Towards a New Generation of Agricultural System Models, Data, and Knowledge Products

January 31, 2015

Model Design, Improvement and Implementation
Each paper of the series ‘Towards a New Generation of Agricultural System Models, Data, and Knowledge Products’, is to be cited individually as follows.


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7 University of Chicago
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Towards a New Generation of Agricultural System Models, Data, and Knowledge Products: Model Design, Improvement and Implementation


Outline

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Executive Summary

This paper presents ideas for a new generation of agricultural system models and data that could meet the needs of a growing community of end-users exemplified by a set of Use Cases. We envision new models and knowledge products that could accelerate the innovation process that is needed to achieve the goal of achieving sustainable local, regional and global food security. We identify desirable features for models, and describe some of the potential advances that we envisage for model components and their integration. We also discuss possible advances in model evaluation and strategies for model improvement, an important part of achieving our vision. We conclude with a multi-pronged implementation strategy that includes more thorough testing and evaluation of existing models, the development and testing of modular model components and integration, improvements in data management and visualization tools, and development of knowledge-products for end users.
1. Introduction

The idea of creating a new generation of agricultural system models and knowledge products is motivated by the convergence of several powerful forces. First, there is an emerging consensus that a sustainable and more productive agriculture is needed that can meet the local, regional and global food security challenges of the 21st Century. This consensus implies there would be value in new and improved tools that can be used to assess the sustainability of current and prospective systems, design more sustainable systems, and manage systems sustainably. These distinct but inter-related challenges in turn create a demand for advances in analytical capabilities and data. Second, as discussed in the companion paper on *The State of Agricultural System Science*, we now have a large and growing foundation of knowledge about the processes driving agricultural systems. Third, rapid advances in data acquisition and management, modeling, computation power, and information technology provide the opportunity to harness this knowledge in new and powerful ways to achieve more productive and sustainable agricultural systems, as discussed in the companion paper on *Building an Open, Web-Based Approach*.

Our vision for the new generation of agricultural systems models is to accelerate progress towards the goal of meeting global food security challenges sustainably. In this paper and the companion paper on information technology and data systems, we employ the Use Cases presented in the Introductory paper, and our collective experiences with agricultural systems, data, and modeling, to describe the features that we think the new generation of models, data and knowledge products need to fulfill this vision. A key innovation of the new generation that we foresee would be their linkage to a suite of knowledge products – which could take the form of new, user-friendly analytical tools and mobile technology “apps” – that would enable the use of the models and their outputs by a much more diverse set of stakeholders than is now possible. Because this new generation of agricultural models would represent a major departure from the current generation of models, we call these new models and knowledge products “second generation” or NextGen.

We organize this paper as follows. First, we return to the Use Cases and identify key features that NextGen models require to meet the needs of the Use Case personas. Second, we discuss new approaches that could be used to advance model development that go beyond the ways that first generation models were developed, and in particular, the idea of creating a more collaborative “pre-competitive space” for model development and improvement, as well as a “competitive space” for knowledge product development. Then we describe some of the potential advances that we envisage for the components of NextGen models and their integration. We also discuss possible advances in model evaluation and strategies for model improvement, an important part of the approach. Finally, we consider both near-term and longer-term strategies for implementation.

2. Use Cases: Implications for Next Generation Models

We now discuss the implications of the five Use Cases for the development of second generation models and knowledge products. Table 1 summarizes their characteristics.

2.1 Farm Extension in Africa

Sizani is working as a farm extension officer in an area in Southern Africa where many farms are very small, incomes are very low, and farmers typically grow maize and beans as staple crops for their family’s subsistence and to sell for cash. She needs to have access to analyses that help her tailor advice to specific farmers whose land and other endowments may vary considerably. Cropping system models are needed in this use case, either for Sizani to run through an application on her smart phone after keying in the location of the farm (to access soil, weather, market and other databases for the simulation analyses) or to access results that have been pre-run to provide best management options for the particular farming system. In either case, models of cropping systems and of the farm household are essential, in addition to databases that contain information on soil, weather, markets, diets, nutrition, and crop varieties that are available for the farmer to use. Ideally, the models would have been run ahead of time so that information could be provided to
the farmer relative to costs of the new heat, drought, and disease-tolerant maize varieties and their performance in terms of grain yield and fodder production using current management practices. Also, the app would provide information on the benefits of rainfall harvesting in terms of increasing productivity and stability of yield across years when rainfall is limited. Sizani also has access to information from farm-scale analyses that take into account the labor available to the farmer and needed to implement and manage the rainfall harvesting approach, and the overall costs and benefits to the farmer.

Cropping and farming systems models and data are needed to produce the results for the smart phone application, and thus help Sizani deliver farm-specific advice to increase maize productivity and stability and to increase the economic and nutrition well-being of the farm family. The cropping system models are needed to simulate maize, beans, and vegetables that are produced by the farmer. In addition, the models need to take into account the benefits of using new varieties of maize and beans that are tolerant to high temperature and drought, since these are projected to increase under changing climate conditions. Furthermore, the crop models need to be able to simulate the effects of small increases in inorganic fertilizer as well as organic matter, and to simulate the effects of partially harvesting rainfall. A crop disease module is needed to simulate the effects of foliar diseases for susceptible and tolerant varieties. Together, these modules need to provide output information on grain, vegetable, and fodder production under alternative management systems. The farming system model will take into account the labor requirements, costs of adopting and managing new systems, and markets, providing information to the farmer on average benefits and risks of losses in particular years associated with climate variability and variability in disease pressure.

After the information is accessed by Sizani, she is able to inform the farmer of the economic benefits and risks associated with adoption of the new varieties, fertility management, and water-harvesting approaches on his farm. Sizani also informs the farmer of an app in the local language that can be accessed to learn more about the varieties, water harvesting, and nutrient management, and she leaves the farmer an Extension Fact Sheet that provides more general information, also in the local language, about these technologies and where to obtain them.

2.2 Developing and Evaluating Improved Crop and Livestock Systems for Sustainable Intensification

Xiaoming is a plant breeder/geneticist working on developing a drought- and heat-tolerant hybrid of maize.

<table>
<thead>
<tr>
<th>Use cases</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Farming System</td>
<td>small-holder</td>
<td>small-holder</td>
<td>small-holder</td>
<td>commercial corp</td>
<td>commercial corp</td>
</tr>
<tr>
<td>Information User</td>
<td>Farm advisor</td>
<td>Agricultural research team/program</td>
<td>Analyst/adviser</td>
<td>Management consultant</td>
<td>Corporate analyst</td>
</tr>
<tr>
<td>Beneficiaries</td>
<td>Farm family</td>
<td>Research institution/ farm population</td>
<td>NGO &amp; clients</td>
<td>Farm business</td>
<td>Agri-business firm</td>
</tr>
<tr>
<td>Outcomes</td>
<td>Improved livelihood (income, nutrition, food security)</td>
<td>Improved technology</td>
<td>Sustainable technology</td>
<td>Income, soil conservation &amp; water quality</td>
<td>Profit, risk management, sustainability objectives</td>
</tr>
</tbody>
</table>

Table 1. Characteristics of Five Use-Cases
She would like to be able to evaluate the potential adoption and impact of maize varieties with particular characteristics across the widely varying conditions in Africa.

A maize cropping system model is needed that has the capability to predict the benefits of the new drought and heat-tolerant maize varieties under the range of soils, weather, and management conditions across the regions of interest in Africa. Furthermore, a household economic model is needed to evaluate the adoption of the new maize varieties, resources (e.g., access to credit, labor, and fertilizer inputs) needed to produce the new variety. One question would be about the costs of purchasing the new variety, as well as the benefits and risks of growing it relative to traditional varieties. Therefore, information is needed on the household resources and constraints as well as information on the yield gains expected by switching to the new variety and the overall impacts on the economic livelihood of the farm family. Costs of inputs and likely prices of grain are needed for the economic model. Also, soil, weather, and management information are needed as inputs to run the crop and household models to evaluate the switch to the new variety.

The model-based analysis needs to take into account the risks associated with weather variability in the short term as well as responses to changes in climate that are projected for the longer term. Assuming that the farmer grows other crops for food/fodder and for sale and has livestock, models for these other enterprises are also needed. Ideally, the crop and household economic model would be used to perform simulation experiments, similar to how a randomized controlled trial might be performed if that were possible. Results from these simulation or optimization experiments would allow Debora to evaluate multiple factors, such as variability in maize grain and fodder yield, income, return on investment, and nutrition.

2.3 Investment in Agricultural Development to Support Sustainable Intensification

Carlos is an investment manager for a prominent Foundation, and he needs to evaluate a project for small farms in Kenya that will increase the intensity of production by increasing fertilizer use per hectare on cash crops while maintaining the current sustainable nutrient balance between pasture grasses, crop residues and animal manure. Carlos wants to evaluate whether the higher crop yields would induce a non-sustainable system once the initial period of fertilizer subsidies and extension was completed.

Given that the proposed project extends over a substantial area of many thousands of hectares, any analysis will have to be presented on the landscape basis. However it’s equally important that the heterogeneity of the agricultural resource base, and thus the differing yields and potential fertilizer response, is also represented. To achieve this, an integrated whole-farm system model is needed with crop, livestock, economic and environmental components.

Sampling sets of regional parameters that can be representative of the landscape as a whole is necessary before implementing crop or livestock production models. The analyst is faced with balancing the accuracy of representation of the landscape against the proliferation of model runs and their associated expenses. This first step in project design requires careful summaries of the range of soils, altitudes, microclimates, and water resources systems in the whole area.

Since animal production is an integral part of the farming system, the livestock model should be integrated with the smallholder crop models. Ideally both livestock and crop models can be run simultaneously thus showing the nutrient flows between different production sectors and the sustainability of the system as a whole. The type of cropping system model used, will have year-after year carry-over of soil carbon, soil fertility, residue return, and use of both animal manures and inorganic fertilizer.

Samples of crop yields, input changes, and responses to fertilizer policy are generated by the integrated plant growth and livestock models. They are then used to populate the distribution of productivity and economic and social impacts from changes in fertilizer extension policy in the different regions sampled on the landscape. For this stage of analysis, Carlos can use an economic impact assessment model driven by an empirical distribution of characteristics across the landscape. The change in risks to different metrics
such as income level, nutritional balance, and distribution of benefits across farm sizes is essential for assessment of the project.

To integrate the information from these three stages into the decision model Carlos needs a dashboard application that he can access from his laptop computer. Using this application, he can set up an assessment, enter data supplied with the project proposal, and link to general data layers available for the region. The dashboard provides a variety of ways for Carlos to visualize the model outputs and prepare them for presentations to his organization.

2.4 Management Support for Precision Agriculture in the US for Profitability, Soil Conservation and Water Quality Protection

Greg is among an increasing number of commercial growers with interests in Precision Agriculture. Despite the rapid advancements of sophistication and automation of farm equipment in recent decades, there is still a vital part of the equation that remains incomplete—the analysis of the vast amount of available data that gives farmers like Greg a map of what action to take where and when. Most of the variable rate application he and others currently rely on is based on rules of thumb and empirical approaches, as opposed to a systems approach that accounts for the interaction of soil, crop, management, and weather.

Process-oriented crop growth models simulate the effects of genetics, management, weather and stresses on the daily growth of crops using carbon, nitrogen and water balance principles. The strength of these models is their ability to account for stress by simulating the temporal interaction of stress on plant growth each day during the season. Thus, they tend to be sensitive to temporal patterns of stress. However, these models were designed for homogeneous areas, and as a result, inputs that are spatial in nature must be assumed to be uniform. Furthermore, spatial characteristics are often unknown or difficult and expensive to measure. The advent of Precision Agriculture has resulted in the need to extend the use of point-based crop models to account for spatial processes. Crop models can provide useful estimates of potential economic return for management recommendations, along with the sensitivity of a recommended management action in response to weather variability. The next generation of crop models for Precision Agriculture will account for spatially connected processes and use publicly available data on soil type, weather forecasts, along with location specific data from farmers’ yield maps, to provide a prescriptive crop management plan on a very high spatial resolution.

2.5 Supplying Food Products that Meet Corporate Sustainability Goals

Sophia is an economic analyst in a corporate sustainability group. This group has embarked on efforts to make sustainability the core of their mission: marketing food while conserving resources. She is assessing the life cycle of food products to find ways to conserve energy, save water, minimize waste and reduce greenhouse gas emissions in an effort to make these products more sustainable from the farm to fork.

The system models needed to support supply chains in their pledge for sustainability are the same system models described in the precision agriculture use case. Crop system models are able to simulate the annual fluxes of N2O from soils under different pedo-climatic and management conditions rather well, but their performance requires improvements when simulating the daily fluxes of N2O. As N2O is directly linked to the amount of fertilizer used, the next-gen models will play a crucial role in identifying the optimal N rate that maximizes profits and reduces nitrous oxide emissions and nitrate leaching.

2.6 Implications for Second Generation Models and Data

Table 2 summarizes a number of agricultural system model features that are suggested by the Use Cases. These have important implications for the design of new-generation models and knowledge products.

- All of the small-holder use cases (1-3) require whole-farm models, and decision-makers in the commercial crop use cases (4 and 5) are likely to
Table 2. *Model and Data Features Implied by the Use Cases Defined in Table 1*

<table>
<thead>
<tr>
<th>Use Cases</th>
<th>Farm Extension</th>
<th>Improved Systems</th>
<th>Investment in Sustainable Intensification</th>
<th>Precision Ag</th>
<th>Sustainable Value Chains</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>System Features</strong></td>
<td>?</td>
<td>?</td>
<td>x</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>- single production activity</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>- multiple production activities</td>
<td>x</td>
<td>x</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>- interacting activities</td>
<td>?</td>
<td>?</td>
<td></td>
<td>?</td>
<td>?</td>
</tr>
<tr>
<td>- whole farm</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>?</td>
<td>?</td>
</tr>
<tr>
<td><strong>Data (spatially referenced)</strong></td>
<td></td>
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<tr>
<td>- single activity</td>
<td>?</td>
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<tr>
<td>- individual farm</td>
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<tr>
<td>- representative sample</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
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<tr>
<td><strong>Outputs</strong></td>
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<td></td>
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<tr>
<td>- bio-physical production (yield)</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
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<tr>
<td>- economic (profit, income)</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
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<tr>
<td>- environmental</td>
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<tr>
<td>- social</td>
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<tr>
<td><strong>Output Access</strong></td>
<td>?</td>
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<tr>
<td>- model</td>
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<tr>
<td>- mobile app</td>
<td>x</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>- computer dashboard</td>
<td>?</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td><strong>Spatial Scale</strong></td>
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<td></td>
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<tr>
<td>- field</td>
<td></td>
<td></td>
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<td></td>
<td></td>
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<tr>
<td>- farm</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>- region (many farms)</td>
<td></td>
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<tr>
<td><strong>Temporal Scale</strong></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>- within-season</td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>- season</td>
<td></td>
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<td></td>
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<tr>
<td>- multiple seasons</td>
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</table>
want whole-farm information as well, even if the specific use case (e.g., precision nitrogen application) does not require it.

• All cases need spatially referenced data, but the type and resolution of data required varies across the Use Cases.

• All of the Use Cases need biophysical production outputs and economic outputs. The need for environmental and social outputs is case-specific.

• Most, if not all, of the personas in the Use Cases would want to access model outputs via a dashboard application that would probably run on a laptop or larger tablet to facilitate visualization and integration of outputs with other applications and data, although some farm decision-makers or farm advisers might only want mobile applications.

• Only one of the Use Cases might want direct access to model output (the scientist Use Case 2).

• The spatial scale of the data needed varies by case, but all cases need season-specific data. Some farm-level uses will need within season data (e.g., for pest management or precision nutrient application).

There are several striking findings: All the Use Cases require whole-farm systems models; all require both biophysical production and economic outputs: all would need at least season-specific, spatially referenced data; and the farm-level decision makers are likely to need within-season data. Also striking is the fact that only one of the personas (the scientist) might want direct access to model output. The science community itself that is developing and using models for research. Even among the scientists themselves, it is often the case that one user (say, an economist) does not require the output of another model (say, a crop model) in the form it comes out of the model, but would rather have the output put into a format suitable for further manipulation. As these use cases illustrate, this is even more so for non-scientist users: there are few if any users that require direct access to the model output.

From the companion paper on The State of Agricultural Systems Science, we know that few if any agricultural models currently available meet the needs of the five Use Cases. Few provide whole-farm analysis capabilities, for example, or make model outputs accessible through user-friendly web-based dashboard applications. Thus, we can conclude that there is a substantial gap to be bridged between current models and the capabilities needed to provide information that would be useful to most potential users.

3. Designing Next Generation Models

Given the gap between the current state of agricultural systems models and the needs of actual and potential users, this section discusses how the new generation of models can be created to bridge this gap and realize the vision for next generation models presented in the Introduction.

3.1 A Demand-Driven, Forward-Looking Approach

A first step towards realizing the potential for agricultural systems models is to recognize that until now, most model development has been motivated by research and academic considerations, not by user needs. This means that the model development community needs to turn the model development process “on its head” by starting with outcomes and working back to the models and data needed to quantify relevant model outputs. For example, the Use Cases show that in most cases whole-farm models are needed, and particularly for small-holder farms, models are needed that take into account interactions among multiple crops and often livestock. Yet, many agricultural systems models represent only single crops and have limited capability to simulate inter-cropping or crop-livestock interactions.

Another feature is that many models produce only estimates of biophysical quantities of crop or livestock production (e.g., crop yield) or basic economic variables such as net returns to a crop activity. Why? Models of single crops are easier to create, require less computational resources, and are driven by a smaller set of data than models of crop rotations, inter-crops or crop-livestock systems. But perhaps more impor-
tantly, researchers are typically responding to the incentives of scientific institutions that reward advancements in science above all else. As a result, research on component processes within single crops may be more researchable within a laboratory or institutional setting, and may result in more publishable findings. The reward for producing useful decision tools for farmers or policy decision-makers may be minimal in academic settings.

While it is clear that model development should be much more driven by user needs, it is also important to recognize that science informs stakeholders, about what may be important, and about what may be possible. People know, in a general way, what they want, but they may have no idea what kind of science is needed to meet that need. Henry Ford famously said, “If you had asked people what they wanted, they would have said ‘faster horses’.” We can safely assume that potential users of agricultural systems models want a secure and sustainable supply of food. Who imagined even a few years ago that we might accomplish that goal, in part, by using data collected by aerial drones linked to agricultural systems simulation models?

So while model and data development need to be driven by user-defined needs, they must also be forward-looking, using both the best science and the imagination.

### 3.2 A Systems Approach

The Use Cases show clearly the need for whole-farm systems approaches. Agricultural systems are managed ecosystems (or agro-ecosystems) comprised of biological, physical and human components operating at various scales (e.g., cell, organism, field, farm). Farms are embedded within larger ecological and human systems operating at regional scales (e.g., watershed, population), as well as larger (continental, national, global) scales. It is typically important to consider many different interactions within and among these systems if we are to meet stakeholder needs for actionable outcomes.

The systems approach has several important implications for second generation models. Within each system level, a set of interacting sub-systems is involved. This suggests the possibility of constructing models of large, complex systems by combining models of modular sub-systems. The level at which modularization may be possible remains an important question, and this in turn has implications for software engineering. For example, as discussed in the companion State of Science paper, many crops are now modeled individually and separate from livestock. Systems with multiple interacting crops (e.g., through rotations or inter-crops), livestock, and crop-livestock interactions, are needed for various Use Cases, raising the question whether these interacting components can be incorporated in a modular “plug and play” system. Also, these biophysical production system components interact with economic-behavioral components and environmental components. These interactions among sub-systems imply the need for standard ways to link inputs and outputs among sub-systems.

Another important issue raised by the systems approach is the appropriate level of complexity for Use Cases, an issue discussed further in section 4.7. Research in environmental modeling indicates there are often diminishing returns to complexity. Similarly, experience with economic modeling has shown the value to “minimum data” or “parsimonious” approaches (Antle, Stoorvogel and Valdivia 2014). These ideas also relate to the need for a more generic approach (section 3.4 below).

The small-holder Use Cases illustrate the need for a systems approach at the farm level. In order to assess the well-being of the farm family in terms of income and nutrition, all relevant economic activities of the farm household need to be taken into consideration, including the income generated by the farming activities as well as other non-agricultural activities of the household members (e.g., off-farm work). Additionally, because the farm often involves multiple production activities, including crops and livestock, all of these activities and their key interactions need to be represented, as illustrated by the circular flow of nutrients from crops to livestock in the form of crops, crop residues and household waste fed to livestock, and then back to crops in the form of manure and composted materials.

The commercial-crop Use Cases also illustrate the
need for a systems approach. Crop rotations are important to the management of soil fertility and soil pests, and thus play a key role in achieving more sustainable management of input-intensive systems. It is also likely that to improve the sustainability of large-scale systems, it will be necessary to move towards more diversified systems that use crop rotations and integrate crops with livestock. The commercial-crop Use Cases also illustrate the need for assessments of landscape-scale impacts, including water quality (through soil and chemical runoff and chemical leaching), biodiversity (through impacts of fish and other wildlife), and greenhouse gas emissions (e.g., through soil management and fertilizer use). Similar types of assessment are needed to design and evaluate systems that meet the goals of “sustainable intensification” and “climate-smart agriculture.”

3.3 An Open, Pre-Competitive Space for Model and Platform Development Linked to a Competitive Space for Knowledge Product Development

Figure 1 presents a diagram of the linkages between the “pre-competitive space” of basic science and model development, and the “competitive space” of knowledge product development. The arrows between these two “spaces” point both ways to represent the inevitable and important give-and-take. There is a need for a demand-driven but forward-looking process that enhances interactions between these two realms. The concept of “pre-competitive space” grew out of the efforts of the pharmaceutical industry to collaborate on basic research while competing in product development. We think this distinction is also useful for thinking about how we might develop and apply agricultural systems models, while recognizing that there is also a competitive element among the researchers in the model development arena.

Facilitating a pre-competitive environment is likely to require innovations in the way research organizations operate, and may need to involve public-private partnerships (PPPs). PPPs are one way that science and industry can collaborate to generate new applied knowledge that can feed into the creation of new business and services. In PPPs it is common that both private and public partners provide funding and jointly formulate the research questions that can subsequently be tackled by research institutes and universities. There are a number of challenges in structuring PPPs. For example, in the European Union PPPs have been regulated to avoid unfair competition. The EU regulations stipulate that there always has to be more than one private partner involved and intellectual property rights of the knowledge developed (e.g., tools, models, articles, methods) belong to the research partner, which can then license the use to private partners for commercial purposes.

An important aspect for a NextGen community of practice is openness. Open here means: first, inviting and engaging others to join and become involved; second, being ready to jointly set priorities with a broader stakeholder community (i.e. research programming, private partners, policy partners, non-governmental organizations); and third, being transparent for scientific and public scrutiny of methods, tools and results through not-so-ly scientific venues. Only a few of the

Fig. 1. Possible Linkages between the Pre-Competitive Space of Model and Data Development and the Competitive Space of Knowledge Product Development
agricultural systems models now in use can be said to be “open” in the sense that both the model equations and programming code are fully documented and freely available to the community of science. Establishing an open approach consistent with the principles of good science, including sufficient documentation and sharing of code to allow replication of results with reasonable effort, should be a priority of the practitioner community. Such an approach would facilitate model improvement through peer review, model inter-comparison and more extensive testing, new modes of model improvement and development such as crowd sourcing, and education of the next generation of model developers and users. Creating this open approach would also raise challenges related to incentives and intellectual property that would need to be addressed. The recent positive experience with the Agricultural Model Inter-comparison and Improvement Project (AgMIP; Rosenzweig et al. 2013), a new community of science dedicated to an open approach, suggests that researchers are now ready and willing to participate.

An open approach will also encourage the emergence of competing models and modeling approaches, rather than a single “super model.” One dominant “super-model” could eventually emerge. But the only way to know that such a model is desirable is to allow a multi-model environment to flourish. We also expect to see alternative approaches emerge as modelers tackle challenging features such as representation of heterogeneity and dynamics and linkages across scales. For models to be tractable, tradeoffs have to be made, and an open approach is needed to facilitate the testing of alternative solutions.

There are important examples of recent efforts at creating a more open approach to agricultural model development. The bio-economic farm model FSSIM (Janssen et al. 2010) was made available as open source in 2010 after completion of its main project-related development and published with a license that allowed further use and extension. The open sourcing of the model was combined with training sessions, but this did not lead to spontaneous community uptake and large-scale development. The DSSAT crop modeling community is undertaking an effort to make its code open-source with the participation of more than 20 developers. The Global Trade and Analysis Project has provided extensive documentation of its model and data and allows user-modification of its standard model (Global Trade Analysis Project, 2014), and there is a large number of users of the model globally. The IMPACT model developed by the International Food Policy Research Center is publicly documented and available to other researchers (Rosegrant 2012). The TOA-MD regional model for technology adoption and sustainability assessment of agricultural systems is fully documented along with a self-guided learning course. Model code is available to “registered users” who have signed an end-user license agreement that requires acknowledgment of the developers and allows only research and other public-good uses (Antle, Stoorvogel and Valdivia 2014). There are now more than 500 registered users of the model, but only a few have shown interest in modifying or further developing the model independently, possibly because it is programmed in a language that relatively few researchers use.

To achieve the goal of demand-driven model development, it will be necessary to strengthen the linkages between the pre-competitive space of model development and the competitive space of knowledge product development. The current state of affairs appears to be that, on the one hand, the modeling community is strong on analytical capability but weak on linkage to user demand; while on the other hand, the developers of user-related farm-level products (e.g., providing data from mobile devices) are weak on analytics. Thus, there appears to be the opportunity for “gains from trade” by facilitating more interaction between the two communities. An important part of this interaction has to be to identify the key research that could enable better service delivery to knowledge-product users. Additionally, as emphasized in the Use Cases, there is a public good value to enhancing a broader community that can provide both data and analytics for public investment and policy decision-making. These issues are further developed in the companion paper on Building an Open Web-Based Approach.

3.4 New Approaches to Data Acquisition, Management and Use

The explosion in the availability of many kinds of data and the capability to manage and use it creates new opportunities for systems modeling at farm and land-
scape scales. Figure 2 presents an example of the possible types of private and public data that could be generated and used for both farm-level management (as in Use Cases 1, 4 and 5) and landscape-scale investment and policy analysis (Use Cases 2, 3 and 5). Some of these data would be generated and used at the farm-level, others would be generated and used for landscape-scale analysis to support investment decision-making and science-based policy-making. While farm-level decision making and landscape-scale analysis have different purposes, they both depend on two kinds of data:

- **Private data**: site- and farm-specific characteristics of the land and the farm operation, and the site- and farm-specific management decisions that are made. These data can be used to evaluate the farm's biophysical, economic, and environmental performance.

- **Public data**: weather, climate, soils, and other physical data describing a specific location, as well as prices and other publicly available economic data (note that not all public data is accessible).

A key question for the design of the agricultural knowledge infrastructure is how both types of data can be collected, managed and utilized efficiently and securely. Figure 2 is a design envisaged for a setting where farm decision-makers are able to utilize advanced decision tools that would be integrated with cloud-based data and computing resources. Although such tools may currently only be feasible in high-income countries, we expect they will become increasingly available throughout the world.

### 3.5. Credibility, Uncertainty and Model Improvement

A clear message from the NextGen Stakeholder Workshop was that model credibility is a key issue limiting the use of models for decision-making. In some areas of commerce where long-term projections are important, for example the insurance industry, there has been growing acceptance and use of quantitative climate models and impact assessment models. But for many decision-makers, ranging from farmers and agribusiness, to the development donor community and government, quantitative models remain an arcane and poorly understood part of science.

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**Fig. 2.** Possible linkages between data and decision tools at farm and landscape scales (source: Antle, Capalbo and Houston 2014).
There are many aspects to establishing, maintaining and improving model credibility. First and foremost, models must be relevant to user’s information needs. In addition, the participants in the Stakeholder Workshop emphasized the need to communicate what models are, what they can and cannot do, and to quantify and communicate model uncertainty effectively so that users understand how to use model outputs. But besides being relevant to users’ needs, models must perform well enough to be judged credible and useful. As the companion paper on The State of Agricultural Systems Science shows, there are many short-comings of current models’ capabilities that limit their relevance and usefulness for the Use Cases described here and the others discussed in the NextGen Stakeholder Workshop. Thus, achieving NextGen goals will involve developing better data and methods to evaluate model performance, both to help developers improve them and to help inform end-users about their validity and reliability.

There are potentially many different uses of models, from basic science to on-farm management to policy decision-making. The criteria for a “useful” model differ among these. For some science purposes, a high level of precision may be needed, whereas for policy analysis, the timeliness of the information produced may be much more important than its precision or accuracy. Thus model evaluation involves devising appropriate performance criteria, including overall model performance in providing outputs desired by end-users, as well as criteria for modules that can be used for component improvement.

Several types of formal model evaluation techniques have been developed to assess complex systems model performance under current as well as future conditions. Evaluation under current conditions can be based on comparison with observed data through numerical, graphical, and qualitative methods. An extensive survey of general classes of direct value comparison, coupling real and modeled values, preserving data patterns, indirect metrics based on parameter values, and data transformations is presented in Bennet et al. (2013). As explained by the authors, systems modeling requires the use and implementation of workflows that combine several methods, tailored to the model purpose and dependent upon the data and information available. A five-step procedure for performance evaluation of models is suggested, with the key elements including: (i) (re)assessment of the model’s aim, scale and scope; (ii) characterization of the data for calibration and testing; (iii) visual and other analysis to detect poorly or non-modeled behavior and to gain an overview of overall performance; (iv) selection of basic performance criteria; and (v) consideration of more advanced methods to handle problems such as systematic divergence between modeled and observed values.

The evaluation of integrated models under future conditions cannot be directly assessed as available data may not be representative; this is particularly the case where the model includes an intervention that will change the behavior of the system. Instead, conceptual understanding of the system weighed against future projections can provide complementary lines of evidence in the assessment of the model. Global sensitivity and uncertainty analysis (GSA/UA) of future projections based on tailored scenarios provides a rich platform in the conceptual analysis of the models (Saltelli et al. 2004). GSA/UA provides a detailed understanding of the important factors and underlying processes driving the numerical model output variance under particular scenarios that can be compared with conceptual models of the system. The statistical techniques used also offer the opportunity to identify surprises in the future system behavior, as well as important feedbacks and non-linearities. GSA/UA also allows the modeler to: (1) examine model behavior (model check); (2) simplify the model based only on its important components; (3) identify important input factors and interactions to guide the calibration of the model; (4) identify input data or parameters that should be measured or estimated more accurately to reduce the uncertainty of the model outputs; (5) identify optimal locations where additional data should be measured to reduce the uncertainty of the model; and (6) quantify the uncertainty of the modeling results (Saltelli et al. 2005).

Another approach to model improvement that has been pioneered in the climate modeling field is intercomparison of models, implemented through the establishment of the Coupled Model Intercomparison Project (Taylor et al. 2012. By establishing protocols
for the use of “reference scenarios” it is possible to inter-compare model results, identify important differences in model outputs, and through this process ultimately improve the models and their performance relative to the criteria described above. The use of model “ensembles” is also considered by some researchers as a way to characterize model uncertainty, although this interpretation is controversial. Model ensembles have been shown to perform better in some respects than individual models, suggesting the use of ensembles as a way to improve performance (Martre et al. 2014). A limitation of the ensemble approach is that it requires a relatively large number of alternative, independently developed models. In many cases, there are not enough distinct models to make model inter-comparison or ensemble approaches useful.

4. Potential Advances in Model Components

We next present examples of potential improvements that are important and may be achievable in the disciplinary components of agricultural systems models. We begin with a set of cross-cutting issues that are common to all of the model components, and then focus on disciplinary themes.

4.1 Cross-Cutting Issues

4.1.1 Representing and Incorporating Human Behavior into Agricultural Systems Models

Agricultural systems are managed by people for people. The objectives of the people using the information generated by models, and the behavior of decision makers whose behavior is represented in models, must influence model design. Most existing models have a limited capability to represent economic or other behavioral motivations of decision makers. This is a cross-cutting theme in modeling because the management decisions made by farmers related to crop and livestock productivity as well as to economic costs and returns as well as environmental and social outcomes. There are several ways that behavior needs to be incorporated into NextGen models.

First, a better understanding of decision maker objectives is needed if we are to develop models that provide information to farm managers to improve decision making. For example, if production risk management is an important objective of decision makers, then they will need different kinds of information than if production risk is not a major issue. Thus, modelers need to know what managers think are the major production risks. Note, however, that in this case the actual behavior of the decision makers does not need to be modeled. The goal is to inform decision making, not to make decisions for farmers.

Second, for models that are designed to predict or project plausible outcomes or impacts of decisions made by farmers, the behavior of the decision makers must also be modeled. This need adds a large amount of additional complexity above and beyond the capability of modeling bio-physical production processes. Knowing what behavioral models are most useful for the Use Cases (e.g., profit maximization, risk management, achieving social status, other social or environmental objectives) is a key issue that needs to be addressed in NextGen model development.

Third, the social dimension of farmer decision making needs to be better understood and represented in models, including how social interactions influence decision making. Agent-based models incorporate interactions among “agents”, i.e. farmers, but lack a rigorous foundation for the rules that govern behavior. Modeling social interactions is an active area of economic research, but data demands are high and as yet empirical generalizations that could be used to structure models are not available. Other social scientists also study social interactions, but typically using qualitative methods that also are difficult to translate into quantitative models.

4.1.2 Representing Heterogeneity

A key fact that has emerged from the increasing availability of field- and farm-level data is the high degree of biological, physical, economic and social heterogeneity of agricultural systems, in both space and time. The farms represented by the use cases demonstrate this point: among smallholder maize-based farms in Kenya, for example, coefficients of variation of
key characteristics like farm size are on the order of 100% or more; for commercial crop farms in the United States, they are also large, ranging from 50-150%. This heterogeneity has several important implications for how we represent agricultural systems in models:

- Accurate representation of bio-physical processes (e.g., crop growth, chemical leaching, erosion, chemical runoff) requires site-specific data (i.e., soils, slope, weather, management).

- Accurate representation of economic and social processes and outcomes (e.g., income and nutritional and food security) requires person- or household-specific data.

- Modeling environmental outcomes requires an integrated treatment of bio-physical processes and farmer decision making processes, and thus consistency between the spatial and temporal units of both types of processes.

- Representation of important economic, social and environmental outcomes at scales relevant to investment or policy decision making requires population-level outcomes that can be expressed not only as means or averages but more generally as distributions of outcomes. Only then is it possible to use indicators based on threshold concepts to represent vulnerability (e.g., poverty rates, risk of food insecurity, environmental risk, etc.).

- Behavioral heterogeneity is recognized in economics as one of the most important but also methodologically challenging aspects of modeling, because decision maker characteristics (e.g., experience, capability, motivations) are difficult to quantify and typically unobserved by the analyst.

### 4.1.3 Representing Dynamics

Agricultural systems are inherently dynamic. For example, crop growth occurs over time within the growing season, and crop productivity across growing seasons depends on crop rotations and other dynamics of the system. Most bio-physical system component models (crop growth, livestock growth, environmental processes) are inherently dynamic, but can only represent heterogeneity to limited degrees. Economic behavior depends on expectations of future outcomes, and decisions are made sequentially, with information being acquired as decisions are made and realizations are observed. Some management decisions like fertilization rates are based on intra-seasonal processes (getting the highest profit that season); other longer-term decisions span multiple growing seasons (multi-season crop rotations; machinery investments; livestock purchases and sales, and perennial crop planting and management decisions). Similarly, it is challenging to represent both dynamics and heterogeneity in economic models, and most dynamic models are highly simplified or stylized. The challenge is even greater when multiple dynamic model components are linked, due to differences in spatial and temporal units and overall model complexity.

Dynamics are often critically important at the regional scale. Witness, for example, the impact of weather shocks on regional food prices in some parts of the world, particularly in less-developed regions. Progress in modeling system dynamics is thus essential. How to achieve this progress in a tractable and useful way should be a priority for NextGen research.

### 4.1.4 Pathway and Scenario Design

Everything that influences an agricultural system, whether at the field, farm or regional scale, cannot be modeled. Consequently, most modeling is based on a logical structure in which some factors (“drivers”, or exogenous variables) take on values specified by the modeler or the model user. How these drivers are set or modified to represent the conditions under which the analysis is being carried out is a key aspect of modeling that has been under-studied. The issue is now receiving more attention in climate research (cite Moss, SSPs), but needs to receive more attention from the model development community. In particular, if models are to be linked to end-users through knowledge products, the user needs to understand the context in which the analysis or “simulation experiment” is being conducted. There has been little attention paid to how end-users could define or select those conditions or assumptions in which the modeling is carried out. These issues relate directly to the considerations of relevance and credibility discussed above.
Towards a New Generation of Agricultural System Models, Data, and Knowledge Products: Model Design, Improvement and Implementation

For agricultural systems modeling AgMIP has been developing more systematic approaches to development of “pathways” (plausible future conditions) and “scenarios” (specific parametric representations of a system consistent with a pathway), using the concept of Representative Agricultural Pathways (Valdivia et al. 2014). Further work is needed to better develop these methods for use at farm, regional and global scales.

4.2 Crop Systems

Next steps in developing next-generation crop models fall into several categories: significant improvements in simulation of important crop processes and responses to stress; extension from simplified crop models to complex cropping systems models; and scaling up from site-based models to landscape, national, continental, and global scales.

4.2.1 Key crop processes that require quantum leaps in improvement

Several crop processes require major advances in understanding and simulation capability in order to narrow uncertainties around how crops will respond to changing atmospheric conditions. Experimentalists and modelers need to work together from the outset to ensure that the right research questions are posed as experiments are planned, critical field data are gathered at appropriate times, and process-based understanding is captured so as to transfer new insights from the field to the crop models directly and expeditiously.

*Genetics.* Developing predictive capacity that scales from genotype to phenotype is challenging due to biological complexities associated with genetic controls, environmental effects, and interactions among plant growth and development processes. Crop model improvements are needed to link complex traits at gene network, organ, and whole plant levels. Phenotypes are linked to changes in genomic regions via associations with model coefficients (Hammer et al., 2006).

*Carbon, temperature, water, and nitrogen.* Crops are already experiencing higher levels of carbon dioxide (CO₂) and temperature in agricultural regions around the world. Understanding of how accelerated rates of CO₂ and temperature rise will interact to affect crop growth and productivity is growing, but this improved understanding needs to be incorporated into crop models (Leakey et al., 2009). Water relations of soils and crops are also of perennial importance and carbon-nitrogen cycling plays a crucial role in sustainable intensification. The simulation of all of these processes and their interactions and management, especially under conditions of stress, needs to be radically improved.

*Ozone.* The magnitude of ozone damage is expected to be comparable to climate change in the next several decades, but ozone damage is rarely considered in crop modeling studies (Leisner and Ainsworth, 2012). Information about ozone impacts on crop yields is available, but damage processes and functions need to be developed. Model improvements in regard to ozone effects on crops include inclusion of ozone response functions and comparison of response functions with process-based approaches such as leaf conduction, aerodynamic boundary-layer resistance, and whole canopy conductance parameterizations. In order to learn much more about the different responses of different crop species and varieties, ozone data collection should be incorporated into the AgMIP protocols for sentinel sites experimental design.

*Nutrition.* Crop modelers, breeders, physiologists, and human health and nutrition researchers need to broaden the scope of modeling to include key nutritional processes and future risk of hunger. This requires moving from a yield-only perspective to one that includes processes that affect nutritional quality. Non-staple crops, for which crop models have not been developed, are likely to become increasingly important (Müller et al. 2014).

4.2.2 Extension from ‘crop models’ to ‘cropping system models’

The field of crop modeling has been built on a single crop-by-crop approach. It is now time to create a new paradigm, moving from ‘crop’ to ‘cropping system.’

*Intercrops and complex rotations.* A first step is to set up the simulation technology so that modelers can rapidly incorporate multiple crops within fields, and multiple crops over time. Then the response of these
more complex cropping systems can be tested under different sustainable intensification management strategies utilizing the updated simulation environments. Similarly, studies can be performed to determine optimal cropping systems and management strategies for particular desired outcomes.

Pests, diseases, and weeds and their management. Diseases, pests, and weeds (DPW) are important yield-reducing factors in terms of food production and economic impact, and pose significant simulation challenges due to complex processes that occur over fine temporal but broad spatial scales. For each crop species, there is a portfolio of diseases, pests, and weeds, interacting over a range of time and space scales. Model improvements for DPWs include developing process-based models for important diseases and vectors, frameworks for coupling air-borne diseases to crop models, gathering significantly more data on crop impacts, and enabling the evaluation of pest management strategies.

Linkages to livestock production. Most smallholder farming in the world involves integrated crop-livestock systems that cannot be represented by crop modeling alone. Thus, next-generation cropping system models need to include key linkages to livestock. Livestock linkages to be incorporated include growth and productivity models for grasslands and rangelands as well as the usual annual crops. Information from local experiments (such as the AgMIP sentinel sites) will be required to develop and test the grassland and rangeland models. These models will then be capable of deployment with livestock models, regional farm data, and inputs on management and climate. On the management side, the effects of animal labor need to be included as well.

4.2.3 Scaling up from field scale to landscape scale

Cropping system models need to be able to simulate easily a diverse set of farms rather than just one representative farm, as has been common practice in the past. There are several approaches for scaling up, including use of gridded models and development of simpler quasi-empirical models for landscape-scale analysis (Lobell and Burke 2010). Large-scale computation can allow for much more extensive use of gridded models than in the past (Elliott, Kelly, et al. 2014). Soils and climate input datasets become important as simulation goes from field to landscape scale. There are several types of dynamic process gridded crop models: those developed from the site-based models such as DSSAT and APSIM; ecosystem-based models; and dynamic land-surface models. An example of a more statistical model is the agroecological zone (AEZ) approach developed by IIASA and the FAO (Fischer et al. 2002).

4.2.4. Crop Model Interoperability and Improvement

A key question for the next generation of cropping system models is the degree of interoperability. Historically, scientists (as individuals or groups) tended to have exposure to, and in-depth knowledge of, a single crop model (Thorburn et al. 2014). The Agricultural Model Intercomparison and Improvement Project (AgMIP) aims to increase efficiency of model improvement and application by sharing information between different models and encouraging the use of multiple models in impact assessment (Rosenzweig et al., 2013). Ideally, parameters from one crop model can be uploaded into databases and then downloaded, reformatted for use in another model. However, AgMIP has found that this sharing of parameter values between models is not necessarily straightforward.

The AgMIP Program is bringing different modeling groups together to compare and thus improve their models. The aims are to develop a better understanding of different crop models across the agricultural modeling community; improve both individual crop models and the entire group of models for a particular crop; and improve the efficiency and effectiveness of multi-model applications in agriculture.

4.3 Soils and Precision Management

Integrated agricultural technologies, defined as the integration of improved genetics, agronomic input, information technology, sensors, and intelligent machinery, will play a pivotal role in agriculture in the years to come. These innovations will be driven by economic forces, by the need to produce more food
with limited land and water for the increasing population, and at the same time by the push to save resources to reduce the environmental impact associated with food production. While these changes are occurring now in the commercial-scale industrialized agricultures of the world, many of these technologies have the capability to be adapted to conditions in other parts of the world. The cell phone now allows farmers in rural areas almost everywhere in the world to have low-cost information about prices, for example. Similarly, it is likely that unmanned aerial vehicles will rapidly be adapted to conditions around the world and used to carry out activities such as monitoring crop growth and pest occurrence, and improve management decisions. In large-scale, capital-intensive agricultural systems, these technologies are rapidly leading to the automation of many production activities, particularly machinery operation and decisions about input application rates.

The automation of agriculture began in the mid-nineties, resulting in large amounts of data available to farmers and agribusiness companies. Farm machinery and tools sold today are largely equipped with high precision global positioning system (GPS) driven controllers, which allow all activity on the farm to be recorded, geo-referenced, and stored on remote computers: “in the cloud.” All modern tractors collect data on a continuous basis and are equipped with wireless connectivity for data transmission. Harvesters record the yield at a particular location, planters can vary the plant spacing or type of seed by location, and sprayers can adjust quantity and type of fertilizer, fungicide or pesticide by location; all to a granularity of just a few square meters. Yield monitoring can now be linked to UAV imagery to produce a prescription map for the farmer to implement. These private data could also provide tremendous benefit to the researcher community, should access be increased.

Producers in the developed world now have historical crop yield data for their fields, at a few square meter resolution, for the last twenty years. Combined with advanced satellite-based imagery, high-resolution spectral and thermal data obtained from unmanned aerial vehicles (UAVs), and weather forecasts, growers have most of the critical inputs required to convert this “big data” into a proper actionable management plan that allows for the application of inputs to vary spatially within the same field. Despite these rapid advances in the sophistication and automation of farm equipment, a vital piece of the equation is still lacking: the analysis of the vast amount of newly available data in order to provide the farmer with a map of what action to take where and when. Most variable rate application is currently managed by farmers, using rule-of-thumb and empirical approaches, and not by using a systems approach that accounts for the interaction of soil, crop, management, and weather. Thus much of the power of automation remains unexploited.

In order to realize the full potential of more sophisticated equipment, new modeling systems for precision agriculture are needed. These systems could be based on comprehensive predictive crop yield models that combine publicly available data, such as soil type, weather, and others, along with location-specific data from farmers’ yield maps of their fields, to provide a prescriptive crop management plan at high spatial resolution, as in Figure 2. This type of system could deliver automated crop simulations, crop management strategy recommendations, process-based variable rate prescriptions, risk assessments, continual in-season simulations, integration of in-season crop scouting UAVs flight information, pesticide/fungicide/ herbicide prescriptions and accurate harvest recommendations via simple-to-use apps, websites, and/or smart phone texting.

The NextGen system will help farmers in two primary ways: better yields and higher profit margins. The ancillary benefits of improved compliance with environmental mandates and better stewardship of natural resources are also important motivators.

In this scoping study we have chosen purposefully to limit our scope to the farm and landscape scale. Increasingly, there will be demand for agricultural systems models to simulate and integrate the different components of the agricultural value chain (Fig. 3). Genetics, agronomic management (production input), weather, soil, information technology and machinery need to be linked in a system approach.
4.4 Pests and Diseases for Crops and Livestock

As noted above, a major limitation of existing models is how they represent pests and diseases. We expand here upon some of the important areas that must be improved in NextGen models.

Improved statistical modeling of within-season pest and disease threats using automated data collection and cloud computing. It is now possible to collect weather data continuously from ground-based sensors and to merge these data with medium-term weather forecasts and remote sensing data on crop growth and pest and disease damage. (Both growth and damage can be detected by satellite or drone by monitoring the crop’s spectral properties.) Then, using sophisticated statistical modeling done centrally, real-time advice can be distributed to farmers through the web or through mobile phones enabling them to take precautionary actions.

Understanding the consequences of climate change for weed, pest and disease threats. The IPCC has reviewed the existing evidence for how climate change may affect weeds, pests, and diseases. One issue with this evidence base is that there is a clear publication bias towards reports of increased threats – people often do not bother to write up no-effect results. There is a general recognition that we need good models to help tease out the different effects that changing weather will have simultaneously on both crops and the organisms that compete with or attack them. There has already been some work applying crop physiology-type models to weeds, and developing more mechanistic models of the effect of temperature on insect pests. There is an opportunity and need for more integrated models that include interactions between organisms, for example between weeds and crops, and between pests and the predators and parasites that attack them. A variety of different approaches are possible, and there is a need for an AGMIP-type approach to help the community decide how best to move forward.

Livestock disease. Highly contagious diseases of livestock present a major threat to agriculture, both in the developed and developing worlds. Diseases may be...
chronic in livestock populations, emerge from wildlife reservoirs, or possibly be introduced deliberately by man as an act of bioterrorism. Models are required to help understand how a disease will spread, and to help policymakers design optimal interventions. These models must encompass not only the epidemiology of the disease but also how it is affected by agricultural practices and in particular the movement of livestock by farmers. There have been significant recent advances in this area, often building on work on human diseases. For example, it is now possible to take livestock movement data and use it to parameterize an epidemiological model (Kobayashi, Carpenter, Dickey and Howitt 2007; Brooks-Pollock, Roberts, and Keeling 2014). There are the beginnings of a model comparison movement in human epidemiology; livestock disease epidemiology would also benefit from this approach.

Novel genetic control methods. There is intense current research activity into novel genetic methods of insect control. Most of this work, much funded by the Gates Foundation, is currently directed at the insect vectors of human diseases such as malaria, though the same methodology can be applied to insect pests of crops and of course the vectors of livestock diseases. The greatest advantage of these approaches is that they involve self-sustaining interventions that spread naturally through a pest population, although because they are nearly all classified as genetically modified, the regulatory issues surrounding them are complex. Cutting-edge modeling work in this field involves joint population and genetic dynamic models, many of which are explicitly spatial. This topic is likely to be one of the most important and exciting areas of modeling as applied to agriculture over the next few decades.

4.5 Livestock Production

There are a number of areas in which advances in livestock modeling could improve the information needed to support the Use Cases identified in Box 1, for farm-level and landscape-scale decisions.

For farm-level decision support:

More comprehensive livestock models covering a wide diversity of ruminant species, adequately pre-parameterized for most common situations and with default values for users to parameterize models to their conditions.

Summary models from comprehensive, dynamic models for on-farm support. This work includes summary models for intake, production and greenhouse gas emissions calculations. Some of these summary models could be developed as mobile phone technologies.

Development of extensive, standardized feed libraries linked to a GEO-WIKI for improving our mapping of feeds globally, but also to build a library that can be used for deriving functions of feed quality for different agroecological conditions. One way this could be accomplished would be to expand existing household data collection protocols to include suitable data for livestock.

For regional investment and policy analysis:

Development of high resolution improved crop and livestock production systems typologies. These typologies could be derived from existing farm household, agro-ecology, farm, rangeland, population, markets and other spatial data. NextGen production systems mapping needs to include intensification, gender dimensions of family labor and control over assets and income, and operation size indicators.

Spatially explicit standardized feeds and productivity data. Ideally these data would be linked to crowdsourcing and large data rescue initiatives.

Standardized linkages to global integrated assessment and economic models of different types (from Globiom, IMPACT to GTAP and others).

Improved spatially explicit farm and regional data on production costs for different livestock technologies. This information is seldom available and is crucial for both regional and global analyses.

Livestock yield gap analysis. A much deeper and better quantified bio-spatial analysis of livestock yield gaps is needed to guide investments and to identify opportunities to use livestock as a vehicle for agricultural development, poverty reduction, and environmental protection.
Livestock scenarios. Improved and consistent story-lines are required for the livestock sector in all scenarios. These story-lines can be produced as part of global and regional “representative agricultural pathways” being developed by AgMIP and other research teams. (Currently, such story-lines exist only for the global “shared socio-economic pathways” used in climate impact assessments; see Havlik et al 2014; Herrero 2014.)

4.6 Pastures and Rangelands

Pastures and rangelands are integral to all livestock production systems and are often closely integrated with crop production systems (e.g., pasture in rotation). The biophysical components of these systems and driving data required to model them are largely similar to those of crop production systems (see first chapter), but management data tend to be sparsely available and representing continuity of plant populations is challenging. Advancing our ability to understand how grasslands are managed – to understand, for example, what species are planted, what inputs (irrigation, fertilization, etc.) are provided, what grazing management (timing, intensity) is applied – is centrally important for improving our ability to model pasture and rangeland systems. At the same time, we have identified several features of next generation models necessary to improve the utility of models for pasture and rangeland systems, as we now discuss.

Planted pastures and native grazing lands both contain a variety of species, some of which are more palatable, nutritious, grazing-resistant, or fire-resistant than others. A more open, data-rich environment could facilitate evaluation of a variety of approaches for representing long-term dynamics, which could address several important grassland management/assessment issues. Managing grass swards (and desirable forb and species) to maintain desirable plants is a primary goal of grassland management, but one for which modeling tools have offered limited assistance. Models that represent vegetation dynamics are also desirable for understanding longer-term changes in species that can impact productive capacity, sensitivity to degradation, and carbon dynamics (particularly woody encroachment). Year-to-year variability is a key component for understanding potential utility and risk of relying on grassland forage resources. Next generation models that enhance our ability to forecast this risk would mark a substantial and meaningful advance.

The primary use of forage resources is for grazing animals, yet most grassland models are only loosely coupled with grazers (livestock or wildlife). Better integration between grassland and livestock models – through grazing effects on grasslands, grazer distributions across landscapes, forage demand/consumption, livestock/wildlife movement, etc. – would enhance the ability of models to contribute to important emerging issues. For example, holistic grazing management, in which several aspects of management vary in response to a variety of different cues from the land and expectations about future conditions, can be impossible to evaluate with current modeling frameworks. A system that integrated user demand into the model development process could lead to implementation of new data-management feedback loops within models. Such interactions between users and producers of information could direct data collection (e.g., by drone or remote sensing) to facilitate model use. Models that better represent grazer-grassland interaction are also crucial for understanding how efficiently livestock use forage resources, what is necessary to sustain wildlife populations, and how much grassland output might be available for other uses (e.g., biofuels).

4.7 Economics

Areas in which advances in economic modeling could improve the information needed to support the Use Cases identified in Box 1 also correspond to farm-level and regional decision support.

4.7.1. Farm-level decision support

Advanced analytics need to be coupled with the data on management decisions that are becoming available through mobile technologies (e.g., tracking soil conditions, seeding and fertilizer application rates, pesticide applications) and their results (e.g., crop growth, yield). An example of this analytical capability is the AgTools software developed by several university extension programs, which allows managers to calculate short-term profitability and rates of return on long-term investments (www.agtools.org). Similar proprietary
software tools are being developed and used. These analytical tools could be linked with modules that track or predict environmental outcomes such as soil erosion and net greenhouse gas emissions (e.g., Ag-Balance by BASF). Low-bandwidth versions of these tools need to be developed for use in areas where mobile phone technology is a limiting factor. Analytical tools need to be adapted to fit small-holder systems.

**Dynamic Estimation and Learning.** The flood of data on physical land-use, water availability and use, and yields coming from mobile devices and remote sensing systems suggest that both the biophysical and behavioral aspects of farm production at specific locations can be estimated by sequential learning processes. Recent advances in numerical approximation to dynamic estimators have reduced the dimensional and computational restrictions on their use. Two of several approaches that seem practical for remotely sensed data sets are Ensemble Kalman filters which use numerical sampling approaches to avoid inverting large matrices, and Cross Entropy filters that use the Kullback formulation to reduce the Bayesian solution to a nonlinear finite optimization problem. These recent advances in remote sensing are evident in analysis of the impact of the 2009 and 2014 droughts on California agriculture, which demonstrated the advantages of better data (Howitt, Medellin-Azuara, MacEwan, Lund, and Sumner 2014).

### 4.6.2 Regional investment and policy analysis

**Modularization and input standardization.** Models need to be incorporated into modules with standardized inputs and outputs, including farm-level optimization models, regional positive quadratic programming models, econometric land-use models, and regional impact assessment models. With this investment, these models could then be coupled more effectively for landscape-scale and population-level analysis of technology investments and other policy analysis.

**Model linkages across scales.** Methods and protocols are required to link regional economic models (price-taking land use and impact assessment models) with market equilibrium models (e.g., regional partial or general equilibrium models). Some progress has been made on this front but much more development is needed (Antle, Stoorvogel and Valdivia 2014).

**Richer characterization of behavior.** Generalization of behavioral assumptions and investigation of their effects on investment and policy analysis. Most economic models make simple profit maximization assumptions. There is a rich literature on risk modeling which could be incorporated. Recent advances in the expectations formation literature and the behavioral economics literature could be investigated for use in agricultural systems models.

### 4.7 Environment and System Complexity

Current agricultural system models typically operate at the point/field scales (Fig. 4a) with an emphasis on vertical fluxes of energy, water, C, N and nutrients between the atmosphere, plant and soil root zone continuum. A holistic upscaling from the point source to the landscape scale (Fig. 4b) requires incorporation of several interacting, complex components, adding substantial complexity above and beyond the agricultural system itself. Thus, a major consideration in environmental modeling is how to best capture essential interactions while maintaining models that are feasible to implement with available data and computational resources.

Figure 4 illustrates the various components linking point to landscape scales. A first element for the linkage from point to landscape is estimation of surface and subsurface fluxes and ecological transitions along the lateral scale. Coupling with landscape microclimate models provides the vertical inputs used by the agricultural systems models, as well as gradients (precipitation, temperature, wind, vapor pressure deficit) along the landscape. Coupling with hydrological models provides water flow paths like surface run-off, vertical and lateral groundwater flow, and interactions between vadose and groundwater zones and with adjacent surface water bodies (channels, rivers, lakes and coastal waters). Water quality models provides sediment and solute transport along the landscape controlled by water flows (Fig. 4b), and other effects like wind erosion. Integration and upscaling of landscapes into the watershed scale (Fig. 4c) requires 3-dimensional coupling of the surface and subsur-
face water, energy and mass transfers. At this scale, the groundwater aquifer system typically transcends the boundaries of the watershed and necessitates analysis at the regional scale to evaluate not only the impacts of the cropping and animal production systems on water quantity and quality, but also feedbacks from the hydrological system in the agricultural system (shallow water table effects, drought or low water availability for irrigation). Further, mesoscale rainfall and evapotranspiration distribution models control the local surface and subsurface flow intensities, pollution and abatement. At this scale, human effects through land-use changes as well as ecological (vegetation, wildlife) dynamics and transitions on natural or protected lands (riparian zones, conservation areas, water resource management infrastructure etc.) are also an important and critical component to evaluate the overall sustainability of the agricultural system.

It is important to recognize that although current crop modeling upscaling approaches based on land use maps are an efficient first approximation, the next generation models should consider the lateral con-

*Fig 4. Lateral connections across scales with other environmental components needed in the next generation agrisystems models, from (a) point vertical scales typical of current agrisystem models, (b) lateral hillslope/landscape surface and subsurface energy/water/C,N/nutrients transfers and ecological and human interactions (adapted from Kirby, 1976), to (c) watershed and regional surface and subsurface connections and teleconnections.*
nections through the landscape and regional scales to evaluate the sustainability of the integrated system, including effects on water and soil resources quality and quantity and ecological value.

The complexity resulting from the proposed integration at a landscape scale cannot be understated. In particular, additional emphasis is urgently needed on rational approaches to guide decision making through uncertainties surrounding the integrated agricultural system across all scales. As with all models (Raick et al. 2006; Kotz and Dorp 2004), those predicting agricultural production changes and interactions with the coupled natural and human components produce unavoidable uncertainty around the predicted responses. These two issues – the need for coupled models that can answer the pertinent questions and the need for models that do so with sufficient certainty – are the key indicators of a model’s relevance. Model relevance is inextricably linked with model complexity.

Although model complexity has advanced greatly in recent years and is a natural outcome of the proposed next generation integrated modeling, there has been little work to rigorously characterize the threshold of relevance in integrated and complex models. Formally assessing the relevance of the model in the face of increasing complexity would be valuable because there is growing unease among developers and users of complex models about the cumulative effects of various sources of uncertainty on model outputs (McDonald and Harbaugh 1983; Manson 2007; Cressie et al. 2009; Morris 1991). New approaches have been proposed recently to evaluate the uncertainty-complexity-relevance modeling trilemma (Muller, Muñoz-Carpena and Kiker 2011).

Due to the complexity of the coupling process needed in the upscaling and integration processes, innovative approaches to simplify model outcomes to make them relevant in decision-making will be central to the next generation modeling efforts. New methods for evaluating uncertainty also can be used to devise model simplification strategies. For example, the identification of non-important processes for particular scenarios might lead to their removal or fixing (variance cutting) without affecting the overall results while reducing the overall output uncertainty. The identification of the important model factors and the output response surfaces obtained from the analysis for particular scenarios can inform meta-modeling efforts, were simplified functions or databases of the model outputs are used in place of the full model for decision analytics (Ratto et al. 2007; Villa-Vialaneixa, N. et al. 2011; Ruane et al. 2014).

4.8 Social Dimensions

As noted in section 3, a demand-driven approach is needed that begins with user-selected outcomes. Various outcomes are of interest in the context of sustainability. Here we identify some key outcomes that need to be incorporated into modeling approaches.

**Income distribution and poverty.** Most economic models provide an estimate of some components of income, but a complete characterization of income sources is needed to evaluate income distribution and poverty. Population-level outcomes are needed, not only means or averages.

**Food and nutritional security.** Existing models represent food production, but no existing model characterizes all factors that affect food security (availability, access, stability, utilization) at the household or regional levels. A major limitation is data on food consumption at the household and personal levels over time. New methods of collecting these data using mobile devices are being developed. Additionally, it is necessary to express these data in other nutrient currencies beyond kilocalories, in order to explore nutritional diversity issues, as well as sustainable diets (Müller et al. 2014).

**Health.** Earlier work on health impacts of pesticide use on farm workers and other occupational risks could be used to construct health impact modules (Antle and Pingali 1994). As elsewhere, big data (e.g., in this case, data from medical records or insurance claims) can be used to improve understanding of impacts (Rzhetsky et al. 2014).

**Age, Gender and Health Status.** Research on various aspects of gender impacts and outcomes has advanced, primarily in terms of relevant measures. With better data, analysis of gender impacts associated
with new technologies could be incorporated into existing farm household models and impact assessment models. A similar situation exists for analysis of impacts by age and health status.

Vulnerability and equity. The application of different farm improvement methods has explicit winners but also unintended ‘casualties’ and perverse incentives. From a development standpoint, it is essential to understand these dynamics to ensure that appropriate policies are developed to maintain equal opportunities for all sectors of society. For example, in many cases, rich farmers are the ones who adopt technologies early. This factor could potentially disrupt power relationships in markets, thus affecting poorer farmers. In this case it is essential to design alternative options and safety nets for poorer farmers to prevent widening the gap and making them more vulnerable. New models should improve our understanding of these processes, as we move from single farm models to multi-farm and regional models.

Understanding structural change and rural development. When is rural development really about agriculture? New models should help us to target this question more effectively, and to find out when interventions in the agricultural sector will not be efficient in lifting the livelihood status of farmers or a region. Identification of thresholds in farm sizes, farm-derived incomes and others, will be a necessary feature of some NextGen models.

5. Towards Implementation

A long-term strategy for implementation of NextGen models could be to encourage developments on both the demand side and the supply side of the “market” for agricultural system models and knowledge products. On the demand side, we see a need for knowledge product developments to be linked with improved engagement of traditional end-users including both small-holders in the developing world and larger-scale commercial agriculture, as well as new potential end-users such as the crop insurance and reinsurance industries. On the supply side, we see a role for private-public partnerships to facilitate data and collection and sharing, as well as collaborative model development and testing, combined with better communication with the demand side to help guide the researchers in the “pre-competitive space” towards the model developments that could be useful in the “competitive space” of knowledge products. One such initiative has already been started through collaboration between AgMIP and CIMSANS. (see President’s Climate Data Initiative, https://www.whitehouse.gov/the-press-office/2014/07/29/fact-sheet-empowering-america-s-agricultural-sector-and-strengthening-fo)

The concept of “competitive space” is typically conceived as the development of knowledge products that are provided through commercial markets – i.e., as “private goods.” There is also an important public good aspect to these knowledge products. Some of these public goods are for public policy and investment decision making. In addition, it is important to consider the possibility that there could be obstacles, in the form of up-front fixed costs, to the development of decision support tools needed by small-holder farmers in the developing world, even though these tools could ultimately have substantial private and social value. Thus, there is arguably a role for some form of public or private charitable support for the development of these tools.

In order to facilitate the development of NextGen models, we see value in a multi-pronged approach.

First, we see a need for better testing and inter-comparison of existing models, extending the model-inter-comparison work already pioneered by AgMIP. In addition to the work begun to inter-compare and improve process-based crop models and global economic models, there is a need for similar work with livestock models and farm-level and regional economic models. This type of work could be facilitated by the identification of some “test areas” where high-quality data are available for important types of agricultural systems. Using these test areas, various types model inter-comparisons and model testing and validation exercises could be carried out using standard evaluations protocols.

Second, in parallel with this testing, we see great need for investments in the design and testing of modular open-source model components and in the testing of
alternative model integration strategies. AgMIP has begun work in this area, and is encouraging participation across the modeling community.

Third, as discussed further in the companion paper on Building an Open Web-Based Approach, there is a need for parallel development of ITC tools to support the software engineering, data input and output, and data visualization needed to make NextGen models useful to knowledge product developers and end-users.

References


