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An agent based model to simulate structural and land use changes in agricultural systems of the argentine pampas

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A B S T R A C T

The Argentine Pampas, one of the main agricultural areas in the world, recently has undergone significant changes in land use and structural characteristics of agricultural production systems. Concerns about the environmental and societal impacts of the changes motivated development of an agent-based model (ABM) to gain insight on processes underlying recent observed patterns. The model is described following a standard protocol (ODD). Results are discussed for an initial set of simplified simulations performed to understand the processes that generated and magnified the changes in the Pampas. Changes in the structure of agricultural production and land tenure seem to be driven by differences among farmers' ability to generate sufficient agricultural income to remain in business. In turn, as no off-farm or credit is modeled, economic sustainability is tied to initial resource endowment (area cropped). Farmers operating small areas are economically unviable and must lease out their farms to farmers operating larger areas. This leads to two patterns: (a) a concentration of production (fewer farmers operating larger areas) and, (b) an increase in the area operated by tenants. The simulations showed an increase of soybean area, linked to the higher profitability of this crop. Despite the stylized nature of initial simulations, all emerging patterns are highly consistent with changes observed in the Pampas.

1. Introduction

The region of central-eastern Argentina known as the Pampas is one of the main cereal and oilseed producing areas in the world (Calviño and Monzón, 2009). Climate fluctuations, technological innovations, and institutional and economic contexts have shaped agricultural production in the Pampas. This region has shown significant trends in precipitation during the second half of the 20th century (Berbery et al., 2006). A marked increase in late spring and summer rainfall (Minetti et al., 2003) displaced westward the transition to semi-arid regions that marks the boundary of rainfed agriculture (Berbery et al., 2006; Magrín et al., 2005). Technological innovations such as the wheat/soybean double crop (that allowed two harvests in one cycle), no-tillage planting, and genetically modified (GM) crops have played a large role in the expansion, intensification and specialization of agricultural systems (CASAFE, 2009; Qaim and Traxler, 2005). Institutional factors such as the creation of governmental and stakeholder institutions for agricultural research and extension enhanced dissemination of technologies and fostered growth of agricultural output (Barsky and Gelman, 2009). Economic drivers also favored agricultural expansion: political and economic reforms in the early 1990s unleashed Argentina's natural comparative advantages in the production of field crops (Eakin and Wehbe, 2009; Schnepf et al., 2001). Demand for animal protein in fast-growing economies-in-transition created a large market for Argentine grains, and demand for biofuels is an increasingly strong driver (Lamers et al., 2008).

The intertwined effects of climatic, technological, institutional, and economic drivers induced significant changes in land use patterns and the distribution of production and tenure (i.e., structural characteristics) of agricultural production systems of the Pampas (Baldi and Paruelo, 2008; Viglizzo et al., 1997). Agriculture has expanded considerably, displacing other crops, pastures, and native grasslands (Magrín et al., 2005; Pengue, 2005; Viglizzo et al., 2011).

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The most remarkable change in land use has been the dominance of soybean: introduced in the early 1970s, soybean area (production) reached 5.1 Mha (11 Mtons) in 1990 and exploded to 18.0 Mha (40 Mtons) in 2006. The 1996 introduction of GM herbicide-tolerant soybean played an exceedingly important role in the soybean expansion, due to clear cost reductions from better weed control and lower energy costs, and much simplified agronomic management (Qaim and Traxler, 2005; Trigo and Cap, 2003).

A second observed pattern is the increase in the average area operated by farmers, accompanied by a decrease in the number of smaller farms (Gallacher, 2009). As in most market-oriented agricultural production systems (Miljkovic, 2005; Wolf and Sumner, 2001), there is a trend for the number of farms to decrease progressively, often to the benefit of a relatively higher number of larger farms. According to Argentine agricultural censuses, the average area of a production unit increased from 375 ha to 776 ha between 1988 and 2002; the proportion of total area corresponding to smaller production units (< 200 ha) decreased from 8.6% to 1.6% over the same period (Reboratti, 2005).

A third historical pattern is the rapid change in land tenure (i.e., the land ownership regime) in the last few decades. Currently, about half of the area cropped in the Pampas is not owned by farmers cultivating it (Piñeiro and Villarreal, 2005). A number of studies suggest that rented land is managed differently from owned land (Carolan, 2005; Soule et al., 2000). Our examination of farmers' records in the Pampas confirms that land owners often follow a rotation of crops that is ecologically beneficial; tenants, on the other hand, tend to maximize short-term profits. The differences in goals between land owners and tenants suggest that land tenure regime may induce quite dissimilar land use patterns.

Despite its economic importance, the agricultural sector of Argentina historically has received very little government support. A national agricultural policy – understood as long-term planning at regional or national level – has been almost inexistent (Deybe and Flichman, 1991; Schnepf et al., 2001). As a result, the evolution of land use and agricultural production in the Pampas has been mainly the result of individual decisions influenced by relative profits across competing activities, rotational considerations, and other contextual factors (Eakin and Wehbe, 2009). While agricultural decisions typically are made by individuals at a farm scale, larger-scale (regional, national) complex land use patterns often emerge that cannot be predicted from the simple summation of individual behaviors (Beratan, 2007).

Although Argentina is enjoying the economic benefits of increased agricultural production, worries are growing about long-term environmental and societal impacts: the sustainability of production, life support systems and farmers' livelihood is receiving increased attention (Altieri and Pengue, 2006; Binimelis et al., 2009; Kessler et al., 2007; Manuel-Navarrete et al., 2009; Pengue, 2005; Viglizzo et al., 2011). Such concerns motivate our development of an agent-based model (ABM) of agricultural production in the Pampas to gain insight on processes underlying recent observed changes.

2. Modeling approach

We adopt agent-based modeling as a suitable approach to quantitatively model agricultural systems, their structural change, and endogenous adjustment to policy interventions (Happe et al., 2004). Agent-based modeling is a powerful technique for simulating the actions and interactions of autonomous individuals to assess emerging system level patterns (Gilbert, 2008; North and Macal, 2007). An ABM consists of a collection of autonomous and heterogeneous decision-making entities (agents) interacting with one another and an environment. Agents have information about attributes or state of other agents and the environment, and have access to past and current values of their own state variables (e.g., economic outcomes). Agents make decisions using both prescribed rules and analytical functions; decisions are based on the information agents have available (Gilbert, 2008). An ABM also includes rules that define the relationship between agents and their environment, and rules that determine scheduling of actions in the model (Parker et al., 2003).

Agent-based models (ABMs) have been applied to a variety of problems in recent years (Heath et al., 2009; Heckbert et al., 2010). There is a vast literature on ABMs and land use changes; see reviews by Parker et al. (2003) and Matthews et al. (2007). Agricultural applications are described in Berger (2001), Berger et al. (2006), Happe et al. (2008, 2009), Nolan et al. (2009), Freeman et al. (2009) and Schreinemachers and Berger (2011). In the region for study, the only previous use of ABMs is, to our knowledge, the simulation of changes in rangeland use in Uruguay by Morales Grosskopf et al. (2010). Our model has many similarities with other agricultural land use models such as FEARLUS (Polhill et al., 2010), AgriPoliS (Happe et al., 2004), MP-MAS (Juhola and Westerhoff, 2011; Schreinemachers and Berger, 2011) and a model of the Canadian Prairies by Freeman et al. (2009). FEARLUS and AgriPoliS are the two models most similar to ours and, indeed, our main source of inspiration for many of the processes we included. Table 1 summarizes and compares the main characteristics of these two models and our model of agricultural production in the Pampas.

The paper is organized into four major parts. In the first part, the initial version of our model is described to the extent possible within the space constraints of the paper. In the second part, we provide some details about the verification and validation process of our model. In the third part, we describe a set of simplified scenarios simulated with our model. Finally, we present and discuss results from the simulations.

3. The simulation model

Our model description follows closely the ODD (Overview, Design Concepts and Details) protocol originally proposed by Grimm et al. (2006) and subsequently reviewed and updated by Grimm et al. (2010). Examples of ODD protocol use can be found in Polhill et al. (2008) and Schreinemachers and Berger (2011). The organization of the sections of this paper follows the elements of the ODD protocol. However, we acknowledge that alternative approaches have been proposed for representing land use models, for example, ontology-based descriptions (Beck et al., 2010; Janssen et al., 2009). To present an alternative model description, we organized the comparison Table 1 following the main classes of the Conceptual Design Pattern (also known as the "Mr. Potatohead" approach) proposed by Parker et al. (2008).

3.1. Overview

3.1.1. Purpose of the model

Our model is intended to explore and understand evolving structural changes and land use patterns in agricultural systems of the Argentine Pampas. Special emphasis is placed on three structural patterns observed in recent decades: (a) an increase in the area operated by individual farmers,[1] accompanied by a decrease in the number of active farmers, (b) an increase in the amount of land operated by tenants and, (c) changes in land use patterns, in particular, the increasing dominance of soybean.

[1] We do not refer here to "larger" or "smaller" farms, as farm sizes are fixed and set at the beginning of a model run; what changes is the total amount of land operated by an individual – that may include one or more separate farms.

Table 1
Brief description of the main elements of the agent based model of agricultural systems in the Argentinean Pampas (Pampas Model) and the two models most similar to this: FEARLUS and AgriPoliS. Each row corresponds to the classes (and their main elements) of the CDP (Conceptual Design Pattern) proposed by Parker et al. (2008). We used the question mark when we could not find or identify the details for an element.

	Pampas model	FEARLUS	AgriPoliS
Information/data classes	Abstract cellular landscape. Each cell represents a farm of specific size and soil type (6 equally sized parcels/plots per farm; plots are units of decision-making for land use)	Abstract cellular landscape. Each cell has associated biophysical characteristics. A group of cells form a parcel for which separate land use decisions are made; various parcels make up a farm	Abstract cellular landscape. Each cell represents a plot of specific size with different biophysical characteristics. Plots are units of decision-making for land use. A group of cells form a farm
	Agents may operate one owned farm and many rented farms	Agents may own (and operate) multiple farms	Agents may operate multiple owned and rented farms Agents interact indirectly with all other agents through factor (e.g. land) and product markets
	Only physical neighborhood (Moore)	Social and physical neighborhood (hexagonal, Moore and von Neumann)	?
	Climate and economic conditions referred as external conditions	Climate and economic conditions referred as external conditions	
	Only agricultural production activities considered	Agricultural and livestock production activities considered	Agricultural, livestock, short-term capital and labor production activities considered
	Crop yields read from lookup tables and economic results are computed from yields, prices and costs (input data)	Yields and economic results read from lookup tables	Activity outputs read from table
Interfaces to other models	DSSAT cropping system model used to simulate crop yields	?	?
Demographic classes	One main type of agent that represents a farm household	Agents that represent farming business or family (*land managers*). Agents that represent government	Agents represent farms or agricultural holdings. A market agent coordinates the working of markets
	Agents decide how much land they farm and assign land use to their farm(s)	Agents assign land use to their farm(s)	Agents decide investments (building, machinery, equipment) and land use (referred as production) All agents maximize farm household income (decisions made using recursive mixed-integer linear program)
		Agents have different *algorithms* to choose land use and particular parameter values	
	Individual agents may have different mechanisms to choose land use and parameter values for each mechanism	Algorithm is defined by subpopulation to which agent belongs	?
	Agents store their wealth, aspiration levels, recent land use, and economic results for farms they operate	Agents store their wealth, age, subpopulation membership, land use algorithm, recent land use and yields in parcels they own	
Land use decision	Agents form dynamically an economic aspiration level (AL). AL is used as input to land use decisions	A fixed aspiration threshold (AT) is specified exogenously for each land manager (depending on his subpopulation). AT is used as input to land use decisions	Agents form expectations about prices and costs, following *Adaptive expectations theory*
	First, an agent's economic outcome is compared with his AL. If AL is met or exceeded, previous land use is repeated; otherwise, a new land use is adopted. Second, if necessary, a new land use is selected using agent-specific mechanisms and parameters such as optimization of expected utility or imitation of strategies by physical neighbors (the neighbor to be imitated is selected with a probability proportional to economic outcome)	First, the yield of a parcel is compared with the agent's AT. If AT is met or exceeded, previous land use is repeated; otherwise, a new land use is adopted. Second, if necessary, a new land use is selected using "experimental" or "imitative" strategies. The experimental strategy involves random selection of a new land use. The imitative strategy implies the selection of a new land use by weighting the frequency and yields of the set of land uses appearing in an agent's social neighborhood	Agents aim to maximize household income. They make production and investment decisions simultaneously based on a recursive mixed-integer linear program. Agents differ in specialization, farm size, factor endowment, technology, and managerial ability. They do not know about other farms' production decisions, factor endowments, size, etc
Land exchange class	The model includes only land rental market; no land sales Land rental price is exogenous (current version)	The model includes a land sales market with endogenous formation of sales price An auction mechanism is behind the land sales market (using first-price or Vickery mechanisms)	The model includes a land rental market with endogenous formation of rental price An auction mechanism is behind the land rental market (using various mechanisms)
	Land owners who do not have sufficient wealth must rent out their farms (supply). Agents with surplus wealth may rent in additional land (demand). Tenants select suitable farms from the supply list (excluding farms they cannot afford and farms too small to be of interest; distance to home is not an issue). Landlords may return to active farming if they accumulate sufficient wealth. All rental contracts are renegotiated every cropping cycle	Land managers with negative wealth are considered bankrupt, and must sell all their land. Land managers with sufficient wealth use a bidding strategy to decide how much they would offer for parcels available for sale (but only in their physical or social neighborhood). Finally, the "land allocator" special agent assigns a new owner for each parcel for sale	Farms become available for rental due to (i) expired rental contract, (ii) illiquidity or (iii) farmer retirement or (iv) low income expectations. Each actor interested in available land plots communicates bids to the land owner (not public)

3.1.2. Entities, state variables and scales

The model consists of three main entities: the environment, the farm and the farmer. The current model environment aims to represent the northern part of Buenos Aires Province, the most productive sub-region of the Pampas that has a long agricultural history (Calviño and Monzón, 2009); this region encompasses about 10,000 km^2 (1,000,000 ha). The model environment is a stylized 2D grid including a number of farms defined at initialization. Each grid cell represents a farm of variable size, also defined during initialization. The main state variables of the farms include size, soil type, owner, operator, land allocation and operator's aspiration level (specific for a farmer-farm combination). All modeled farms have the same soil and experience the same climate in the version of the model presented here. Although the current environment does not represent real geography, the model is spatially explicit because there is a topological relation among farms (a Moore neighborhood is considered).

The model involves one main type of agent: farmer households or family businesses (i.e., no corporate farms, which have different decision-making procedures) that operate owned and/or leased farms. As such, we do not model the life cycle of specific individuals who enter farming, get old and retire. Instead we assume that farming exit is only due to lack of capital. The main state variables of the farmers include operated farms, operational status and working capital. As in other land use models – such as the FEARLUS, AgriPoliS, MP-MAS and the Canadian Prairies model – agents may have different land allocation strategies and financial characteristics. A special agent type is a "Manager" that performs calculations that need to be available to all agents. A more detailed description of the state variables that characterize each entity is provided in the "Supplementary Data" accompanying this manuscript and available online.

3.1.3. Process overview and scheduling

One model time step represents a cropping cycle (from April to March of the next calendar year). In the simulations presented here, the model loops through 100 simulated cropping cycles (labeled with numbers starting at 1900) after performing all initialization steps. Fig. 1 shows the order in which model processes take place within a cropping cycle and for a single farmer; details about each process are given in Section 3.3.

At the beginning of each production cycle a farmer adjusts her economic aspirations for the current cycle based on the *expected* status of context factors (climate conditions, output prices, input costs). Then, the farmer decides whether she can (a) farm additional land, (b) maintain the same area as in the previous cycle or, instead, (c) must release some or all of the previously farmed area. Currently, the only way to expand cropped area is by renting in additional land (i.e., the model does not include land sales). Subsequently, farmers allocate their land among a realistic choice set of Activity/Managements (AMs), defined by the combination of (a) an Activity (maize, full-cycle soybean and wheat-soybean) and (b) agronomic Management. After land is allocated, the physical outcome (yield) of each selected AM is retrieved from lookup tables built using biophysical crop models and experienced climate conditions. From simulated yields and experienced crop prices and input costs (specified as model inputs), economic returns are calculated: the end result is an updated value of a farmer's Working Capital (WC) at the end of the production cycle. Achieved economic returns are then assessed in relation to the farmer's initial aspiration and peers' performance. This assessment drives an adaptation of the farmer's Aspiration Level – AL, a special value that separates outcomes perceived as successes or failures (Diecidue and van de Ven, 2008) – that may be used as input to decisions in the following cropping cycle. This schedule, at high level, is broadly similar in terms of events and events ordering to that of FEARLUS model (Polhill et al., 2008).

3.1.4. Software environment

Multiple software frameworks exist that reduce significantly the programming effort and time required to develop ABMs and the chances of making errors (Nikolai and Madey, 2009; Railsback et al., 2006). Our model is implemented in REPAST, the REcursive Porous Agent Simulation Toolkit (repast.sourceforge.net), a free, Java-based, open-source toolkit (North et al., 2006).

3.2. Model design concepts

3.2.1. Emergence

Four main regional-level features emerge from individual farmers behavior and interactions among agents: (a) regional land use (area planted with each crop), (b) regional production of major crops, (c) regional farm structure (frequency distribution of areas operated by active farmers), and (d) regional land tenure (the areas operated by owners and tenants).

3.2.2. Adaptation

In each cropping cycle, farmers may use three adaptation mechanisms: (a) increasing or reducing the area farmed, depending on available working capital (WC), (b) choosing a different land allocation if they are unsatisfied with previous outcomes, and (c) adjusting their AL; details on aspiration adjustments are provided in the "Sub-models" section.

3.2.3. Objectives

Farmers aim to maintain or increase their WC, and to maintain or expand cropped area. If a farmer's WC drops below the minimum required for production, she must reduce the area cropped or even exit farming. During the land allocation process, farmers seek to achieve economic outcomes above their AL, otherwise they will be unsatisfied and will search for a different allocation.

3.2.4. Learning

No learning is included in the model version described here.

3.2.5. Prediction

Farmers who decide to switch land allocation – because of dissatisfaction with achieved results – implicitly assume that their most recent allocation also is likely to be unsatisfactory during the following cropping cycle. Farmers also may have expectations about the status of context factors in the upcoming cycle based on external information (e.g., seasonal climate forecasts, commodity price projections or futures markets).

3.2.6. Sensing

Farmers are aware of their current WC and consider this variable in decisions about renting land in or out. Farmers have access to past and current land allocations and farm-wide gross margins (FGMs) for all farms over which they make production decisions. Farmers are assumed to know the economic outcomes achieved by their peers (in this case, their eight Moore neighbors) during a cropping cycle. Finally, farmers are aware of the expected and experienced status of external context factors and of current land rental prices.

3.2.7. Interaction

Farmers may imitate the land use of neighbors (see Section 3.3.1.2). Landlords and tenants interact indirectly through the land rental process; the interaction is mediated by the Manager, who matches the supply and demand of rental land.

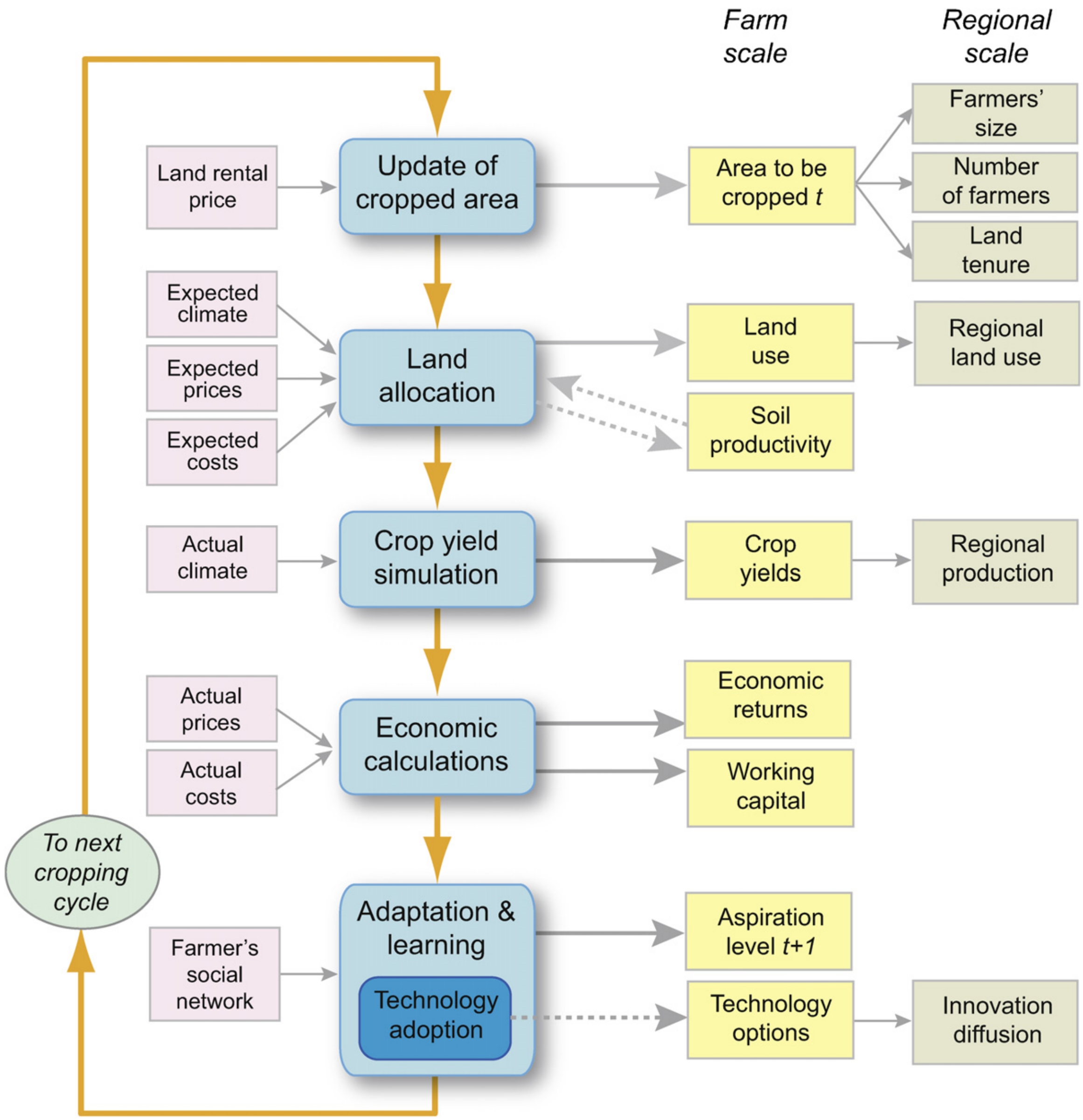

Fig. 1. Conceptual diagram of the sequence of processes for a single farmer in a production cycle. External context drivers are listed on the left of the diagram, and state variables associated with each process are shown on the right. Farm-level state variables can be subsequently aggregated into regional-level variables (e.g., farm-level crop yields can be aggregated into regional production of each crop).

3.2.8. Stochasticity

Stochasticity is present in multiple model components. During initialization (i) farm sizes are generated stochastically (in some scenarios) so that size distribution is consistent with agricultural census data; (ii) farmers are randomly assigned to each farm (but respecting observed proportions of owner- and tenant-operated farms); and (iii) AMs are stochastically assigned to each farm plot. Once the model starts iterating, a stochastic mechanism decides if landlords with sufficient WC return to active farming. The order in which potential tenants choose rental farms is stochastic. Finally, land use selection mechanisms involve either random selection or imitation (in which the peer to be imitated is selected randomly).

3.2.9. Collectives

There are no aggregations of individuals or intermediate levels of organization in the current version of the model.

3.2.10. Observation

Multiple low-level and aggregated variables are collected after each production cycle and written to output files at the end of a simulation. The output variables are organized into four text files containing separate results for farm plots, farms, farmers, and the Manager.

3.3. Model details

In this section we provide brief descriptions of (a) the main sub-models and mechanisms involved in the model, (b) the initialization process and, (c) the main input variables. Additional details about the initialized values of some state variables and the prescribed trajectories of input variables are provided in Section 4 (where specific simulated scenarios are described).

3.3.1. Main sub-models

3.3.1.1. Update of area cropped by each farmer. This sub-model defines the area to be farmed by an agent on a production cycle. The only way to expand production is by renting in additional land; the current model does not include land sales (a reasonable approximation, as farm sales volume in the Pampas is very low). Land rental price is exogenously defined; endogenous price formation has been included in a newer version and initial details can be found in Bert et al. (2010).

The area update sub-model involves two main stages: (a) definition of supply and demand of for-rent farmland, and (b) matching of supply and demand. The first stage identifies potential tenants (demand) and farms offered for rent (supply) on a cropping cycle. Given sufficient WC, all farmers will seek to increase cropped area by renting in additional land; these farmers are potential tenants. Conversely, farmers with insufficient WC must release some or all rented land, or even rent out their own farms (in the case of owners). Landlords who have accumulated the necessary WC can return to active production. Two stochastic mechanisms are used to define whether landlords return to farming: (i) a constant probability of return ($P = 0.25$) on every cropping cycle, and (ii) a probability of return that starts at $P = 0.50$ and decreases to 0 after six cycles. Both mechanisms reflect the real-world low proportion of landlords who return to active status after they get used to steady rental incomes with minimal risk. Furthermore, the second mechanism reflects the empirical fact that farmers are increasingly unlikely to return to production the longer they stay as landlords, as they become technically outdated.

The second stage of the sub-model matches farmland supply and demand. In this stage, each potential tenant evaluates the list of farms available for rental and excludes farms that either (a) she cannot afford to operate (e.g., farms that are too large) or (b) are too small to be of interest. Because farmers who operate large areas generally will not consider renting small farms, a "minimum area acceptable" for leasing is defined as a function of the total area operated by a farmer. The potential tenant picks the farm with higher expected gross margin from the list of suitable rental farms. If farms remain for rent after cycling through all potential tenants, inactive agents (created at initialization) are assigned to the remaining farms and given WCs sufficient to operate them.

3.3.1.2. Land allocation. This sub-model defines land use in a farm on each production cycle: it allocates an Activity/Management (AM) to each plot. An AM is defined as the combination of a production Activity and a specific agronomic Management (AMs are termed "land uses" in FEARLUS). The model includes three agricultural Activities: (a) full-cycle soybean, (b) maize, and (c) wheat/soybean double crop. In turn, each Activity has two possible agronomic Managements, defined by unique combinations of genotypes, planting dates, densities and fertilization. That is, a total of six AMs are defined that are representative of current practices in the target region. AMs were defined with experts from the Asociación Argentina de Consorcios Regionales de Experimentación Agrícola (AACREA, www.aacrea.org.ar), the farmers' organization partnering in this project.

The first step in the land allocation module is the definition of the choice set. We assume that all farms have six equally sized plots; therefore, the proportion of farmland allocated to each AM may take seven possible values: [0, 1/6, . . ., 6/6]. With six AMs and six plots per farm, there are 462 Activity/Management/Proportions (or AMPs). This number, however, is valid for farmers who do not have crop rotation restrictions. For farmers who follow a strict rotation (e.g., 1/3 of the land *must* be assigned to each Activity) the number of AMPs quickly decreases to 27.

The second step involves a search triggering process, in which farmers decide whether they will repeat the land allocation used in the previous cycle or, alternatively, search for a new one. Search triggering is supported by empirical research elsewhere (Polhill et al., 2010). The model includes two alternative search triggering mechanisms: (a) "random", and (b) "*N* out of *M*." In the random mechanism, the farmer defines randomly on every cycle if he will repeat the previous land use or will search for a new land allocation. In the "*N* out of *M*" mechanism, search is triggered if the farmer has been "unsatisfied" with *N* economic outcomes (consecutive or not) in the *M* most recent production cycles. A farmer is unsatisfied when his economic outcome is lower than his AL. *N* and *M* are defined for each agent at initialization (we used $N = 2$ and $M = 3$ for all simulations). Similar mechanisms are used in other models: for instance, in FEARLUS a farmer changes land use after being unsatisfied for *N* consecutive years.

In a third step, a farmer who has decided to change land allocation must select a new AMP using one of two mechanisms: (a) "random," in which an AMP is randomly selected from the choice set – but excluding the previous (unsatisfactory) AMP – or (b) "margin-weighted" selection of a peer to be imitated, in which the farmer imitates the AMP previously used by one of his peers (here, the eight Moore neighbors of the farm for which the agent is deciding land use). Only neighbors with similar rotation preferences are considered. The agent to be imitated is selected stochastically with a probability proportional to his achieved economic profit (i.e., successful neighbors are more likely to be imitated). In simulations presented here, both land use selection mechanisms were tested (Table 2). Other models use various forms of imitation to select land use. In FEARLUS, for example, the land use selected is a combination of uses selected by neighbors (weighted according to various schemes).

Finally, once a farmer has selected a land use for the current cropping cycle, she must assign AMs to specific farm plots. There is no temporal overlap among activities, so all transitions are theoretically possible. Nevertheless, a preferred sequence has agronomic advantages: (1) full-cycle soybean, (2) followed by wheat-soybean, (3) followed by maize. Whenever possible, a farmer attempts to respect this sequence. If this proves impossible (e.g., if one of the Activities is not included in the selected AMP), the farmer tries to allocate to each plot an activity different to that used in the previous cycle. The farmer repeats the same activity in a plot only if there is no other option. No farm lot is left fallow.

3.3.1.3. Crop yield simulations. In the model version described in this manuscript, we use highly simplified yield trajectories (a see–saw pattern) for each AM. As in the FEARLUS model, these simplified trajectories are retrieved from pre-defined lookup tables. The yields in our regular pattern (i.e., the high, medium and low yields for each AM), however, are based on simulations using crop models in the Decision Support System for Agrotechnology Transfer (DSSAT) package (Jones et al., 2003), that have been calibrated and validated for the Pampas (Guevara et al., 1999; Mercau et al., 2007). In newer model versions, the simplified yield trajectories have been replaced by yields simulated with actual weather data for specific years. This approach allows us to describe better the actual variability of outcomes.

3.3.1.4. Economic calculations. This sub-model calculates the WC accumulated by a farmer's household at the end of a cropping cycle as the balance of (i) carried-over WC, (ii) income received and (iii) household expenses incurred during the cycle. Calculations follow standard AACREA protocols (Colombo et al., 1990). Household income can include only (a) total net farming income (TNFI) from land (owned and/or rented) operated by active farmers or (b) rental fees received by landlords. Household withdrawal – the only expense considered – is set at

Table 2
Description of the model mechanisms used, initial values assigned to the main state variables and trajectories of the input variables in each scenario.

Scenarios	1	2	3	4	5	6	7	8
1. Mechanisms								
Economies of size						X		
Wealth-weighted selection of tenants						X		
Decreasing probability of tenants' return					X	X	X	
2. Initialization								
2.1. Farms								
Farm number and size								
5041 farms[a], all farms same size (300 ha)	X							
5041 farms of 70 (2/8), 300 (5/8) and 1000 (1/8) hectares		X						
NAC60 farm number (4884) and size distribution			X	X	X	X	X	X
Tenure regime								
No rented farms at initialization	X	X	X		X			X
Proportion of rented farms at initialization in NAC60 (10%)				X		X	X	
2.2. Farmers								
Search triggering mechanism								
Random for all farmers	X	X						
N out of *M* for all farmers (*N* = 2, *M* = 3)			X	X	X	X	X	X
Land use selection mechanism								
Random for all farmers	X	X	X	X	X	X	X	
Margin-Weighted Imitation for all farmers								X
Working capital – owners								
$500 for all farmers[b]	X							
$0, $500 and $20,000 for farmers of 70, 300 and 1000 ha, respectively		X						
$0 for farmers until 400 ha and $20,000 for farmers over 400 ha			X	X	X			X
$500 for farmers until 100 hectares, $750 for farmers between 101 and 400 ha and $1000 for farmers over 400 ha						X	X	
Working capital – tenants								
$1100 per rented hectare[c]				X				
$2000 per rented hectare						X	X	
Owner rotator type								
All owners and all tenants are "not rotators"	X	X	X	X	X			X
All owners follow rotations, all tenants are "non-rotators"						X	X	
3. Input data								
Land rental price								
1.8 tons of soy (around $308) per hectare (constant)	X	X	X	X	X			X
1.4 tons of soy (around $240) per hectare (constant)						X	X	
Activities Managements yields								
Constant (average)	X							
Seesaw pattern (quantiles 5, 40 and 60 of simulated yields)[d]		X	X					X
Seesaw pattern (quantiles 5, 50 and 70 of simulated yields)					X			
Seesaw pattern (quantiles 5, 50 and 90 of simulated yields)				X				
Seesaw pattern (quantiles 20, 50 and 90 of simulated yields)						X	X	

[a] This is an arbitrary number of farms, rounded to 5041 to generate a square grid of 71 × 71.
[b] The amount needed by a land owner to cover initial costs for two cropping cycles. This reference value was varied according farmers' total operated area in other scenarios in order to test the model sensitivity to the farmers' initial WC.
[c] The amount needed by a land tenant to cover initial cost and land rental for two cropping cycles. This reference value was increased in other scenarios in order to promote tenants economic viability.
[d] A see–saw pattern of yields for each AM was used in several scenarios. To define the sequence for each AM, specific quantiles were estimated from yields simulated using the historical record; for example, for one scenario the 5%, 40% and 60% quantiles of yields were assumed to represent "unfavorable", "normal" and "favorable" yields, respectively. Then, the cyclical yield sequence was assembled by concatenating values in a seesaw pattern: unfavorable-normal-favorable-average-unfavorable, and so forth. Quantiles values used to build the see–saw patterns in some scenarios were relatively low in order to induce agents bankruptcy and generate heterogeneity among them.

a constant 18,000 $ yr^{-1} for all farmers, regardless of income level.

Calculation of TNFI involves computations at three spatial levels. First, the gross margin for an AM is calculated for each farm-plot as gross income (yield times product price) minus direct costs. Direct costs are associated with a specific AM and include fixed and variable components. Fixed direct costs do not depend on an AM's physical yield (e.g., seed and agrochemicals). Variable direct costs, in contrast, are a function of yields (e.g., harvest, marketing fees and grain transportation). Second, gross margins for all plots are aggregated into a farm-wide gross margin (FGM). Indirect costs (that apply to the farm as a whole) are then subtracted, yielding farm-level "production profits." Third, production profits are aggregated for all farms operated by an agent during cycle t: the end result is the TNFI received by a farmer. The calculation of TNFI includes realistic economies of size (Hallam, 1991; Stefanou and Madden, 1988) that introduce differences in profits among agents cropping different land areas. Cost reductions as a function of size were defined in collaboration with AACREA experts and are consistent with published reports (Díaz Hermelo and Reca, 2010).

3.3.1.5. Adaptation. In making risky choices, decision makers often focus on reaching a special outcome – an aspiration level or AL. Outcomes above and below the AL are respectively coded as *successes* and *failures* (Diecidue and van de Ven, 2008). By setting ALs and comparing them with performance, decision-makers seek signals about their performance that may guide future behavior (Lant, 1992). For these reasons, an AL is included in the model as a relevant component of individual choice processes.

This sub-model describes how aspirations change over time in response to experience. Our endogenous, dynamic AL adjustment is largely based on processes reported in the literature (details below). Other land-use ABMs include an AL or aspiration threshold (Gotts et al., 2003), but often it is exogenous and static. A series of AL adjustments are scheduled at different stages of a production cycle, starting from an initial value defined at the end of the previous cycle. These adjustments are briefly described in the paragraphs below. AL updates are performed for each farm, as a farmer may have separate ALs for each farm he operates because outcomes considered as successes or failures vary with the production potential of a farm's soil and climate.

A first AL adjustment (early in the cycle) is based on expected states – "favorable", "normal" or "unfavorable" – of three external context factors: climatic conditions, output prices, and input costs. For instance, if the expected climate context is "favorable", the initial AL – defined at the end of the previous cycle – is increased by 20%.

Once a farmer has made production decisions and actual contexts have been experienced, a second AL adjustment is based on comparing expected and experienced contexts. For instance, during the planning stage a farmer may expect crop prices at harvest to be "normal." If, however, commodity prices fell between planning and harvest (i.e., the context actually experienced is "unfavorable"), the previous AL may not be achievable in the updated, less favorable context. The farmer, therefore, adjusts his AL downwards. The comparison between experienced and expected states of external drivers, to our knowledge, has not been considered previously in the literature; nevertheless, the concept appears reasonable, as the context-adjusted AL weaves together a farmer's expectations of future states of the world and his own experience (Lant and Shapira, 2008).

The third AL adjustment is based on the learning and adaptation model by Levinthal and March (1981). AL for the following decision cycle (AL_{t+1}) is calculated as a weighted average of current AL (AL_t) after previous adjustments and achieved economic performance, described by farm-wide gross margin (FGM_t). That is, the current AL serves as an anchor from which incremental adjustments are made. An important cue for adjustment is the "attainment discrepancy," the difference between actual performance and aspirations ($AD = FGM_t - AL_t$) (Lant, 1992). AL is adjusted upward when achievements equal or surpass aspirations (i.e., $AD \geq 0$), and downward otherwise (Mezias et al., 2002). This adjustment is formalized as $AL_{t+1} = \lambda\, AL_t + (1 - \lambda)FGM_t$, where $\lambda \in (0, 1)$ describes an individual's "resistance" or "inertia" to adjusting AL (Karandikar et al., 1998). We use different λ values for positive and negative ADs (0.45 and 0.55 respectively) to reflect the fact that people "get used" to higher payoffs more rapidly than to lower ones, thus showing greater resistance to downward changes (Gilboa and Schmeidler, 2001).

As described above, both AL and AD are inherent to a particular individual. The model, however, was extended to include the influence of the physical (Moore) neighbors (Herriott et al., 1985; Mezias et al., 2002). In this approach, the average of peers' outcomes $\overline{FGM}_t^{peers}$ influences how a farmer assesses his own performance (FGM_t^{own}). If a farmer's achieved outcome is higher than his peers' average, the farmer is content and his AD will be simply $FGM_t^{own} - AL_t$. In contrast, if his peers achieve on average a higher result, then AD will be computed as $FGM_t^{adj} - AL_t$, where $FGM_t^{adj} = \gamma \cdot FGM_t^{own} + (1 - \gamma) \cdot \overline{FGM}_t^{peers}$ is an adjusted outcome reflecting a weighted average of achievements for the farmer and his peers; we used $\gamma = 0.5$, as no empirical values are reported in the literature.

A final AL adjustment is scheduled at the end of a production cycle. This adjustment reflects the observation that aspirations tend to remain higher than justified by a decision maker's experience (March, 1994). Lant (1992) speculated that this bias could be generated by optimism or overconfidence, or by motivational or strategic reasons for aspirations to consistently exceed performance. This effect is captured by an "optimism" multiplicative factor applied after all other AL adjustments are made.

3.3.2. Initialization

This section describes the model initialization process. All initialization data are managed through a relational initialization data base (IDB) read in at the beginning of each simulation. The scenarios explored here involve differences in the values assigned at initialization to most state variables; specific details are presented in Section 4.

3.3.2.1. Initialization of farms. The number of simulated farms and their respective areas are specified via the IDB. Farm numbers and sizes vary among experiments; details are given below. The farms are randomly distributed on a square grid, with their position defined by X and Y grid coordinates. Each farm is assigned an owner, an initial operator and a soil type (only one soil, a typical Argiudol, is considered here). Each plot in a farm is randomly assigned an initial Activity/Management.

3.3.2.2. Initialization of farmers. Active farmers, landlords and "reserve" farmers are created at initialization. The number of farms and total area cropped by a farmer are a result of the farm initialization step. Each active farmer is assigned an initial WC that is a function of his initial cropped area and land tenure. All farmers are assigned an initial AL of 317 $ ha^{-1}, the average FGM per unit area for the soil modeled. Each farmer is assigned search triggering and land use selection mechanisms that remain unchanged throughout the simulation. Each farmer also is given a preference about crop rotation: two types of farmers are considered: (a) "rotators" who maintain an inflexible rotation of activities, and (b) "non-rotators" whose land allocation is not restricted by rotation considerations. Actual records indicate that adherence to rotation is strongly tied to land tenure (farmers tend to not rotate crops on rented land), thus each farmer is assigned separate rotation preferences for owned and rented land.

3.3.3. Input data

This section describes the data provided as input to the model. The trajectories defined for some variables changed among scenarios; specific values used are discussed in Section 4.

3.3.3.1. Crop yields. Time series of crop yields (in tons of grain per hectare) for each AM are provided as exogenous input. In the experiments described here we use only simplified yield trajectories for each AM: a repeating see–saw pattern of low, intermediate, high, and intermediate yields. The three see–saw levels correspond to different percentiles (e.g., 20, 50 and 80) of yields simulated for each AM using process models and the historical weather record.

3.3.3.2. Output crop prices. This input involves time series of prices of maize, soybeans and wheat extracted from the Argentine trade magazine "Márgenes Agropecuarios" (http://www.margenes.com). In all experiments we assumed constant output prices equal to median prices for 2002–2007.

3.3.3.3. Input prices. These input data involves time series of input prices (e.g., fertilizer, seed) required by each modeled AM. In all experiments we assumed constant prices for each input equal to the median value for 2002–2007. Values were extracted from "Márgenes Agropecuarios."

3.3.3.4. Land rental price. This input includes a time series of land rental price (expressed in tons of soybean per hectare). Different land rental values were used in various simulated scenarios and are discussed as part of the results.

3.3.3.5. Expected and actual states of external context factors. This input includes time series of the expected and experienced states of three external context factors (Section 3.3.1.5). The possible states include three mutually exclusive conditions: favorable, normal and unfavorable. In every experiment, the expected and experienced states coincided. The only context factor varied was climate: expected and experienced climate states were unfavorable, normal and favorable for low, intermediate and high crop yields, respectively. All other contexts were kept constant and assumed as normal.

4. Model verification and validation

Verification of a model means "getting the model right." Model validation is "getting the right model", meaning that the correct abstract model was chosen and accurately represents the real-world phenomena. Verification and validation of ABMs deserves much attention (Fagiolo et al., 2007; Moss, 2008), but will only be briefly discussed here for the sake of space and because the experiments performed so far involve highly stylized inputs.

4.1. Verification

Verification is intended to ensure that the model implementation matches its design; it involves checking that the model behaves as expected (Crooks et al., 2008; North and Macal, 2007). After development and implementation of each component, we follow three complementary verification procedures. First, the team performs a code walk-through in which the lead programmer reads each line of code and explains its functionality. This process ensures that all design concepts and specifications be correctly reflected in the code. Second, we implement unit tests for each sub-model that run parts of the model in a controlled way (the "context" of the run is specified in the unit test). The unit tests let us compare numerical results produced by the model and an independent system. Finally, to verify that all different sub-models are working together correctly, we run the model with very few agents (order 10–15) and examine results closely (e.g., following the life history of a specific agent).

4.2. Validation

There are a number of approaches to ABM validation (Crooks et al., 2008; Ligtenberg et al., 2010). One intuitive approach is to compare simulated output with available historical data. Because our current simulations include highly simplified scenarios, such comparisons are fairly meaningless for now. Instead, the focus of our validation is to ensure that the fundamental structural and behavioral components in the model capture the main aspects of the actual system (Happe, 2005). Our model development process involves regular discussion with, and criticism by AACREA technical experts. The design of a model component starts with a review of the relevant literature and a simple initial design. This design is subsequently discussed with 3–5 regional experts. Such discussions ensure, on one hand, "face validity" of concepts included in the model (Moss, 2008). On the other hand, the resulting "user community view" provides a foundation for evaluation guided by the expectations, anticipations and experience of potential users of results (Ahrweiler and Gilbert, 2005). This approach is consistent with the view that "validity" is dependent on the purpose of the models under examination (Küppers and Lenhard, 2005).

5. Simulations

The overarching purpose of the model presented here is to gain insight on the likely processes that generated observed changes in agricultural systems of the Pampas. As a first step, we performed initial experiments using extremely simple scenarios. These initial simulations were intended to (a) complement prior model verification efforts, and (b) facilitate initial interpretation of emerging patterns. We increased progressively the complexity of subsequent scenarios by activating previously turned-off mechanisms and through more realistic initialization of model entities and the trajectories of some input variables. In this section we present results from eight selected scenarios. Table 2 gives a summary description of these scenarios, including (a) the mechanisms involved, (b) the range of initial values assigned to state variables that differed among scenarios, and (c) the trajectories of input variables that changed among scenarios.

6. Simulations results

6.1. Inducing heterogeneity among agents

The simplest simulation scenario (Scenario 1, Table 2) involved complete uniformity in the initial characteristics of farms and farmers, and constant, near-average trajectories of climatic and economic conditions. In these simulations, no changes develop from initial conditions. Simulated profits are sufficient to keep all farmers viable (they even increase their WC by $54,124 on each cycle). Therefore, all farmers can continue operating the area initially assigned to them, and there is no exit or entry of agents – and thus no change in the area operated by each farmer. Although this result was expected *a priori*, it is reassuring for model verification. As all agents have the same characteristics, mechanisms involving priorities (e.g., priority of wealthier farmers in renting land) or relative advantages (e.g., economies of size) do not influence results: these mechanisms only can *magnify* existing differences among agents, but do not *generate* them.

Simulations assuming uniform initial conditions and constant context trajectories provide a useful baseline but not much insight on structural changes in agricultural systems. In a second set of experiments, therefore, we sought to generate divergence from initial conditions. For such dynamics to occur, two conditions were found to be necessary: (a) agents must operate farms of different initial sizes, and (b) the incomes received by agents under various contexts have to fall in a particular range (not too high, not too low) such that differences in economic viability arise among agents. If incomes received are very high (low), all agents are economically viable (unviable) regardless of area operated. Conversely, with intermediate incomes, agents operating larger areas remain economically viable, whereas farmers cropping smaller areas go out of business and must lease out their land.

6.2. Concentration of cropped area

An important assumption is that no farmer (owner or tenant) will exit active production unless she no longer has sufficient WC to operate; no exit due to age or other non-economic reasons is modeled. Consequently, concentration of agricultural production – a decrease in the number of active farmers and a corresponding increase in the average area cropped by each active farmer – can only emerge when agents exit active production and their land is rented in by farmers who already are in the system.

A farmer's economic viability – i.e., his sustained ability to remain in active production – is linked, to first order, to the size of the area cropped. We explored farmed area effects using Scenario 2

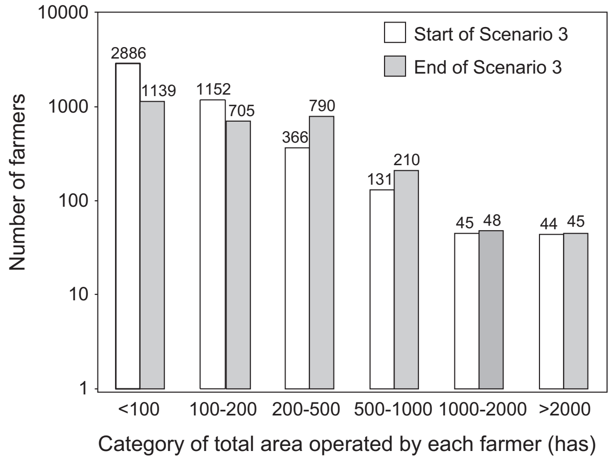

Fig. 2. Number of farmers in each category of total operated area at the start and end of Scenario 3. Note that the initial farm size distribution of Scenario 3 is consistent with the 1960 Argentine Agricultural Census.

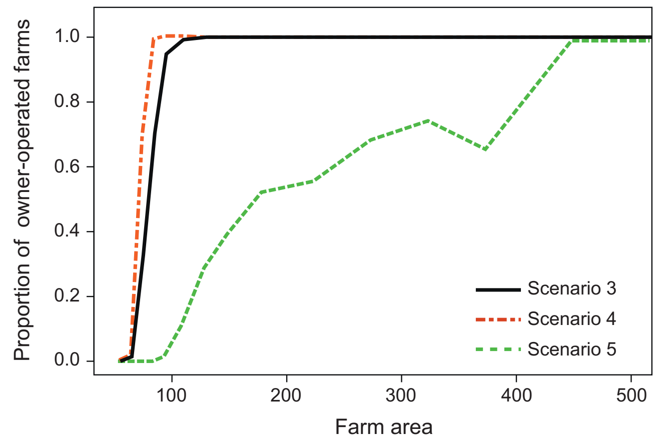

Fig. 3. Proportion of farms operated by their owners in the last production cycle of Scenarios 3, 4 and 5 for different farm areas.

that includes only three farm sizes: 70, 300 and 1000 ha (Table 2). In this scenario, the smallest farms (70 ha) are not viable: their annual WC accumulation ranges from $-22,733 to $5773 (depending on year and land use) whereas they need 18,732 $ yr^{-1} to continue farming. Consequently, as soon as these agents exhaust their initialized WC they must rent out their land and become landlords. As landlords, these farmers can accumulate 926 $ yr^{-1} from rental fees after household expenses and eventually (after 30–40 years, depending on how much capital they lost in their last active year) are able to return to farming. However, because their incomes still are insufficient, these farmers soon exit production again, repeating the cycle. Conversely, farmers operating 300 or 1000 ha are permanently viable (i.e., they can overcome low-yield years because they can generate surplus WC during medium- and high-yield years). In fact, these "large" farmers can accumulate enough WC to rent in land from unviable farmers. Consequently, in Scenario 2 there is a concentration of production, with a decrease of about 21% in the number of active farmers (from 5041 to about 3900 when the regime state is reached); this decrease is at the expense of farmers operating smaller areas.

A more diverse distribution of farm sizes allows better understanding of linkages between farm size and economic viability. The initial farm size distribution in Scenario 3 – consistent with that in the 1960 Census – involves a large proportion of small farms (Fig. 2). In this scenario, the number of active agents decreases ≈37% (Fig. 2) and the median area operated by each agent increases ≈138% (from 58 to 138 ha) with respect to initial conditions. Scenario 3 allowed us to identify three clear situations of economic viability, defined by cropped area. *Permanently viable farmers* operate areas large enough to generate surplus capital to cope with low-yield years: in Scenario 3, these farmers operate 125 ha or more (Fig. 3, solid line). In contrast, *permanently unviable* farmers are those who farm areas (in Scenario 3, <65 ha) that cannot generate sufficient income (no off-farm income is modeled) and eventually must rent out their farms. Moreover, permanently unviable farmers never accumulate sufficient WC as landlords to return to active status, so their exit is permanent. Finally, *partially viable* farmers cannot generate sufficient WC to operate their farms continuously, but eventually can accumulate capital from rental fees to return to active farming: in Scenario 3 this category includes agents operating ≈65–125 has (Fig. 3, solid line). In summary, two thresholds are identified which define the economic viability of farmers as a function of the area they operate: (i) a 'viability threshold', above which farmers are permanently viable, and (ii) an 'unviability threshold', below which farmers are permanently unviable; between these two thresholds lies a range of cropped areas for which farmers are only partially viable.

The identified economic thresholds clearly depend on the context, which defines the income received by farmers. Because economic conditions are assumed constant in all simulations, incomes are only a function of simulated AM yields. A trajectory involving higher yields (Scenario 4, see details in Table 2) in all cropping cycles leads to lower viability thresholds (i.e., smaller farms can remain in business, cf. Fig. 3, solid versus dot-dashed lines). Conversely, the cropped area needed to stay in business is larger when yields are lower. This may be the case for areas with marginal agro-ecological conditions.

Thresholds of economic viability also vary with the specific mechanisms included in the simulations. In previous experiments, we had assumed that landlords who accumulated sufficient WC could return to active production (with a fixed probability of 0.25 on each year) even after 30–40 years. Nevertheless, it is more realistic to assume a shorter interval beyond which landlords do not return to active status: for example, in Scenario 5 the probability of return to active farming becomes zero after six years. In this case, viability thresholds increase significantly – larger farm areas are required to stay in business. Permanently unviable farmers crop <100 ha (*vs.* <65 ha in Scenario 3); permanently viable farmers must operate >400 ha (*vs.* >125 ha in Scenario 3). The increase in thresholds is due to the fact that landlords have a much shorter time to accumulate the necessary WC, thus return to active farming is much less likely.

We also explored whether concentration of production arises from mechanisms that provide advantages to larger farmers. Two such mechanisms were activated in Scenario 6: (i) economies of size (Section 3.3.1.4) and (ii) priority of wealthier farmers when competing for rental farms. These mechanisms, however, did not produce marked effects (results not shown). Realistic economies of size reduce total costs by about 2.6, 9.5 and 12.2% for operated areas of 500, 1000 and 2500 ha, respectively. Because the areas operated by most farmers at initialization are fairly small (only 5.1% of farmers operate more than 500 ha), the economies of size are correspondingly small and do not play a central role. The priority of wealthier farmers when selecting rental farms does not appear to have a significant role on concentration of production either. This is probably because we had defined a "minimum area of interest" for farmers seeking rental farms. As most farms that become available for rent are small, they are not considered suitable by large farmers, thus the smaller farms are taken over by small-to-medium farmers.

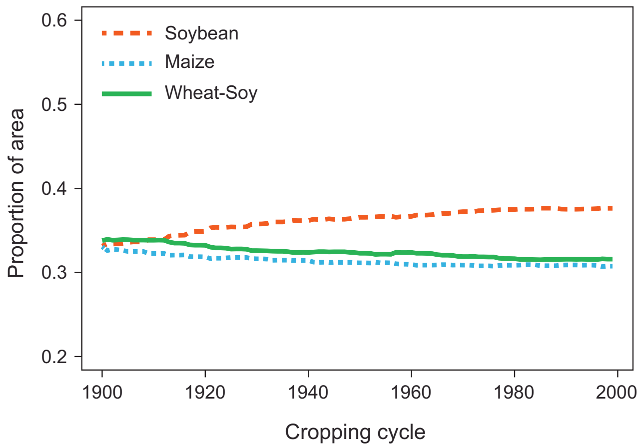

Fig. 4. Proportion of area devoted to each activity in Scenario 3.

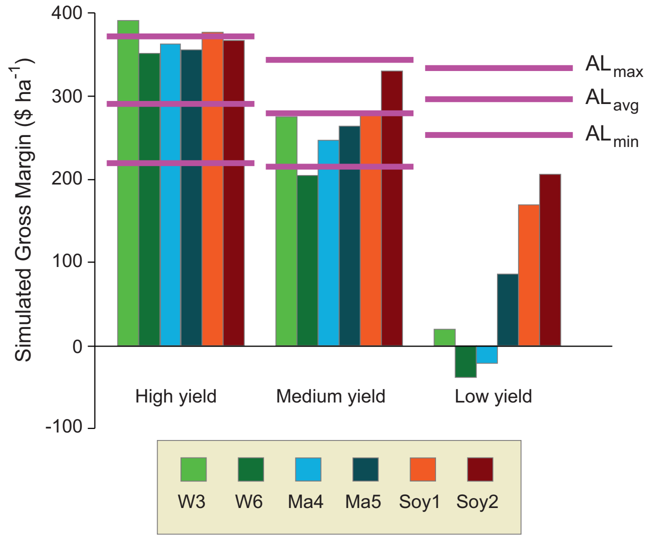

Fig. 5. Simulated gross margin ($ ha^{-1}) for each Activity/Management (AM) for randomly selected high-, medium- and low-yield years. The lines show the minimum, average and maximum aspiration level (for all agents) for each selected year.

6.3. Changes in land tenure

Simulated changes in land tenure patterns are closely tied to the economic viability of agents, and also to changes in the number of farmers and the area cropped by each farmer. This link is due to the assumption that, as long as an owner has sufficient WC, she will not leave active production of her land.

Scenarios leading to significant differences in the concentration of production (e.g., Scenarios 3 and 5 discussed in Section 6.2) also show large differences in the proportions of owned and rented areas. In Scenario 3, the equilibrium proportion of rented area ranges between 14.5 and 17.5% (the proportion is variable due to periodic entry and exit of "partially viable" agents). Conversely, in Scenario 5, for which a higher concentration was observed, the proportion of rented land is considerably higher: 44.5% (this value does not vary because the decreasing probability of landlord return permanently excludes most "partially viable" farmers).

Farmers responsible for the emerging land concentration are mostly "owner-tenants" (i.e., farmers who operate both owned and rented land). These agents receive higher profits from owned farms (they do not pay rental fees) and thus can accumulate WC to rent additional land and to keep operating it, even after low-yield years. In contrast, "tenants-only" (agents who operate only rented land) are not economically viable under most conditions, mainly because they have higher costs (i.e., they pay rental fees for all land operated). In Scenario 3 (in which land rental price is 1.8 tons of soy ha^{-1}) none of the tenants-only, regardless of their operated area, can generate sufficient income to continue farming. Conversely, a few tenants-only become viable in Scenario 7, that involves a lower land rental price (1.4 tons of soy ha^{-1}) and higher yields (Table 2).

6.4. Changes in land use

When random mechanisms are used for search triggering and land allocation, the end result is, as expected, a relatively uniform distribution of AMs. Instead, when the "*N* out of *M*" search triggering mechanism is activated (Scenario 3) the soybean area progressively dominates that of other activities (Fig. 4), although this mechanism does not involve explicitly land allocation decisions. This result is linked to the relationship between the economic outcomes of each AM and the agents' ALs. Fig. 5 shows that during high-yield years, the gross margins of all AMs are close to the highest AL (AL_{max}) calculated for all active farmers, thus most agents are likely to be satisfied (gross margin >AL) regardless of land allocation chosen. Conversely, in low-yield years the gross margins of all AMs are well below the minimum AL (AL_{min}), therefore all agents are unsatisfied – again, regardless of land allocation. It is during medium-yield years (the half of the years in the trajectory) when differences in agent satisfaction are most marked: as soybean (and, particularly, Soy6) is the most profitable AM, farmers choosing a higher proportion of soybean are more likely to be satisfied and, consequently, will not switch land allocation. Conversely, search for a new allocation will be triggered more frequently for farmers using a low proportion of soybean.

When the Margin-Weighted Imitation land use selection mechanism is assigned to all agents (Scenario 8), the area allocated to soybean increases significantly, reaching 52.5% of total area, versus 24.5% and 23% for wheat and maize, respectively (Fig. 6). As discussed in the previous paragraph, most agents are satisfied during high-yield years (Fig. 5), therefore the '*N* out of *M*' mechanism triggers search following low- or medium-yield years. Farmers who used a high proportion of soybean during low- or medium-yield years have a higher probability of achieving higher profits and, thus, are more likely to be imitated by their unsatisfied peers.

In a previous section, we showed that few tenants-only were economically viable. Their viability is strongly dependent on the land use chosen. A tenant-only who follows crop rotations (i.e., allocates 1/3 of the land to each activity) needs at least 340 ha to be viable in Scenario 7. Conversely, a tenant-only who assigns all his land to soybean, the most profitable activity during recent years,

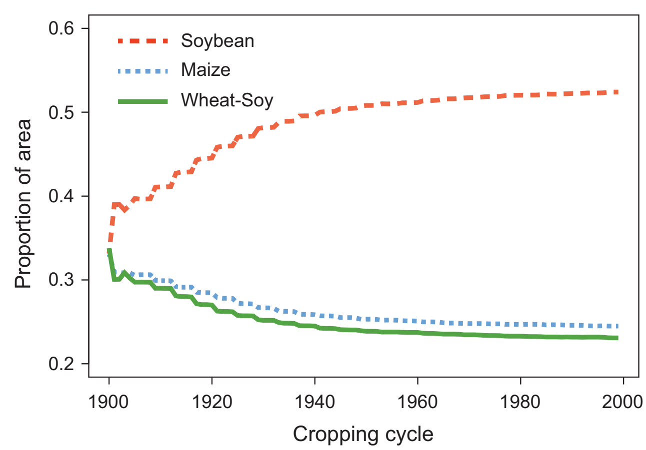

Fig. 6. Proportion of area devoted to each activity in Scenario 8.

needs only 195 ha to remain in business. The best strategy for small tenants-only, then, seems to be to allocate all their land to the most profitable activity. An increase in the number of tenants-only and the higher profitability of soybean may explain, at least partially, the large expansion of this crop in the Pampas during recent years.

7. Final comments

This paper described an agent-based model designed to understand and explore structural changes and evolving land use patterns in agricultural production systems of the Argentine Pampas, one of the main world cereal and oilseed producing regions. Despite the large importance of agriculture for Argentina's economy, to our knowledge modern agent-based approaches have not been used in the Pampas to provide a "bottom-up" simulation of patterns emerging from the intertwined, cross-scale effects of human behavior and external drivers. Successful design, implementation and assessment of agricultural policies require an understanding of these linkages.

Our ABM helped identify likely drivers and understand plausible dynamics of changes observed in the Pampas. Despite the simplified nature of simulations presented, emerging structural and land use patterns are very consistent with historical developments in the real-world system. First, our model simulated a clear concentration of production – an increase in the average area operated by farmers, accompanied by a decrease in the number of smaller farms – consistent with reported patterns (Gallacher, 2009; Reboratti, 2005). The simulated concentration seems to be linked to the long-run economic viability of individual farmers which, in turn, depends on the area initially operated. Under the economic and technological context assumed (representative of the period 2002–2007), farmers operating smaller areas were much more likely to exit production due to their inability to generate sufficient income to cover household, crop implantation and – if applicable – land rental costs, and to buffer against unfavorable years. In contrast, farmers initially endowed with larger land holdings were significantly more likely to survive and to expand. The concentration observed in the Pampas, was made possible not only by the ability to accumulate surplus capital, but also by a simplification of production processes resulting from both a reduction in labor needs (partly due to rapid adoption of new technologies) and an increase in specialization, i.e., systems increasingly focused on agriculture, particularly soybean, instead of a mixed crop/cattle system (Gallacher, 2009).

The association between the long-term economic viability of farmers and initial land endowment is strengthened by the fact that the model currently does not include any off-farm income, access to credit or outside investment. Because these processes can be crucial to the survival of many small farms (Buchenrieder et al., 2007; Gallacher, 2009), they should be considered and endogenized in future versions of the model. The importance of initial resource endowment on economic sustainability also was found by Freeman et al. (2009) for farms in the Canadian Prairies.

A plausible goal of Argentine agricultural policy may be to preserve the economic sustainability of small farmers. Our results suggest that policy interventions should aim to minimize the likelihood of small farmers having to rent out their land, because once these farmers exit active production it is unlikely that they can/will return. This result agrees with the real-world observation that farmers tend not to return to active farming, even if they have sufficient WC, after some time as landlords. Possibly this reflects obsolescence of technical knowledge or habituation to steady, quasi-riskless income. The economic viability of small farmers might be preserved through differential crop prices and export taxes, or via subsidized input costs. It is unlikely that one-time rescue subsidies following low-profit years that trigger massive exit will succeed, as they do not change the small farmers' intrinsic capacity to generate surplus agricultural income.

The model simulated correctly an increase in the area cropped by land tenants. This result agrees with the observation that over half of the Pampas currently is cropped by tenants (Reboratti, 2005). The increase in rented area is tied to the same mechanisms that induce concentration of production. As in the real system, our simulations show that a significant proportion of rented land is operated by owners of other farms seeking to expand production: they do not pay land rental costs and therefore they have surplus income that can be invested in expanding production. In contrast, only a small area is cropped by farmers who do not own any land (tenants-only). Despite recent increases in profitability of agriculture, a concomitant rise in land rental fees has transferred most profits to land owners and thus did not enhance significantly the economic viability of tenants-only (Reca et al., 2010).

An association emerged between land tenure and land use, as the long-term viability of tenants-only seems to be associated to the land use selected. To remain viable, tenants must maximize the area allocated to the most profitable activity (in recent years, soybean) instead of following ecologically beneficial crop rotations. A soil conservation policy should include mechanisms to alleviate the tenants' costs and increase their profitability but, at the same time, commit the tenant to follow appropriate rotations. Given the lack of such legislation, some land owners already are entering into contracts with slightly lower lease prices and longer durations, but that require rotation with cereals to avoid continuous soybean cropping.

Finally, the model simulated an increase in the area planted with soybean, a pattern aligned with the observed expansion of soybean in the Pampas. The soybean expansion is primarily tied to its higher profitability relative to other activities – a situation representative of the 2002–2007 input and output prices used in the simulations. As discussed previously, soybean expansion also appeared to be linked to land tenure, as tenants must allocate most land to this highly profitable crop in order to remain in business. Other real-world factors that facilitated the fast spread of soybean, such as the easier management of genetically modified herbicide-tolerant soybean and the lower up-front investment required by this crop (about half as much as maize, its main competitor), have not been included in the model.

While Argentina enjoys the economic benefits of soybean exports, concerns are increasing about the environmental consequences of soybean monoculture (Manuel-Navarrete et al., 2009). Our results suggest that policies oriented to enhancing the relative profitability of maize and wheat (e.g., differential export taxes, input cost reductions, etc.) might have an impact on land use. Another alternative to limit soybean expansion involves the regulation of land rental contracts (e.g., requiring rotation of cereals and soybean). Indeed, regulation of land leases is being considered by the Argentine Congress. Nevertheless, use of leased land may be very difficult to monitor and enforce – unless done directly by land owners – given the current institutional framework of Argentine agriculture.

We involved regional experts in the conceptualization and specification of the model to ensure that it would capture relevant features of the real-world system. For this reason, we feel confident about the "face validity" of concepts included in the model (Moss, 2008). Although stakeholder engagement has become a buzz word in environmental assessments and modeling efforts, we confirmed previous findings that this involvement can improve drastically the value of the resulting model in terms of its usefulness to decision makers and its credibility within the community (Voinov and Bousquet, 2010).

Despite the simplicity of simulations presented here, our ABM proved to be a useful tool to gain insight on processes underlying recent changes in the Pampas. Nevertheless, we are performing new simulations with more realistic conditions (i.e., historical output prices, input costs, climate conditions and crop yields). We need to ensure consistency between observed and simulated patterns, reproducing not only the magnitude of historical changes but also the rate at which they occurred. Once we demonstrate a reasonable performance in reproducing past changes, we can use the model as a laboratory to explore future paths of agricultural systems under plausible climate, technological, economical and institutional scenarios, and to assess the impacts and effectiveness of alternative policies for the agricultural sector.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.ecolmodel.2011.08.007.

References

Ahrweiler, P., Gilbert, N., 2005. Caffè Nero: the evaluation of social simulation. Journal of Artificial Societies and Social Simulation 8, 14.

Altieri, M., Pengue, W., 2006. GM soybean: Latin America's new coloniser. Seedling, 13–17.

Baldi, G., Paruelo, J., 2008. Land-use and land cover dynamics in South American temperate grasslands. Ecology and Society 13, 6.

Barsky, O., Gelman, J., 2009. Historia del agro argentino: desde la conquista hasta fines del siglo XX, third ed. Sudamericana, Buenos Aires.

Beck, H., Morgan, K., Jung, Y., Grunwald, S., Kwon, H.-y., Wu, J., 2010. Ontology-based simulation in agricultural systems modeling. Agricultural Systems 103, 463–477.

Beratan, K.K., 2007. A cognition-based view of decision processes in complex social–ecological systems. Ecology and Society 12, 27.

Berbery, E.H., Doyle, M.E., Barros, V., 2006. Tendencias regionales en la precipitación. In: Barros, V., Clarke, R., Silva Días, P. (Eds.), El cambio climático en la Cuenca del Plata. CONICET, Buenos Aires, pp. 67–92.

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

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

Bert, F., Podestá, G.P., Rovere, S., North, M., Menéndez, A., Laciana, C.E., Macal, C., Weber, E.U., Sydelko, P., 2010. Agent-based modelling of a rental market for agricultural land in the Argentine Pampas. In: Swayne, D.A., Yang, W., Voinov, A.A., Rizzoli, A., Filatova, T. (Eds.), International Congress on Environmental Modelling and Software, "Modelling for Environment's Sake". International Environmental Modelling and Software Society (iEMSs), Ottawa, Canada.

Binimelis, R., Pengue, W., Monterroso, I., 2009. "Transgenic treadmill": responses to the emergence and spread of glyphosate-resistant Johnson grass in Argentina. Geoforum 40, 623–633.

Buchenrieder, G., Möllers, J., Happe, K., Davidova, S., Fredriksson, L., Bailey, A., Gorton, M., Kancs, D.A., Swinnen, J., Vranken, L., Hubbard, C., Ward, N., Juvančič, L., Milczarek, D., Mishev, P., 2007. Conceptual framework for analysing structural change in agriculture and rural livelihoods. Discussion Paper No. 113. Leibniz Institute of Agricultural Development in Central and Eastern Europe.

Calviño, P.A., Monzón, J.P., 2009. Farming Systems of Argentina: Yield Constraints and Risk Management. Crop Physiology: Applications for Genetic Improvement and Agronomy. Elsevier Academic Press, San Diego, California.

Carolan, M.S., 2005. Barriers to the adoption of sustainable agriculture on rented land: an examination of contesting social fields. Rural Sociology 70, 387–413.

CASAFE (Cámara de Sanidad Agropecuaria y Fertilizantes), 2009. La Argentina 2050: la revolución tecnológica del agro. Cámara de Sanidad Agropecuaria y Fertilizantes, Buenos Aires, Argentina, 744 pp.

Colombo, F., Olivero Vila, J.M., Zorraquín, T., 1990. Normas para calcular los resultados económicos económicos de las empresas, Asociación Argentina de Consorcios Regionales de Experimentación Agrícola, Buenos Aires.

Crooks, A., Castle, C., Batty, M., 2008. Key challenges in agent-based modelling for geo-spatial simulation. Computers, Environment and Urban Systems 32, 417–430.

Deybe, D., Flichman, G., 1991. A regional agricultural model using a plant growth simulation program as activities generator – an application to a region in Argentina. Agricultural Systems 37, 369–385.

Díaz Hermelo, F., Reca, A., 2010. Asociaciones productivas (APs) en la agricultura: una respuesta dinámica a fallas de mercado y al cambio tecnológico. In: Reca, L.G., Lema, D., Flood, C. (Eds.), El crecimiento de la agricultura argentina. 1st ed. Editorial Facultad de Agronomía. Universidad de Buenos Aires, Buenos Aires, pp. 207–229.

Diecidue, E., van de Ven, J., 2008. Aspiration level, probability of success and failure, and expected utility. International Economic Review 49, 683–700.

Eakin, H., Wehbe, M., 2009. Linking local vulnerability to system sustainability in a resilience framework: two cases from Latin America. Climatic Change 93, 355–377.

Fagiolo, G., Birchenhall, C., Windrum, P., 2007. Empirical validation in agent-based models: introduction to the special issue. Computational Economics 30, 189–194.

Freeman, T., Nolan, J., Schoney, R., 2009. An agent-based simulation model of structural change in Canadian Prairie Agriculture, 1960–2000. Canadian Journal of Agricultural Economics/Revue canadienne d'agroeconomie 57, 537–554.

Gallacher, M., 2009. The changing structure of production: Argentine agriculture 1988-2002. Documento de Trabajo 415. Universidad del CEMA, Buenos Aires. Available online from: http://www.ucema.edu.ar/publicaciones/download/documentos/415.pdf.

Gilbert, N., 2008. Agent-based Models. SAGE Publications, Los Angeles, 98 pp.

Gilboa, I., Schmeidler, D., 2001. Reaction to price changes and aspiration level adjustments. Review of Economic Design 6, 215–223.

Gotts, N.M., Polhill, J.G., Law, A.N.R., 2003. Aspiration levels in a land use simulation. Cybernetics and Systems 34, 663–683.

Grimm, V., Berger, U., Bastiansen, F., Eliassen, S., Ginot, V., Giske, J., Goss-Custard, J., Grand, T., Heinz, S.K., Huse, G., 2006. A standard protocol for describing individual-based and agent-based models. Ecological Modelling 198, 115–126.

Grimm, V., Berger, U., DeAngelis, D.L., Polhill, J.G., Giske, J., Railsback, S.F., 2010. The ODD protocol: a review and first update. Ecological Modelling 221, 2760–2768.

Guevara, E., Meira, S., Maturano, M., Coco, G., 1999. Maize simulation for different environments in Argentina. In: International Symposium: Modelling Cropping Systems, European Society of Agronomy, University of Lleida, Catalonia, Spain, pp. 193–194.

Hallam, A., 1991. Economies of size and scale in agriculture: an interpretative review of empirical measurement. Review of Agricultural Economics 13, 155–171.

Happe, K., 2005. Agent-based modelling and sensitivity analysis by experimental design and metamodelling: an application to modelling regional structural change. In: XIth International Congress of the European Association of Agricultural Economists, The Future of Rural Europe in the Global Agri-Food System, Copenhagen, Denmark.

Happe, K., Balmann, A., Kellermann, K., 2004. The Agricultural Policy Simulator (AgriPoliS) - An agent-based model to study structural change in agriculture (Version 1.0). Discussion Paper No. 71. Institute of Agricultural Development in Central and Eastern Europe.

Happe, K., Balmann, A., Kellermann, K., Sahrbacher, C., 2008. Does structure matter? The impact of switching the agricultural policy regime on farm structures. Journal of Economic Behavior & Organization 67, 431–444.

Happe, K., Schnicke, H., Sahrbacher, C., Kellermann, K., 2009. Will they stay or will they go? Simulating the dynamics of single-holder farms in a dualistic farm structure in Slovakia. Canadian Journal of Agricultural Economics/Revue canadienne d'agroeconomie 57, 497–511.

Heath, B., Hill, R., Ciarallo, F., 2009. A survey of agent-based modeling practices (January 1998 to July 2008). Journal of Artificial Societies and Social Simulation 12, 9.

Heckbert, S., Baynes, T., Reeson, A., 2010. Agent-based modeling in ecological economics. Annals of the New York Academy of Sciences 1185, 39–53.

Herriott, S.R., Levinthal, D., March, J.G., 1985. Learning from experience in organizations. The American Economic Review 75, 298–302.

Janssen, S., Ewert, F., Li, H., Athanasiadis, I.N., Wien, J.J.F., Thérond, O., Knapen, M.J.R., Bezlepkina, I., Alkan-Olsson, J., Rizzoli, A.E., Belhouchette, H., Svensson, M., van Ittersum, M.K., 2009. Defining assessment projects and scenarios for policy support: use of ontology in integrated assessment and modelling. Environmental Modelling & Software 24, 1491–1500.

Jones, J.W., Hoogenboom, G., Porter, C.H., Boote, K.J., Batchelor, W.D., Hunt, L.A., Wilkens, P.W., Singh, U., Gijsman, A.J., Ritchie, J.T., 2003. The DSSAT cropping system model. European Journal of Agronomy 18, 235–265.

Juhola, S., Westerhoff, L., 2011. Challenges of adaptation to climate change across multiple scales: a case study of network governance in two European countries. Environmental Science and Policy 14 (3), 239–247.

Karandikar, R., Mookherjee, D., Ray, D., Vega-Redondo, F., 1998. Evolving aspirations and cooperation. Journal of Economic Theory 80, 292–331.

Kessler, J.J., Rood, T., Tekelenburg, T., Bakkenes, M., 2007. Biodiversity and socioeconomic impacts of selected agro-commodity production systems. The Journal of Environment & Development 16, 131–160.
Küppers, G., Lenhard, J., 2005. Validation of simulation: patterns in the social and natural sciences. Journal of Artificial Societies and Social Simulation 8, 3.
Lamers, P., McCormick, K., Hilbert, J.A., 2008. The emerging liquid biofuel market in Argentina: implications for domestic demand and international trade. Energy Policy 36, 1479–1490.
Lant, T.K., 1992. Aspiration level adaptation: an empirical exploration. Management Science 38, 623–643.
Lant, T.K., Shapira, Z., 2008. Managerial reasoning about aspirations and expectations. Journal of Economic Behavior & Organization 66, 60–73.
Levinthal, D., March, J.G., 1981. A model of adaptive organizational search. Journal of Economic Behavior and Organization 2, 307–333.
Ligtenberg, A., van Lammeren, R.J.A., Bregt, A.K., Beulens, A.J.M., 2010. Validation of an agent-based model for spatial planning: a role-playing approach. Computers, Environment and Urban Systems 34, 424–434.
Magrín, G., Travasso, M.I., Rodríguez, G., 2005. Changes in climate and crop production during the 20th century in Argentina. Climatic Change 72, 229–249.
Manuel-Navarrete, D., Gallopín, G., Blanco, M., Díaz-Zorita, M., Ferraro, D., Herzer, H., Laterra, P., Murmis, M., Podestá, G., Rabinovich, J., Satorre, E., Torres, F., Viglizzo, E.F., 2009. Multi-causal and integrated assessment of sustainability: the case of agriculturization in the Argentine Pampas. Environment, Development and Sustainability 11, 621–638.
March, J.G. (Ed.), 1994. A Primer on Decision Making. The Free Press, New York, p. 289.
Matthews, R., Gilbert, N., Roach, A., Polhill, J., Gotts, N., 2007. Agent-based land-use models: a review of applications. Landscape Ecology 22, 1447–1459.
Mercau, J.L., Dardanelli, J.L., Collino, D.J., Andriani, J.M., Irigoyen, A., Satorre, E.H., 2007. Predicting on-farm soybean yields in the pampas using CROPGRO-soybean. Field Crops Research 100, 200–2009.
Mezias, S.J., Chen, Y.-R., Murphy, P.R., 2002. Aspiration-level adaptation in an American financial services organization: a field study. Management Science 48, 1285–1300.
Miljkovic, D., 2005. Measuring and causes of inequality in farm sizes in the United States. Agricultural Economics 33, 21–27.
Minetti, J.L., Vargas, W., Poblete, A.G., Acuña, L.R., Casagrande, G., 2003. Non-linear trends and low frequency oscillations in annual precipitation over Argentina and Chile, 1931–1999. Atmósfera 16, 119–135.
Morales Grosskopf, H., Arbeletche, P., Bommel, P., Burges, J.C., Champredonde, M., Corral, J., Tourrand, J.F., 2010. Modéliser le changement dans la gestion des terres de parcours en Uruguay. Cahiers Agricultures 19, 112–117.
Moss, S., 2008. Alternative approaches to the empirical validation of agent-based models. Journal of Artificial Societies and Social Simulation 11, 5.
Nikolai, C., Madey, G., 2009. Tools of the trade: a survey of various agent based modeling platforms. Journal of Artificial Societies and Social Simulation 12, 2.
Nolan, J., Parker, D., van Kooten, G.C., Berger, T., 2009. An overview of computational modeling in agricultural and resource economics. Canadian Journal of Agricultural Economics/Revue canadienne d'agroeconomie 57, 417–429.
North, M.J., Macal, C.M., 2007. Managing Business Complexity: Discovering Strategic Solutions with Agent-based Modeling and Simulation. Oxford University Press, Oxford, 313 pp.
North, M.J., Collier, N.T., Vos, J.R., 2006. Experiences creating three implementations of the repast agent modeling toolkit. ACM Transactions on Modeling and Computer Simulation 16, 1–25.
Parker, D., Manson, S.M., Janssen, M.A., Hoffmann, M.J., Deadman, P., 2003. Multi-agent systems for the simulation of land-use and land-cover change. Annals of the Association of American Geographers 94, 314–337.
Parker, D.C., Hessl, A., Davis, S.C., 2008. Complexity, land-use modeling, and the human dimension: fundamental challenges for mapping unknown outcome spaces. Geoforum 39, 789–804.
Pengue, W., 2005. Transgenic crops in Argentina: the ecological and social debt. Bulletin of Science Technology Society 25, 314–322.
Piñeiro, M., Villarreal, F., 2005. Modernización agrícola y nuevos sectores sociales. Ciencia Hoy 15, 32–36.
Polhill, J.G., Parker, D., Brown, D., Grimm, V., 2008. Using the ODD protocol for describing three agent-based social simulation models of land-use change. Journal of Artificial Societies and Social Simulation 11.
Polhill, J.G., Sutherland, L.-A., Gotts, N.M., 2010. Using qualitative evidence to enhance an agent-based modelling system for studying land use change. Journal of Artificial Societies and Social Simulation 13, 10.
Qaim, M., Traxler, G., 2005. Roundup ready soybeans in Argentina: farm level and aggregate welfare effects. Agricultural Economics 32, 73–86.
Railsback, S.F., Lytinen, S.L., Jackson, S.K., 2006. Agent-based simulation platforms: review and development recommendations. Simulation 82, 609–623.
Reboratti, C.E., 2005. Efectos sociales de los cambios en la agricultura. Ciencia Hoy 15, 52–61.
Reca, L.G., Lema, D., Flood, C., 2010. El Crecimiento de la Agricultura Argentina, 1st ed. Editorial Facultad de Agronomía, Buenos Aires, p. 488.
Schnepf, R.D., Dohlman, E., Bolling, C., 2001. Agriculture in Brazil and Argentina: developments and prospects for major field crops. Economic Research Service Agriculture and Trade Report. U.S. Department of Agriculture, Washington, DC, p. 85.
Schreinemachers, P., Berger, T., 2011. An agent-based simulation model of human–environment interactions in agricultural systems. Environmental Modelling & Software 26, 845–859.
Soule, M.J., Tegene, A., Wiebe, K.D., 2000. Land tenure and the adoption of conservation practices. American Journal of Agricultural Economics 82, 993–1005.
Stefanou, S.E., Madden, J.P., 1988. Economies of size revisited. Journal of Agricultural Economics 39, 125–132.
Trigo, E.J., Cap, E.J., 2003. The impact of the introduction of transgenic crops in Argentinean agriculture. AgBioForum 6, 87–94.
Viglizzo, E.F., Roberto, Z.E., Lertora, F., Gay, E.L., Bernardos, J., 1997. Climate and land-use change in field-crop ecosystems of Argentina. Agriculture, Ecosystems & Environment 66, 61–70.
Viglizzo, E.F., Frank, F.C., Carreño, L.V., Jobbágy, E.G., Pereyra, H., Clatt, J., Pincén, D., Ricard, M.F., 2011. Ecological and environmental footprint of 50 years of agricultural expansion in Argentina. Global Change Biology 17, 959–973.
Voinov, A., Bousquet, F., 2010. Modelling with stakeholders. Environmental Modelling & Software 25, 1268–1281.
Wolf, C.A., Sumner, D.A., 2001. Are farm size distributions bimodal? Evidence from kernel density estimates of dairy farm size distributions. American Journal of Agricultural Economics 83, 77–88.