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Farm household models to analyse food security in a changing climate: A review

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ABSTRACT

We systematically reviewed the literature on farm household models, with emphasis on those focused on smallholder systems. The models were evaluated on their predictive ability to describe short term (3–10 years) food security of smallholder farm households under climate variability and under different scenarios of climate change. The review of 126, mainly production-oriented, farm household models, showed that integrated analyses of food security at the farm household level are scarce. Some models deal with elements of food security, but the models covered in this review are weak on decision-making theory and risk analyses. These aspects need urgent attention for dealing with more complex adaptation and mitigation questions, in the face of climatic change. Approaches that make use of decision making theory and combine the strengths of (dynamic) mathematical programming and expert systems decision models seem promising in this respect. They could support the robust evaluation of climate change impacts and adaptive management options on smallholder systems.

1. Introduction

Demand for food, fibre, and biofuel drives land use change throughout the world (Foley et al. 2011; DeFries and Rosenzweig, 2010). In the coming decades climate change is likely to have significant impacts on livelihoods and food systems (IPCC, 2007). Some of these impacts are going to be large in smallholder systems in the developing world, due to their low capacity to adapt (Thornton et al., 2002). Increasing the food security of these farmers in a sustainable way requires an understanding of the agricultural systems are affected by social and economic drivers. To better understand how socio-economic and environmental conditions can change in the future, a substantial body of work has gone into the development of global and regional scenarios (e.g., IPCC, 2007; Vervoort et al. 2014). These studies provide information on the vulnerability of certain regions (Ericksen et al., 2011), changes in prices and production of key staples, and land use (see for example Nelson et al., 2009, Vervoort et al. 2013). There is an increasing need to assess the impacts of these changes on the functioning of farm households, and especially on their food security, and to identify suites of adaptation options (Herrero et al. 2014).

Household models have been one of the workhorses of the agricultural community for ex-ante analysis and priority setting of technological interventions (crop, livestock, land management) and for examining trade-offs in the use of natural resources (Thornton and Herrero 2001). Existing farm household models can handle temporal variability (through simulation), farming systems differentiation (through adjustments to resource and production mixes) and the representation of interactions at farm household level (through linking different components of the farm household) (e.g. Dixon et al., 2001). A range of different techniques and approaches to simulate farm households is available but models from different disciplines (e.g. economics, agronomy) tend to have a different representation of core concepts, data types and state variables in space and time (Ewert et al., 2011; Laniak et al., 2013). Several reviews have been written on the quantitative tools used to analyse and predict the behaviour of farm systems (Janssen and van Ittersum, 2007; Le Gal et al., 2011; McCown et al., 2009; Thornton and Herrero, 2001; An, 2012; Rossing et al., 2007), showing that rapid developments take place in the different ways of modelling farm level decision-making (An, 2012), in

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bio-economic modelling (Janssen and van Ittersum, 2007) and in modelling exercises aiming at farm design (Le Gal et al., 2011). However, none of these reviews focused specifically on the representation of food security as a key indicator of farm household performance, on how to analyse important components of food security (e.g. production, economic performance and food availability) and how these components are affected by household decision making and farm management in a world undergoing climate change. In this review we assess the current state of production oriented farm and household level models with a focus on their capability to address food security in a changing climate, and identify key features and constraints and sensible future developments.

2. Methods

2.1. Models included and the definition of 'food security' used in this review.

We systematically reviewed publications between 1970 and 2014 on farm household models, with a special focus on smallholder systems. The models were evaluated on their predictive ability to describe short term (3–10 years) food security of farm households under climate variability and under different scenarios of climate change. Because of this last aspect, empirical studies that used econometric or statistical models were excluded. 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). 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 activities (Rudie, 1995). The household level also includes off-farm activities that can bring in food and cash.

The food security definition used in this review was the one developed at the World Food Summit, 1996, which states that 'food security exists when all people, at all times, have physical and economic access to sufficient safe and nutritious food that meets their dietary needs and food preferences for an active and healthy life (FAO, 1996). There are 4 aspects to this definition: the physical availability of food, the economic and physical access to food, food utilisation and the stability of these three dimensions over time. As the focus of this study was especially on bio-physical production oriented models, detailed nutrition aspects, i.e. food utilisation were not included in this review beyond the typical representation using energy and protein balances.

2.2. Characterising models according to their model attributes

A set of key attributes (see Table 1) was defined to characterise the application possibilities of the models of interest for food security and its different aspects. Profit and food self-sufficiency deal with how models represent the access side of food security, climate variability and risk deal with how models represent and analyse the stability of food security, while climate change and adaptation deal with the ability of farm household to deal with change and how it affects the farm household decision making within the model.

Table 1
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
Gross 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.
Food self-sufficiency	Ratio between energy (or protein)in on-farm produce and energy needed to meet WHO energy (or protein) requirements
Climate variability	Between and within year variations in climate and weather
Climate change	Longer term changes in CO_2, temperature, precipitation and cloud cover
Risk	Probability of the occurrence of a hazard, in this study the occurrence of a failure of achieving food self-sufficiency, food security or economic welfare
Adaptation	Changes in farm management to deal better with climate variability and possible change

2.3. Organising the literature through a systematic review

The literature review was carried out using the search engine of SCOPUS (http://www.scopus.com/home.url), which covers the greatest 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 A1 in the Supplementary Material). This search resulted in approximately 16,000 articles. The articles corresponding to each combination of target and domain terms went through an initial scanning to select those publications dealing specifically with model development or application. About 2500 papers were selected in this step. We then focused on studies that explicitly included the farm or farm-household level, and excluded those focusing on farm component levels (e.g. crop, livestock, soils) or landscape, regional or global levels without explicitly taking into account interactions at farm or household level. As a result, 480 papers were selected in which 126 models were evaluated in detail.

The models were then classified into three major categories: dynamic simulation, mathematical programming (MP), and multi-agent modelling. This is a simple categorisation, and many models actually use combinations of these techniques. We grouped the models according to the most important technique listed in the model description, and only created a separate class called 'MP models together with simulation models' because of the relative large number of publications using this combination.

3. Results

3.1. Overview of the systematic review

The number of publications per year, in which farm household level models are used, has increased substantially over time (Fig. 1A). The number of peer reviewed publications presenting new models has increased as well, but more slowly. This shows that in recent years relatively more studies are applications of existing models rather than newly developed models. The number of publications in which combinations of modelling techniques are used is increasing substantially over time (Fig. 1A). The ratio of publications presenting new models over the total number of publications does not differ substantially between the different techniques (Fig. 1B). Over time there is a trend that relatively more

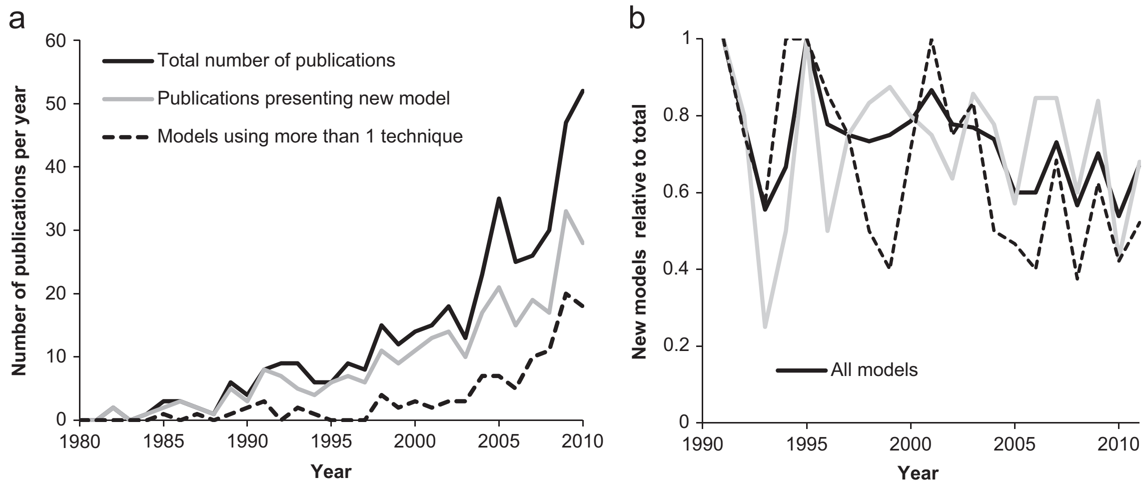

Fig. 1. Time trend of number of published model studies per year at farm level (a) and of the ratio of publications presenting new models over total number of farm level publications over time (b).

studies present model applications, although large variability is visible from year to year. Some care in interpreting the results is needed because of the relatively low number of publications and the inherently slow process of scientific publication. In particular the results of the years before 2000 should be interpreted with care because the numbers of publications per year are small and individual studies have large effects on the results of Fig. 1B.

The full list of attributes of the 126 models is presented in Tables A2–A4 in the supporting material. Here we present the main findings with regard to the analysis of the different attributes, with a particular focus on food security.

3.2. Attributes of the MP models

The 24 MP models analysed included static linear programming models and five dynamic or recursive MP models (Cittadini et al., 2008; Shively, 2000; Louhichi et al., 2004; Nicholson et al., 1994; Hansen and Krause, 1989). Five models are used to perform multiple goal or multiple criteria analyses (Rossing et al., 1997; Senthilkumar et al., 2011; Val-Arreola et al., 2006; Dake et al., 2005). Two studies took market and/or climate risk explicitly into account: one by analysing the trade-off between average gross margin and variations in gross margin driven by environmental fluctuations (Dake et al., 2005) and the other study analysed the consequences of climate variability (represented by nine explicit 'season' types) on optimal management (Kingwell et al., 1993). In all models decision making is based on optimisation and optimal management is described with production coefficients and market prices.

3.3. Attributes of the MP models that are combined with simulation models

In the 36 combined MP –simulation models a wide range of modelling approaches was used for the simulation models. The MP techniques included (Multiple Goal) Linear Programming, dynamic or recursive LP (Popp et al., 2009), non-linear optimisation (García-Vila and Fereres, 2012; Grove and Oosthuizen, 2010), mixed integer optimisation (Dogliotti et al., 2005; Gibbons et al., 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 included in one model, IMPACT-HROM (Zingore et al., 2009; Herrero et al. 2007; Waithaka et al., 2006, Herrero and Fawcett 2002), and food self-sufficiency by two (Waithaka et al., 2006; Thornton et al., 2004). Most 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 rare. Grove and Oosthuizen (2010) analysed drought risk on a farm by assessing gross margin as a function of a risk aversion factor, which differed between farmers. Holman et al. (2005) optimised the weighted value of gross margin and a production risk indicator. Several studies analyse the consequences of different market and/or climate conditions for management and system behaviour (García-Vila and Fereres, 2012; 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), and others apply sensitivity analyses to assess the robustness of the optimised strategies (Amir et al., 1991; 1993).

3.4. 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: GAMEDE (Vayssières et al., 2009), APS-FARM (Rodriguez et al., 2011), 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., 2009) and the model of Luckert et al. (2000) use seasonal or annual time-steps. 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. 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., 2011). 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 within the given 'what-if' decision-making options of the analyses.

Model with a distinct approach are the Tradeoff Analysis Model (TOA), a spatially explicit integrated assessment model that links site-specific bio-physical process models and econometric process models to assess tradeoffs between economic, environmental and social outcomes (Antle and Capalbo, 2001; Stoorvogel et al., 2004), the Tradeoff Analysis for Multi-Dimensional Impact Assessment (TOA-MD), a model based on advanced statistical methods to simulate economic, environmental and social impacts of agricultural systems of populations of heterogeneous households (Antle and Valdivia, 2006; Antle, 2011; Antle, Stoorvogel and Valdivia, 2014), and the FarmDESIGN model (Groot et al., 2012) which uses genetic algorithms to generate trade off curves between production and environmental objectives (see also DeVoil et al., 2006; Tittonell et al., 2007). Most dynamic farm models include climate variables such as air temperature and rainfall. Detailed climatic risk analyses at household level were performed using 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 per cent 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 (Tittonell et al., 2007; Sulistyawati et al., 2005; Thornton et al., 2003) 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). Models that were used to analyse household food self-sufficiency and/or food security were Savanna-PHEWS, NUANCES, and the models of Cabrera et al. (2005), Pfister et al. (2005),Bontkes and Van Keulen (2003), Luckert et al. (2000), and Shepherd and Soule (1998). Aspects of food security was assessed only with the models of Bontkes and Van Keulen (2003) and Shepherd and Soule (1998), although neither of them included food storages in their estimations nor assessed stability of food supply.

3.5. Attributes of the agent-based models

The 14 agent-based models analysed in this study 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, 2005), 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 et al., 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, 2005). 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.

4. Discussion

Food security is a key indicator for the functioning and sustainability of smallholder farming systems across the world (e.g., Thornton and Herrero, 2001). Surprisingly, it has received relatively little attention in the models reviewed in this study. This review focused on three of the four elements of food security, i.e. food availability, food access and stability. Food available in first instance seems to be the easiest element to quantify with production oriented models. This certainly holds for the production of major crops (e.g. maize, millet, sorghum, rice, many legumes, etc.) (e.g. Rodriguez et al., 2011), but minor crops, which can play an important role in the diet and cash provision of smallholders (e.g., vegetables), are much more difficult to simulate with the existing models. Also the decision making around food storage from one season to another season is difficult to generalise and incorporate in a model, although this could be analysed through scenarios of different risk avoidance strategies (e.g. Waithaka et al., 2006). Other items affecting the amount of food available like wild food collection and sharing are difficult to quantify, as they are highly variable from season to season and from year to year, but in many smallholder systems can play an important role (Woittiez et al., 2014). A pragmatic approach to deal with all this uncertainty could be to define a variable that quantifies the socially mediated access to food, i.e. food sharing, collection and aid, simply as the gap between food requirements and availability through production, purchase and storage. The simulated dynamic output of this variable could be used as an indicator to evaluate the consequences of climate change and potential intervention measures and adaptation options, and allow the model to perform a risk analysis of food insecurity. Certainly multi-agent models offer the flexibility to study food exchanges among community members.

To assess the different aspects of food security we defined 6 attributes (Table 1). They represent simple indicators that can be calculated by the different models. No models exist that calculate all 6 attributes (see Table 1 in the supporting information), and probably in terms of data needs and model complexity it is also not a wise approach to develop such comprehensive models. Several of the 6 attributes could be refined if more detail information in the study sites of interest is available. An example is the economic performance indicator which is now gross return. The financial returns above a reference value, e.g. a minimum family income as set by various governments, will do more justice to food access than gross profit by itself, and could be implemented easily.

Despite the fact that climate variability is an important driver in many models, climate related risks for food self-sufficiency and food security at household level are not yet well described. There are now quite a number studies focusing on climate related risk analyses of crop production (Akponikpè et al., 2010; Traore et al., 2014; Rurinda et al., 2014), and some of these calculate the consequences for household level food self-sufficiency expressed in energy. However, full household level risk analyses of food self-sufficiency that take into account livestock products are missing. There is a long history in risk related research in household modelling, although with a focus on economic indicators, which could be used to improve the current analyses of food security and its variability. The earliest risk models used the safety-first principle, and minimised the probability that income could fall below a minimum income needed for the economic survival of the farm (Roy, 1952). A variation of the safety-first concept is the Minimisation of Total Absolute Deviation (MOTAD) indicator introduced by Hazell (1971). The MOTAD indicator consists of the dual criteria of maximising net return and minimising the variance of net return. In several MP models MOTAD is now used as the objective function and the safety-first criterion (e.g. a minimum level of income that should be attained by the household) is used as a constraint (e.g. Umoh, 2008). These analyses typically focus on short-term risk estimations.

These short-term risk analyses in general do not take into account the economic buffer capacity of a household, to use cash availability, assets or credits facilities, to deal with short term shocks in food production and achieve food security by buying food. Also the models analysed in this review typically focus on short term economic performance indicators like gross margin. To address questions related to the cumulative effects of continuous climate change on the performance of farming systems and the food security of farm households, there is a need to quantify better longer term economic performance indicators, for example cash availability over time (Hansen et al., 1997; Bell et al., 2010). The definition of economic performance indicators is also essential for the modelling of decision-making.

There are three important weak points in the current models of decision-making which affects their reliability when analysing food security in the face of climate change. First, the temporal dimension: models tend to have one time horizon for the formulation of the rules or the objective function determining the decision making (e.g. Schreinemachers and Berger, 2011). They either focus on short term decision making (rules of objectives for one season or year) or on longer term decision making (rules or objectives for 10 or 20 years), whereas in reality a mixture of these determines the outcome of the decision making process. However, this is changing due to the dynamic implementation of some models (Herrero et al., 2014). Second, models analysed in this review 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 important strategies of adaptation to climate change and is essential for assessing food security. A third problem is that the investment costs of the options to be implemented are difficult to take into account, for example when technical infrastructure is a pre-requisite for a new practice. Such investment decisions, for example through access to credit facilities, are difficult to quantify with any degree of certainty.

In the models analysed in this survey MP is the only technique that can analyse the many options available to the model 'farmer' to make a decision (Janssen and van Ittersum, 2007), and can quantify the optimal solution (e.g., Anderson et al., 1977). New genetic search algorithms are now being used in static farm models like FarmDESIGN (e.g. Groot et al., 2012), but these are still more constrained in the number of options they can evaluate robustly than MP. MP models are most useful when a specific objective function and explicit constraints can be specified. The surveyed MP models of this study 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?"). This limitation applies to both single as well as to multiple objective optimisation problems of the models analysed here. Production oriented models could incorporate methods like Positive Mathematical Programming, in which constraints and weighting parameters in used in MP models are calibrated based on observed data (e.g. Howitt, 1995), Multi Criteria Decision Making techniques (e.g., Romero and Rehman, 2003) allowing different weighting of the individual criteria in goal programming models to perform trade off analyses (Klapwijk et al. 2014), and elements of decision theory, for example the portfolio theory and integration of production and consumption objectives in the utility function (e.g. Singh et al., 1986) or aspects of the prospect theory in which risk and returns are combined (Kahneman and Tversky, 1979).

Several models use MP to study continuous adaptation over time. In MPMAS the settings of the constraints and potentially the values of the objective or utility functions can change over time (Schreinemachers and Berger, 2011). In such a setup the optimal management options that the MP model identifies will change over time, and these outputs could be used to study continuous adaptation to changing conditions. Dynamic MP is also used for this type of analysis (e.g. Cittadini et al., 2008). Another approach are the decision models, also called 'expert systems', that have been developed to simulate decision making of farmers through a set of 'if … then …' rules, and then use biophysical models to assess the consequences of the simulated decisions (e.g. Merot and Bergez, 2010). When dealing with a limited number of options this approach seems powerful, and can link up easily to information given by farmers on their decision making. It would be interesting to combine (dynamic) MP and expert system techniques to make use of the strength of both approaches: for example similar to the MPMAS model where parameters and constraints of the internal MP model of the agents can change over time because of interactions between agents, a similar approach through decision models at farm household level could add flexibility and more realism to optimisation based approaches. By embedding the weights given to different objectives and to different constraints in a rule based decision model the flexibility of dynamic MP models to show different responses under different conditions and over time could be enhanced, while the decision models will be easier to communicate and test with farmers than traditional parameter based approaches.

Past reviews (e.g., An, 2012; Le Gal et al., 2011; McCown et al., 2009; Janssen and van Ittersum, 2007; Rossing et al., 2007; Thornton and Herrero, 2001), showed that rapid developments take place in the different ways of modelling farm households, but another recent review (Robertson et al., 2012) showed that efforts are scattered: many new models are being developed to analyse specific systems, and generalisability of these tools is an issue. Furthermore, while being developed for specific systems, the main focus of the model studies is often scientific ('to increase our understanding') rather than to inform policy making, extension or farmers. To ease this tension between the site-specificness of the analyses and the aim of generic scientific advance, Robertson et al. (2012) defined 6 key criteria for future model based publications in scientific literature. Of those the criteria that a new insight beyond the system of study should be created and that validation of model behaviour should take place are most relevant for this study. A key development that needs to take place in farm household modelling is that models are applied in contrasting systems to generate generic understanding of the functioning of farm household and are rigorously tested in each of those systems to create trust in the reliability of the simulated responses. In crop growth modelling rapid developments take place to increase the larger scale applicability of a wide set of crop growth models (see the AgMIP project, e.g., Asseng et al. (2013)), and similar work needs to be done for farm household models. So while further developing the individual components of farm household models (e.g. decision making, calculation of key elements of food security, risk analyses, etc.), the farm household modelling community should avoid the trap of developing complicated models for site-specific analyses that difficult to apply to other sites because of data demands (see also Antle et al., 2014).

This review did not focus on a detailed analysis of nutrition models. At the moment these models are not integrated yet with existing farm household models, which typically only focus on energy and protein as key indicators of food availability for the household members. It is clear that this is an important research area to explore, and including more detailed nutritional analysis in the current household level analyses can make the outputs generated by the farm household models more relevant to developmental organisations. Although analyses of food supply and food security are relevant for a range of stakeholders, from scientists to policy makers to farmers, most models analysed in this review are primary research tools, and the methods for assessing the consequences of system interventions are very much researcher driven (see also Robertson et al. (2012) and Klapwijk et al. (2014) for a detailed discussion). New developments in participatory approaches are being developed, to make models more useful in the policy arena and for advice at farm household level. For example Sterk et al. (2011); 209 developed a framework for participatory modelling. Another approach is the development of participatory scenarios (e.g. Herrero et al., 2014; Rosenzweig et al., 2013; Claessens et al., 2012). The models reviewed in this study can typically be used for 'discussion support' rather than decision support (see for example Sterk et al., 2011; 2009; McCown, 2002). The power of models is to say something about "what if we did this" and get farmers and other stakeholders to start talking about the constraints determining food security, productivity and economic returns.

5. Conclusion

From a food security perspective the requirements of farm household models to be useful in designing climate-resilient agricultural systems are clear: models should be able to analyse adaptive decision making and risk profiles in a model framework that is flexible, integral, stochastic, dynamic, and simple enough to be applied across contrasting sites. Terms like 'flexible', 'integral' and 'simple' are relative terms however, and will depend strongly on the research question at hand and the preferences of the researcher. This said, the study does show that models included in the review do not perform integral analyses of climate change effects on the food security of farm households yet (especially the food access and stability parts of food security are missing), and the review showed that the production oriented models should incorporate more knowledge from other research fields, especially socio-economics and nutrition. The way forward for integral dynamic analyses lies in the systematic development of building blocks for the different aspects of food security, and combining these building blocks in a framework that quantifies the uncertainty of predictions, while keeping model complexity low. The data needed for parameterizing and 'ground-truthing' of the building blocks are sometimes lacking, and can constrain their application. Modelling of farm level decision making continues to be a challenge, but approaches that make use of decision theory and combine the strengths of techniques like (dynamic) mathematical programming and expert system decision models seem promising in this respect and can result in robust evaluations of climate change effects and adaptive management options.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at http://dx.doi.org/10.1016/j.gfs.2014.05.001.

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