Jul 1st, 12:00 AM

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Arnold, Thorsten, "Farm decisions under dynamic meteorology and the curse of complexity" (2010). International Congress on Environmental Modelling and Software. 171.
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Farm decisions under dynamic meteorology and the curse of complexity

Thorsten Arnold

Abstract For agricultural production, climate change will have the greatest impact on water availability. At the same time, rural farming communities are at the heart of poverty reduction strategies. Furthermore, healthy rural societies must be maintained to contain urbanization and associated sprawl. Thus, sustainable adaptation strategies must take into account the complexity of societal responses. However, scientific tools to assess such interactions are lacking. A promising approach is the integration of data and models across scientific disciplines and in collaboration with local stakeholders. Empirical, process-oriented models can even quantify these interactions and feedback. As a contribution to this challenge, the project ‘Integrating governance and modeling’ combined the agricultural economics multi-agent farm decision model MP-MAS and the hydrological model WASIM-ETH dynamically. Models were calibrated empirically, with increasing level of detail and interactions. The stepwise and iterative integration/calibration of these coupled models allowed for sensitivity assessment across disciplines but it also pointed to the relevance of knowledge gaps along disciplinary divides: production risk at multiple decision horizons, the unequal susceptibility of different marketing venues in case of production failures, and farmers’ unequal access to water under fluctuating supply.

Keywords: Integrated assessment; Watershed; Climate change impact; Farming system

1 Introduction

The ‘International Assessment on Agricultural Science, Technology and Development’ calls for a shift toward more holistic research for natural resource management, to resolve the biophysically and socially complex issues of NRM using formal, local and traditional knowledge, and collective, participatory and anticipatory decision making with diverse stakeholders across multiple scales, and to adopt a holistic or systems-oriented approach [...] to address the complexity of food and other production systems in different contexts (p. 59, IAASTD [2008]).

Climate change is a global phenomenon. Its impacts, however, will be felt locally. Agriculture is one of the economic sectors that is most susceptible to climate change because it is nature that provides many of the most relevant inputs – fertile soils, pollination, and clean and sufficient water. However, it is the farmers who must cope with the impacts of climate change, while providing food for the world’s growing population. Ultimately, it is the individual characteristics of a farmer that define his/her personal vulnerability as well as his/her adaptive capacity (ibid.).

With improvements in climate change modelling, the scientific focus has shifted from global circulation models toward regional and more local impacts [Kundzewicz et al., 2007]. Currently, a holistic assessment of impacts on heterogeneous farming systems is still lacking [IAASTD, 2008], even though promising prototype approaches exist that consider the heterogeneity of food producers within their local circumstances (e.g. Rivington et al. [2007]). Agricultural economics, irrigation engineering, hydrology, meteorology, soil sciences, ecology and social sciences are disciplines that all offer certain perspectives on the circumstances of food producers, but no single discipline can fathom the complexity of the rapidly changing environment that most farmers face today.

Climate change impacts can be thought of as several components: a change in mean characteristics such as sea level, temperature and CO2 content of the atmosphere; a change in weather variability and extreme conditions; and indirect impacts because societies function differently after the climate regime has shifted. Global change science has evolved beyond the assessment of mean characteristics toward the analysis of variability and its impact. However, to understand how farming societies may react to weather with changed
variability, an essential starting point is to understand how farmers deal with current weather variability, and their capacity to manage those risks imposed by their biophysical environment.

Integrated, model-based assessment has been suggested as a way to understand cause-effect-chains and feedbacks faced by individual farmers [Rivington et al., 2007], [Berger et al., 2007]. To link these chains and address knowledge gaps along the interfaces of ‘hard’ and ‘soft’ sciences [Ekasingh and Letcher, 2008] with complex, process-oriented and dynamic models, the project ‘Integrating Governance and Modelling’ aimed to improve the usefulness of existing models for irrigation water management, looking at both individual incentives of water users and at the watershed scale.

This paper summarizes how such a complex modelling system can help to describe the environmental constraint ‘weather variability’ which farmers face, as well as their coping strategies. This dual perspective is a first step in understanding the impact of climate change on farmers, because it allows for the assessment of the direct impact of weather variability and also how farmer’s vulnerability depends on his/her access to coping options. Other impacts of a shift of irrigation practices – on water quality and quantity in rivers, on groundwater recharge and groundwater level, and on the natural ecosystem is acknowledge but at this time not investigated further. The paper exemplifies one important interface between hydrology and agricultural economics, by illustrating how the index ‘long-term irrigation security’ is used to fine-calibrate variable irrigation water supply as one major production risk. Furthermore, implications for other interfaces that depend on this link are briefly elaborated. Finally, the challenge of integrated modelling are discussed in a larger context.

2 INTEGRATED MODELLING OF IRRIGATION AGRICULTURE

2.1 Modelling Context

The system of study covers the watersheds of the Putagán, Ancoa, Achibueno and Longaví rivers, in the Maule Region of Chile, between Santiago and Concepcion. At a total area of 5300 km², this region contains approximately 100,000 hectares of agriculturally used lands. During the hot and dry summers, temperatures often exceed 30°C and precipitation is as low as 4mm/month, so all summer crops and pastures require irrigation. Winters are temperate and wet (200 mm/month). During the hot summer months (December-February), irrigation water is taken from rivers that originate in the Andean mountains and are fed by precipitation and snow melt, which starts with the spring thaw in August and lasts well into January. Water is delivered by river organizations through a complex canal system, to smaller user organizations who oversee secondary irrigation canals (irrigation sectors), and finally to farmers. Using inputs such as land, labour, water, fertilizer, knowledge and technology, farmers produce products such as apples, pears, berries, vegetables, rice, corn, wheat and meat, which they sell at prices determined by markets. Over time, meteorology, prices, technology and knowledge evolves dynamically, as does the income and capital of each farmer. Farmers belong to different groups that employ adapted strategies, ranging from small, specialized family farms to large, commercial farm enterprises.

Integrated Modelling System. Under a (semi-) predictive modelling paradigm, a model system was built that integrates the basin-scale distributed hydrological model WASIM-ETH [Schulla and Jasper, 2007] and a bio-economic, agent-based model MP-MAS used for agricultural water use analysis [Berger et al., 2007]. Further, an intermediate model EDIC for connecting channels and intermediate user organizations (sectors) links both scales [Arnold, 2009]. The MP-MAS model uses Mixed Integer Linear Programming, a method established in agricultural economics for farm-level production analysis, and for developing optimal production plans under constrained asset endowments and expected future conditions of markets and the environment [Hazell and Norton, 1986]. Over time, a learning model is implemented that updates and improves expectations. Finally, a crop model is integrated that estimates yield deficit under water stress, based on plant- and location specific parameters and a reduction factor approach. Together, the modelling system allows for the simulation of a vast range of interactions across disciplinary boundaries and for the specification of the interfaces between these disciplines, both quantitatively and dynamically.
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A wide range of empirical data was collected to parameterize the extended model, including two full agricultural censuses (INE 1997, 2007) that provided data on land use, farming and irrigation technologies and crops [Troost, 2009], market prices, local crop parameters and hydro-meteorological time series, and complete land- and water right registries, which were compiled with the help of local water user organizations [Uribe et al., 2009].

**Calibration.** Model components can be used and calibrated as standalone software, to facilitate calibration by disciplinary experts. Then, interactions variables remain external boundary conditions taken from a data base that all team members use. To study the relevance of interactions, more complex model setups are used that internalize one or more interaction processes, including a full hierarchical coupling scheme [Arnold, 2009]. With each integration step, boundary conditions that were external are internalized as dynamic interfaces between model components, and become subject to additional calibration. A fundamental challenge of calibrating a complex, integrated model is the organization of such a step-by-step process in a research team [Arnold, 2009]. On one hand, disciplinary model components should be sophisticated so that researcher partners can publish their disciplinary work in specialized journals, to maintain interest of disciplinary experts. On the other hand, user interfaces for integration must remain simple enough so that specialized and experts are enabled to extend their knowledge beyond their disciplinary expertise and embrace integration with other disciplines. Finally, step-by-step calibration requires that the results of several sub groups are joined into one larger product that is consistent with empirical data. Eventually, models must be refined with improved understanding of interfaces and affected components must be re-calibrated.

2.2 Irrigation Security (IS) and Weather Variability

To calibrate the interaction between transient hydrological conditions and a recursive farm economics model MP-MAS, the transfer of water from rivers to farmers must be understood well. For individual farmers, weather variability results in the economic risk to lose harvest of specific crops, and thus income. The water distribution model Edic is used to simulate and calibrate the fluctuations of water supply to each irrigation sector and total reuse within these sectors.

For a single year, water availability to farmers could be determined and parameterized, with costly measurement efforts for each farm. For a long-term and integrated analysis of the impact of irrigation water use, a more complex calibration index is needed that captures the uncertainty of fluctuating irrigation water supply.

Chilean institutions use two indices to measure irrigation security: (1) the ‘plant satisfaction factor’, which measures the ratio of plant irrigation demand that was actually met, and (2) the percentage of years in which the planned water supply is ‘served’, using the National Irrigation Commission’s (CNR) definition from the ‘Chilean Water Code’. More precisely, two conditions are used to define ‘served’ years: (a) during no more than one month, less than 90% of irrigation demand was supplied; and (b) during no month, less than 85% of irrigation demand was available to farmers.

To compute the irrigation security index, Chilean institutions usually estimate water demand from the total water rights endowment of an area. However, this computation rule is of little use when assessing individual farms – partly because farmers accept a certain yield deficit for some crops, and also because many farmers rely on ‘traditional’ water access that complements water rights-based access [Arnold et al., 2010].

With detailed data and knowledge of complex farming strategies, water demand can be estimated from the cropping pattern of an area, which allows for more detailed analysis and insight: For some traditional crops, water deficiency is quiet common and farmers accept yield reductions in many years, because they irrigate only if enough water and labour resources are available. Other crops are highly sensitive to water deficit and require a high level of irrigation security. In addition, many farmers irrigate not only to increase the yields of pastures, but also for less obvious purposes, e.g. to affirm their customary water entitlements in years of excess supply [Uribe et al., 2009]. To reflect such heterogeneous processes at the micro scale of a farming system, IS can also be computed for each individual crop. By assuming a constant land use
over the full time horizon, $IS$ is estimated using precipitation, plant irrigation demand and water supply for each crop.

In situations of irrigation water shortage, farmers prioritize the crops they irrigate. Local experts group crops by irrigation priority (‘IPG’), starting with 1. perennial investments with high economic value, export vegetables and contract farming (‘fruit plantations’), 2. horticulture, 3. annual higher-value field crops (corn, beans, rice), 4. annual low-value field crops (‘wheat’), and 5. fodder crops, wood plantations and irrigated pastures (‘pastures’) [Berger, 2001]. Local farmers irrigate higher IPGs first and reduce water supply for low-priority crop groups, if necessary. Therefore, any crop-specific $IS$ measure should take such practice into account.

**Calibration of a Model Interface.** To calibrate the water supply for the transient farm production model MP-MAS, the interface model EDIC was calibrated using crop-level irrigation security. This bucket model uses time series data on river flows and precipitation and the total water rights in each irrigation sector. It also routes return flows from upstream to downstream sectors and computes internal reuse. Other input data are land use data from agricultural census, local crop water requirement data and method-specific irrigation efficiency corrections. Irrigation security ($IS$) data was taken from DOH/SMI [2004]: $IS$ ranges from 85% for fruit plantations and horticulture, 75% for annual crops, 85% for spring wheat and 40% for pastures. For spring wheat, $IS$ is high even though it has low priority, because it is harvested before water shortage is severe.

The interface model was re-implemented in MatLab as a slim function with minimum overhead. For each calibration run, the model was executed for 50 years and sector-parameters were modified, ranging from canal efficiency losses, within-sector distribution losses, between-sector return flows and within-sector reuse.

**Calibration Results.** With many degrees of freedom in uncertain and effective parameters (reuse, losses, canal efficiency), calibration can identify a set of parameter combinations that reproduce empirical data (called ‘behavioral’). These are all ‘equifinal’ [Beven, 2001] because empirical data does not allow for the identification of which of these combinations is true. Thus, structural uncertainty within the interface model EDIC remains. However, the complex indicator ‘irrigation security’ allows for the parameterization of the MP-MAS model consistently to weather volatility.

Figure 1 illustrates the effect of proportional reduction of total water supply (x-axis), for one sector ‘05d’, with a variation factor of $(1.0)$ reproducing a ‘behavioral’ set of parameters. On the left side, the y-axis shows the CNR irrigation security index, in the middle it shows the mean plant factor of satisfaction (FoS). From top to bottom, the $IS$ decreases with decreasing irrigation priority. Variability within each group depends on the crop-specific annual cycle of irrigation water demand: crops that grow during early spring are least sensitive (highest $IS$), and plant water demand during during the driest summer months are more sensitive (lowest $IS$).

Furthermore, the CNR $IS$ criteria is more sensitive than the factor of satisfaction and thus better suited for calibration. Finally, for the sector-level aggregation, perfect distribution of water supply among farmers is assumed within each sector.

**Implications for Other Model Components.** The improved description and parameterization of one model-model interface points to a cascade of inconsistencies of other interfaces that must be adjusted, and require additional conceptualization, implementation and data collection. For example, informal water allocation rules seem to play a relevant role when assessing the individual water supply to farmers. Water that is distributed through these informal rules (or even by open access) fluctuates stronger than legalized water, and farmers who rely on it are more vulnerable (for detail see [Arnold et al., 2010]). Another inconsistency is between the farm expectation model and the crop growth model: Full yields can only be harvested in those years when water is plenty, while deficits occur in many years for crops with low $IS$ under dynamic meteorological conditions. From the perspective of the individual farmer, a certain water
deficit and thus a yield reduction must be expected for all crops with irrigation security below 1. As rational actors, farmers would take this into account during planning and adapt their yield expectations accordingly. Further, farmers’ expectations on unreliable water supply and uncertain yield would be consistent with expected crop irrigation demand. The mathematical formalism of the MP-MAS production plan model must thus use reduced (effective) yield demand expectations, typical water supply and effective plant irrigation demand to reproduce reduced yields consistently. In contrary, a crop model that computes actual yield reduction as function of actual water supply would also use actual parameters for maximum yields, water supply and plant irrigation demand. Thus, if irrigation security is used for calibration and conceptual model consistency is to be maintained, then the parameterization of the farm planning model and the crop growth model must be adjusted (for details, see Arnold [2009]). Under dynamic boundary conditions, the adaptive expectation model must also be expanded (ibid).

### 2.3 Coping Strategies of Farmers

The chain of causes and effects starts with water availability in the natural system, its supply to irrigation sectors and then to farmers (according to water endowments), to meeting plant water demand and crop harvest. The chain of events continues with incomes generated from this harvest and ends in savings and investments into farm production assets. Along this cause-effect chain, farmers have several options to minimize the negative impact of weather variability and cope with water shortage. Coping mechanisms that were identified from literature, with farmers and extension workers range from improving water supply and reducing irrigation demand, the (re-)allocation of water endowments and an improved marketing of produce. Coping options range from modification of on-farm practices and technologies, over water management at the level of irrigation sector or the watershed, and finally the marketing strategy.

On-farm practices to reduce water demand range from investing in technology that improves irrigation efficiency (automated sprinklers, drip or pigote) [Troost, 2009]; an adjustment of the crop mix, either with drought-resistant varieties, or by buffering crops with high security demands with crops that are less
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Sensitive to temporary water shortage. Some farmers own water rights far beyond their requirements in normal years, when they leave surplus water for the use of others. Only in dry years, their water entitlements are fully utilized [Arnold et al., 2010]. In recent years, farmers increasingly utilize alternative sources of water more intensely: supplemental irrigation with groundwater is increasing rapidly. More research is recommended on how this will impact the water cycle, especially with a concurrent decrease of inefficient irrigation from surface water sources that contributed to recharge.

Increases of water supply occur either at a larger scale, at watershed or at sector level. In our study region, the Melado canal supplies water from a neighboring watershed. Through these additional and anti-cyclical inflows, water shortages are alleviated. Also at watershed level, a reservoir is being build that dams the Ancoa river, thus adds a new and safe supply [Latynskiy, 2009]. At sector level, farmers may strengthen their engagement in water management organizations and improve the physical canal infrastructure, its maintenance and the enforcement of endowments, partly by accessing financial support through the Chilean government. Such reduction of losses increases the value of every water right, but may interfere with informal water sharing agreements [Arnold et al., 2010].

The improvement of allocative water use efficiency is defined as the transfer from water rights from those holders that create low economic returns to others that can create higher returns. This was the main governmental objective when water rights were established as a tradeble market commodity. Within the study region, little empirical evidence was found that such transfers occur at significant quantity.

Finally, farm income not only depends on the quantity and quality of harvest, but also on the prices that farmers obtain for it. Thus, the conditions of markets and access to these markets may greatly impact the risk with respect to weather variability. Statistical data from ODEPA indicates that the harvest of fruits and especially vegetables is seldom impacted during drought years, while the harvest of wheat and rice fluctuates significantly and in a correlated manner. However, the price impact of such fluctuating production quantities is heterogeneous across market segments: global prices are not impacted by the production of a small region in Chile. National prices, especially for the supply of large supermarket chain, can partly mitigate local production gaps by buying from (slightly more expensive) international markets. In Chile, prices on local markets are usually far below supermarket prices and fully depend on supply from local farmers. These prices strongly fluctuate with weather conditions, with a maximum that is set by supermarket prices. Especially during dry years, the anti-cyclical price response of local markets makes direct marketing an effective risk reduction strategy. Many farmers have diversified marketing strategies and sell to more than one segment, partly because quality and certification requirements can be balanced out, and partly because the lower prices on local markets are still beneficial because intermediaries are cut out. However, little studies are done the relevance of these ‘inferior’ local markets and data availability is poor, because direct marketing is difficult to trace on behalf of the government. Nevertheless, the relevance of this direct marketing and anti-cyclical price fluctuations should be investigated futher.

Several coping strategies were identified that help farmers to mitigate the impact of weather variability. However, most of these options have more than one benefit. For example, supplemental irrigation with groundwater is not only a safe irrigation water source in drought years; it also guarantees that water has consistently high quality, as required for advanced irrigation methods (drip, micro sprinkler). With improved consistency of production inputs and thus harvest quality, marketing can be diversified to supermarkets and export markets. Also, groundwater gives independence from surface water management organizations and personal politics. Thus, the financial viability of one coping mechanisms must also take a broader and integrated perspective.

3 DISCUSSION AND CONCLUSION

By integrating existing modelling software from agricultural economics and surface hydrology, we analyzed farm decisions under dynamic meteorology. Its understanding is a precondition to assess the impact of a climate change on agriculture.

This paper uses the concept of irrigation security to calibrate temporally variable water supply to farmers.
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consistently. To demonstrate the sensitivity of the irrigation security index, total water supply was reduced proportionally. Location-specific plant water demands during each month and the way that farmers prioritize crops in this local context result in different impact of this reduced water supply for each crop.

Even complex coping strategies of farmers can be described within the modelling framework in a process-oriented, theory-based manner. Supply-side mechanisms were already implemented into the software and successfully tested. Calibration of individual model components and of model-to-model interface processes used the best data available and is successful for single processes. This calibration revealed model inconsistencies that could be resolved [Arnold et al., 2010]. Other mechanisms require further research – for conceptual understanding, for technical solutions and regarding the collection of empirical data.

The improved conceptualization and calibration of one model-to-model interface resulted in a cascade of further improvements needed in other model components. While each of these improvements may be relatively simple and within the existing body of knowledge, these inconsistencies only become apparent at a late project stage, after other model components were calibrated with empirical data. If integration is performed in a large research consortium, then these inconsistencies may be located within several model components and managed by multiple researchers from different disciplines and institutions. With more researchers involved, transaction costs increase and significant resources are needed for planning, communication and error management. This cascade is an organizational challenge of orchestration and of timing. The complexity of systems is mirrored in organizational complexity to assess it.

For integrated assessment of global or regional systems that require numerical modelling (oceans, weather, climate change), the spatial scope justifies government investment into large specialized model agencies, for example climate change research centers or meteorological services. Here, departments can respond to the organizational complexity: departments specialize on data management, visualization, data collection, data quality assurance, calibration and analysis, model architecture, numerics and model component development. Also, longer-term funding is secured to minimize staff turnover and knowledge loss.

The limited scope of smaller watersheds and irrigation management confines the resources that can be justified for their assessment. Nevertheless, local impacts of climate change are equally complex and their analysis requires knowledge that is equally dispersed across multiple disciplines. Furthermore, cause-effect chains must be assessed within their local context, and they may vary qualitatively at each location. Currently, researchers must use ‘patience and perseverance’ [Ekasingh and Letcher, 2008] to resolve the host of interfaces and data transfers between model components. However, as long as the timing of a research process conflicts with the pace of the world of policy making, then integrated modelling remains confined to the academic realm. Only by reconciling these time frames, the ‘outcome gap’ [K.B. Matthews, in IMACS 2009] of research for NR management can be bridged, and the ‘yet another modelling framework - phenomenon’ of current research [Evert et al., 2005] can be overcome.

Little procedural knowledge exists on how to apply integrated modelling under a given resource constraint and a given research setting (compare [IMACS, 2009]). Can lessons from successful global change modelling be translated to smaller systems, for example small watersheds? What would an institution look like that provides integrated, meaningful and timely support to watershed management? What organizational form would be required to use complex modelling in a local context? While scientists agree on the importance of integrated modelling and have proven its feasibility in numerous projects, the IAASTD concluded that agricultural research has failed to deliver its promises to meet development goals in praxis so far. The intergovernmental panel concludes that ‘Business as usual is not an option’ [IAASTD 2008].

ACKNOWLEDGEMENTS

We thank the CGIAR Challenge Program on Water & Food and Alechile (DAAD/CONICYT) for financial support. We also thank all researchers, local partners and farmers who supported this research project, especially Hamil Uribe and his family. This paper was written under the direct impression of the earthquake that struck Chile in Feb. 27, 2010. The study region around the city of Talca is among the areas hit hardest, and left in rubbles.
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