Systems Modelling Approaches to the Sustainable Intensification of Agriculture

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ABSTRACT. The sustainable intensification of food production at both sides of the OECD (Organization for Economic Co-operation and Development) split face different though equally challenging and complex problems and opportunities, requiring new science and tools. In one case, the limited availability of resources (e.g. land, finance, labour), lack of access to input and product markets, infrastructure, constrain the opportunities and incentives smallholder farmers have to change and improve their production systems. On the other hand, farmers in the developed world are reaching the point where further improvement of their production systems becomes uneconomical, too risky (Sadras and Rodriguez 2010), or inconsistent with environmental outcomes. This is taking place in a world where the number of hungry people reached record levels in 2009. Despite a slight recovery in 2010, the number of hungry people remains far higher than the level that existed when a hunger-reduction target was agreed at the World Food Summit in 1996. Even though the challenges are significant we should be able to feed 9 billion people by 2050. Evidence for this can be found in the fact that over the last 50 years the increase in agricultural production fed an additional 4 billion people with only an 11% increase in land area. More recent examples of considerable transformations in food and fibre production can be found in the sustainable intensification of broad acre agriculture in Brazil; in the generation of incentives through the introduction of changes in land ownership in Vietnam; and in the introduction of smart subsidies on agricultural inputs in Malawi. Nowadays Brazil is leading the world as a global net food exporter; small-holder farmers from Vietnam are increasingly accessing international markets; and Malawi, one of the poorest countries in the world, exports maize to neighbouring countries. Even though small, these are significant examples of the potential from adopting the right technologies and policies required to generate incentives, opportunities and economic growth from agriculture. Reducing food insecurities and poverty around the globe will require a high level of pragmatism to identify best fit intervention that solve inefficiencies, close yield gaps, and sustainably increase farmers' profits, on nearly the same area of land, and (mostly) using farmers' own resources (Rodriguez and Sadras 2011). In this paper we propose that high farm productivity is the result of the best combination of management variables that influence the yield of individual crops in individual fields, and the way limited resources e.g. labour, land, finances, are allocated across enterprises and fields at the whole-farm level (Rodriguez *et al*. 2009 and 2011; Power *et al*. 2011). Here, we also propose that irrespective of the intensity and scale of the production system, the design of more productive, profitable and sustainable farming systems, will require more integrative approaches based on basic crop eco-physiological principles, that account for local constraints on resources, socio-economic, and value chain factors.

Introduction

Nowadays in Australia most research, development and extension projects incorporate systems modelling as an irreplaceable methodology to support co-learning and practical management decision-making at all levels of scale (McCown 2009 and 2012). Typical applications have included promoting co-learning between researchers and practitioners on "best fit" practices, tactics and farm business strategies; from quantifying complex interactions at a range of temporal and spatial scales e.g. the field – farm - catchment, the season - the few seasons - climate change.

Examples can be found in the management of variability and risk at the field level (Hochman and Carberry 2011); understanding whole farm strategies that increase resilience and increase adaptiveness to variability and change (Rodriguez *et al*. 2011 and 2012); to better understand potential impacts from new technology packages (Whitbread *et al.* 2009); or the allocation of limited resources across competing farmers' objectives (Giller *et al.* 2008), and enterprisers (Tittonell *et al.* 2009; Giller *et al.* 2011). Interestingly, in contrast to the widespread availability of information that supports incremental adaptation processes such as autonomous adaptations in response to intra to inter-seasonal variations in climate (http://www.climatekelpie.com.au/), analyses and tools to support the more expensive and critical medium and long term adaptation processes are mostly absent. Here we provide a brief recount of successes, mishaps, and opportunities in the development and application of modelling tools to better inform discussions between farmers and researchers in the search for more profitable and sustainable farming systems designs.

How Do We Learn and Make Decisions?

We all constantly adapt and make decisions: Irrespective of the levels of wealth/poverty or the scale of the agricultural practice, we all intuitively adapt in response to perceived changes in the environment we operate; a process that requires access to relevant experiential information (Schwartz and Sharpe 2006), - farms and farmers are no different to this. The decision making processes that underlie decision making has been described as the combined operation of two systems: a fast, automatic, effortless, unconscious system resembling a neural network; and a slow, deliberate, effortful, conscious system better described as being organised by rules (Kahneman 2003). Operation of the former (intuition or practical wisdom – after Schwartz and Sharpe 2006) is mandatory; operation of the second one (conscious, rules based) is optional. Practical wisdom, requires the right goals, the right motives, and builds over time - with practice, as it requires practical knowledge for the decision maker to change old habits – 'it takes an enormous amount of practice to change your intuition' (Kahneman 2009). It also requires enough flexibility, autonomy, and confidence in the available options e.g. technological or managerial, for the decision maker to respond appropriately to a given situation. An interesting problem, therefore, arises in the absence of relevant experiential practice (e.g. in the face of unprecedented change such as climate change, or when new technologies are presented to farmers). This is because practical wisdom cannot be taught as it is context sensitive (Schwartz and Sharpe 2006). For example, for the case of adapting to climate change, little or no experience might be available for farmers to relate to, and identify possible actions. This means that medium and long-term farm planning in the face of unprecedented change (e.g. climate change) will require far greater levels of attention and support than received so far. For smallholder farmers in low-income countries, new technologies e.g. conservation agriculture principles, or risk management strategies, have the potential to present similar challenges, as they might be perceived as too difficult, too risky, and even traditionally/culturally wrong. A key output from a survey (n=23) among users of agricultural decision support systems (DSS) in Australia (Hofman and Carberry 2011) showed that 83% of the respondents agreed or strongly agreed with the statement that "DDS should aim to educate farmer's intuition, not to replace it with optimised solutions", while 80% agreed or strongly agreed that "DSS should enable users to experiment with options that satisfy their needs rather than attempt to present 'optimised solutions". This is crucial, and indicates that there is no single DSS that would fit all, as farms are complex systems, and we are far from rational when making decisions under risk and uncertainty (Kahneman 2011).

Farms are complex systems (Figure 1). Irrespective of their level of endowment, farmers use incomplete or imperfect knowledge to make technical (e.g. fertilizers, irrigation scheduling, and herbicides) and financial (e.g. marketing, loans, and off-farm investment) decisions, in a context of risk and uncertainty associated with climate variability, market volatility and political and global changes. Owing to Darwinian pre-adaptations, the long-term trajectory of the biosphere and the global economy are unpredictable (Kauffman 2008). Nonetheless many processes and components relevant to the farm and the farmer can be quantified using bio-physical and socio-economic approaches. Many variables are known e.g. available land, labour, and cash while others are measurable e.g. soil water and nutrients at sowing. The likely outcome from others e.g. in crop rainfall, date of last frost, could be narrowed down significantly, as extensive climate records are usually available and probabilities and risks could be calculated. In addition, seasonal climate forecasts may be available to further narrow down expected seasonal conditions (Stone *et al*. 1996; Hansen *et al.* 2011). However the future remains uncertain, as market volatility and/or near time climate changes will affect important near and long-term investment decisions e.g. buying a new farm, investing in new irrigation equipment, or to change the mix of cropping and grazing enterprises on a farm. Decisions that could define the success or failure of the whole business, with associated downstream implications on communities, and the whole value chain. However the uncertainty remains high, the likely impacts from a range of drivers of change could be understood. For example in a context of climate variability, "climate risks" can be

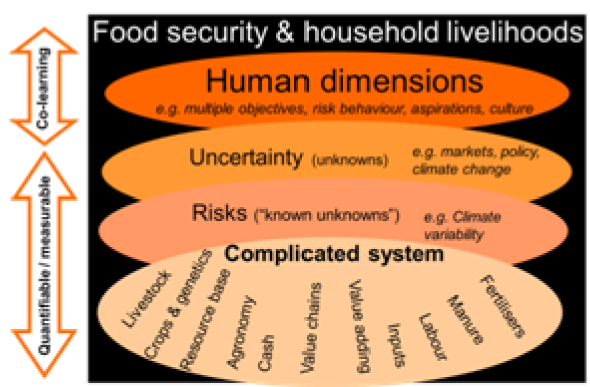

Figure 1. Conceptualization of the complexities in the management of a farm business and its disaggregation into quantifiable or measurable components, and the social-human dimension accessible via discussion, reflexion, and learning.

quantified by assuming that the unknown near future is likely to resemble the near past, whenever historical climate records are available. The advent of computational feasibility has seen global climate models develop from partial-ocean or atmospheric models, to the current generation of coupled global circulation models (Moss *et al.* 2010). This means that the impacts from changes in climate could be further bounded, e.g. if the impact of downscaled climate projections from likely emission scenarios and outputs of global circulation models are used to explore the outcome of alternative adaptation pathways. So, the message is that complicated farm decisions can be informed if we use the outputs of bio-physical models in association with socio-economic analyses as those shown in Figure 2. Though still the final word will be with the farmer, his/her personal circumstances, own personal objectives, aspirations, values and preferences. This makes a farm business a complex system, as we cannot avoid taking a stand about what is the right thing to do.

When dealing with complex problems, participatory approaches can facilitate the formulation and evaluation of a range of options that incorporate different viewpoints. Here we propose that, when the analysis of farmers' decisions is removed from the farm business context, the disconnect between the more technical issues, e.g. choosing a cultivar or a particular rate of fertilization, and the final decision made on the farm, can conspire against understanding why an individual piece of technology is not adopted, or why apparently a "sub-optimal" decision is finally made. Consider the simplest case of two resources, water and nitrogen. A narrow focus on water leads to the conclusion that Australian wheat growers are inefficient by operating below the attainable water use efficiency of 22 kg/ mm/ha (Sadras and Angus 2006). A combined focus on water and nitrogen indicates that, by operating below

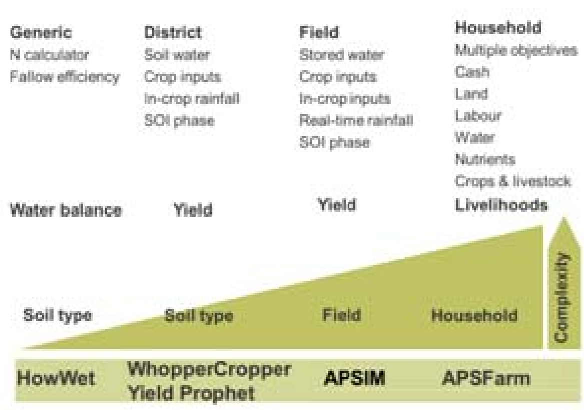

Figure 2. Some of the systems analysis tools derived from the Agricultural Production Systems Simulator (APSIM).

this benchmark, farmers are solving the nitrogen-driven trade-off between efficiency in the use of water and nitrogen (Sadras and Rodriguez 2010). Some of these concepts will be explored in two case studies one from a mixed cropping – grazing farm from Roma, Queensland Australia, and one from a small-holder farmer in Mandela Village, Morogoro, Tanzania.

A Mixed Cropping and Grazing Farm from Roma, Queensland, Australia

Mixed grain and grazing farms in Queensland usually allocate the more favourable soils (lower slope, fewer stones and higher water-holding capacity) to grain cropping i.e. wheat and sorghum. The remainder of the farm is usually on native or improved grass pastures. The pasture areas are used for maintenance and cattle fattening. Forage crops are also grown on soils that could be cropped although they may have some constraints compared to the areas used for grain cropping. The forage is used for quicker fattening of animals, especially when pasture growth is limited.

The farm in question occupies 4,000 ha with approximately 40% of the farm suitable for cropping enterprises. The farm carries 1,100 to 1,500 cattle. Cropping involves four wheat crops in succession followed by a chickpea crop. Five fields, each of 220 ha, are allocated solely to cropping. The soils were divided into two water-holding capacities: a high plant available water capacity (PAWC) soil in 75% of the land area; a medium PAWC soil in 25% of the land area. The farmer was interested to understand the impact of alternative allocations of lands of different suitability for cropping enterprises, between his cropping and grazing enterprises, on the trade-offs between profits and economic risk, in face of present climate variability and expected climate change. As a mixed-farming business, the balance between cropping and livestock enterprises is of paramount importance. This is driven by the returns from the separate enterprises. According to the farmer, the main factors of influence (apart from climate) are: commodity prices, input prices, land area capability (soil effect), farmer preferences for cropping or livestock enterprises, availability of labour, and distance from markets.

Following the methodology in the framework in Figure 3 (Gibbons and Bunderson 2005; NUANCES www.africanuances.nl; Giller *et al*. 2011) a participatory modelling program was developed in which we:

- Described farms and farmers' current farming system, their socio-economic settings and their problems, needs, priorities, and objectives;

- Explained, using whole farm simulation models, the implications of present farmers' decisions on attributes of importance to the farmer e.g. trade-offs between profits and risks;
- Quantitatively explored farmer's options, "what if?" type questions, and feasible scenarios of their interest;
- Discussed the results with farmers in terms of the implications from alternative interventions within the bounds of existing constraints in resources, and farmers' preferences, and learnt (all of us) on farm attributes that increased its performance and capacity to cope with variability and change.

The performance of present farmer's management, both under the Baseline and tested climate change scenario (CCS 2030 projection assuming an A1FI emissions scenario, and MRI-GCM232), was closer to the efficiency frontier (i.e. open circles in Figure 4). This indicates that based on the tested management strategies, this farmer is a very good operator and that his options to increase profits without increasing risks would be limited. However still he could move along the efficiency frontier, i.e. towards higher or lower profits and risks. Figure 4 also shows that none of the tested combinations of allocation of land to cropping, or forages, were able to mitigate the expected impacts from this CCS. Figure 4 shows both under the Baseline and CCS, increases in the allocation of land to cropping will increase profits and risks, and conversely reducing the area to cropping would reduce profits and risks under the CCS. The impacts of the CCS on the profits on this farm were small. This confirmed the expected higher resilience of diversified grazing systems from the more arid regions in western Queensland. We also estimated that an allocation of land to cropping of 45%, both for the Baseline and CCS, split the levels of profit on the Pareto front in two groups, i.e. mean profits of $332,000/year and $653,000/year for the Baseline; and of $214,000/year and $470,000/year for the CCS.

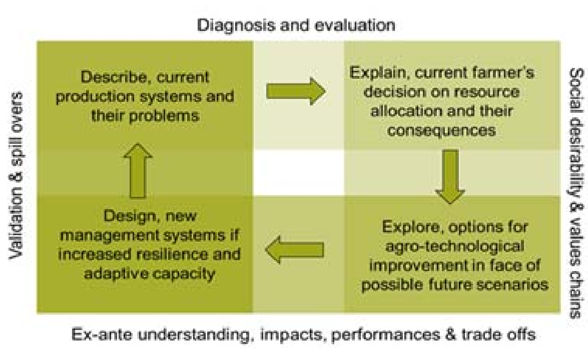

Figure 3. Phases of the continuous improvement process in which impacts and vulnerabilities are identified, described, options for adaptation explored, and new farming systems designed with participation of farmers and other stakeholders.

Smallholder Farming Systems in Africa Investing in Fertilizers

The dependence of farmers on low and or highly variable rainfall across most of south eastern Sub-Saharan countries, in combination with depletion of soil fertility, makes the effort of intensifying maize based production systems and lift farmer's incomes a rather daunting and complex problem. In general, climate risk acts as a disincentive for farmers to invest in needed technologies and markets, reducing our chances of increasing yields and reducing risks. Across the region, lifting the productivity of crops, i.e. grains and biomass, is paramount to start building more sustainable and profitable cropping systems amid achieving the Millennium Development Goals in Africa. Farmers' perception of risk and its consequences is paramount here. How farmers' perceptions relate to the actual variability in yields driven by climate variability, and to what extent existing yield gaps driven by poor agronomic practice or lack of use of agricultural

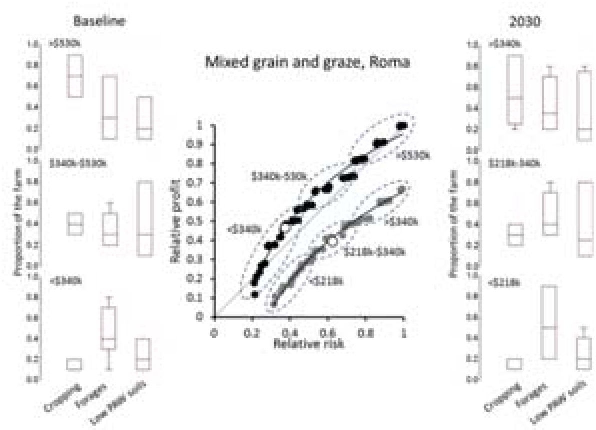

Figure 4. Relationship between profits and risks (relative to the farming system having the highest profits) for a mixed grain and grazing farm case study from Roma, Queensland. The two simulated scenarios include a Baseline (1961-2010) (black circles), and a 2030 climate change scenario i.e. A1FI emissions scenario, and MRI-GCM232 model (grey circles). Only farming systems within the top 10th percentile of the Pareto rank are shown. The profits for the top, middle and bottom terciles are shown with the dashed envelopes, and the performance of the present farm management is represented by an empty circle. The boxplots show the changes within each profit range for the fraction of land allocated to cropping, and from the non-cropping land the fraction allocated to forages.

inputs are responsible for farmer's risk averse attitudes. For example, the farmers in the example below i.e. Mandela Village, Tanzania, did not use chemical fertilizers, applied conventional agricultural practices, and performed limited weeding in his fields, and only during the wet season. In general, innovations that could increase productivity were avoided as they are seen as risky.

Smallholder farmers at Mandela have limited capacity to invest in crop improvement technologies and crop yields for staple (maize) and cash crops (sunflower, sesame) are persistently low (eg. average farmer yield = 730 kg maize / ha, 1999-2011, no. = 8). Experience with and use of fertilizer inputs by farmers at Mandela is almost non-existent and hence water productivity is also extremely low (eg. 0.5-2 kg maize grain/mm/ha). Even where fertilizer has been applied in recent years, yield responses (WP = 2-4kg/mm/ ha) are restricted by poor agronomic practice (inadequate, late weeding, low populations etc) and widespread use of recycled seed. Using a combination of farmer participatory methods (focal group discussion, questionnaires, resource allocation maps) and crop simulation, we engaged with farmers at Mandela over a 3 day period to explore what technology options could reliably increase their crop yields with limited investments under rainfed conditions.

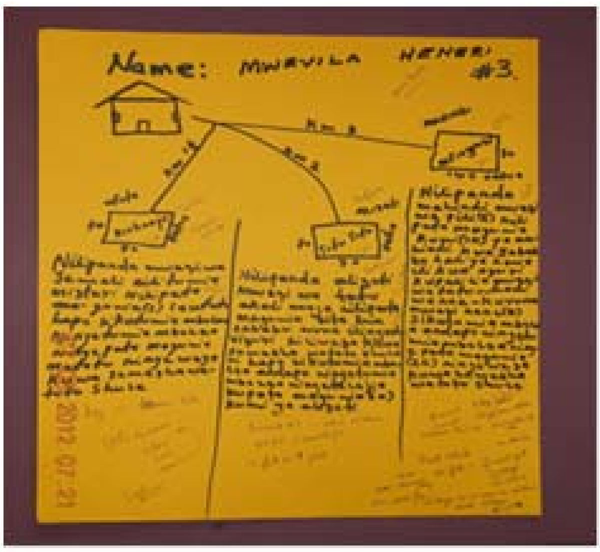

Figure 5. Farmer resource allocation map at Mandela village, Tanzania

Farmers drew resource allocation maps (Figure 5), providing a description of farmer's field soils, management practices and yield outcomes for the 2011 cropping season. Farmer scenarios were modelled using long term climate records from Ilonga Research station (1999-2011, within 50 km of Mandela). Simulated yield outputs for one farmer's situation were shared with the farmer group to explore management changes in relation to fertilizer use, weeding frequency and interactions with seasonal rainfall.

The rainfall data presented to farmers showed only 1 season (2000) in 13 as having less than 400 mm of in-crop rainfall (Figure 6, left picture) and the model also simulated crop failure in this particular season (Figure 6, right picture). This compared with farmer survey results that reported 1 in 3 seasons as being drought affected in this environment. Clearly, the farmers displayed a much higher perception of rainfall risk in this environment than the rainfall and model outputs suggested.

Figure 6. Seasonal (Feb-Jun) rainfall totals (left), and simulated maize grain yield (bags x 100 kg /acre) for farmer's field and management (described at top) at Mandela (right). Yield outcomes for alternative management (50 kg urea/ha, one weeding in crop) are shown at bottom (bags/acre)

Using farmer's management in the 2011 season (clay soil, improved maize planted Feb 10, weeded twice, no manure or fertilizer, see Figure 6, right picture, top of the graph), simulated maize yield was very close to the farmer's yield. Using the same management across years, the average simulated yield was also close to the farmer's average for the field, but yields were not close in all seasons discussed with the farmer (Figure 6, right picture, see asterisks). However, this comparison is complicated by the assumption of identical management across seasons. With a limited investment in fertilizer (50 kg urea /ha), maize yield across seasons was 140% higher than farmer practice and this response was highly reliable across seasons, including the driest season. This demonstrated to the farmers that a small investment in fertilizer was not risky and they agreed to do on-farm trials in the following cropping season to test fertilizer responses in their own fields. With one weeding, instead of two, simulated maize yield was zero in 4 of the 13 seasons and 75% lower than farmer practice across seasons. For farmers with labour resources but limited capital, this result demonstrated the value of an extra weeding for their maize production.

Conclusions

The examples here showed that context relevant information generated in participatory modelling exercises has the potential to give researchers, agri-businesses, policy and farmers:

- more confidence on opportunities for investment in research and development programs;
- unbiased quantitative information on the likely outcomes from the application of new technologies, or new crop, animal and farm management strategies;
- quantitative information on benefits and trade-offs from alternative policy interventions.

We concluded that irrespective of the level of income, e.g. commercial or smallholder farming, systems modelling approaches like those described here could be used to support better-informed discussions between a range of stakeholders. The expected outcome of these discussions should be for people to improve their understanding opportunities, risks and uncertainties and in this way generate incentives for people to invest in their farming systems, and increase crop yields, and improve their economic and food security status, and ultimately promote the economic growth of rural communities.

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