhuis (2009) Vulnerability of smallholder farmers to ENSO-related drought in Indonesia. *Climate Research,* 38**,** 155-169.

Kikuhara, K. & H. Hirooka (2009) Application of a simulation model for dairy cattle production systems integrated with forage crop production: The effects of whole crop rice silage utilization on nutrient balances and profitability. *Asian-Australasian Journal of Animal Sciences,* 22**,** 216-224.

Kikuhara, K., H. Kumagai & H. Hirooka (2009) Development and evaluation of a simulation model for dairy cattle production systems integrated with forage crop production. *Asian-Australasian Journal of Animal Sciences,* 22**,** 57-71.

Kingwell, R. S., D. J. Pannell & S. D. Robinson (1993) Tactical responses to seasonal conditions in whole-farm planning in Western Australia. *Agricultural Economics,* 8**,** 211-226.

Kulshreshtha, S. N. & K. K. Klein (1989) Agricultural drought impact evaluation model: A systems approach. *Agricultural Systems,* 30**,** 81-96.

Kuyvenhoven, A., R. Ruben & G. Kruseman (1998) Technology, market policies and institutional reform for sustainable land use in southern Mali. *Agricultural Economics,* 19**,** 53-62.

Laborte, A. G., R. A. Schipper, M. K. Van Ittersum, M. M. Van Den Berg, H. Van Keulen, A. G. Prins & M. Hossain (2009) Farmers' welfare, food production and the environment: A model-based assessment of the effects of new technologies in the Northern Philippines. *NJAS - Wageningen Journal of Life Sciences,* 56**,** 345-373.

Le Gal, P. Y., P. Dugué, G. Faure & S. Novak (2011) How does research address the design of innovative agricultural production

systems at the farm level? A review. *Agricultural Systems,* 104**,** 714-728.

Leenhardt, D., J. L. Trouvat, G. Gonzalès, V. Pérarnaud, S. Prats & J. E. Bergez (2004) Estimating irrigation demand for water management on a regional scale: I. ADEAUMIS, a simulation platform based on bio-decisional modelling and spatial information. *Agricultural Water Management,* 68**,** 207-232.

Leffelaar, P. A. 1999. *On systems analysis and simulation of ecological processes; with examples in CSMP, FST and FORTRAN*. Kluwer academic publishers.

Louhichi, K., V. Alary & P. Grimaud (2004) A dynamic model to analyse the bio-technical and socio-economic interactions in dairy farming systems on the Réunion Island. *Animal Research,* 53**,** 363-382.

Luckert, M. K., J. Wilson, V. Adamowicz & A. B. Cunningham (2000) Household resource allocations in response to risks and returns in a communal area of western Zimbabwe. *Ecological Economics,* 33**,** 383-394.

Manson, S. M. & T. Evans (2007) Agent-based modeling of deforestation in southern Yucatán, Mexico, and reforestation in the Midwest United States. *Proceedings of the National Academy of Sciences of the United States of America,* 104**,** 20678-20683.

Martin, G., R. Martin-Clouaire, J. P. Rellier & M. Duru (2011) A simulation framework for the design of grassland-based beef-cattle farms. *Environmental Modelling and Software,* 26**,** 371-385.

Matthews, R. B. & C. J. Pilbeam. 2005a. Modelling the long-term productivity and soil fertility of maize/millet cropping systems in the mid-hills of Nepal. 2130-2137.

Matthews, R. B. & C. J. Pilbeam. 2005b. Modelling the long-term productivity and soil fertility of maize/millet cropping systems in the mid-hills of Nepal. In *MODSIM 2005 Proceedings*, 2130-2137.

McCall, D. G., D. A. Clark, L. J. Stachurski, J. W. Penno, A. M. Bryant & B. J. Ridler (1999) Optimized dairy grazing systems in the Northeast United States and New Zealand. I. Model description and evaluation. *Journal of Dairy Science,* 82**,** 1795-1807.

McCown, R. L., P. S. Carberry, Z. Hochman, N. P. Dalgliesh & M. A. Foale (2009) Re-inventing model-based decision support with Australian dryland farmers. 1. Changing intervention concepts during 17 years of action research. *Crop and Pasture Science,* 60**,** 1017-1030.

Merot, A. & J. E. Bergez (2010) IRRIGATE: A dynamic integrated model combining a knowledge-based model and mechanistic biophysical models for border irrigation management. *Environmental Modelling and Software,* 25**,** 421-432.

Merot, A., J. E. Bergez, A. Capillon & J. Wery (2008) Analysing farming practices to develop a numerical, operational model of farmers' decision-making processes: An irrigated hay cropping system in France. *Agricultural Systems,* 98**,** 108-118.

Messina, C. D., J. W. Hansen & A. J. Hall (1999) Land allocation conditioned on El Nino-Southern Oscillation phases in the Pampas of Argentina. *Agricultural Systems,* 60**,** 197-212.

Meyer-Aurich, A. (2005) Economic and environmental analysis of sustainable farming practices - A Bavarian case study. *Agricultural Systems,* 86**,** 190-206.

Meyer-Aurich, A., P. Zander, A. Werner & R. Roth (1998) Developing agricultural land use strategies appropriate to nature conservation goals and environmental protection. *Landscape and Urban Planning,* 41**,** 119-127.

Mimouni, M., S. Zekri & G. Flichman (2000) Modelling the trade-offs between farm income and the reduction of erosion and nitrate pollution. *Annals of Operations Research,* 94**,** 91-103.

Moghaddam, K. S. & G. W. DePuy (2011) Farm management optimization using chance constrained programming method. *Computers and Electronics in Agriculture,* 77**,** 229-237.

Moore, A. D., M. J. Robertson & R. Routley (2011) Evaluation of the water use efficiency of alternative farm practices at a range of spatial and temporal scales: A conceptual framework and a modelling approach. *Agricultural Systems,* 104**,** 162-174.

Moriondo, M., C. Pacini, G. Trombi, C. Vazzana & M. Bindi (2010) Sustainability of dairy farming system in Tuscany in a changing climate. *European Journal of Agronomy,* 32**,** 80-90.

Müller, B., K. Frank & C. Wissel (2007) Relevance of rest periods in non-equilibrium rangeland systems - A modelling analysis. *Agricultural Systems,* 92**,** 295-317.

Naivinit, W., C. Le Page, G. Trébuil & N. Gajaseni (2010) Participatory agent-based modeling and simulation of rice production and labor migrations in Northeast Thailand. *Environmental Modelling and Software,* 25**,** 1345-1358.

Nendel, C. (2009) Evaluation of Best Management Practices for N fertilisation in regional field vegetable production with a small-scale simulation model. *European Journal of Agronomy,* 30**,** 110-118.

Ngambeki, D. S., R. R. Deuson & P. V. Preckel (1992) Integrating livestock into farming systems in Northern Cameroon. *Agricultural Systems,* 38**,** 319-338.

Nicholson, C. F., R. W. Blake, C. I. Urbina, D. R. Lee, D. G. Fox & P. J. Van Soest (1994) Economic comparison of nutritional management strategies for Venezuelan dual-purpose cattle systems. *Journal of animal science,* 72**,** 1680-1696.

Nousiainen, J., M. Tuori, E. Turtola & P. Huhtanen (2011) Dairy farm nutrient management model. 1. Model description and validation. *Agricultural Systems,* 104**,** 371-382.

Nyikal, R. A. & W. O. Kosura (2005) Risk preference and optimal enterprise combinations in Kahuro division of Murang'a district, Kenya. *Agricultural Economics,* 32**,** 131-140.

Ogle, S. M., F. J. Breidt, M. Easter, S. Williams, K. Killian & K. Paustian (2010) Scale and uncertainty in modeled soil organic carbon stock changes for US croplands using a process-based model. *Global Change Biology,* 16**,** 810-822.

Pardo, G., M. Riravololona & N. M. Munier-Jolain (2010) Using a farming system model to evaluate cropping system prototypes: Are labour constraints and economic performances hampering the adoption of Integrated Weed Management? *European Journal of Agronomy,* 33**,** 24-32.

Parsons, D., C. F. Nicholson, R. W. Blake, Q. M. Ketterings, L. Ramírez-Aviles, J. H. Cherney & D. G. Fox (2011) Application of a simulation model for assessing integration of smallholder shifting cultivation and sheep production in Yucatán, Mexico. *Agricultural Systems,* 104**,** 13-19.

Parton, W. J., D. S. Schimel, C. V. Cole & D. S. Ojima (1987) Analysis of factors controlling soil organic matter levels in Great Plains grasslands. *Soil Science Society of America Journal,* 51**,** 173-1179.

Pattee, H. H. 1973. *Hierarchy theory: the challenge of complex systems*. Braziller, New York.

Pfister, F., H. P. Bader, R. Scheidegger & P. Baccini (2005) Dynamic modelling of resource management for farming systems. *Agricultural Systems,* 86**,** 1-28.

Ponsioen, T. C., H. Hengsdijk, J. Wolf, M. K. van Ittersum, R. P. Rotter, T. T. Son & A. G. Laborte (2006) TechnoGIN, a tool for exploring and evaluating resource use efficiency of cropping systems in East and Southeast Asia. *Agricultural Systems* 87**,** 80-100.

Popp, A., S. Domptail, N. Blaum & F. Jeltsch (2009) Landuse experience does qualify for adaptation to climate change. *Ecological Modelling,* 220**,** 694-702.

Power, B., D. Rodriguez, P. deVoil, G. Harris & J. Payero (2011) A multi-field bio-economic model of irrigated grain-cotton farming systems. *Field Crops Research,* 124**,** 171-179.

Quintero, M., S. Wunder & R. D. Estrada (2009) For services rendered? Modeling hydrology and livelihoods in Andean payments for environmental services schemes. *Forest Ecology and Management,* 258**,** 1871-1880.

Ramilan, T., F. G. Scrimgeour, G. Levy, D. Marsh & A. J. Romera (2011) Simulation of alternative dairy farm pollution abatement policies. *Environmental Modelling and Software,* 26**,** 2-7.

Rigby, D. & T. Young (1996) European environmental regulations to reduce water pollution: An analysis of their impact on UK dairy farms. *European Review of Agricultural Economics,* 23**,** 59-78.

Rodriguez, D., P. deVoil, B. Power, H. Cox, S. Crimp & H. Meinke (2011a) The intrinsic plasticity of farm businesses and their resilience to change. An Australian example. *Field Crops Research,* 124**,** 157-170.

Rodriguez, D., P. deVoil, B. Power, H. Cox, S. Crimp & H. Meinke (2011b) The intrinsic plasticity of farm businesses and their resilience to change. An Australian example. *Field Crops Research*.

Roetter, R. P., M. van den Berg, A. G. Laborte, H. Hengsdijk, J. Wolf, M. van Ittersum, H. van Keulen, E. O. Agustin, T. Thuc Son, N. Xuan Lai & W. Guanghuo (2007) Combining farm and regional level modeling for integrated resource management in East and South-east Asia. *Environmental Modelling and Software,* 22**,** 149-157.

Rossing, W. A. H., J. E. Jansma, F. J. De Ruijter & J. Schans (1997) Operationalizing sustainability: Exploring options for environmentally friendly flower bulb production systems. *European Journal of Plant Pathology,* 103**,** 217-234.

Rotmans, J. & M. Asselt (1996) Integrated assessment: a growing child on its way to maturity. *Climatic Change,* 34**,** 327.

Rotz, C. A., G. H. Kamphuis, H. D. Karsten & R. D. Weaver (2007) Organic dairy production systems in Pennsylvania: A case study evaluation. *Journal of Dairy Science,* 90**,** 3961-3979.

Rotz, C. A., P. J. A. Kleinman, C. J. Dell, T. L. Veith & D. B. Beegle (2011) Environmental and economic comparisons of manure application methods in farming systems. *Journal of Environmental Quality,* 40**,** 438-448.

Rotz, C. A., D. R. Mertens, D. R. Buckmaster, M. S. Allen & J. H. Harrison (1999) A dairy herd model for use in whole farm simulations. *Journal of Dairy Science,* 82**,** 2826-2840.

Rotz, C. A., F. Taube, M. P. Russelle, J. Oenema, M. A. Sanderson & M. Wachendorf (2005) Whole-farm perspectives of nutrient flows in grassland agriculture. *Crop Science,* 45**,** 2139-2159.

Rounsevell, M. D. A., F. Ewert, I. Reginster, R. Leemans & T. R. Carter (2005) Future scenarios of European agricultural land use: II. Projecting changes in cropland and grassland. *Agriculture, Ecosystems and Environment,* 107**,** 117-135.

Ruben, R. & A. Van Ruijven (2001) Technical coefficients for bio-economic farm household models: A meta-modelling approach with applications for Southern Mali. *Ecological Economics,* 36**,** 427-441.

Rudie, I. 1995. The significance of eating: Cooperation, support and reputation in Kelantan Malay

households. In *'Male' and 'female' in developing Southeast Asia,* ed. W. J. Karim, 227 - 247. Oxford, Washinton: Berg Publishers.

Rufino, M. C., J. Dury, P. Tittonell, M. T. van Wijk, M. Herrero, S. Zingore, P. Mapfumo & K. E. Giller (2011) Competing use of organic resources, village-level interactions between farm types and climate variability in a communal area of NE Zimbabwe. *Agricultural Systems,* 104**,** 175-190.

Rufino, M. C., M. Herrero, M. T. Van Wijk, L. Hemerik, N. De Ridder & K. E. Giller (2009) Lifetime productivity of dairy cows in smallholder farming systems of the Central highlands of Kenya. *Animal,* 3**,** 1044-1056.

Ruiz, D. E. M., L. Pardo Sempere, A. García Martínez, J. J. Rodríguez Alcaide, J. O. Pamio, F. Peña Blanco & V. Domenech García (2000) Technical and allocative efficiency analysis for cattle fattening on Argentina Pampas. *Agricultural Systems,* 65**,** 179-199.

Salinas, H., R. G. Ramirez & A. Rumayor-Rodríguez (1999) A whole-farm model for economic analysis in a goat production system in Mexico. *Small Ruminant Research,* 31**,** 157-164.

Sanchez-Zazueta, E. & F. J. Martinez-Cordero (2009) Economic risk assessment of a semi-intensive shrimp farm in Sinaloa, Mexico. *Aquaculture Economics and Management,* 13**,** 312-327.

Saqalli, M., B. Gérard, C. Bielders & P. Defourny (2010) Testing the impact of social forces on the evolution of Sahelian farming systems: A combined agent-based modeling and anthropological approach. *Ecological Modelling,* 221**,** 2714-2727.

Saqalli, M., B. Gérard, C. L. Bielders & P. Defourny (2011) Targeting rural development interventions: Empirical agent-based modeling in Nigerien villages. *Agricultural Systems,* 104**,** 354-364.

Savoie, P., L. D. Parsch, C. A. Rotz, R. C. Brook & J. R. Black (1985) Simulation of forage harvest and conservation on dairy farms. *Agricultural Systems,* 17**,** 117-131.

Schlüter, M., H. Leslie & S. Levin (2009) Managing water-use trade-offs in a semi-arid river delta to sustain multiple ecosystem services: A modeling approach. *Ecological Research,* 24**,** 491-503.

Schönhart, M., T. Schauppenlehner, E. Schmid & A. Muhar (2011) Integration of bio-physical and economic models to analyze management intensity and landscape structure effects at farm and landscape level. *Agricultural Systems,* 104**,** 122-134.

Schreinemachers, P. & T. Berger (2006) Land-use decisions in developing countries and their representation in multi-agent systems. *Journal of Land Use Science,* 1**,** 29-44.

Schreinemachers, P. & T. Berger (2011) An agent-based simulation model of humane-environment interactions in agricultural systems. *Environmental Modelling and Software* 26**,** 845-859.

Schreinemachers, P., T. Berger & J. B. Aune (2007) Simulating soil fertility and poverty dynamics in Uganda: A bio-economic multi-agent systems approach. *Ecological Economics,* 64**,** 387-401.

Schultheiß, U., P. Jäger, H. Döhler & B. Eurich-Menden (2005) Effects of water protection measures on the profitability of farms. *Water Science and Technology,* 51**,** 383-391.

Senthilkumar, K., M. T. M. H. Lubbers, N. de Ridder, P. S. Bindraban, T. M. Thiyagarajan & K. E. Giller (2011) Policies to support economic and environmental goals at farm and regional scales: Outcomes for rice farmers in Southern India depend on their resource endowment. *Agricultural Systems,* 104**,** 82-93.

Shepherd, K. D. & M. J. Soule (1998) Soil fertility management in west Kenya: Dynamic simulation of productivity, profitability and sustainability at different resource endowment levels. *Agriculture, Ecosystems and Environment,* 71**,** 131-145.

Shively, G. & I. Coxhead (2004) Conducting economic policy analysis at a landscape scale: Examples from a Philippine watershed. *Agriculture, Ecosystems and Environment,* 104**,** 159-170.

Shively, G. E. (1998) Economic policies and the environment: The case of tree planting on low-income farms in the Philippines. *Environment and Development Economics,* 3**,** 83-104.

Shively, G. E. (2000) Soil conservation and consumption risk in a model of low-income agriculture. *Environmental Monitoring and Assessment,* 62**,** 55-69.

Stoorvogel, J. J. (1995) Integration of computer-based models and tools to evaluate alternative land-use scenarios as part of an agricultural systems analysis. *Agricultural Systems,* 49**,** 353-367.

Stoorvogel, J. J., J. M. Antle & C. C. Crissman (2004) Trade-off analysis in the Northern Andes to study the dynamics in agricultural land use. *Journal of Environmental Management,* 72**,** 23-33.

Sulistyawati, E., I. R. Noble & M. L. Roderick (2005) A simulation model to study land use strategies in swidden agriculture systems. *Agricultural Systems,* 85**,** 271-288.

Tamubula, I. & J. A. Sinden (2000) Sustainability and economic efficiency of agroforestry systems in Embu District, Kenya: An application of environmental modelling. *Environmental Modelling and Software,* 15**,** 13-21.

Tauer, L. (1983) Target MOTAD. *American Journal of Agricultural Economics,* 65**,** 606-610.

Ten Berge, H. F. M., M. K. van Ittersum, W. A. H. Rossing, G. W. J. van de Ven & J. Schans (2000) Farming options for The Netherlands explored by multi-objective modelling. *European Journal of Agronomy,* 13**,** 263-277.

Thomas, D. T., J. Finlayson, A. D. Moore & M. J. Robertson (2010) Profitability of grazing crop stubbles may be overestimated by using the metabolisable energy intake from the stubble. *Animal Production Science,* 50**,** 699-704.

Thornton, P. K., R. H. Fawcett, K. A. Galvin, R. B. Boone, J. W. Hudson & C. H. Vogel (2004) Evaluating management options that use climate forecasts: Modelling livestock production systems in the semi-arid zone of South Africa. *Climate Research,* 26**,** 33-42.

Thornton, P. K., K. A. Galvin & R. B. Boone (2003) An agro-pastoral household model for the rangelands of East Africa. *Agricultural Systems,* 76**,** 601-622.

Thornton, P. K. & M. Herrero (2001) Integrated crop-livestock simulation models for scenario analysis and impact assessment. *Agricultural Systems,* 70**,** 581-602.

Tichit, M., B. Hubert, L. Doyen & D. Genin (2004) A viability model to assess the sustainability of mixed herds under climatic uncertainty. *Animal Research,* 53**,** 405-417.

Tittonell, P., M. T. van Wijk, M. Herrero, M. C. Rufino, N. de Ridder & K. E. Giller (2009) Beyond resource constraints - Exploring the biophysical feasibility of options for the intensification of smallholder crop-livestock systems in Vihiga district, Kenya. *Agricultural Systems,* 101**,** 1-19.

Tittonell, P., M. T. van Wijk, M. C. Rufino, J. A. Vrugt & K. E. Giller (2007) Analysing trade-offs in resource and labour allocation by smallholder farmers using inverse modelling techniques: A case-study from Kakamega district, western Kenya. *Agricultural Systems,* 95**,** 76-95.

Turner, B. L., R. E. Kasperson, P. A. Matson, J. J. McCarthy, R. W. Corell, L. Christensen, N. Eckley, J. X. Kasperson, A. Luers, M. L. Martello, C. Polsky, A. Pulsipher & A. Schiller (2003) A framework for vulnerability analysis in sustainability science. *Proceedings of the National Academy of Sciences of the United States of America,* 100**,** 8074-8079.

Val-Arreola, D., E. Kebreab, J. A. N. Mills, S. L. Wiggins & J. France (2004) Forage production and nutrient availability in small-scale dairy systems in central Mexico using linear programming and partial budgeting. *Nutrient Cycling in Agroecosystems,* 69**,** 191-201.

Val-Arreola, O., E. Kebreab & J. France (2006) Modeling small-scale dairy farms in central Mexico using multi-criteria programming. *Journal of Dairy Science,* 89**,** 1662-1672.

Valbuena, D., A. K. Bregt, C. McAlpine, P. H. Verburg & L. Seabrook (2010) An agent-based approach to explore the effect of voluntary mechanisms on land use change: A case in rural Queensland, Australia. *Journal of Environmental Management,* 91**,** 2615-2625.

Valderrama, D. & C. R. Engle (2002) Economic optimization of shrimp farming in Honduras. *Journal of the World Aquaculture Society,* 33**,** 398-409.

van Ittersum, M. K., F. Ewert, T. Heckelei, J. Wery, J. A. Olsson, E. Andersen, I. Bezlepkina, F. Brouwer, M. Donatelli, G. Flichman, L. Olsson, A. E. Rizzoli, T. van der Wal, J. E. Wien & J. Wolf (2008) Integrated assessment of agricultural systems - A component-based framework for the European Union (SEAMLESS). *Agricultural Systems,* 96**,** 150-165.

Van Meijl, H., T. van Rheenen, A. Tabeau & B. Eickhout (2006) The impact of different policy environments on agricultural land use in Europe. *Agriculture, Ecosystems & Environment,* 114.

van Wijk, M. T., P. Tittonell, M. C. Rufino, M. Herrero, C. Pacini, N. de Ridder & K. E. Giller (2009a) Identifying key entry-points for strategic management of smallholder farming systems in sub-

Saharan Africa using the dynamic farm-scale simulation model NUANCES-FARMSIM. *Agricultural Systems,* 102**,** 89-101.

van Wijk, M. T., P. Tittonell, M. C. Rufino, M. Herrero, C. Pacini, N. d. Ridder & K. E. Giller (2009b) Identifying key entry-points for strategic management of smallholder farming systems in sub-Saharan Africa using the dynamic farm-scale simulation model NUANCES-FARMSIM. *Agricultural Systems,* 102**,** 89-101.

Vatn, A., L. Bakken, M. A. Bleken, O. H. Baadshaug, H. Fykse, L. E. Haugen, H. Lundekvam, J. Morken, E. Romstad, P. K. Rørstad, A. O. Skjelvåg & T. Sogn (2006) A methodology for integrated economic and environmental analysis of pollution from agriculture. *Agricultural Systems,* 88**,** 270-293.

Vayssières, J., F. Guerrin, J. M. Paillat & P. Lecomte (2009) GAMEDE: A global activity model for evaluating the sustainability of dairy enterprises Part I - Whole-farm dynamic model. *Agricultural Systems,* 101**,** 128-138.

Veysset, P., D. Bebin & M. Lherm (2005) Adaptation to Agenda 2000 (CAP reform) and optimisation of the farming system of French suckler cattle farms in the Charolais area: A model-based study. *Agricultural Systems,* 83**,** 179-202.

Veysset, P., M. Lherm & D. Bébin (2010) Energy consumption, greenhouse gas emissions and economic performance assessments in French Charolais suckler cattle farms: Model-based analysis and forecasts. *Agricultural Systems,* 103**,** 41-50.

Villalba, D., G. Ripoll, R. Ruiz & A. Bernués (2010) Long-term stochastic simulation of mountain beef cattle herds under diverse management strategies. *Agricultural Systems,* 103**,** 210-220.

Vrugt, J. A., P. H. Stauffer, T. Wohling, B. A. Robinson & V. V. Vesselinov (2008) Inverse modeling of subsurface flow and transport properties: A review with new developments. *Vadose Zone Journal,* 7**,** 843-864.

Waithaka, M. M., P. K. Thornton, M. Herrero & K. D. Shepherd (2006) Bio-economic evaluation of farmers' perceptions of viable farms in western Kenya. *Agricultural Systems,* 90**,** 243-271.

Walker, B., C. S. Holling, S. R. Carpenter & A. Kinzig (2004) Resilience, adaptability and transformability in social-ecological systems. *Ecology and Society,* 9**,** Art. 5.

Waugh, F. (1951) The minimum-cost dairy feed. *Journal of Farm Economics,* 33**,** 229-310.

Weikard, H. P. & L. Hein (2011) Efficient versus Sustainable Livestock Grazing in the Sahel. *Journal of Agricultural Economics,* 62**,** 153-171.

Wise, R. M. & O. J. Cacho (2011) A bioeconomic analysis of the potential of Indonesian agroforests as carbon sinks. *Environmental Science and Policy,* 14**,** 451-461.

Wu, J. & H. L. David (2002) A spatially explicit hierarchical approach to modeling complex ecological systems: theory and applications. *Ecological Modelling,* 153**,** 7-26.

Wui, Y. S. & C. R. Engle (2004) A mixed integer programming analysis of effluent treatment options proposed for pond production of hybrid striped bass, Morone chrysops x M. saxatilis. *Journal of Applied Aquaculture,* 15**,** 121-158.

Zander, P. & H. Kächele (1999) Modelling multiple objectives of land use for sustainable development. *Agricultural Systems,* 59**,** 311-325.

Zingore, S., E. González-Estrada, R. J. Delve, M. Herrero, J. P. Dimes & K. E. Giller (2009) An integrated evaluation of strategies for enhancing productivity and profitability of resource-constrained smallholder farms in Zimbabwe. *Agricultural Systems,* 101**,** 57-68.

Figure 1: General overview of position of farm and household models within different levels of analyses

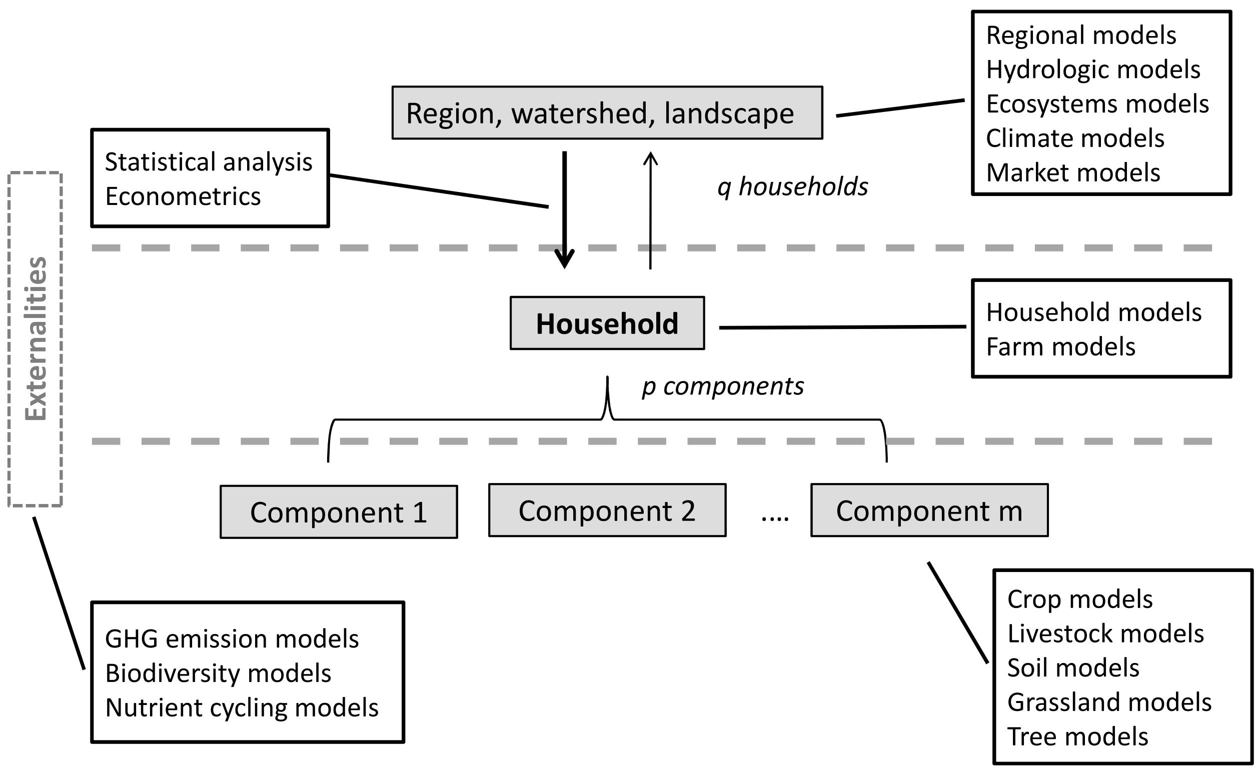
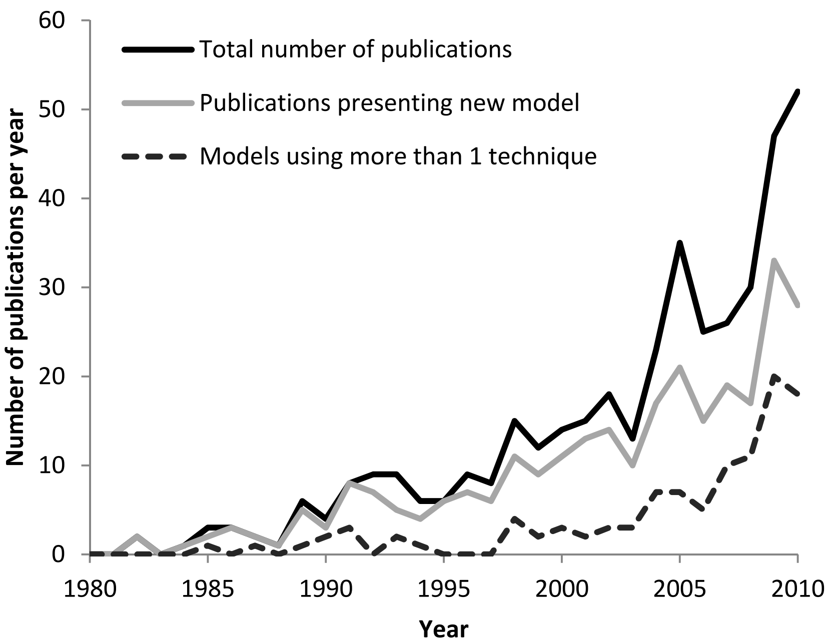


Figure 2: Time trend of number of published model studies per year at farm level (a) and of the ratio of publications presenting new models over total number of farm level publications over time (b)



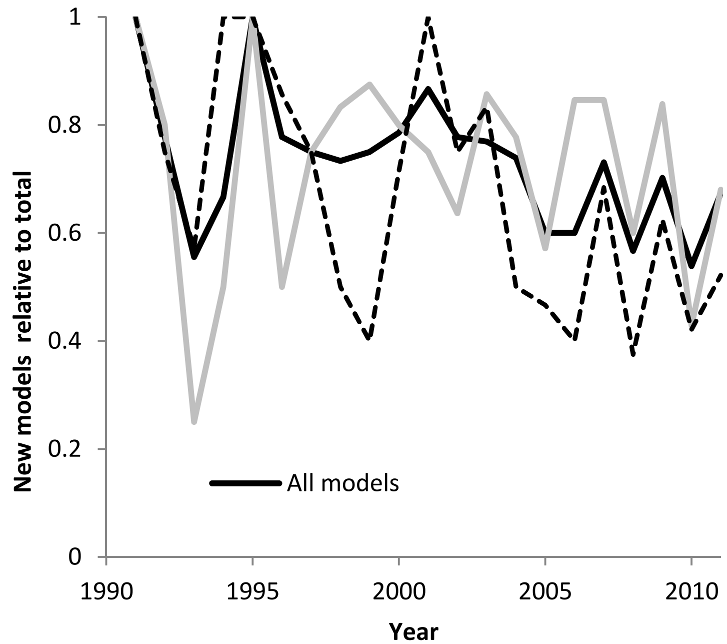


Figure 3: Simple representation of how a sensitivity and risk analysis could be set up. Model outcomes will show uncertainty, and multiple farming strategies can result in acceptable system behaviour.

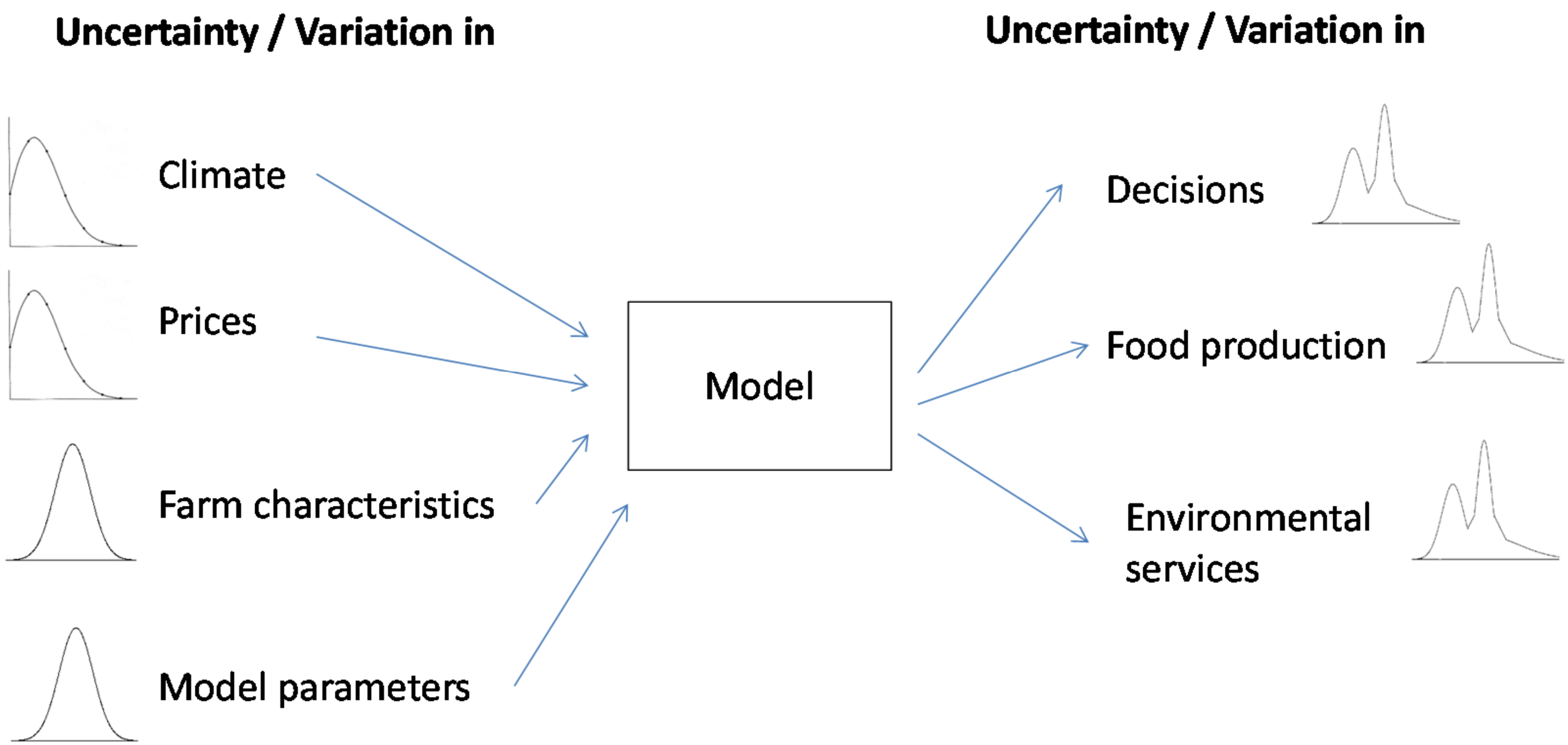


Table 1: Search terms used in literature search (organised hierarchically from the top downwards). To capture multiple terms uses we used 'fisher* used in Scopus to capture terms fishery and fisheries; 'optimi*' for optimization, optimisation; 'minimi*/maximi*' for maximization or maximisation; minimization or minimisation, etc.

Central search terms 'Model' AND 'Farm' OR 'agriculture' OR 'household'
Target search terms 1. 'Livestock' OR 'poultry' OR 'cattle' OR 'pig' OR 'dairy' OR 'beef' OR 'sheep' OR 'goat' OR 'small ruminant' 2. 'Fisheries' OR 'aquaculture' 3. 'Crop' OR 'horticulture' OR 'tree' OR 'grass' 4. 'Soil' OR 'landscape' OR 'land use' 5. 'Water' OR 'hydrology' OR 'nutrient' 6. 'Ecosystem'
Domains of application terms 1. 'Adaptation' OR 'mitigation' 2. 'Smallholder' OR 'peasant' OR 'small-scale' OR 'commercial' 3. 'Productivity' OR 'yield' 4. 'Production' OR 'consumption' 5. 'Biodiversity' OR 'wildlife' OR 'conservation' 6. 'Emission' OR 'pollution' OR 'leaching' OR 'loading' OR 'runoff' OR 'erosion' 7. 'Profit' OR 'income' OR 'utility'
Techniques 'Econometric' OR 'optimization' OR 'simulation' OR 'mathematical programming' OR 'agent based' OR 'agent based' OR 'numerical' OR 'maximization' OR 'minimization'

Table 2: The set of key model attributes that are important for the study of possible effects of climate change and variability on the functioning of farm households.

Attribute	Working definition: Possibility to quantify on the basis of model output
Profit	Net revenue after variable costs (or expenses) are covered. It can also be expressed as cash income or non-cash income when farm products are consumed and can take into account depreciation.
Food self-sufficiency	Ratio between energy (or protein)in farm produce and energy needed to meet WHO energy (or protein) requirements
Food security	Ratio between household total net income and the costs of the household diet
Climate variability	Relationship between climate variability and farm productivity
Climate change	The effects of changes in CO_2, temperature, precipitation and cloud cover on food production and security
Risk	Probability of occurrence of component production failure to result in food self-sufficiency, food security or economic welfare over time
Adaptation	Potentials for changes in farm management to deal better with climate variability and possible change
Mitigation	Human intervention to reduce the sources or enhance the sinks of greenhouse gases

Table 3: Number of scientific publications for each combination of target system and domain variable

Target	Domains							
	Adaptation	Smallholder	Productivity	Production	Biodiversity	Emission	Profit	Total per target
Livestock	62	139	220	610	127	353	222	1685
Fisheries	12	33	31	102	25	50	39	292
Crop	145	191	1214	1243	409	891	428	4339
Soil	127	147	831	900	504	1277	298	4084
Water	115	163	813	983	505	1403	333	4315
Ecosystem	43	23	153	195	154	233	61	862
Total per Domain	504	692	3197	4010	1688	4105	1381	15577

Table 4: Information on how attributes 'Economic performance', 'Food self-sufficiency' and 'Food security' are represented by each model framework; Mathematical Programming (MP) models (A), MP models combined with simulation models (B), (dynamic) simulation models (C) and agent based models (D)

A

Economic performance	Food self-sufficiency	Food security
MP models		
Profit maximisation (Nyikal and Kosura 2005); (Engle 1997); (Ruben and Van Ruijven 2001); (Hansen and Krause 1989); (Sanchez-Zazueta and Martinez-Cordero 2009); (Veysset, Bebin and Lherm 2005); (Weikard and Hein 2011); (Valderrama and Engle 2002)	(Nyikal and Kosura 2005); (Engle 1997); (Kaya et al. 2000); (Shively 2000); (Senthilkumar et al. 2011)	(Engle 1997); (Kaya et al. 2000)
Income maximisation (Kingwell et al. 1993); (Kaya, Hildebrand and Nair 2000); (Laborte et al. 2009); (Louhichi et al. 2004); (Nicholson et al. 1994); (Salinas, Ramirez and Rumayor-Rodríguez 1999); (Schultheiß et al. 2005); (Shively 1998); (Shively 2000); (Val-Arreola et al. 2004)		
Income maximisation within trade off / multicriteria analysis (Rossing et al. 1997); (Senthilkumar et al. 2011); (Val-Arreola et al. 2006); OPFROP-FRUPAT (Cittadini et al. 2008); FSRM (Dake et al. 2005)		
Cost minimisation (Ruiz et al. 2000)		

B

Economic performance	Food self-sufficiency	Food security
MP together with simulation models		
Profit maximisation APSIM, GRAZPLAN and MIDAS (Moore, Robertson and Routley 2011); (Kikuhara and Hirooka 2009, Kikuhara, Kumagai and Hirooka 2009); (Jalvingh et al. 1993, Jalvingh, Dijkhuizen and Van Arendonk 1994); (McCall et al. 1999); (Messina et al. 1999); (Moghaddam and DePuy 2011); (Moriondo et al. 2010); (Ngambeki, Deuson and Preckel 1992); (Popp et al. 2009); (Quintero et al. 2009); (Rigby and Young 1996); (Schönhart et al. 2011); Opt'INRA-PLANETE (Veysset, Lherm and Bébin 2010); (Wise and Cacho 2011); ISFARM (Amir et al. 1991, Amir et al. 1993); FASSET-LP (Berntsen et al. 2003);MCID (Borges Jr et al. 2008); GAMS-MINOS (Carvallo et al. 1998);AQUACROP-LP (García-Vila and Fereres); FARM-ADAPT (Gibbons, Ramsden and Blake 2006); MoFEDS (Greiner 1997); SAPWAT-LP (Grove and Oosthuizen 2010) **Income maximisation** (Mimouni, Zekri and Flichman 2000); Savanna-MP (Thornton et al. 2004); DSSAT-LP (Hatch et al. 1999); (Dinar, Aillery and Moore 1993, Dinar 1994); GRAZPLAN-MIDAS (Donnelly et al. 2002, Thomas et al. 2010); (Keil et al. 2009); IMPACT-HROM (Zingore et al. 2009, Waithaka et al. 2006); SFRAMOD-ACCESS (Holman et al. 2005); IRMLA (Roetter et al. 2007); **Income maximisation within trade off / multicriteria analysis** (Herrero, Fawcett and Dent 1999); (Meyer-Aurich et al. 1998); MODAM (Meyer-Aurich 2005); ROTAT-MILP (Dogliotti, Van Ittersum and Rossing 2005)	APSIM, GRAZPLAN and MIDAS (Moore et al. 2011); Savanna-MP (Thornton et al. 2004); DSSAT-LP (Hatch et al. 1999); (Herrero et al. 1999); (Keil et al. 2009); (Moriondo et al. 2010); (Ngambeki et al. 1992); IMPACT-HROM (Zingore et al. 2009, Waithaka et al. 2006); SFRAMOD-ACCESS (Holman et al. 2005); IRMLA (Roetter et al. 2007);	IMPACT-HROM (Zingore et al. 2009, Waithaka et al. 2006);

Cost minimisation DairyNZ (Ramilan et al. 2011);

C

Economic performance	Food self-sufficiency	Food security
(dynamic) Simulation models		
Profit SCUAF (Tamubula and Sinden 2000); (Sulistyawati et al. 2005); SAVANNA-PHEWS (Thornton et al. 2003, Boone et al. 2006); GAMEDE (Vayssières et al. 2009); NODRIZA (Villalba et al. 2010); (Pardo et al. 2010); (Hansen et al. 1997); (Hansen et al. 2009); DAFOSYM (Harrigan, Bickert and Rotz 1996); DYNAMOF (Howden et al. 1996); FASSET (Hutchings et al. 2007); ADIEM (Kulshreshtha and Klein 1989); (Bell et al. 2010); WFM (Beukes et al. 2005, Beukes et al. 2008, Beukes et al. 2010); (Bontkes and Van Keulen 2003); (Brennan et al. 2008); (Cabrera et al. 2005); UDDER (Chapman et al. 2008c, Chapman et al. 2008b, Chapman et al. 2011); (Clark et al. 2010); CEEOT-LP (Gassman et al. 2006); APS-FARM (Rodriguez et al. 2011b, Power et al. 2011); IFSM (Rotz et al. 2005, Rotz et al. 2007, Rotz et al. 2011); (Savoie et al. 1985); (Shepherd and Soule 1998); BANAD (Blazy et al. 2010); Simsdairy (Del Prado et al. 2011); CIS-APSIM (Brown, Cochrane and Krom 2010); **Income** (Tichit et al. 2004); COTFLEX (Helms et al. 1990); @RISK (Jackson et al. 2011); (Luckert et al. 2000); (Parsons et al. 2011); (Tittonell et al. 2007); TOA	SCUAF; (Sulistyawati et al. 2005); SAVANNA-PHEWS; NUANCES-FARMSIM (Tittonell et al. 2009, van Wijk et al. 2009b, Giller et al. 2011, Rufino et al. 2011); GAMEDE; (Hansen et al. 1997); (Hansen et al. 2009); DAFOSYM; NUTMON (Hengsdijk et al. 2005); FASSET; @RISK; ADIEM; (Bontkes and Van Keulen 2003); (Brennan et al. 2008); (Cabrera et al. 2005); (Dueri, Calanca and Fuhrer 2007); CEEOT-LP; SEDIVER (Martin et al. 2011); (Luckert et al. 2000); (Pfister et al. 2005); (Parsons et al. 2011); APS-FARM; IFSM; (Savoie et al. 1985); (Shepherd and Soule 1998); (Tittonell et al. 2007); TOA(Claessens et al. 2010, Stoorvogel et al. 2004)(Claessens et al., 2010; Stoorvogel et al., 2004)(Claessens et al., 2010; Stoorvogel et al., 2004); CSWM (Balderama 2009, Balderama 2010); BANAD; Simsdairy; CIS-APSIM;	(Shepherd and Soule 1998); (Cabrera et al. 2005); (Bontkes and Van Keulen 2003); NUTMON;

(Claessens et al. 2010, Stoorvogel et al. 2004); FLIPSIM (Anderson 1993);

D

Economic performance	Food self-sufficiency	Food security
Agent based models		
Profit (Schlüter, Leslie and Levin 2009); (Holtz and Pahl-Wostl 2011); **Income** (Valbuena et al. 2010); SimSahel (Saqalli et al. 2010, Saqalli et al. 2011); (Naivinit et al. 2010); SAMBA-GIS (Castella et al. 2005); SAMBA (Castella et al. 2005, Bousquet et al. 2007, Boissau, Anh and Castella 2004); AgriPolis (Happe et al. 2011); (Heckbert 2011); PALM (Matthews and Pilbeam 2005a); (Shively and Coxhead 2004); HELIS (Manson and Evans 2007); MPMAS (Schreinemachers and Berger 2006, Schreinemachers et al. 2007, Schreinemachers and Berger 2011, Berger and Schreinemachers 2006)	(Holtz and Pahl-Wostl 2011); SimSahel; (Naivinit et al. 2010); SAMBA-GIS; SAMBA; PALM; (Shively and Coxhead 2004); HELIS(Manson and Evans 2007)(Manson and Evans, 2007)(Manson and Evans, 2007); MPMAS	SAMBA-GIS; SAMBA; PALM; (Manson and Evans 2007) (Manson and Evans, 2007) (Manson and Evans, 2007) MPMAS

Table 5: Information on how attributes 'Climate variability and change', 'Risk', 'Mitigation' and 'Adaptation' are represented by each model framework; Mathematical Programming (MP) models (A), MP models combined with simulation models (B), (dynamic) simulation models (C) and agent based models (D)

A

Climate variability and change	Risk	Mitigation	Adaptation
MP models			
(Kingwell et al. 1993); (Kaya et al. 2000); (Schultheiß et al. 2005); (Senthilkumar et al. 2011); (Shively 2000); (Val-Arreola et al. 2004); (Val-Arreola et al. 2006); (Weikard and Hein 2011); FSRM	Nyikal and Kosura 2005); (Ruben and Van Ruijven 2001); (Kingwell et al. 1993); (Sanchez-Zazueta and Martinez-Cordero 2009); (Kaya et al. 2000); (Louhichi et al. 2004); (Nicholson et al. 1994); (Rossing et al. 1997); (Salinas et al. 1999); (Senthilkumar et al. 2011); (Shively 1998); (Shively 2000); (Valderrama and Engle 2002); (Veysset et al. 2005); (Weikard and Hein 2011); OPFROP-FRUPAT; FSRM		All models represent this attribute in one way or another; optimal management change when socio-economic or biophysical drivers changes

B

Climate variability and change	Risk	Mitigation	Adaptation
MP together with simulation models			
APSIM, GRAZPLAN and MIDAS; (Kikuhara and Hirooka 2009, Kikuhara et al. 2009); (Messina et al. 1999); (Moghaddam and DePuy 2011); (Moriondo et al. 2010); (Ngambeki et al. 1992); (Popp et al. 2009); (Quintero et al. 2009); (Schönhart et al. 2011); ISFARM; FASSET-LP; MCID; GAMS-MINOS; AQUACROP-LP; MoFEDS; SAPWAT-LP; (Mimouni et al. 2000); Savanna-MP; DSSAT-LP; (Dinar et al. 1993, Dinar 1994); GRAZPLAN-MIDAS; (Keil et al. 2009); IMPACT-HROM; SFRAMOD-ACCESS; (Herrero et al. 1999); (Meyer-Aurich et al. 1998); MODAM; DairyNZ;	All models can potentially assess price and production related risks; explicit analyses were performed with / in: Savanna-MP; GRAZPLAN-MIDAS; (Keil et al. 2009); (Messina et al. 1999); (Moghaddam and DePuy 2011); (Rigby and Young 1996); SFRAMOD-ACCESS; ISFARM;	FARM-ADAPT; ROTAT-MILP; FASSET-LP; (Wise and Cacho 2011); IMPACT-HROM; Opt'INRA-PLANETE; (Schönhart et al. 2011); (Kikuhara and Hirooka 2009, Kikuhara et al. 2009)	All models represent this attribute in one way or another; optimal management change when socio-economic or biophysical drivers changes

C

Climate variability and change	Risk	Mitigation	Adaptation
(dynamic) Simulation models SCUAF (Tamubula and Sinden 2000); SAVANNA-PHEWS (Thornton et al. 2003, Boone et al. 2006); GAMEDE (Vayssières et al. 2009); (Pardo et al. 2010); (Hansen et al. 1997); (Hansen et al. 2009); DAFOSYM (Harrigan et al. 1996); DYNAMOF (Howden et al. 1996); FASSET (Hutchings et al. 2007); ADIEM (Kulshreshtha and Klein 1989); (Bell et al. 2010); WFM (Beukes et al. 2005, Beukes et al. 2008, Beukes et al. 2010); (Bontkes and Van Keulen 2003); (Brennan et al. 2008); (Cabrera et al. 2005); UDDER (Chapman et al. 2008c, Chapman et al. 2008b, Chapman et al. 2011); (Clark et al. 2010); CEEOT-LP (Gassman et al. 2006); APS-FARM (Rodriguez et al. 2011b, Power et al. 2011); IFSM (Rotz et al. 2005, Rotz et al. 2007, Rotz et al. 2011); (Savoie et al. 1985); (Shepherd and Soule 1998); BANAD (Blazy et al. 2010); Simsdairy (Del Prado et al. 2011); CIS-APSIM (Brown et al. 2010); (Tichit et al. 2004); COTFLEX (Helms et al. 1990); @RISK (Jackson et al. 2011); (Luckert et al. 2000); (Parsons et al. 2011); (Tittonell et al. 2007); TOA (Claessens et al. 2010, Stoorvogel et al. 2004); NUANCES-FARMSIM (Tittonell et al. 2009, van Wijk et al. 2009b, Giller et al. 2011, Rufino et al. 2011); NUTMON (Hengsdijk et al. 2005); SEDIVER (Martin et al. 2011); CSWM (Balderama 2009, Balderama 2010);	Basically all models can potentially assess climate related risks for production, and some also market – related risks; explicit analyses were performed with / in: (Hansen et al. 1997); (Hansen et al. 2009); COTFLEX; (Clark et al. 2010); (Savoie et al. 1985); CSWM;	DairyMod, SGS and EcoMod (Johnson et al. 2008); IFSM; FASSET; SALSA;	For all models adaptation could be implemented through what-if scenarios for the management rules. In the TOA model trade offs and management options within those will change depending on climate and prices and farm configuration.

D

Climate variability and change	Risk	Mitigation	Adaptation
Agent based models			
PUMANI (Hervé, Genin and Migueis 2002); (Holtz and Pahl-Wostl 2011); PALM (Matthews and Pilbeam 2005a); (Shively and Coxhead 2004); MPMAS (Schreinemachers and Berger 2006, Schreinemachers et al. 2007, Schreinemachers and Berger 2011, Berger and Schreinemachers 2006);	Potentially: PUMANI; (Holtz and Pahl-Wostl 2011); PALM; (Shively and Coxhead 2004); (Schlüter et al. 2009); (Happe et al. 2011); (Heckbert 2011); only with MPMAS a risk / uncertainty related analysis is performed	PALM; MPMAS;	Agent behaviour can change depending on conditions; could also be assessed through what-if scenarios for the decision rules

Supplementary material

Table S1: Information on the components included in each model framework

Name of model	Reference	Components included							
		Soil		Crop		Livestock		Household	
MP models									
-	(Nyikal and Kosura 2005)							X	Model maximises income, constrained by risk preferences and food requirements
	(Engle 1997)			X	Production as technical coefficients	X	Fish production as technical coefficients	X	Model maximises income, while fulfilling needs for food
	(Ruben and Van Ruijven 2001)	X	Soil degradation parameters as technical coefficients	X	Production as technical coefficients	X	Livestock production as technical coefficients	X	Profit maximisation
	(Hansen and Krause 1989)							X	Household profit optimisation; surplus of income can be accumulated
MUDAS	(Kingwell et al. 1993)	X	Simple description	X	Production as technical coefficients	X	Simple description	X	Optimises income through tactical responses to seasonal weather.
	(Sanchez-Zazueta and Martinez-Cordero 2009)							X	Optimises income of a shrimp farm
	(Kaya et al. 2000)	X	Soil parameters as technical coefficients	X	Production as technical coefficients			X	Specifies household food production, sales, purchases and consumption
	(Laborte et al. 2009)							X	Assesses potential technology adoption; different households defined through a cluster analysis
	(Louhichi et al. 2004)					X	Production values as technical coefficients	X	Policy, bio-technical and socio-economic constraints assessed in a dairy farm optimisation problem

Name of model	Reference	Components included			
		Soil	Crop	Livestock	Household
MP models continued					
	(Nicholson et al. 1994)			X Production values are used as technical coefficients	X Nutritional management strategies were compared for dual purpose herds for a representative farm
	(Rossing et al. 1997)		X Flower bulb production levels are included as technical coefficients		X Determines trade off between economic objectives and crop protection for 2 reference farm types
	(Ruiz et al. 2000)			X Beef production values are used as technical coefficients	X Analysis optimises beef production given energy and time constraints to production
	(Salinas et al. 1999)			X Goat production values are used technical coefficients	X Net income of household is optimised under 2 price and 2 technology scenarios
	(Schultheiß et al. 2005)	X Nutrient losses represented as technical coefficients			X For four representative farm types were the effects of water protection strategies on farm profitability and nutrient losses assessed
	(Senthilkumar et al. 2011)	X Nutrient balance values as technical coefficients	X Rice production as technical coefficients		X Adaption of different rice cultivation options were assessed for four rice-based farm types
	(Shively 1998)				X Analysis of how changes in agricultural prices influence tree-planting decisions and environmental indicators of low-income farmers

Name of model	Reference	Components included							
		Soil		Crop		Livestock		Household	
MP models continued									
	(Shively 2000)	X	Erosion and soil conservation effects are technical coefficients	X	Effects of soil conservation on maize included as technical coefficients			X	Adoption of soil conservation measures by farmers is assessed through dynamic income maximisation
	(Val-Arreola et al. 2004)					X	Dairy production as technical coefficients	X	Land use is optimised for forage production and nutrient availability, and economic impacts are quantified
	(Val-Arreola et al. 2006)					X	Dairy production as technical coefficients	X	Multi-criteria analysis using income and forage quality maximisation and purchase minimisation for different farms
	(Valderrama and Engle 2002)					X	Shrimp production values as technical coefficients	X	Analyses optimal management strategies and outline for an annual activities schedule for shrimp farming
	(Veysset et al. 2005)	X	Crop production as technical coefficients			X	Cattle production as technical coefficients	X	Maximises gross margin for 2 different farm types (mixed and cattle) for different suckler farm management options
	(Weikard and Hein 2011)					X	Livestock production as technical coefficients	X	Maximises gross margin through stocking densities for pastoralists in Sahel

Name of model	Reference	Components included					
		Soil	Crop		Livestock	Household	
MP models continued							
OPFROP-FRUPAT	(Cittadini et al. 2008)		X	Crop coefficients used		X	Net present value and labour requirements evaluated
FSRM	(Dake et al. 2005)		X	Crop coefficients used which can be varied stochastically		X	Gross margin and variance in gross margin are evaluated

Name of model	Reference	Components included							
		Soil		Crop		Livestock		Household	
MP together with simulation models									
	(Mimouni et al. 2000)	X	Erosion and nitrogen losses are simulated	X	EPIC calculates crop production based on daily simulation			X	Opportunity costs of erosion control are evaluated; farm income is maximised
APSIM, GRAZPLAN and MIDAS	(Moore et al. 2011)	X	Soil module of APSIM	X	Through daily simulations of APSIM and GRAZPLAN	X	Livestock production in GRAZPLAN	X	MIDAS model optimises farm income
Savanna-MP	(Thornton et al. 2004)	X	Soil model in Savanna	X	Grassland productivity	X	Livestock productivity in Savanna	X	Information produced by the model includes resource use, economic parameters, climate risk, and household nutrition
DSSAT-LP	(Hatch et al. 1999)	X	Soil model in DSSAT	X	Through DSSAT simulations			X	The farm model simulates adaptation to climate-induced changes in yield, by selecting a different mixture of crops that maximises income
	(Herrero et al. 1999)	X	Soil model included in crop production	X	Crop production model	X	Livestock production model	X	Management strategies which make the most efficient use of the farm's resources (i.e. land, animals, pastures) are analysed with MGLP.
	(Kikuhara and Hirooka 2009, Kikuhara et al. 2009)			X	Rice paddy systems	X	Livestock production model is included	X	Optimal diet formulation to maximise profit

Name of model	Reference	Components included			
		Soil	Crop	Livestock	Household
MP together with simulation models continued					
	(Dinar et al. 1993, Dinar 1994)	X Soil hydrology model included	X Crop production as technical coefficients		X Farm-level decisions such as water-related technology substitution and cropping patterns on groundwater and farm income are optimised
GRAZPLAN-MIDAS	(Donnelly et al. 2002, Thomas et al. 2010)		X Pasture productivity is included	X Livestock productivity and herd management is simulated	X Aims at improving the profitability and environmental sustainability of grazing enterprises
	(Jalvingh et al. 1993, Jalvingh et al. 1994)			X Dynamic probabilistic simulation model of a dairy herd	X Gross margin of farm is optimised, the influence of seasonal variation in performance and prices on the optimal calving pattern of a herd are assessed
	(Keil et al. 2009)		X Crop production in relation to water plus stochastic crop simulation for the crop determining factors		X Assesses the impact of El Niño on agricultural incomes of smallholder farmers
	(McCall et al. 1999)		X Grassland production through coefficients	X Simple conversion model to estimate production	X Maximisation of annual gross margin through rotational grazing and seasonal dairying options
	(Messina et al. 1999)		X Crop production is simulated with models		X Utility of wealth is analysed at the end of a 1-year decision period based on current costs and prices, and crop yields simulated for each year of historical weather, estimating effect of ENSO

Name of model	Reference	Components included							
			Soil		Crop		Livestock		Household
MP together with simulation models continued									
	(Meyer-Aurich et al. 1998)	X	Nitrate leaching is simulated	X	Crop production based on simulation models			X	Trade offs assessed between nitrate leaching, impact of land use on amphibians and gross margin of the crop production, caused by different production techniques
MODAM	(Meyer-Aurich 2005)	X	Nitrate leaching is simulated	X	Crop production based on simulation models			X	Trade off at farm level assessed between economic return and soil erosion, nitrogen balance, global warming potential and gross energy input
	(Moghaddam and DePuy 2011)			X	Stochastic hay production determined by weather			X	The optimal number of acres of hay together with hay to purchase and sell to maximise the total profit of a horse farm
	(Moriondo et al. 2010)	X	Soil erosion coefficients	X	Crop production under current and changing (rainfall, radiation) climate			X	Ecological (i.e., water balance, soil erosion, nitrogen leaching) and economic (i.e., gross margin) indicators were integrated in a farm level decision making tool
	(Ngambeki et al. 1992)			X	Crop production model is used	X	Livestock production model is used	X	Analyses of integrated cropping and livestock production system by maximising gross margin
	(Popp et al. 2009)			X	Grassland production is simulated	X	Livestock production model is used	X	Assesses rangeland management strategies in arid systems for optimising livestock productivity
	(Quintero et al. 2009)	X	(soil) hydrology model SWAT is used					X	The LP model specification was for a single ‘typical’ farm, with linkages to hydrology and environmental effects at the watershed level
DairyNZ	(Ramilan et al. 2011)	X	Simple nitrogen discharge functions			X	Livestock production is simulated	X	Marginal abatement costs of pollution control measures are estimated for different farm wealth types

Name of model	Reference	Components included							
		Soil		Crop		Livestock		Household	
MP together with simulation models continued									
	(Rigby and Young 1996)	X	N loss estimates used			X	Livestock production in coefficients	X	Calculation of trade off between livestock production and N pollution
	(Schönhart et al. 2011)	X	Soil module of EPIC is used	X	Crop production simulated with EPIC			X	Evaluation of environmental and economic indicators at farm level
Opt'INRA-PLANETE	(Veysset et al. 2010)			X	Crop production as coefficients	X	Livestock production in coefficients	X	Farm level gross margin evaluation together with consequences for greenhouse gas emissions
	(Wise and Cacho 2011)	X	Soil carbon model is used	X	Crop production model is used			X	The financial viability of agroforestry systems as carbon sinks under carbon credit payment schemes, was explored in a profit maximisation problem
IMPACT-HROM	(Zingore et al. 2009, Waithaka et al. 2006)	X	Soil model of APSIM	X	APSIM is used to estimate crop production	X	RUMINANT is used to estimate livestock production	X	Net income is maximised while also indicators as food security and food self sufficiency are calculated at household level
SFRAMOD-ACCESS	(Holman et al. 2005)	X	N leaching and hydrology models	X	Daily crop growth model			X	Farm income and risk indicator (not specified) are optimised at farm level
IRMLA	(Roetter et al. 2007)			X	Crop growth model used for coefficients			X	Farm income is optimised

Name of model	Reference	Components included							
		Soil		Crop		Livestock		Household	
MP together with simulation models continued									
ISFARM	(Amir et al. 1991, Amir et al. 1993)	X	Hydrological balance estimated	X	Expert model system			X	Value of crop and inputs costs compared at farm level
FASSET-LP	(Berntsen et al. 2003)	X	Detailed soil model for nutrients and water	X	Daily crop and grass growth models	X	Livestock production model	X	Gross margin optimised at farm level
MCID-LP	(Borges Jr et al. 2008)	X	Soil hydrology model	X	Crop model related to hydrology			X	Gross margin evaluation at farm level
GAMS-MINOS	(Carvallo et al. 1998)	X	Simple water balance equation	X	Crop yield – hydrology function used			X	Gross margin optimised at farm level
Farm Images	(Dogliotti et al. 2005)	X	Simple soil organic matter model used	X	Crop rotation generator used			X	Family income optimised
AquaCrop-LP	(García-Vila and Fereres 2011)	X	Water balance model used	X	Aquacrop used to predict water-yield responses for different crops			X	Farm gross margin optimised
FARM-ADAPT	(Gibbons et al. 2006)	X	Soil emission factors used	X	Crop response coefficients for fertiliser, emission factors	X	Livestock methane emission factors, and manure emission factors	X	Farm net margin optimised
MoFEDS	(Greiner 1997)	X	Erosion model used	X	Crop production – salinity response curves, crop – rainfall responses estimated by PERFECT model			X	Farm net margin optimised
SAPWAT-LP	(Grove and Oosthuizen 2010)	X	Soil water balance	X	Crop yield determined by evaporation reduction caused by soil water stress			X	Farm gross margin optimised

Name of model	Reference	Components included: Soil	Crop	Livestock	Household
(dynamic) Simulation models					
	(Müller, Frank and Wissel 2007)	X Simple soil model	X Rangeland model	X Herd dynamics included	X Only as a manager, no separate calculations
SCUAF	(Tamubula and Sinden 2000)	X Simple soil model	X Crop and Napier grass production in agroforestry systems		X Uses @Risk model for calculating economic returns at household level
EU-Rotate_N	(Nendel 2009)	X Simple N leaching model	X Vegetable production model		X Production and N losses at farm level
Lypsikki	(Nousiainen et al. 2011)		X Empirical crop yield equations	X Dynamic cattle herd model with empirical milk yield equation	X Produces farm level nutrient balances
	(Sulistyawati et al. 2005)		X Crop production values of rice and rubber		X Economic welfare of households is simulated by simple cash balance
Savanna-PHEWS	(Thornton et al. 2003, Boone et al. 2006)	X Soil module of Savanna	X Grassland production in Savanna	X Livestock production model of Savanna	X Cash and human diets are followed over time for farm household using simple rules
	(Tichit et al. 2004)			X Livestock (llama and sheep) production and herd dynamics model	X Productivity of pastoral production systems in Andes is assessed for different management options
NUANCES-FARMSIM	(Tittonell et al. 2009, van Wijk et al. 2009a, Giller et al. 2011, Rufino et al. 2011)	X Simple seasonal soil model	X Simple crop nutrient use efficiency model	X Dynamic livestock production model	X Household food production and nutrient flows can be analysed over time
GAMEDE	(Vayssières et al. 2009)	X Basic soil processes	X Crop growth model	X Livestock production model	X Production and gross margin at farm level simulated

Name of model	Reference	Components included							
			Soil		Crop		Livestock		Household
(dynamic) Simulation models continued									
NODRIZA	(Villalba et al. 2010)					X	Livestock production	X	Partial financial budgeting at farm level
	(Pardo et al. 2010)			X	Crop growth			X	Profit calculations at farm level
SALSA	(Eriksson et al. 2005)	X	Soil emissions	X	Crop production, coefficients and emissions	X	Pig production and emissions	X	Emissions at farm scale
	(Hahn et al. 2005)			X	Grassland production equations	X	Goat production model	X	Farm management of goat herd can be assessed through herd productivity
	(Hansen et al. 1997)	X	Soil module of DSSAT	X	DSSAT crop production model			X	Household level economic analysis
	(Hansen et al. 2009)	X	Soil module of APSIM	X	APSIM model for crop production			X	Household level economic analysis
DAFOSYM	(Harrigan et al. 1996)	X	Basic soil model in crop simulation	X	Daily crop growth model	X	Livestock production model	X	Farm level gross margin is calculated, but nutrient flows can be followed at farm level
COTFLEX	(Helms et al. 1990)			X	Empirical relations with climate and effects of extreme events and pests			X	Farm level production and income is evaluated to advice cotton farmers to crop insurance yes or no
NUTMON	(Hengsdijk et al. 2005)	X	Simulation of hydrology and erosion	X	WOFOST is used as daily crop growth model			X	Farm level nutrient budgets are simulated
DYNAMOF	(Howden et al. 1996)	X	Soil hydrology and nutrients are simulated, and N2O emissions	X	Daily pasture growth model	X	Goat production model	X	Farm level income and methane and N2O emissions are evaluated

Name of model	Reference	Components included							
			Soil		Crop		Livestock		Household
(dynamic) Simulation models continued									
FASSET	(Hutchings et al. 2007)	X	Detailed soil model for nutrients and water	X	Daily crop and grass growth models	X	Livestock production model	X	Farm level production, GHG emissions and nutrient balances are evaluated. Gross margin can also be quantified, but not used in this study
@RISK	(Jackson et al. 2011)							X	Analyses water, energy and emissions at farm level
	(Jogo and Hassan 2010)	X	Simple water balance model	X	Crop production equation based on water availability			X	Simulation at population level in area, disaggregated to household level
DairyMod, SGS and EcoMod	(Johnson et al. 2008)	X	Soil water balances and nutrient cycling are simulated	X	Grass production model	X	DairyMOD livestock production model is used	X	Production, nutrient cycling and emissions at farm level. No economics
SEBIEN	(Jouven and Baumont 2008)			X	Pasture growth model	X	Livestock production model	X	Production at farm level, no economic evaluation
ADIEM	(Kulshreshtha and Klein 1989)	X	Soil hydrology is simulated	X	A crop yield hydrology model is used			X	Production and profitability are estimated at farm level
FDMS	(Andrieu et al. 2007b, Andrieu et al. 2007a)	X	Soil hydrology is simulated	X	Pasture growth model	X	Livestock production model	X	Production is estimated at farm level, no economic analysis
	(Bell et al. 2010)	X	Simple model of soil hydrology	X	Pasture growth model at yearly basis	X	Simple livestock production equations	X	Production and ranch profitability are calculated
WFM	(Beukes et al. 2005, Beukes et al. 2008, Beukes et al. 2010)			X	Pasture growth model	X	Livestock production model	X	Production and profitability are evaluated at farm level

Name of model	Reference	Components included							
			Soil		Crop		Livestock		Household
(dynamic) Simulation models continued									
	(Bontkes and Van Keulen 2003)	X	Simple soil nutrient model	X	Crop and pasture production equations are used	X	Monthly livestock production model	X	Production and profitability can be evaluated at farm level
	(Brennan et al. 2008)	X	Soil and hydrology model	X	Crop production simulated with APSIM			X	Through partial budgeting profitability at farm level is evaluated
	(Cabrera et al. 2005)			X	Fixed crop production coefficients	X	Simple reproduction model for chicken	X	Farm level calculation of food needed and economic balance
UDDER	(Chapman et al. 2008a, Chapman et al. 2008b, Chapman et al. 2011)			X	Pasture growth model	X	Livestock production model	X	Production and profitability are evaluated at farm level
	(Clark et al. 2010)					X	Shrimp production values	X	Net present values are calculated for different management options against background of stochastic factors
SEPATOU	(Cros et al. 2001, Cros et al. 2003)	X	Soil water model	X	Pasture growth model	X	Livestock production model	X	Production at farm level is assessed, no economics
GrazeIn	(Delagarde et al. 2011a, Delagarde et al. 2011b, Faverdin et al. 2011)			X	Pasture growth model	X	Livestock production model	X	Production is evaluated at farm level, no economics included
	(Dueri et al. 2007)	X	Simple soil nutrient model	X	Crop production functions, based on detailed model analyses			X	Farm level N balance is assessed
CEEOT-LP	(Gassman et al. 2006)	X	Soil model present, N leaching	X	Crop and pasture production models	X	Livestock simulation model	X	Farm level production, N balance and income evaluation

Name of model	Reference	Components included: Soil		Crop		Livestock		Household	
(dynamic) Simulation models continued									
	(Luckert et al. 2000)			X	Crop production coefficients	X	Livestock production coefficients for cattle and goats	X	Farm level income and food available evaluated
SEDIVER	(Martin et al. 2011)	X	Simple soil water balance model	X	Grassland production model	X	Livestock (beef) production model	X	Farm level production is evaluated
	(Parsons et al. 2011)	X	Soil model included	X	Crop and grassland production model	X	Livestock production model	X	Farm level production and economics are evaluated
	(Pfister et al. 2005)			X	Logistic crop growth models	X	Simple livestock production model	X	Farm level food production is evaluated
APS-FARM	(Rodriguez et al. 2011a, Power et al. 2011)	X	Soil model of APSIM	X	APSIM crop growth model			X	Farm level production and economics are evaluated
IFSM	(Rotz et al. 2005, Rotz et al. 2007, Rotz et al. 2011)	X	Soil models included	X	Crop and grassland growth models	X	Livestock model included	X	Farm level production and economics are evaluated
	(Savoie et al. 1985)			X	Crop production values of 25 year dataset used			X	Farm level production and net returns evaluated
	(Shepherd and Soule 1998)	X	Simple soil model	X	Crop growth model per season	X	Simple livestock production model	X	Cash and food balance at household level
	(Tittonell et al. 2007)	X	Daily soil nutrient balance model	X	Daily crop growth model			X	Simple cash balance at farm level, production evaluated at farm level
TOA	(Claessens et al. 2010, Stoorvogel et al. 2004)	X	Soil models included	X	Crop production model included	X	Livestock production included	X	Trade offs between Socio-economic and environmental indicators assessed at farm level and aggregated to a regional level

Name of model	Reference	Components included			
		Soil	Crop	Livestock	Household
(dynamic) Simulation models continued					
FLIPSIM	(Anderson et al. 1993)		X Pasture production values	X Livestock production values	X Farm income assessed
CSWM	(Balderama 2009, Balderama 2010)	X Water balance model	X Simple response type of crop production model		X Food production could be assessed
BANAD	(Blazy et al. 2010)	X Water balance model	X SIMBA model is used to predict banana productivity		X Household cash balance is evaluated
Simsdairy	(Del Prado et al. 2011)	X Simple soil models included, soil emissions simulated	X Crop and pasture models included	X Livestock models included, emissions simulated	X Household level evaluation of productivity and gross margin
CIS-APSIM	(Brown et al. 2010)	X Soil hydrology model	X APSIM used as crop model		X Farm profit is optimised with inverse modelling

Name of model	Reference	Components included							
		Soil		Crop		Livestock		Household	
Agent based models									
	(Valbuena et al. 2010)							X	Agent characteristics, income evaluation
SimSahel	(Saqalli et al. 2010, Saqalli et al. 2011)			X	Crop production values included and response to manure			X	Agent level evaluation of income and social indicators like status
	(Naivinit et al. 2010)			X	Crop production values included, plus management info			X	Agent level evaluation of food production, labour and income
SAMBA-GIS	(Castella et al. 2005)			X	Crop production values included			X	Agent level evaluation of food production, labour and income
SAMBA	(Castella et al. 2005, Bousquet et al. 2007, Boissau et al. 2004)			X	Crop production values included			X	Agent level evaluation of food production, labour and income
	(Schlüter et al. 2009)			X	Crop production values included			X	Agent level evaluation of income
AgriPolis	(Happe et al. 2011)			X	Crop production values included	X	Livestock production values	X	Agent level maximises net farm income
	(Heckbert 2011)			X	Crop production response to inputs included			X	Agent level income assessed
PUMANI	(Hervé et al. 2002)			X	Crop production response to climate included	X	Manure and age of animals are quantified	X	Agent level food availability is assessed
	(Holtz and Pahl-Wostl 2011)			X	Crop yields of 20 years in Spain used			X	Agent level evaluation of gross margin
PALM	(Matthews and Pilbeam 2005b)	X	Century model included	X	DSSAT model included			X	Agent level evaluation of food production and income

Name of model	Reference	Components included			
		Soil	Crop	Livestock	Household
Agent based models					
	(Shively and Coxhead 2004)	X Soil erosion and a soil ‘stock’ are simulated over time	X Crop production as a function of soil ‘stock’		X Agent optimises farm based income
HELIS	(Manson and Evans 2007)				X Multicriteria fitting of land use and change data to derive decision rules for agents
MPMAS	(Schreinemachers and Berger 2006, Schreinemachers et al. 2007, Schreinemachers and Berger 2011, Berger and Schreinemachers 2006)	X Can be included in framework	X Simple crop growth model included	X Simple livestock model can be included	X Agent level evaluation of income, food production and other indicators depending on application

Table S2: Information on general model characteristics

Name of model	Reference	Spatially explicit	Dynamic / Multi-period	Time-step	Climate as input	Feedbacks	Inputs	Decision making	Regions of application
MP models									
	(Nyikal and Kosura 2005)	No	No	-	No	No	Prices	Optimisation through LP	Kenya
	(Engle 1997)	No	No	-	No	No	Prices	Optimisation through LP	Rwanda
	(Ruben and Van Ruijven 2001)	No	No	-	No	No	Prices	Optimisation through LP	Mali
	(Hansen and Krause 1989)	No	Yes, multi-period	1 yr	No	No	Prices	Optimisation through LP	Australia
MUDAS	(Kingwell et al. 1993)	No	No	-	Yes	No	Prices, 9 climate season types	Optimisation through LP	Australia
	(Sanchez-Zazueta and Martinez-Cordero 2009)	No	No	-	No	No	Prices	Optimisation through LP	Mexico
	(Kaya et al. 2000)	No	No	-	No	No	Prices, production levels, land areas	Optimisation through LP	Mali
	(Laborte et al. 2009)	No	No	-	No	No	Prices	Optimisation through LP	Philippines
	(Louhichi et al. 2004)	No	Yes, multi-period	1 yr	No	No	Prices	Optimisation through LP	Le Reunion
	(Nicholson et al. 1994)	No	Yes, multi-period	1 yr	No	No	Prices	Optimisation through LP	Venezuela
	(Rossing et al. 1997)	No	No	-	No	No	Prices, disease levels	Trade off assessed through MGLP	Netherlands
	(Ruiz et al. 2000)	No	No	-	No	No	Prices	Optimisation through LP	Argentina
	(Salinas et al. 1999)	No	No	-	No	No	Prices and technology availability	Optimisation through LP	Mexico

Name of model	Reference	Spatially explicit	Dynamic / Multi-period	Time-step	Climate as input	Feedbacks	Inputs	Decision making	Regions of application
MP models continued									
	(Schultheiß et al. 2005)	No	No	-	No	No	Prices and water protection technologies available	Optimisation through LP	Germany
	(Senthilkumar et al. 2011)	No	No	-	No	No	Prices and policies	Trade off assessed through MGLP	India
	(Shively 1998)	No	No	-	No	No	Prices	Optimisation through LP	Philippines
	(Shively 2000)	No	Yes, dynamic optimisation	1 yr	No	Yes, short term consumption optimisation and long term soil conservation measures	Prices, consumption shortfall risk	Optimisation through dynamic programming	Philippines
	(Val-Arreola et al. 2004)	No	No	-	No	No	Prices	Optimisation through LP and partial budgeting	Mexico
	(Val-Arreola et al. 2006)	No	No	-	No	No	Prices	Multi criteria optimisation and compromise programming	Mexico
	(Valderrama and Engle 2002)	No	No	-	No	No	Prices, stocking densities, through flow rates of water	Optimisation through LP	Honduras
	(Veysset et al. 2005)	No	No	-	No	No	Prices, European policies	Optimisation through LP	France
	(Weikard and Hein 2011)	No	No	-	No	No	Prices	Optimisation through LP	Sahel

Name of model	Reference	Spatially explicit	Dynamic / Multi-period	Time-step	Climate as input	Feedbacks	Inputs	Decision making	Regions of application
MP models continued									
OPFROP - FRUPAT	(Cittadini et al. 2008)	No	Yes	1 month	No	No	Prices	Optimisation through dynamic LP	Argentina
FSRM	(Dake et al. 2005)	No	No	-	Not explicitly, implicitly in stochastic analysis	No	Prices, stochastic production levels	Optimisation of trade off between gross margin and variance in gross margin	New Zealand

Name of model	Reference	Spatially explicit	Dynamic / Multi-period	Time-step	Climate as input	Feedbacks	Inputs	Decision making	Regions of application
MP together with simulation models									
	(Mimouni et al. 2000)	No	Yes, the simulation models	1 day for EPIC	Yes, daily input	Yes, soil feedbacks	Daily meteo, prices	Optimisation through LP	Tunisia
APSIM, GRAZPLAN and MIDAS	(Moore et al. 2011)	No	Yes, at least the simulation models	1 day for APSIM and GRAZPLAN for MIDAS year or longer	Yes, daily input	Yes, soil feedbacks	Daily meteo, prices, farm configuration	Optimisation through LP	Australia
Savanna-MP	(Thornton et al. 2004)	Yes	Yes, Savanna is	1 month	Yes	Yes, soil feedbacks	Climate, prices	Optimisation through LP	South Africa
DSSAT-LP	(Hatch et al. 1999)	No	Yes, DSSAT is	1 day	Yes, daily input	Yes soil feedbacks through nutrients and water	Climate, prices	Optimisation through LP	US
	(Herrero et al. 1999)	No	Yes, the simulation models	1 day	Yes, daily input	Yes, soil feedbacks	Climate prices	Optimisation through MGLP	Costa Rica
	(Kikuhara and Hirooka 2009, Kikuhara et al. 2009)	No	Yes, livestock production model is	1 day	No	No	Feed resources, prices	Optimisation through LP	Japan
	(Dinar et al. 1993, Dinar 1994)	No	Yes, the simulation model	1 day, optimisation over longer periods	Yes, daily input	Yes, soil hydrological feedbacks	Climate, prices	Optimisation through LP	US

Name of model	Reference	Spatially explicit	Dynamic / Multi-period	Time-step	Climate as input	Feedbacks	Inputs	Decision making	Regions of application
MP together with simulation models continued									
Grazplan-MIDAS	(Donnelly et al. 2002, Thomas et al. 2010)	No	Yes, the simulation model	1 day, optimisation over longer periods	Yes, daily input	Yes, soil feedbacks possible	Climate, prices	Optimisation through LP	Australia
	(Jalvingh et al. 1993, Jalvingh et al. 1994)	No	Yes, the herd model	1 month	No	No	Prices	Optimisation through LP	Netherlands
	(Keil et al. 2009)	No	Yes, the crop simulation model	1 day	Yes, daily input	Yes, soil hydrological feedbacks	Climate, prices	Optimisation through LP	Indonesia
	(McCall et al. 1999)	No	No	-	No	No	Prices	Optimisation through LP	US and New Zealand
	(Messina et al. 1999)	No	Yes, simulation model	1 day, optimisation over 1 year	Yes, daily input	No	Prices, initial wealth and risk preference of farmer	Optimisation through LP	Argentina
	(Meyer-Aurich et al. 1998)	No	Yes, the simulation models	1 day, optimisation over longer period	Yes, daily input	No	Prices, climate	Optimisation through LP	Germany
MODAM	(Meyer-Aurich 2005)	No	Yes, the simulation models	1 day, optimisation over longer period	Yes, daily input	No	Prices, climate	Optimisation through LP in which weights of indicators is changed: MGLP	Germany
	(Moghaddam and DePuy 2011)	No	No	-	Yes, yearly values	No	Prices, climate	Stochastic MP model	US

Name of model	Reference	Spatially explicit	Dynamic / Multi-period	Time-step	Climate as input	Feedbacks	Inputs	Decision making	Regions of application
MP together with simulation models continued									
	(Moriondo et al. 2010)	No	Yes, simulation models are dynamic	Day for simulation models, longer for optimisation	Yes, daily input	No	Prices, climate	Optimisation through LP	Italy
	(Ngambeki et al. 1992)	No	Yes, component simulation models	1 day for simulation models	Yes, daily input	No	Prices, climate	Optimisation through LP	Cameroon
	(Popp et al. 2009)	No	Yes, dynamic optimisation and dynamic simulation models	1 year for both simulation model and for optimisation	Yes, yearly	Yes, through rangeland degradation	Prices, climate	Optimisation through dynamic MP	Namibia
	(Quintero et al. 2009)	Yes	Yes, SWAT is dynamic	1 day	Yes, daily input	Yes, through soil water feedbacks	Prices, climate	Optimisation through LP	Peru and Ecuador
DairyNZ	(Ramilan et al. 2011)	No	Yes, livestock production model is	1 day	Yes, daily input	No	Prices, climate	Optimisation through evolutionary search algorithms, followed by constrained programming	New Zealand
	(Rigby and Young 1996)	No	No	-	No	No	Prices	Optimisation through LP	UK
	(Schönhart et al. 2011)	No	Yes, simulation models are dynamic	1 day for EPIC	Yes, daily input	Yes, soil feedbacks present	Prices, climate, policy measures	Optimisation through LP	Austria

Name of model	Reference	Spatially explicit	Dynamic / Multi-period	Time-step	Climate as input	Feedbacks	Inputs	Decision making	Regions of application
MP together with simulation models continued									
	(Wise and Cacho 2011)	No	Yes, simulation models are	1 year for the simulation models, long for the optimisation model	No	Yes, soil feedbacks present	Prices, policy measures	Optimisation through LP	Indonesia
IMPACT-HROM	(Zingore et al. 2009, Waithaka et al. 2006)	No	Yes, simulation models are	1 day for simulation models, for optimisation longer time window	Yes, daily input for APSIM	Yes, in APSIM are soil feedbacks present	Prices, climate, production orientation	Optimisation through LP	Zimbabwe, Kenya
SFRAMOD-ACCESS	(Holman et al. 2005)	Yes	Yes, simulation models are	1 day for simulation models, longer period for optimisation	Yes, daily input	Yes, feedbacks through hydrology	Prices, climate	Optimisation through LP	UK
IRMLA	(Roetter et al. 2007)	No	Yes, crop simulation model is	1 day for crop simulation model	Yes, daily input for crop model	No	Prices, climate	Nested optimisation: LP optimisation both at farm and regional scale	Philippines
ISFARM	(Amir et al. 1991, Amir et al. 1993)	No	No	-	Yes, through expert model affects crop production and water use	No	Prices, climate	Optimisation through LP	France

Name of model	Reference	Spatially explicit	Dynamic / Multi-period	Time-step	Climate as input	Feedbacks	Inputs	Decision making	Regions of application
MP together with simulation models continued									
FASSET-LP	(Berntsen et al. 2003)	No	Yes	1 day	Yes, daily values	Yes, soil feedbacks, herd size	Climate, farm setup and heterogeneity	Optimisation through LP	Denmark
MCID-LP	(Borges Jr et al. 2008)	No	Yes	1 day, optimisation over several years	Yes, daily values	Yes, soil hydrology feedbacks	Climate, prices	Optimisation through LP	Brazil
GAMS-MINOS	(Carvallo et al. 1998)	No	No	-	Yes, yearly values	No	Climate, prices	Optimisation through LP	Chile
ROTAT-MILP	(Dogliotti et al. 2005)	No	Yes	1 year	No	Yes, soil organic matter feedbacks	Prices	Optimisation through MILP	Uruguay
AquaCrop-LP	(García-Vila and Fereres 2011)	No	Yes	1 day, optimisation over 1 year	Yes, daily values	Yes, soil water feedbacks	Prices, climate	Non-linear Optimisation	Spain
FARM-ADAPT	(Gibbons et al. 2006)	No	No	-	No	No	Prices, emission factors, farm setup	MI optimisation	UK
MoFEDS	(Greiner 1997)	No	Yes	1 year optimisation, crop model 1 day	Yes, daily values for crop model	Yes, erosion and soil water feedbacks	Prices, climate, soil conditions	Dynamic LP optimisation	Australia
SAPWAT-LP	(Grove and Oosthuizen 2010)	No	Yes, at least the crop – water model	1 day	Yes, daily values for the model	Yes, soil water feedbacks	Prices, climate ,risk aversion of farmer	Non-linear optimisation	South Africa

Name of model	Reference	Spatially explicit	Dynamic / Multi-period	Time-step	Climate as input	Feedbacks	Inputs	Decision making	Regions of application
(dynamic) Simulation models									
	(Müller et al. 2007)	No	Yes	1 yr	Yes	Yes, soil and vegetation feedbacks	Yearly climate	Rule based	Namibia
SCUAF	(Tamubula and Sinden 2000)	No	Yes	1 yr	Yes	Yes, soil feedbacks	Climate, prices, soil variables	Rule based	Kenya
EU-Rotate_N	(Nendel 2009)	No	Yes	1 day	Yes	Yes, soil feedbacks	Climate	Rule based	Germany
Lypsikki	(Nousiainen et al. 2011)	No	Yes, the herd model	2 days	No	No	Farm management	Rule based	Finland
	(Sulistyawati et al. 2005)	No	Yes	1 yr	No	No	Farm descriptions	Rule based	Indonesia
Savanna-PHEWS	(Thornton et al. 2003, Boone et al. 2006)	Yes	Yes	1 week / 1 month	Yes	Yes, soil feedbacks	Climate, original land use	Rule based	Tanzania
	(Tichit et al. 2004)	No	Yes	1 yr	No	No	Size of herds	Rule based	Bolivia
Nuances-FARMSIM	(Tittonell et al. 2009, van Wijk et al. 2009a, Giller et al. 2011, Rufino et al. 2011)	No	Yes	1 season	Yes, seasonal values	Yes, soil and livestock herd feedbacks	Seasonal climate, farm typology	Rule based	Kenya, Zimbabwe
GAMEDE	(Vayssières et al. 2009)	No	Yes	1 day	Yes, daily values	Yes, soil and livestock herd feedbacks	Daily climate, farm characteristics	Rule based, decision module incorporated	La Reunion
NODRIZA	(Villalba et al. 2010)	No	Yes	1 day	No	No	Feed availability	Rule based	Spain
	(Pardo et al. 2010)	No	Yes	1 day	No	No	Management	Rule based	Western Europe

Name of model	Reference	Spatially explicit	Dynamic / Multi-period	Time-step	Climate as input	Feedbacks	Inputs	Decision making	Regions of application
(dynamic) Simulation models continued									
SALSA	(Eriksson et al. 2005)	No	Yes	1 yr	No	Soil compaction feedbacks	Production data and management	Rule based	Sweden
	(Hahn et al. 2005)	No	Yes	1 yr	Yes, yearly values with seasonal modifiers	Feedbacks through population of goats and feed available	Rangeland structure, production and edible fraction	Rule based	South Africa
	(Hansen et al. 1997)	No	Yes	1 day	Yes, daily values	Feedbacks through soil processes	Climate, prices	Rule based	Colombia
	(Hansen et al. 2009)	No	Yes	1 day	Yes, daily values	Feedbacks through soil processes	Climate, prices	Rule based	Kenya
Dafosym	(Harrigan et al. 1996)	No	Yes	1 day	Yes, daily values	Feedbacks through soil processes and livestock herd	Climate, prices	Rule based	US
COTFLEX	(Helms et al. 1990)	No	No	-	Yes, through stochastic effects on crop production, yearly values	No	Climate, incidence of pests and extreme events	Rule based	US
NUTMON	(Hengsdijk et al. 2005)	No	Yes, the component models. NUTMON is static nutrient	1 day for component models	Yes, daily values	Yes, short term feedbacks in erosion model	Climate, nutrient and organic transport rules in farm	Rule based	Ethiopia

Name of model	Reference	Spatially explicit	Dynamic / Multi-period	Time-step	Climate as input	Feedbacks	Inputs	Decision making	Regions of application
			accounting tool						
(dynamic) Simulation models continued									
DYNAMOF	(Howden et al. 1996)	No	Yes	1 day	Yes, daily values	Yes, nutrient and water feedbacks through soil model, sheep herd feedbacks	Climate, prices, farm setup	Rule based	Australia
FASSET	(Hutchings et al. 2007)	No	Yes	1 day	Yes, daily values	Yes, soil feedbacks, herd size	Climate, farm setup and heterogenei ty	Rule based	Denmark
@RISK	(Jackson et al. 2011)	No	Yes, through simulations of water use	1 day	Yes, daily values for sub model	No	Climate, farm setup	Rule based	Australia
	(Jogo and Hassan 2010)	No	Yes	1 year (not completel y clear for water model)	Yes, yearly input	No	Climate, prices	Rule based	South Africa
DairyMod, SGS and EcoMod	(Johnson et al. 2008)	No, not in GIS format	Yes	1 day	Yes, daily input	Yes, through livestock herd size, and soil water and nutrient feedbacks	Climate, farm setup	Rule based	Australia, New Zealand
SEBIEN	(Jouven and Baumont 2008)	No	Yes	1 day for pasture model, manage-	Yes, daily input	Yes, through livestock herd size	Climate, farm setup	Rule based	France

ment longer

Name of model	Reference	Spatially explicit	Dynamic / Multi-period	Time-step	Climate as input	Feedbacks	Inputs	Decision making	Regions of application
(dynamic) Simulation models continued									
ADIEM	(Kulshreshtha and Klein 1989)	No	Yes	1 day for hydrology model	Yes, daily input	Yes, through soil water	Climate, prices, employment	Rule based	Canada
FDMS	(Andrieu et al. 2007b, Andrieu et al. 2007a)	No	Yes	1 day	Yes, daily input	Yes, through soil water	Climate, farm setup	Rule based	France
	(Bell et al. 2010)	No	Yes	1 year	Yes, yearly drought indices	Yes, through herd size and soil water	Climate, prices, policy	Rule based	Brazil
WFM	(Beukes et al. 2005, Beukes et al. 2008, Beukes et al. 2010)	No	Yes	1 day	Yes, daily input	Yes, through livestock herd size	Climate, farm setup	Rule based	New Zealand
	(Bontkes and Van Keulen 2003)	No	Yes	1 month for cattle model, crops per season	Yes, yearly input	Yes, through soil fertility and herd size	Climate, prices, farm types	Rule based	Mali
	(Brennan et al. 2008)	No	Yes	1 day for APSIM, yearly for partial budgeting	Yes, daily input	Yes, through hydrology and soil feedbacks	Climate, prices	Rule based	Australia
	(Cabrera et al. 2005)	No	Yes	1 year	No	Through livestock numbers	Prices, population growth, crop	Rule based	Peru

							production		

Name of model	Reference	Spatially explicit	Dynamic / Multi-period	Time-step	Climate as input	Feedbacks	Inputs	Decision making	Regions of application
(dynamic) Simulation models continued									
UDDER	(Chapman et al. 2008a, Chapman et al. 2008b, Chapman et al. 2011)	No	Yes	1 day	Yes, daily input	Yes, through livestock herd size	Climate, farm setup	Rule based	Australia
	(Clark et al. 2010)	No	No	-	Yes, through extreme events	No	Climate, prices, diseases	Rule based	US
SEPATOU	(Cros et al. 2001, Cros et al. 2003)	No	Yes	1 day	Yes, daily input	Yes, through soil water and herd size	Climate, farm setup	Rule based	France
GrazeIn	(Delagarde et al. 2011a, Delagarde et al. 2011b, Faverdin et al. 2011)	No	Yes	1 day	Yes, daily input	Yes, through livestock herd size	Climate, farm setup	Rule based	France
	(Dueri et al. 2007)	No	Yes	1 year	Yes, yearly input	Yes, soil feedbacks	Climate, farm setup	Rule based	Switzerland
CEEOT-LP	(Gassman et al. 2006)	Yes	Yes	1 day	Yes, daily input	Yes, soil and livestock herd feedbacks	Climate, prices, farm setup	Rule based	US
	(Luckert et al. 2000)	No	Yes	1 year	Yes, rainfall as yearly input	Yes, soil and livestock herd feedbacks	Climate, prices	Rule based	Zimbabwe
SEDIVER	(Martin et al. 2011)	No	Yes	1 day	Yes, daily input	Yes, soil water and livestock	Climate, farm setup	Rule based	France

herd feedbacks

Name of model	Reference	Spatially explicit	Dynamic / Multi-period	Time-step	Climate as input	Feedbacks	Inputs	Decision making	Regions of application
(dynamic) Simulation models continued									
	(Parsons et al. 2011)	No	Yes	1 day	Yes	Yes, soil and livestock herd feedbacks	Climate, farm setup	Rule based	Mexico
	(Pfister et al. 2005)	No	Yes	1 day	Yes	Yes, livestock herd feedbacks	Climate, farm setup	Rule based	Nicaragua
APS-FARM	(Rodriguez et al. 2011a, Power et al. 2011)	No	Yes	1 day	Yes, daily input	Yes, soil water and fertility feedbacks	Climate, prices, setup	Rule based	Australia
IFSM	(Rotz et al. 2005, Rotz et al. 2007, Rotz et al. 2011)	No	Yes	1 day	Yes, daily input	Yes, soil and livestock number feedbacks	Climate, prices, setup	Rule based	US, the Netherlands
	(Savoie et al. 1985)	No	No	-	No	No	Prices, crop production	Rule based	US
	(Shepherd and Soule 1998)	No	Yes	1 year	Yes, yearly values	Yes, through livestock and soil fertility	Climate, prices	Rule based	Kenya
	(Tittonell et al. 2007)	No	Yes	1 day for crop and soil model, optimisation over 1 year	Yes, daily input	Yes, through soil and cash availability	Climate, farm setup	Rules that are optimised in inverse modelling exercise	Kenya

Name of model	Reference	Spatially explicit	Dynamic / Multi-period	Time-step	Climate as input	Feedbacks	Inputs	Decision making	Regions of application
(dynamic) Simulation models continued									
TOA	(Claessens et al. 2010, Stoorvogel et al. 2004)	Yes	Yes, at least the simulation models	1 day (crop model), agricultural season (land allocation) Analysis over longer periods	Yes, daily input	Yes, soil feedbacks	Soil, Climate, prices, Management	Maximisation of net returns based on output supply and input demand equations (econometric simulations)	Andes, Kenya, Senegal, Netherlands, USA, Panama
FLIPSIM	(Anderson et al. 1993)	No	Yes	1 year	No	No	Prices, production values of pasture and livestock	Economic calculations of consequences of production values	US
CSWM	(Balderama 2009, Balderama 2010)	No	Yes	1 day (not made explicit)	Yes, daily inputs	Yes, soil water feedbacks	Climate	Rule based	Philippines
BANAD	(Blazy et al. 2010)	No	Yes	1 week	Yes, weekly input	Yes, soil feedbacks	Prices, climate, farm setup	Rule based	Guadeloupe
Simsdairy	(Del Prado et al. 2011)	No	Yes	1 month	Yes, monthly input	Yes, feedbacks through soil and livestock herd	Prices, climate, farm setup	Rule based	UK
CIS-APSIM	(Brown et al. 2010)	No	Yes	1 day for crop model, 1 year for optimisation	Yes, daily values	Yes, hydrological feedbacks	Climate, prices	Optimisation through simulated annealing	Australia

Name of model	Reference	Spatially explicit	Dynamic / Multi-period	Time-step	Climate as input	Feedbacks	Inputs	Decision making	Regions of application
Agent based models									
	(Valbuena et al. 2010)	Yes	Yes	1 yr	No	Agent feedbacks	Prices	Rule based	Australia
SimSahel	(Saqalli et al. 2010, Saqalli et al. 2011)	No	Yes	1 yr	No	Agent feedbacks	Prices	Rule based	Niger
	(Naivinit et al. 2010)	No	Yes	1 day	No	Agent feedbacks plus hydrological feedbacks	Manageme nt rules	Rule based	Thailand
SAMBA-GIS	(Castella et al. 2005)	Yes	Yes	1 yr	No	Agent feedbacks	Prices	Rule based	Vietnam
SAMBA	(Castella et al. 2005, Bousquet et al. 2007, Boissau et al. 2004)	No	Yes	1 yr	No	Agent feedbacks	Prices	Rule based	South East Asia
	(Schlüter et al. 2009)	No	Yes	1 yr	No	Agent feedbacks, fish population	Prices	Rule based	Central Asia
AgriPolis	(Happe et al. 2011)	No	Yes	1 yr	No	Agent feedbacks	Prices	Rule based	Denmark
	(Heckbert 2011)	Yes	Yes	1 yr	No	Agent feedbacks, land availability	Prices	Rule based	Australia
PUMANI	(Hervé et al. 2002)	No	Yes	1 day	Yes, through crop production modifier	Agent feedbacks	Climate	Rule based	Andes
	(Holtz and Pahl-Wostl 2011)	No	Yes	1 yr	Yes	Agent feedbacks	Climate	Rule based	Spain

Name of model	Reference	Spatially explicit	Dynamic / Multi-period	Time-step	Climate as input	Feedbacks	Inputs	Decision making	Regions of application
Agent based models continued									
PALM	(Matthews and Pilbeam 2005b)	No	Yes	1 day	Yes, daily input	Agent and soil feedbacks	Climate, prices	Rule based	Nepal
	(Shively and Coxhead 2004)	No	Yes	1 yr	Yes, yearly rainfall	Agent and soil stock feedbacks	Climate, prices	LP optimisation	Philippines
HELIS	(Manson and Evans 2007)	Yes	No	-	No	No	Farm type, location	Multi criteria analysis	US and Mexico
MPMAS	(Schreinemachers and Berger 2006, Schreinemachers et al. 2007, Schreinemachers and Berger 2011, Berger and Schreinemachers 2006)	Yes	Yes	1 year (decision making component models on shorter time scales)	Yes	Agent and soil feedbacks	Climate, prices	LP optimisation	Chile, Germany, Ghana, Thailand, Uganda, Vietnam

Table S3: Information on how attributes 'Economic performance', 'Food self-sufficiency' and 'Food security' are represented by each model framework

Name of model	Reference	Economic performance	Food self-sufficiency	Food security
MP models				
	(Nyikal and Kosura 2005)	X Profit maximisation	X Food requirements are explicitly taken into account in optimisation	
	(Engle 1997)	X Profit maximisation	X Should be fulfilled as a constraint to farm profit maximisation	X Explicitly taken into account
	(Ruben and Van Ruijven 2001)	X Profit maximisation		
	(Hansen and Krause 1989)	X Profit maximisation over time		
	(Kingwell et al. 1993)	X Income maximisation		
	(Sanchez-Zazueta and Martinez-Cordero 2009)	X Profit maximisation		
	(Kaya et al. 2000)	X Income maximisation	X Is calculated at household level	X Food storage is not taken into account, purchase of food is.
	(Laborte et al. 2009)	X Income maximisation		
	(Louhichi et al. 2004)	X Income maximisation		
	(Nicholson et al. 1994)	X Income maximisation		
	(Rossing et al. 1997)	X Income maximised in trade off analysis		
	(Ruiz et al. 2000)	X Cost minimisation		
	(Salinas et al. 1999)	X Income maximisation		
	(Schultheiß et al. 2005)	X Income maximisation		
	(Senthilkumar et al. 2011)	X Income maximised in trade off analysis	X Can be assessed	
	(Shively 1998)	X Income maximisation		
	(Shively 2000)	X Income maximisation	X Is assessed	
	(Val-Arreola et al. 2004)	X Income maximisation		

Name of model	Reference	Economic performance		Food self-sufficiency	Food security
MP models continued					
	(Val-Arreola et al. 2006)	X	Income maximisation within multi-criteria analysis		
	(Valderrama and Engle 2002)	X	Net return maximisation		
	(Veysset et al. 2005)	X	Gross margin optimisation		
	(Weikard and Hein 2011)	X	Gross margin optimisation		
OPFROP-FRUPAT	(Cittadini et al. 2008)	X	Net present value and labour requirement optimisation over time		
FSRM	(Dake et al. 2005)	X	Gross margin and variance in gross margin optimised along trade off curve		

Name of model	Reference	Economic performance	Food self-sufficiency	Food security
MP together with simulation models				
	(Mimouni et al. 2000)	X Farm income maximisation		
APSIM, GRAZPLAN and MIDAS	(Moore et al. 2011)	X Gross margin maximisation	X Could be used for this, not the focus of the study	
Savanna-MP	(Thornton et al. 2004)	X Income maximisation	X Household nutrition is one of focus variables	
DSSAT-LP	(Hatch et al. 1999)	X Income maximisation	X Could be used for this, not focus of the study	
	(Herrero et al. 1999)	X Income maximisation in MGLP setting	X Could be used for this	
	(Kikuhara and Hirooka 2009, Kikuhara et al. 2009)	X Profit maximisation		
	(Dinar et al. 1993, Dinar 1994)	X Income maximisation		
GRAZPLAN-MIDAS	(Donnelly et al. 2002, Thomas et al. 2010)	X Income maximisation		
	(Jalvingh et al. 1993, Jalvingh et al. 1994)	X Maximisation of gross margin per cow		
	(Keil et al. 2009)	X Income maximisation	X Can be used for this, not done in study	
	(McCall et al. 1999)	X Gross margin maximisation		
	(Messina et al. 1999)	X Gross margin maximisation		
	(Meyer-Aurich et al. 1998)	X Crop gross margin is one of the objectives optimised		
MODAM	(Meyer-Aurich 2005)	X Net farm income is one of the objectives optimised		

Name of model	Reference		Economic performance		Food self-sufficiency		Food security
MP together with simulation models continued							
	(Moghaddam and DePuy 2011)	X	Gross margin is optimised				
	(Moriondo et al. 2010)	X	Economic return is optimised	X	Approach could be used to estimate this		
	(Ngambeki et al. 1992)	X	Gross margin is optimised	X	Approach could be used to estimate this		
	(Popp et al. 2009)	X	Discounted net margin is optimised over 30 years				
	(Quintero et al. 2009)	X	Net economic benefits are optimised				
DairyNZ	(Ramilan et al. 2011)	X	Abatement costs are minimised				
	(Rigby and Young 1996)	X	Gross margin is maximised				
	(Schönhart et al. 2011)	X	Farm gross margin is maximised				
Opt'INRA-PLANETE	(Veysset et al. 2010)	X	Gross margin optimisation				
	(Wise and Cacho 2011)	X	Farm profit is maximised				
IMPACT-HROM	(Zingore et al. 2009, Waithaka et al. 2006)	X	Net farm income is maximised	X	Is explicitly analysed	X	Purchased food is taken into account, stored food not
SFRAMOD-ACCESS	(Holman et al. 2005)	X	Net farm income is optimised in weighted objective function	X	Could be analysed, not in this study		
IRMLA	(Roetter et al. 2007)	X	Farm income is optimised, while 4 objectives are optimised are regional level	X	Could be analysed.		

Name of model	Reference	Economic performance	Food self-sufficiency	Food security
MP together with simulation models continued				
ISFARM	(Amir et al. 1991, Amir et al. 1993)	X Current value of production and costs of irrigation are compared		
FASSET-LP	(Berntsen et al. 2003)	X Gross margin optimised	X Could be assessed	
MCID	(Borges Jr et al. 2008)	X Gross margin optimised		
GAMS-MINOS	(Carvallo et al. 1998)	X Gross margin optimised		
ROTAT-MILP	(Dogliotti et al. 2005)	X Family income is one of the objectives optimised		
AquaCrop-LP	(García-Vila and Fereres 2011)	X Farm gross margin is optimised		
FARM-ADAPT	(Gibbons et al. 2006)	X Optimised farm net margin		
MoFEDS	(Greiner 1997)	X Optimised farm net margin		
SAPWAT-LP	(Grove and Oosthuizen 2010)	X Farm gross margin is optimised for different risk aversion values		

Name of model	Reference		Economic performance		Food self-sufficiency	Food security
(dynamic) Simulation models						
	(Müller et al. 2007)					
SCUAF	(Tamubula and Sinden 2000)	X	Calculates gross margin with @Risk	X	Could be used to calculate it, not done in this analysis	
EU-Rotate_N	(Nendel 2009)					
Lypsikki	(Nousiainen et al. 2011)					
	(Sulistyawati et al. 2005)	X	Farm cash balance	X	Could be used to analyse this	
Savanna-PHEWS	(Thornton et al. 2003, Boone et al. 2006)	X	Farm cash balance	X	Simple on-farm diet balance	
	(Tichit et al. 2004)	X	Income calculated, and wealth followed over time			
NUANCES-FARMSIM	(Tittonell et al. 2009, van Wijk et al. 2009a, Giller et al. 2011, Rufino et al. 2011)			X	Has been used for this	
GAMEDE	(Vayssières et al. 2009)	X	Gross margin of the farm is simulated	X	Could be used for this	
NODRIZA	(Villalba et al. 2010)	X	Partial financial budgeting is performed			
	(Pardo et al. 2010)	X	Farm profit is calculated			
SALSA	(Eriksson et al. 2005)					
	(Hahn et al. 2005)					
	(Hansen et al. 1997)	X	Farm profit is calculated	X	Household requirements included	
	(Hansen et al. 2009)	X	Farm profit is calculated	X	Could be used for this	
DAFOSYM	(Harrigan et al. 1996)	X	Farm gross margin is calculated	X	Could be used for this	

Name of model	Reference		Economic performance		Food self-sufficiency		Food security
(dynamic) Simulation models continued							
COTFLEX	(Helms et al. 1990)	X	Farm income is estimated				
NUTMON	(Hengsdijk et al. 2005)			X	NUTMON can be used for this, not in this study	X	NUTMON can be used for this (although not taking into account storage of food), not in this study
DYNAMOF	(Howden et al. 1996)	X	Gross margins are calculated				
FASSET	(Hutchings et al. 2007)	X	Gross margin can be analysed, not in this study	X	Could be assessed		
@RISK	(Jackson et al. 2011)	X	Farm income is calculated by dividing population income by population size	X	Could be assessed roughly (food for population divided by population size)		
	(Jogo and Hassan 2010)						
DairyMod, SGS and EcoMod	(Johnson et al. 2008)						
SEBIEN	(Jouven and Baumont 2008)						
ADIEM	(Kulshreshtha and Klein 1989)	X	Farm level profit could be estimated based on regional data	X	Could be assessed roughly through downscaling of aggregated data		
FDMS	(Andrieu et al. 2007b, Andrieu et al. 2007a)						
	(Bell et al. 2010)	X	Farm profitability is calculated				
WFM	(Beukes et al. 2005, Beukes et al. 2008, Beukes et al. 2010)	X	Farm profit is calculated				

Name of model	Reference		Economic performance		Food self-sufficiency		Food security
(dynamic) Simulation models continued							
	(Bontkes and Van Keulen 2003)	X	Farm profit is calculated	X	Is calculated	X	Food purchase is quantified, food storage not
	(Brennan et al. 2008)	X	Farm profit is estimated through partial budgeting	X	Could be assessed		
	(Cabrera et al. 2005)	X	Farm profit is calculated	X	Is assessed	X	Could be assessed based on info if also food storage would be taken into account
UDDER	(Chapman et al. 2008a, Chapman et al. 2008b, Chapman et al. 2011)	X	Farm profit is calculated				
	(Clark et al. 2010)	X	Net present value of activities is calculated				
SEPATOU	(Cros et al. 2001, Cros et al. 2003)						
GrazeIn	(Delagarde et al. 2011a, Delagarde et al. 2011b, Faverdin et al. 2011)						
	(Dueri et al. 2007)			X	Could be assessed, not a focus of the study		
CEEOT-LP	(Gassman et al. 2006)	X	Farm profit is calculated under different scenarios	X	Could be assessed, not a focus of the study		
	(Luckert et al. 2000)	X	Farm income is calculated	X	Is assessed		
SEDIVER	(Martin et al. 2011)			X	Farm self-sufficiency of hay production is assessed		
	(Parsons et al. 2011)	X	Farm income simulated	X	Can be assessed		
	(Pfister et al. 2005)			X	Is assessed		

Name of model	Reference		Economic performance		Food self-sufficiency		Food security
(dynamic) Simulation models continued							
APS-FARM	(Rodriguez et al. 2011a, Power et al. 2011)	X	Annual operating returns are calculated	X	Could be assessed, not a focus of the study		
IFSM	(Rotz et al. 2005, Rotz et al. 2007, Rotz et al. 2011)	X	Farm gross margin is assessed	X	Could be assessed, not a focus of the study		
	(Savoie et al. 1985)	X	Farm net return is assessed	X	Could be assessed, not a focus of the study		
	(Shepherd and Soule 1998)	X	Farm profit is calculated	X	Is assessed	X	Food purchased included, not food storage
	(Tittonell et al. 2007)	X	Simple cash balance is incorporated	X	Could be assessed, not done in study		
TOA	(Claessens et al. 2010, Stoorvogel et al. 2004)	X	Income maximisation within trade off setting	X	Can be used for this		
FLIPSIM	(Anderson et al. 1993)	X	Simple cash balance is incorporated				
CSWM	(Balderama 2009, Balderama 2010)			X	Could be assessed, not done in study		
BANAD	(Blazy et al. 2010)	X	Gross margin calculated	X	Can be assessed		
Simsdairy	(Del Prado et al. 2011)	X	Farm profit is calculated	X	Could be assessed, not done in this study		
CIS-APSIM	(Brown et al. 2010)	X	Farm profit is optimised	X	Could be assessed, not in this study		

Name of model	Reference	Economic performance		Food self-sufficiency		Food security	
Agent based models							
	(Valbuena et al. 2010)	X	Calculations of income				
SimSahel	(Saqalli et al. 2010, Saqalli et al. 2011)	X	Calculations of income	X	Could be assessed in 2011 application		
	(Naivinit et al. 2010)	X	Income could be calculated	X	Can be assessed		
SAMBA-GIS	(Castella et al. 2005)	X	Income is calculated based on sale of surplus food	X	Is quantified	X	Could be assessed
SAMBA	(Castella et al. 2005, Bousquet et al. 2007, Boissau et al. 2004)	X	Income is calculated based on sale of surplus food	X	Is quantified	X	Could be assessed
	(Schlüter et al. 2009)	X	Farm gross margin is calculated				
AgriPolis	(Happe et al. 2011)	X	Farm income is maximised in rules				
	(Heckbert 2011)	X	Farm income is evaluated				
PUMANI	(Hervé et al. 2002)			X	Is quantified		
	(Holtz and Pahl-Wostl 2011)	X	Farm gross margin is assessed	X	Could be assessed		
PALM	(Matthews and Pilbeam 2005b)	X	Farm income and food production are evaluated	X	Is assessed	X	Is assessed through food purchase, not through food storage
	(Shively and Coxhead 2004)	X	Farm based income is maximised	X	Could be assessed		
HELIS	(Manson and Evans 2007)	X	Income is part of empirical analysis				
MPMAS	(Schreinemachers and Berger 2006, Schreinemachers et al. 2007, Schreinemachers and Berger 2011, Berger and Schreinemachers 2006)	X	Farm income and food production is evaluated	X	Can be quantified	X	Can be quantified

Table S4: Information on how attributes 'Climate variability and change', 'Risk', 'Mitigation' and 'Adaptation' are represented by each model framework

Name of model	Reference	Climate variability and change		Risk		Mitigation	Adaptation	
MP models								
	Nyikal and Kosura 2005)			X	Risk was explicitly taken into account using risk profiles		X	Given different risk perceptions differences in management were calculated
	(Engle 1997)						X	If production changes, simulated decisions can be different
	(Ruben and Van Ruijven 2001)			X	Effects of input prices on welfare of farmer assessed		X	Given different price levels different decision making will be simulated
	(Hansen and Krause 1989)						X	Given different price levels different decision making will be simulated
	(Kingwell et al. 1993)	X	9 season types are represented	X	Climate risk assessed, no assessment of price risks		X	Tactical decisions are adapted in relation to different seasons
	(Sanchez-Zazueta and Martinez-Cordero 2009)			X	Different management options are assessed against background of disease risks		X	Robustness of different optimal decisions under different levels of disease risk assessed through ANOVA
	(Kaya et al. 2000)	X	Could be represented through the production levels of the crops	X	Is not analysed, but could be analysed by assessing consequences of different crop production levels		X	Is assessed through the optimal management decisions
	(Laborte et al. 2009)						X	Given different prices and attitudes of farmers different management options will be predicted
	(Louhichi et al. 2004)			X	Could be assessed through changes in prices		X	Is assessed through changes in market and policy environment for 6 different farm types

Name of model	Reference	Climate variability and change	Risk	Mitigation	Adaptation
MP models continued					
	(Nicholson et al. 1994)		X Could be assessed through changes in prices and production values of livestock		X Depending on prices different management options are optimal, and these can change over time
	(Rossing et al. 1997)		X Risk of disease could be assessed stochastically, not done in this analysis		X Optimal trade offs depend on prices and disease occurrence
	(Ruiz et al. 2000)				X Management options that minimise cost and maximise are assessed
	(Salinas et al. 1999)		X Risk through price changes can be assessed		X Different management options under different market circumstances are optimal
	(Schultheiß et al. 2005)	X Effects on N losses could be assessed			X LP model can be to assess different management options under different price levels of water protection
	(Senthilkumar et al. 2011)	X Can be assessed through rice production values	X Price and production risks could be assessed, not done in the study		X MGLP model used to assess trade offs between N losses, water use and income under different policy scenarios
	(Shively 1998)		X Price risk is explicitly analysed		X Depending on prices different tree crop adoption changes
	(Shively 2000)	X Could be assessed through erosion and maize yield values	X Risk of food shortages assessed under different soil conservation measures, and the interaction between the two		X Under different price levels and farm settings management options will change
	(Val-Arreola et al. 2004)	X Could be assessed through forage production values			X Could be used to assess changes in management if prices and forage production values change

Name of model	Reference	Climate variability and change	Risk	Mitigation	Adaptation
MP models continued					
	(Val-Arreola et al. 2006)	X Could be assessed through forage production values			X Assesses changes in management along the trade off curves
	(Valderrama and Engle 2002)		X Temporal explicit risk analysis performed through price variations		X Can determines optimal management under different market conditions
	(Veysset et al. 2005)		X Could be assessed by price variations		X Under different policy measures optimal management changes
	(Weikard and Hein 2011)	X Could be assessed through grassland productivity	X Could be assessed through grassland productivity and livestock production		X Optimal stocking density will change depending on prices and grassland productivity
OPFROP-FRUPAT	(Cittadini et al. 2008)		X Price related risks could be assesed		X Different prices and production coefficients will lead to different optimal management
FSRM	(Dake et al. 2005)	X Is assessed through random variations in yield levels	X Price and climate related risks are assessed through random variations, and determining the optimal trade of between gross margin and variance in gross margin		X Different prices and production coefficients will lead to different optimal management and trade offs

Name of model	Reference	Climate variability and change	Risk	Mitigation	Adaptation
MP together with simulation models					
	(Mimouni et al. 2000)	X Through daily rainfall and temperature input	X Not in this application, but can be taken into account	X Soil carbon could be assessed, not a focus of this study	X Adaptation to changes in climate could be assessed
APSIM, GRAZPLAN and MIDAS	(Moore et al. 2011)	X Through climate effects on crop production	X Price and climate effects on farm profitability can be assessed	X Soil carbon can be assessed, not in this study	X Through LP optimisation changes in climate and prices will affect decision making
Savanna-MP	(Thornton et al. 2004)	X Through climate effects on grassland production	X El Nino effects are estimated on livestock production and income of farmers	X Soil carbon could be assessed	X Through LP optimisation changes in climate and prices will affect decision making
DSSAT-LP	(Hatch et al. 1999)	X Climate effects on yield are analysed and consequences for optimal crop choice	X Climate – yield risks can be analysed	X Soil carbon could be assessed	X The farm model simulates adaptation to climate-induced changes in yield, by selecting a different mixture of crops that maximises income
	(Herrero et al. 1999)	X Climate effects on yield could be analysed	X Climate – yield risks can be analysed	X Soil carbon effects and methane emissions from cattle could be assessed	X The trade offs for the management strategies can change depending on production levels and prices
	(Kikuhara and Hirooka 2009, Kikuhara et al. 2009)	X Effects on rice yields could be incorporated	X Price and climate risks through rice production risks could be assessed	X Methane emissions of cattle can be assessed	X Profit maximising management will change depending on prices and production levels
	(Dinar et al. 1993, Dinar 1994)	X Climate effects on soil hydrology can be assessed	X Price and climate related risks can be assessed		X Changes in climate and prices will lead to other optimal management decisions

Name of model	Reference		Climate variability and change		Risk	Mitigation		Adaptation
MP together with simulation models continued								
GRAZPLAN-MIDAS	(Donnelly et al. 2002, Thomas et al. 2010)	X	Climate effects on grassland and thereby livestock production can be assessed	X	Risk/uncertainty analyses are performed in relation to prices and climate		X	Changes in climate and prices will lead to other optimal management decisions
	(Jalvingh et al. 1993, Jalvingh et al. 1994)			X	Price risks could be evaluated, not focus of the study		X	Herd management decisions will change under changing market conditions
	(Keil et al. 2009)	X	Climate (rainfall) determines crop yield	X	Risk analyses performed on crop production and agricultural income		X	Changes in climate and prices will lead to other optimal management
	(McCall et al. 1999)			X	Price risks could be assessed, not done in study		X	Changes in market prices will lead to other optimal management
	(Messina et al. 1999)	X	Climate determines crop yield	X	Price and climate related crop production risks are analysed		X	Changes in climate and prices will lead to other optimal management and crop choice
	(Meyer-Aurich et al. 1998)	X	Climate determines crop yield	X	Price and climate related crop production risks could be analysed		X	Changes in climate and prices will lead to other optimal management and crop choice
MODAM	(Meyer-Aurich 2005)	X	Climate determines crop yield	X	Price and climate related crop production risks could be analysed		X	Changes in climate and prices will lead to other trade offs and other optimal management
	(Moghaddam and DePuy 2011)	X	Climate determines hay and other crop yields	X	Through stochastic MP risk related to hay production is assessed		X	Changes in climate and prices will lead to other optimal farm planning and selling and purchase of hay

Name of model	Reference	Climate variability and change		Risk		Mitigation		Adaptation	
MP together with simulation models continued									
	(Moriondo et al. 2010)	X	Climate determines ecological indicators	X	The tool could be used to analyse environmental, production and economic risks related to climate and prices			X	Changes in climate and prices lead to other optimal management in standard and organic farms
	(Ngambeki et al. 1992)	X	Climate determines crop production	X	Climate and price related production risks can be estimated			X	Changes in climate and prices lead to other optimal management
	(Popp et al. 2009)	X	Climate determines grazing land productivity	X	Climate and price risks can be assessed			X	Changes in climate and prices lead to other optimal management
	(Quintero et al. 2009)	X	Climate determines hydrological processes	X	Price risks on farmers' welfare can be assessed, and climate related risks for environmental services related to hydrology			X	Changes in climate and prices lead to other optimal management
DairyNZ	(Ramilan et al. 2011)	X	Climate has effects on N pollution	X	Price related risks for farmers and environmental risks related to climate could be estimated			X	Changes in climate and prices lead to other optimal management
	(Rigby and Young 1996)			X	Risks related to pollution are estimated			X	Changes in market prices lead to changes in optimal management and livestock densities
	(Schönhart et al. 2011)	X	Climate affects crop yields and variables like erosion and N losses	X	Risks caused by climate and prices could be estimated, not done in this study	X	Soil carbon could be analysed	X	Changes in policies, market conditions and climate will lead to changes in optimal management

Name of model	Reference		Climate variability and change		Risk		Mitigation		Adaptation
MP together with simulation models continued									
Opt'INRA-PLANETE	(Veysset et al. 2010)			X	Could be assessed by price variations	X	GHG emissions at farm level are estimated, and linked to different management options	X	Under different policy measures optimal management changes
	(Wise and Cacho 2011)			X	Price related risks could be assessed, not the focus of the study	X	Soil carbon is studied in relation to carbon payment schemes	X	Under different policy measures optimal management changes
IMPACT-HROM	(Zingore et al. 2009, Waithaka et al. 2006)	X	Climate will affect crop production	X	Risks related to prices and climate could be analysed, not in these studies however	X	Soil carbon can be analysed and methane emissions from cattle	X	Changes in prices and climate will lead to shifts in optimal management
SFRAMOD-ACCESS	(Holman et al. 2005)	X	Climate affects crop production, and thereby farm profit, and nitrate leaching	X	Objective to be optimised is weighted sum of farm profit and an indicator of risk. Not explained in paper how the latter is derived.			X	Changes in climate and prices will result in different optimal management
IRMLA	(Roetter et al. 2007)			X	Market related risks could be evaluated			X	Changes in prices will result on different optimal management
ISFARM	(Amir et al. 1991, Amir et al. 1993)	X	Climate affects crop production and water use	X	Climate and market related risks can be analysed; study applies sensitivity analyses to analyse robustness of strategies			X	Changes in climate and prices will result in different optimal management

Name of model	Reference	Climate variability and change		Risk		Mitigation		Adaptation	
MP together with simulation models continued									
FASSET-LP	(Berntsen et al. 2003)	X	Climate affects crop and pasture production, and emissions	X	Production and price related risks can be assessed	X	GHG emissions and relations with management can be assessed	X	Changes in climate and prices will result in different optimal management
MCID-LP	(Borges Jr et al. 2008)	X	Climate (rainfall) affects crop yield	X	Production and price related risks can be assessed			X	Changes in climate and prices will result in different optimal management
GAMS-MINOS	(Carvallo et al. 1998)	X	Climate (rainfall) affects crop yield	X	Production and price related risks can be assessed			X	Changes in climate and prices will result in different optimal management
ROTAT-MILP	(Dogliotti et al. 2005)			X	Price related risks could be assessed	X	Analyses organic matter losses over time	X	Changes in prices and crop production levels will result in different optimal management
AquaCrop-LP	(García-Vila and Fereres 2011)	X	Climate (rainfall) affects crop yield	X	Climate and market related risks can be analysed; model applies different climate and market conditions to analyse optimal strategies			X	Changes in climate and prices result in different optimal management
FARM-ADAPT	(Gibbons et al. 2006)			X	Market related risks could be assessed	X	Analyses GHG emissions under different management strategies	X	Changes in prices and grassland production values will result in different optimal management
MoFEDS	(Greiner 1997)	X	Climate affects erosion and crop yields	X	Drought, market and salinity risks can be assessed			X	Changes in climate and prices lead to different optimal management

Name of model	Reference	Climate variability and change	Risk	Mitigation	Adaptation
MP together with simulation models continued					
SAPWAT-LP	(Grove and Oosthuizen 2010)	X Climate determines variability in crop yields	X Drought risk on a farm is assessed versus a risk aversion factor which can differ between farmers		X Changes in climate, prices and risk aversion lead to different optimal management

Name of model	Reference	Climate variability and change	Risk	Mitigation	Adaptation
(dynamic) Simulation models					
	(Müller et al. 2007)	X Yearly rainfall			X Could be implemented through what-if scenarios for the management rules
SCUAF	(Tamubula and Sinden 2000)	X Through yearly inputs	X Could be used to analyse risks related to drought on annual basis	X Soil carbon can be assessed	X Could be implemented through what-if scenarios for the management rules
EU-Rotate_N	(Nendel 2009)	X Climate affects N leaching			X Could be implemented through what-if scenarios for the management rules
Lypsikki	(Nousiainen et al. 2011)			X Nutrient balances are estimated	X Could be implemented through what-if scenarios for the management rules
	(Sulistyawati et al. 2005)		X Risks related to population growth and market could be analysed		X Implemented through what-if scenarios for the management rules

Name of model	Reference	Climate variability and change	Risk	Mitigation	Adaptation
(dynamic) Simulation models continued					
Savanna-PHEWS	(Thornton et al. 2003, Boone et al. 2006)	X Climate affects grassland productivity and thereby livestock	X Risk related to climate – grassland productivity on farmers' welfare could be assessed, but is not the focus of the study	X Soil carbon inputs and mineralisation can be analysed	X Implemented through what-if scenarios for the management rules
	(Tichit et al. 2004)	X Livestock productivity is affected by rainfall	X Could be assessed with random mortality rates, wealth indicator is followed over time		X Could be implemented through what-if scenarios for the management rules
Nuances-FARMSIM	(Tittonell et al. 2009, van Wijk et al. 2009a, Giller et al. 2011, Rufino et al. 2011)	X Climate affects crop and fodder production	X Climate related system productivity risks could be assessed through seasonal variations	X Soil carbon, manure emissions, and potentially methane emissions by livestock could be assessed	X Could be implemented through what-if scenarios for the management rules
GAMEDE	(Vayssières et al. 2009)	X Climate affects fodder production and thereby dairy production	X Climate related farm production risks can be assessed	X N emissions are simulated, soil carbon, manure emissions, and potentially methane emissions by livestock could be assessed	X Could be implemented through what-if scenarios for the management rules
NODRIZA	(Villalba et al. 2010)		X Price related risks could potentially be assessed	X Potentially methane emissions from cattle could be assessed	X Could be implemented through what-if scenarios for the management rules

Name of model	Reference		Climate variability and change		Risk		Mitigation		Adaptation
(dynamic) Simulation models continued									
	(Pardo et al. 2010)	X	Climate (rainfall) affects 'trafficable' days for weed management	X	Price related risks could be assessed			X	Could be implemented through what-if scenarios for the management rules
SALSA	(Eriksson et al. 2005)					X	Life cycle analyses. Model focus is on GHG emissions	X	Could be implemented through what-if scenarios for the management rules
	(Hahn et al. 2005)	X	Climate (rainfall) affects grassland productivity, and thereby goat production	X	Climate related risks could be assessed on a yearly basis			X	Could be implemented through what-if scenarios for the management rules
	(Hansen et al. 1997)	X	Stochastic climate affects crop production	X	Risk of failure in economic terms (insolvency or inability to cover fixed costs and the household expenditure)	X	Soil carbon could be assessed	X	Could be implemented through what-if scenarios for the management rules
	(Hansen et al. 2009)	X	Stochastic climate affects crop production	X	Climate related risk in farm profit and food production is assessed in stochastic terms	X	Soil carbon could be assessed	X	Could be implemented through what-if scenarios for the management rules
DAFOSYM	(Harrigan et al. 1996)	X	Climate affects crop production	X	Climate and price related risks for system productivity and profitability could be assessed, not in this study	X	Soil and livestock emissions could be assessed with minor adaptations	X	Could be implemented through what-if scenarios for the management rules

Name of model	Reference	Climate variability and change		Risk		Mitigation		Adaptation	
(dynamic) Simulation models continued									
COTFLEX	(Helms et al. 1990)	X	Stochastically included through effects on cotton production and income	X	Climate, pest and price risks are evaluated to advice farmers to take crop insurance yes or no.			X	Chance of occurrence of extreme events could be changed due to climate change, and effects on production and income can be evaluated
NUTMON	(Hengsdijk et al. 2005)	X	Climate affects crop production, hydrology and erosion, and thereby farm level nutrient budgets	X	Risk on negative nutrient balances could be assessed through climate analyses. Not the focus of this study	X	Through transfer functions losses in organic matter and nutrients could be used to estimate parts of GHG emissions	X	Could be implemented through what-if scenarios for the rules of transfers of nutrients and organic matter
DYNAMOF	(Howden et al. 1996)	X	Climate affects methane and nitrous oxide emissions, and grass production	X	Climate related risks for productivity and increased GHG emissions could be assessed	X	Through analyses of management effects on methane and nitrous oxide emissions this can be assessed	X	Could be implemented through what-if scenarios for the management rules
FASSET	(Hutchings et al. 2007)	X	Climate affects crop and pasture production, and emissions	X	Production related risks can be assessed, not in this study	X	Focus is on GHG emissions and relations with management	X	Could be implemented through what-if scenarios for the management rules
@RISK	(Jackson et al. 2011)	X	Through effects on hydrology					X	Could be implemented through what-if scenarios for the management rules
	(Jogo and Hassan 2010)	X	Climate affects hydrology and crop production	X	Climate and price related risks could be estimated; not focus of study			X	Could be implemented through what-if scenarios for the management rules

Name of model	Reference	Climate variability and change	Risk	Mitigation	Adaptation
(dynamic) Simulation models continued					
DairyMod, SGS and EcoMod	(Johnson et al. 2008)	X Climate affects hydrology and pasture production	X Climate related risks could be assessed for grass and livestock production. Not focus of this study	X Emission calculations performed and linked to management options	X Could be implemented through what-if scenarios for the management rules
SEBIEN	(Jouven and Baumont 2008)	X Climate affects pasture production	X Climate related risks could be assessed through pasture production		X Could be implemented through what-if scenarios for the management rules
ADIEM	(Kulshreshtha and Klein 1989)	X Climate affects crop – hydrology	X Climate related risks through hydrology could be assessed		X Could be implemented through what-if scenarios for the management rules
FDMS	(Andrieu et al. 2007b, Andrieu et al. 2007a)	X Climate affects grass productivity and thereby livestock productivity	X Climate related risks could be assessed		X Could be implemented through what-if scenarios for the management rules
	(Bell et al. 2010)	X Climate affects grassland productivity	X Climate related risks on productivity could be assessed through yearly values and drought indices		X Could be implemented through what-if scenarios for the management rules
WFM	(Beukes et al. 2005, Beukes et al. 2008, Beukes et al. 2010)	X Climate affects pasture productivity	X Climate and price related risks could be evaluated		X Could be implemented through what-if scenarios for the management rules
	(Bontkes and Van Keulen 2003)	X Climate affects water availability and crop growth on a seasonal basis	X Climate and price related risks could be evaluated		X Could be implemented through what-if scenarios for the management rules

Name of model	Reference	Climate variability and change		Risk		Mitigation		Adaptation	
(dynamic) Simulation models continued									
	(Brennan et al. 2008)	X	Climate affects hydrology and crop production	X	Climate and price related risks could be assessed			X	Could be implemented through what-if scenarios for the management rules
	(Cabrera et al. 2005)	X	Could be studied indirectly by changing the crop production values	X	Price and population density related risks could be assessed			X	Could be implemented through what-if scenarios for the management rules
UDDER	(Chapman et al. 2008a, Chapman et al. 2008b, Chapman et al. 2011)	X	Climate affects pasture productivity	X	Climate and price related risks could be evaluated			X	Could be implemented through what-if scenarios for the management rules
	(Clark et al. 2010)	X	Extreme climate events are analysed	X	Sources of risk analysed include input and output prices, random-kill events, and hurricane damages on shrimp production and profitability			X	Could be implemented through what-if scenarios for the management rules
SEPATOU	(Cros et al. 2001, Cros et al. 2003)	X	Climate (rainfall) affects grassland productivity	X	Climate related risks could be assessed			X	Could be implemented through what-if scenarios for the management rules
GrazeIn	(Delagarde et al. 2011a, Delagarde et al. 2011b, Faverdin et al. 2011)	X	Climate affects pasture productivity	X	Climate related risks could be evaluated			X	Could be implemented through what-if scenarios for the management rules
	(Dueri et al. 2007)	X	Climate affects crop production	X	Climate related risks could be evaluated	X	Soil carbon and N losses could be assessed	X	Could be implemented through what-if scenarios for the management rules

Name of model	Reference		Climate variability and change		Risk		Mitigation		Adaptation
(dynamic) Simulation models continued									
CEEOT-LP	(Gassman et al. 2006)	X	Climate affects crop production and grassland production	X	Climate related risks and market risks could be evaluated	X	Soil carbon and N losses could be assessed	X	Could be implemented through what-if scenarios for the management rules
	(Luckert et al. 2000)	X	Climate shocks are implemented through effects on crop production	X	Climate and market related risks for production and household welfare could be assessed			X	Could be implemented through what-if scenarios for the management rules
SEDIVER	(Martin et al. 2011)	X	Climate has effects on grassland production	X	Climate related risks for productivity could be assessed			X	Could be implemented through what-if scenarios for the management rules
	(Parsons et al. 2011)	X	Climate has effects on crop and grassland production	X	Climate and price related risk could be assessed	X	Soil carbon and methane emissions by cattle could be assessed through transfer functions	X	Could be implemented through what-if scenarios for the management rules
	(Pfister et al. 2005)	X	Climate has effects on crop production	X	Climate and price related risk could be assessed			X	Could be implemented through what-if scenarios for the management rules
APS-FARM	(Rodriguez et al. 2011a, Power et al. 2011)	X	Climate has effects on crop production	X	Climate and price related risk can be assessed	X	Soil carbon changes could be assessed	X	Could be implemented through what-if scenarios for the management rules
IFSM	(Rotz et al. 2005, Rotz et al. 2007, Rotz et al. 2011)	X	Climate has effects on crop and grassland production	X	Climate and price related risk can be assessed	X	GHG emissions are assessed in 2011	X	Could be implemented through what-if scenarios for the management rules

Name of model	Reference		Climate variability and change		Risk		Mitigation		Adaptation
(dynamic) Simulation models continued									
	(Savoie et al. 1985)			X	Indirect climate risks (based on a 25 year annual production dataset) is assessed; price risks could be assessed			X	Could be implemented through what-if scenarios for the management rules
	(Shepherd and Soule 1998)	X	Climate affects production	X	Climate and market related risks could be assessed on yearly basis	X	Soil carbon could be assessed	X	Could be assessed through what-if scenarios for the decision rules
	(Tittonell et al. 2007)	X	Climate affects crop production	X	Climate related risks could be assessed	X	Soil carbon could be assessed	X	Could be assessed through what-if scenarios for the decision rules or optimisation will results in different trade off curves with changing prices and climate
TOA	(Claessens et al. 2010, Stoorvogel et al. 2004)	X	Climate effects on yield can be analysed and impacts on socio-economic and environmental indicators can be assessed.	X	Price and climate related risks can be assessed (production risk, environmental risk)	X	Soil carbon can be assessed, no part of study	X	Trade offs and management options within those will change depending on climate and prices and farm configuration. Other options can be analyzed through sensitivity analysis
FLIPSIM	(Anderson et al. 1993)			X	Price and climate related risks could be assessed by changing production values and market prices			X	Could be assessed by changing farm setup
CSWM	(Balderama 2009, Balderama 2010)	X	Climate affects crop production	X	Climate related risks are assessed			X	Could be assessed through what-if scenarios for the decision rules

Name of model	Reference	Climate variability and change	Risk	Mitigation	Adaptation
(dynamic) Simulation models continued					
BANAD	(Blazy et al. 2010)	X Climate (rainfall) affects banana production	X Price and climate related production and economic risks could be analysed		X Could be assessed through what-if scenarios for the decision rules
Simsdairy	(Del Prado et al. 2011)	X Climate affects crop and pasture production, and emissions	X Price and climate related risks can be evaluated; droughts are expressed as a monthly index	X Integrated GHG emission analyses are performed	X Could be assessed through what-if scenarios for the decision rules
CIS-APSIM	(Brown et al. 2010)	X Climate (rainfall) affects crop production	X Price and climate related risks can be evaluated		X Changes in prices and climate will change the optimal solutions found by simulated annealing

Name of model	Reference	Climate variability and change	Risk	Mitigation	Adaptation
Agent based models					
	(Valbuena et al. 2010)				X Agent behaviour can change depending on conditions; could also be assessed through what-if scenarios for the decision rules
SimSahel	(Saqalli et al. 2010, Saqalli et al. 2011)				X Agent behaviour can change depending on conditions; could also be assessed through what-if scenarios for the decision rules
	(Naivinit et al. 2010)				X Agent behaviour can change depending on conditions; could also be assessed through what-if scenarios for the decision rules

Name of model	Reference	Climate variability and change	Risk	Mitigation	Adaptation
Agent based models continued					
SAMBA-GIS	(Castella et al. 2005)				X Agent behavior can change depending on conditions; could also be assessed through what-if scenarios for the decision rules
SAMBA	(Castella et al. 2005, Bousquet et al. 2007, Boissau et al. 2004)				X Agent behavior can change depending on conditions; could also be assessed through what-if scenarios for the decision rules
	(Schlüter et al. 2009)		X Market related risks could be assessed		X Agent behavior can change depending on conditions; could also be assessed through what-if scenarios for the decision rules
AgriPolis	(Happe et al. 2011)		X Market related risks could be assessed		X Agent behavior can change depending on conditions; could also be assessed through what-if scenarios for the decision rules
	(Heckbert 2011)		X Market related risks could be assessed		X Agent behavior can change depending on conditions; could also be assessed through what-if scenarios for the decision rules
PUMANI	(Hervé et al. 2002)	X Through crop production modifier	X Climate related risks could be assessed		X Agent behavior can change depending on conditions; could also be assessed through what-if scenarios for the decision rules
	(Holtz and Pahl-Wostl 2011)	X Through effects on crop production	X Climate and market risks could be assessed		X Agent behavior can change depending on conditions; could also be assessed through what-if scenarios for the decision rules

Name of model	Reference	Climate variability and change		Risk		Mitigation		Adaptation	
Agent based models continued									
PALM	(Matthews and Pilbeam 2005b)	X	Affects crop production	X	Climate and market related risks can be assessed	X	Soil carbon could be assessed	X	Agent behaviour can change depending on conditions; could also be assessed through what-if scenarios for the decision rules
	(Shively and Coxhead 2004)	X	Rainfall affects erosion, which affects the soil 'stock' and this one affects crop production	X	Erosion risk can be assessed			X	In agent behaviour optimisation changes in prices and climate will lead to other optimal behaviour
HELIS	(Manson and Evans 2007)							X	Agent's decision to change land use is stochastic
MPMAS	(Schreinemachers and Berger 2006, Schreinemachers et al. 2007, Schreinemachers and Berger 2011, Berger and Schreinemachers 2006)	X	Climate has effects on crop production	X	Climate and market related risks can be assessed	X	Depending on the submodules included in the framework different GHG indicators can calculated	X	In agent behaviour optimisation changes in prices and climate will lead to other optimal behaviour