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ON-FARM TRADE-OFFS FOR OPTIMAL AGRICULTURAL PRACTICES IN MATO GROSSO, BRAZIL

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ABSTRACT

To keep yield advances, farmers in Mato Grosso (MT) have been adopting several technological innovations. Therefore, agricultural production systems in MT have become complex and dynamic since farmers have to consider the increase of decision variables when planning and implementing their farming practices. These variables are widely spread across many distinct topics, bringing them together and summarizing information from diverse fields of research has become a difficult task in farmers' decision-making process. Therefore, we performed an Integrated Assessment simulation experiment with a region-specific bio-economic component to assess trade-offs between different agricultural practices in a double cropping system. The simulation experiment was carried out with MPMAS, a multi-agent software package developed for simulating farm-based economic behavior and human-environment interactions in agriculture. Crop yields were simulated with the Model of Nitrogen and Carbon dynamics in Agro-ecosystems (MONICA). Our simulation results show a trade-off between lower soybean yields with the flexibility of double cropping when soybean with shorter maturity cycle is introduced. Results also captured regional differences in terms of land use share of different crops and farm configurations of double cropping. These results provide key insights into a farmer's decision-making process depending on a multitude of decision variables.

Keywords: Integrated Assessment; Multi-Agent Systems; Crop Modeling.

RESUMO

Produtores rurais de Mato Grosso têm adotado várias inovações tecnológicas a fim de manter o crescimento da produção. Nesse sentido, o sistema de produção agrícola tornou-se complexo e dinâmico dado o grande aumento das variáveis de decisão que os agricultores precisam levar em consideração a cada ano. Por isso, desenvolvemos um modelo bio-econômico que considera as especificidades de cada região com uma abordagem multidisciplinar, a fim de avaliar os *trade-offs* entre diferentes práticas agrícolas e sistemas de produção em Mato Grosso. O presente estudo foi desenvolvido no MPMAS, um software de simulação baseado em agentes desenvolvido para simular o comportamento econômico de fazendas bem como as interações homem-meio ambiente na agricultura. As produtividades das culturas foram simuladas com o MONICA, um modelo de simulação de nitrogênio e dinâmica de carbono em agro-ecossistemas. Os resultados de nossa simulação mostram um *trade-off* entre produtividade da soja e flexibilidade no sistema de produção quando soja precoce é introduzida. Os resultados capturaram também diferenças regionais no uso da terra de diferentes culturas bem como mudanças nos arranjos produtivos. Estes resultados fornecem informações importantes sobre processo de tomada de decisão dos agricultores de sujeito à um amplo conjunto de variáveis de decisão.

Keywords: Avaliação Integrada; Modelo Multi-Agentes; Simulação.

JEL Code: Q12; C61.

INTRODUCTION

Agricultural production places Brazil amongst the most important world-wide economies. For the past three decades, Brazilian grain and livestock production have grown strongly and the total agricultural output more than doubled compared to the early 1990s. According to the Food and Agriculture Organization (FAO), Brazil is the second largest producer of soybean, the third largest producer of maize, and the fifth largest producer of cotton lint (FAOSTAT, 2017).

Located in the Brazilian mid-western region, the state of Mato Grosso is the largest internal producer of agricultural commodities. It leads the production of soybean, maize, cotton and sunflower and holds the largest cattle herd in the country (CONAB, 2017). The state is also known for its biodiversity, holding three different biomes: Cerrado (Brazilian savanna), Pantanal (tropical wetland) and Amazon rainforest. Despite being a large agricultural producer, Mato Grosso still preserves approximately 60% of its native forest (IMEA, 2017).

The main aspect that distinguishes this region from others is the possibility of growing two crops per agricultural year: one during the rainy season and one in the second (dry) season, the so-called "safrinha". This creates new opportunities for farmers to generate revenues, to intensify the use of production factors (land, input, machinery, and labor), and to draw different strategies to overcome market fluctuations and climate instability. Second season maize production is nowadays responsible for 66% of the national maize production while it was 11% two decades ago and, therefore, plays an important role in reducing the pressure for increase in planted area (PIRES et al., 2016).

Brazil's agricultural sector is experiencing an intensification process that led to a considerable increase of production without expanding the cultivated area. Within the last 10 years, grain production grew by 72% while cultivated area increased only by 22% (CONAB, 2017). The state of Mato Grosso has intensified production and expanded the agricultural frontier into the savannas. Although expanding the agricultural frontier partly explains the increase in production, technological innovation in agriculture is the main factor boosting production.

The development of new seeds is the most important innovation enabling crops to adapt in different climatic and soil conditions (VIEIRA FILHO, SILVEIRA, 2011). Technological advances in genetically modified organisms (GMOs) and short maturity cycle seeds with higher productivity, which are designed to overcome natural instabilities and pests were also key factors for this process. Innovations in soybean, maize and cotton seeds broadened possibilities in the decision-making process of production practices, input requirements, and crop management. In Mato Grosso, farmers have access to a wide range of seed varieties with specific genetic characteristics that may optimize production and even reduce operational costs.

Usually, agricultural innovations occur within research institutions as well as high-tech agricultural properties (VIEIRA FILHO, SILVEIRA, 2011).

However, it is observed that diffusion and adoption of technologies in agriculture take place in a modular (FRENKEN, 2006) and heterogeneous (ROGERS, 2003) way, which influences adoption criteria by farmers. This process is considered to be a complex issue because it leads farmers to face more combinations of production practices, drastically increasing the number of decision variables farmers need to consider during their decision-making process.

The agricultural system in Mato Grosso consists of producing soybean, maize, and cotton, which are grown in different crop rotation set-ups during the rainy season and second season. Each crop has different maturity cycle and seed technology (conventional seeds, herbicide tolerance and/or insect resistance), which can be combined with a large range of sowing dates and fertilizer applications. In turn, farmers have a wide range of possibilities when deciding which crop rotation combination would achieve the highest yield and income given market and environmental conditions.

Hence, the general objective of this study is to analyze the trade-offs of different agricultural practices in double cropping systems in Mato Grosso, Brazil. The specific objectives are to: (1) assess the impact of different crop cycles and sowing dates on crop yield; (2) estimate the economic outcome of different crop management practices; and (3) simulate land use of optimal agricultural practices.

In this way, this article aims to address the decision variables farmers need to take into consideration and the decision variables' impact on production system's gross margins and farmers' decision-making. As a research hypothesis, we argue that the technology diffusion process increased farmers' decision variables and the complexity of those systems. In addition, we argue that the decision variables need to be taken into consideration in a holistic approach, in order to achieve an optimal outcome.

We conducted a quantitative analysis with a farm-level approach on farm systems in Mato Grosso and performed a region-specific bio-economic micro-simulation experiment by which we captured the interregional differences between farms, farm-based economic behavior and farmer-environment interactions in agriculture. The simulation results provide detailed information on how the decision variables affect the production systems. Biotechnological innovation broadened the number of crop rotation and crop management practices which, in turn, enabled farmers to better manage and forecast production. The results of this article provide a full understanding of economic and environmental aspects of different combinations of agricultural systems in Mato Grosso.

LITERATURE REVIEW

Since agricultural activities involve a wide range of decision variables in terms of which cropping systems and/or seed varieties to choose, farmers face a series of risks and uncertainties when it comes to the decision-making process. Farmers are confronted with economic uncertainties as well as environmental risks such as severe weather, pests, and seasonality. In order to avoid or reduce impacts from uncertainties and risks, farmers rely on the diffusion of new products and processes, which play an important role in transforming contemporary economies (SILVERBERG, DOSI, ORSENIGO, 1988). This diffusion process changes over time due to the heterogeneity of adopters, who follow different criteria when adopting a certain technology (ROGERS, 2003; DOSI, 1982).

Advances in biotechnology are a key factor in the development of the agricultural sector. According to Valois (2001), genetically modified plants can increase production and yields, reduce production costs and improve pest management. The main transgenic traits are insect-resistant (IR), herbicides-tolerant (HT), and more recently, a combination of the two (HTIR). The impacts of transgenic varieties are diverse and vary across countries especially due to differences in environmental pressures and pest control management. While GMOs in some countries reduced production costs, in others they decreased production due to weak agricultural practices (FINGER et al., 2011).

In Argentina, Qaim and Zilberman (2003) found no economic advantage of HT soybean over conventional (CONV) soybean in terms of gross margin, yield and production costs. However, when regarding herbicides application, there was a cost reduction with HT soybean. Other benefits such as lower demand for pesticide and better pest control management were observed in countries such as China, India (BENNET, ISMAEL, MORSE, 2005; PRAY et al., 2002; QAIM, ZILBERMAN, 2003), South Africa (THIRTLE et al., 2003; GOUSE et al., 2005) and Pakistan (ALI, ABDULAI, 2010). In terms of gross margin, Qaim and Traxler (2005) found that, on average, HT soybean achieved an advantage of US $ 23 per hectare.

In Brazil, HT cotton, compared to conventional varieties, requires less field operations and weed control (ALVES et al., 2012). Additionally, it requires less herbicide and fewer mechanic and manual operations, thus reducing costs and environmental impacts. On the other hand, Seixas and Silveira (2014) found HT soybean production increased environmental impacts. Duarte, Garcia, Mattoso (2006) found evidence that insect-resistant (IR) maize varieties presented agricultural and economic advantages such as lower demand for labor and pesticides. Additionally, compared to conventional varieties, IR maize varieties achieved higher yields.

In addition to technological advances, different types of farming practices impact crop yields and risk levels farmers face. Sowing date is an important decision variable as it allows farmers to draw different production strategies by combining crop rotation and different seed varieties. By adopting seed varieties with shorter maturity period, farmers can increase their cropping frequency (harvest more than one crop per growing season), which has an impact on crop yields. Yields from soybean with shorter maturity cycle may be lower compared to soybean seeds with longer maturity cycle; however, growing an additional crop may offset yield losses adopting soybean seeds with shorter maturity cycle. The possibility of increasing cropping frequency by sowing earlier or adopting seed varieties with shorter maturity cycle, however, is affected by climate variability. According to

Pires et al. (2016), increased climate variability may affect farmers who sow soybeans early to grow either maize or cotton in the second cropping period in northern Brazil. Cohn et al. (2016) indicate that an increase in local mean temperature in Mato Grosso will decrease cropping frequency and vice versa. In case of a higher mean temperature, farmers may offset potential yield losses by sowing soybeans on a later date. However, Pires et al. (2016) suggest that this will then affect the possibility of double cropping and yield levels of maize and cotton.

The sowing date directly affects crop yields due to different rainfall regimes, temperature and incoming solar radiation (CRUZ, PEIXOTO, MARTINS, 2010). Cruz, Peixoto, Martins (2010) observed that maize and cotton varieties sown by the end of the rainy season in the Brazilian savanna presented lower yields than those sown at the beginning of the rainy season.

Sowing date is the main limiting factor for second season cotton yields. Ferreira et al. (2015) evaluated differences in productivity of cotton according to different sowing dates and found an average decrease of 28% in productivity of cotton yields when sown by the end of the rainy season due to low water supply.

As second season cotton is sown immediately after harvesting soybean, sowing dates of both soybean and cotton affect water supply for the second season. This highlights the importance of drawing production strategies to sow cotton as early as possible (FERREIRA et al., 2015).

As shown by Pedrotti (2014), second season maize follows the same pattern. Usually, maize is sown in January, February or March. Crop growth is, therefore, jeopardized by a range of environmental characteristics, such as less water supply, temperature, and solar radiation. Fitting the sowing date, as much as possible, within the rainy season enables crops to grow within a suitable environment, using all production factors available, increasing the probability to achieve greater yield.

Climate variability also affects cropland area and decisions farmers make to either expand or abandon their agricultural land. Results from Cohn et al. (2016) show that an increase in local mean temperature can lead to a decline in cropping area, which can negatively affect crop yields. With unfavorable weather conditions and low quality agricultural land, farmers may go through a process of expand-and-abandon until they find a favorable land (SPERA et al., 2014). Agricultural expansion in Mato Grosso has been declining in recent years, which Spera et al. (2014) reason that scarcity of high quality land may be a contributing factor.

Another key decision variable regarding crop production is nitrogen (N) application because it directly affects crop growth and grain production and, therefore, is an important decision variable when planting cotton and maize (TEIXEIRA, KIKUTI, BORÉM, 2008; ORIOLI JÚNIOR et al., 2011). Thus, applying a suitable source and amount of nitrogen is crucial to achieve high yields and maximize farm income (ORIOLI JÚNIOR et al., 2011).

METHODS AND DATA

Methodology

We implemented an integrated assessment (IA) based on a multi-agent micro-simulation model. IA is an interdisciplinary process that combines research subjects and disciplines to provide a better understanding of a complex phenomenon (VAN ITTERSUM et al., 2008). The methodology applied in this work follows the approach of Carauta et al. (2017).

Micro and macro-economic analyses are suitable tools to analyze agricultural production systems; however, IA presents additional benefits over those. Firstly, it takes into account cross-scale issues, enabling the up-scaling of farm level data into different macro levels (i.e.: market, municipalities, states or regions). It also enables the assessment of policies by reducing the micro-macro gap (VAN ITTERSUM et al., 2008). IA allows analysis of different groups of agents and/or farms due to technical advantages in computational processes. Additionally, it enables the assessment of policy changes and technological innovations. Lastly, the model dynamics are suitable to assess long-term impacts of climate, soil conditions and farm production factors. The model simulation was done with MPMAS (Mathematical Programming-based Multi-Agent Systems), a multi-agent software package for simulating land use change in agriculture that was linked to the crop model MONICA.

To simulate farm decision-making process in agricultural systems, MPMAS uses the constrained optimization approach (SCHREINEMACHERS, BERGER, 2011). MPMAS has been applied in a range of studies of farm-level agricultural production system and on innovation diffusion in agriculture (QUANG, SCHREINEMACHERS, BERGER, 2014; SCHREINEMACHERS et al., 2010; TROOST, WALTER, BERGER, 2015).

Our IA approach combines the economic component of a farm-level decision-making problem with a crop growth model, that was used to simulate crop yield response to different environmental and crop management conditions. The MONICA model is a dynamic, process-based crop model that describes transport and biochemical turnover of carbon, nitrogen, and water in agroecosystems (NENDEL et al., 2011; MONICA, 2017). Both models, MPMAS and MONICA, were linked to an online database stored in a MySQL server. The crop yields were simulated for all climatic conditions and specific characteristics of regions, which are stored in the database. The database application MPMASQL accesses all relevant information in the database and converts it into MPMAS input. Lastly, MPMAS was integrated into a computer cluster with the use of COIN's CBC mixed-integer programming solver, specifically calibrated for this study.

Each farm agent faces three decision problems in each simulation period (one agricultural year): an investment decision, a production decision, and a consumption decision. Those problems are converted into a MILP (Mixed Integer Linear Programming model). The full MP-optimization problem for each agent consists of 2705 decision variables (63 integers) and 1925 constraints, which results in a very large number of choices in regard to the crop production system, crop management, crop rotation, and production factors (e.g. acquisition of inputs, labor, and machinery). Agents in MPMAS maximize expected farm income by choosing the optimal combination of land use, which needs to be done subject to a set of constraints, such as resource availabilities and climatic conditions, which are specified in the form of equations or inequalities. Expected farm income is calculated as the sum of expected revenue from crop production activities minus variable and fix costs.

We applied a parallel bio-economic simulation experiment in order to assess expected gross margin for specific crop production practices. For that, we developed a new MPMAS application which consisted of creating 227 artificial assets to represent all combinations of crops, maturity group, seed technology, fertilization amounts and sowing dates to simulate the impact of each specific crop practice on one individual farm holding. At the end, each simulation step (representing one real world harvest year) consisted of 995 artificial farm holdings, a combination of crop practices and regions. The full MP-optimization problem for each agent consists of 2921 decision variables (288 integers) and 2142 constraints.

A crop calendar was created to capture the timing of agricultural activities and to correctly simulate agents' resource allocation of machinery and labor over time. This calendar has a weekly resolution in MPMAS and defines the weeks in which farm activities are taking place. The crop calendar was created for each cropping system included in the model according to technical recommendation. Therefore, it is specific for each crop management practice (a combination of crop, maturity group, and seed technology). The link between crop calendar and data on labor and machinery provides estimations of weekly requirements for machinery, input, and labor. The crop calendar is also linked to the crop growth model, in which each agricultural activity is connected to daily climate data.

Model parameterization

The MPMAS model was parameterized for five municipalities in Mato Grosso: Sapezal, Sorriso, Campo Verde, Tangará da Serra and Canarana. Mato Grosso Institute of Agricultural Economics (IMEA) considers these municipalities as representative for the following regions respectively: West, Mid-North, Southeast, South Central and Northeast (IMEA, 2010). The agent population includes all crop-producing farm holdings in those five municipalities which are larger than 50 hectares, according to the latest agricultural census available (IBGE, 2006). At that time, there were 720 farm holdings which corresponded to 74% in terms of number and 99% in terms of cultivated area of all crop-producing farms in those municipalities. Based on these data, we produced a statistically consistent population of model agents following the Monte Carlo approach of Berger and Schreinemachers (2006). Simulated land uses are upscaled from municipality to regional level using weighting factors from the Brazilian Agricultural Census (IBGE, 2006).

Soil classes were assigned to each model agent based on the official maps of socio-ecological zoning produced by the Mato Grosso State Secretary of Planning (SEPLAN, 2011). We assigned six different soil classes, resulting in ten possible climate-soil combinations considering the above mentioned municipalities. Soil classes in each municipality were also linked to MONICA in order to simulate crop yield response to different soil conditions. Weather dataset from 1999 to 2013 for each of the five municipalities were taken from the Brazilian Meteorological Institute (INMET, 2017) and contain the following weather data in daily resolution: maximum and minimum air temperature, sunshine hours, precipitation, wind speed and relative air humidity.

The agricultural production practices included in MPMAS correspond to the most common agricultural commodities found in each selected region of Mato Grosso: soybean, maize, and cotton (Figure 1). Our simulation models MPMAS and MONICA include region-specific production practices (e.g. agents in different regions employ different types of pesticides and they choose different intensity of machinery use). For soybean, we considered three different maturity groups (MG7, MG8, and MG9 corresponding to a growing cycle of less than 115 days, 115 to 126 days and more than 126 days), four sowing dates (01-Oct, 15-Oct, 01-Nov and 15-Nov) and three technologies (Conventional - CONV -, Herbicide Tolerant - HT - and Herbicide Tolerant and Insect Resistant - HTIR). While soybean can satisfy large part of its nitrogen requirement through biological N fixation, we considered nitrogen application rates as a decision variable for maize and cotton. For maize, four different sowing dates (20-Jan, 06-Feb, 20-Feb and 06-Mar), five nitrogen applications rates (0, 40, 80, 120 and 160 kg/ha) and three technologies (CONV, IR and HTIR) were considered. For cotton, five sowing dates were considered, two in the first season (15-Dec and 30-Dec) and three in the second season (15-Jan, 30-Jan and 15-Feb); as well as seven nitrogen levels (0, 90, 140, 185, 230, 280 and 450 kg/ha) and four technologies (CONV, HT, IR, and HTIR). In total, we included 227 agricultural production possibilities that were combined with specific soil fertility constraints for each region, resulting into 1990 possible set-ups that each farm agent manages every year. The complexity in an agent's decision making increases even further as favorable climatic conditions allow a double cropping system, resulting in 40 feasible double crop combinations.

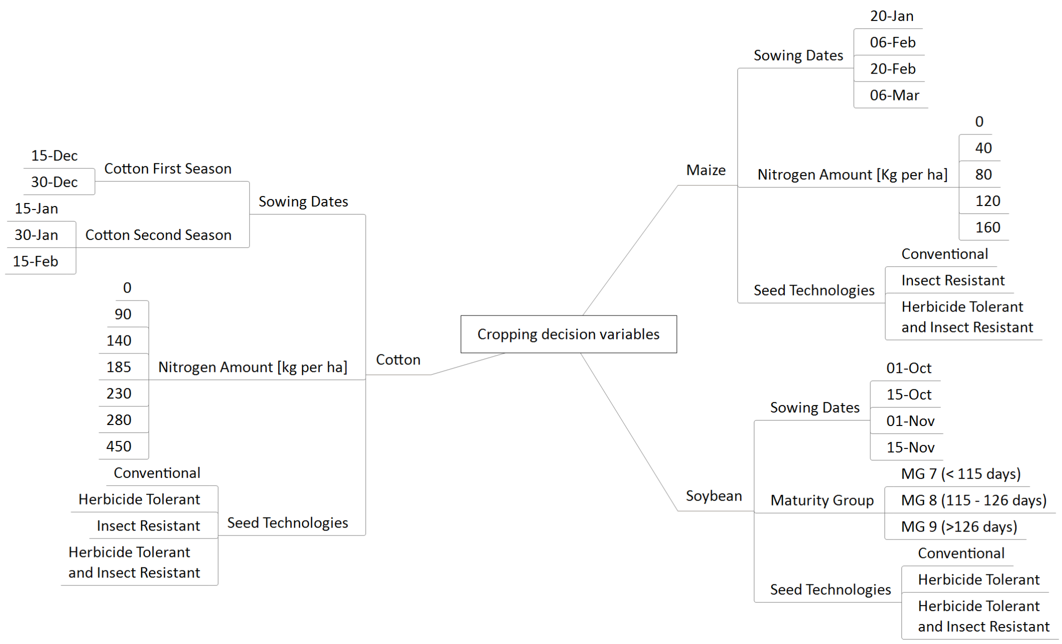

Figure 1. Decision variables of simulated agricultural practices.

Different crop management practices for each agricultural production possibility were also taken into account. Crops with longer maturity cycles require more fungicide and insecticide applications; Insect Resistant (IR) crops require fewer insecticides applications; Herbicide Tolerant (HT) crops require herbicides with different active ingredients; in case of soybean HTIR, the longer the maturity cycle is, the greater is the substitution effect between the insecticide application and the genetically modified (GM) Bt toxin. Different crop technologies require different input quantities (Figure 2), however, also the active ingredients change according to each technology. The crop management options for MPMAS were estimated with a farm-level survey from Céleres – a local agribusiness consulting enterprise – (CÉLERES, 2013), including 157, 299, and 303 observations for soybean, maize and cotton, respectively, as well as technical advice from local experts.

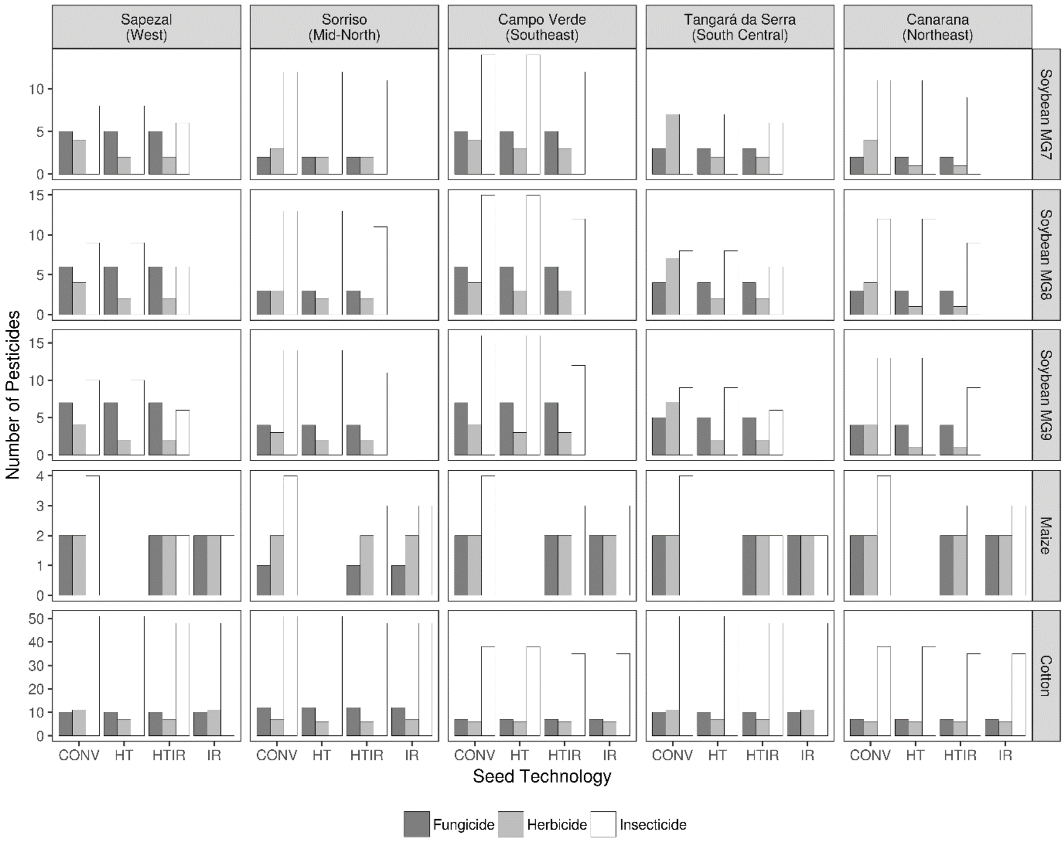

Figure 2. Number of pesticide applications according to different crop management practices in five survey sites in Mato Grosso, Brazil. Seed technology: conventional (CONV), herbicide tolerant (HT), insect resistance (IR) and herbicide tolerant and insect resistance (HTIR). Soybean Maturity Group (MG).

The estimation of production costs for each crop and region is annually done by IMEA (2015). Together with farmers and experts from all stages of the production chain (i.e.: input sellers, machinery sellers, rural union), the production costs are estimated using a collaborative approach in which the concept of "modal farm" is used - a productive unit with characteristics that approximate the local reality profile to the region (CONAB, 2010). From the modal production cost, we estimated production costs for each crop, seed cycle, seed technology (CONV, HT, IR, and HTIR), and region based on technical advice from local experts. Besides the production costs, we also estimated the post-harvest costs, such as transportation, storage, processing, and taxes. The time series data for the agricultural products were also taken from IMEA, including the online price dataset (IMEA, 2015).

Model validation

In order to assess to which extent our combined MPMAS_MONICA simulations are a good representation of the real-world observations, we applied an empirical validation in which the output from the simulation models was compared to the corresponding observed data (FAGIOLO, MONETA, WINDRUM, 2007). For our IA approach, we used a three-step process, one for the biophysical model component and two for the bio-economic model component. The first step considered the validation of the output from the crop growth model MONICA. The validation process considered Mato Grosso`s soil and climatic conditions and used municipality-level crop yield estimations from the IBGE as observed data (IBGE, 2017). The observed yield data were compared to the simulated yield data from MONICA (and later integrated into MPMAS) (Figure 3). Due to lack of farm-level information on individual crop yields and management, it was not possible to validate the simulated yield at farm agent level. Instead, we compared simulated yields against observed yields at municipality-level.

We used three different statistical indices to assess the crop model´s performance: Mean absolute error (MAE), root mean square error (RMSE) and Willmott´s index of agreement (d), a standardized measure of the degree of model prediction error. The validation of the crop growth model suggests that its predictions match both with the municipality level average yields and with the yield responses due to different climate conditions over the years (MAE of 385.1; 603.16; 363.6 (kg ha^{-1}); RMSE of 481.84; 836.78; 513.29 (kg ha^{-1}); d of 0.4; 0.66; 0.62, respectively for soybean, maize, and cotton - Figure 3).

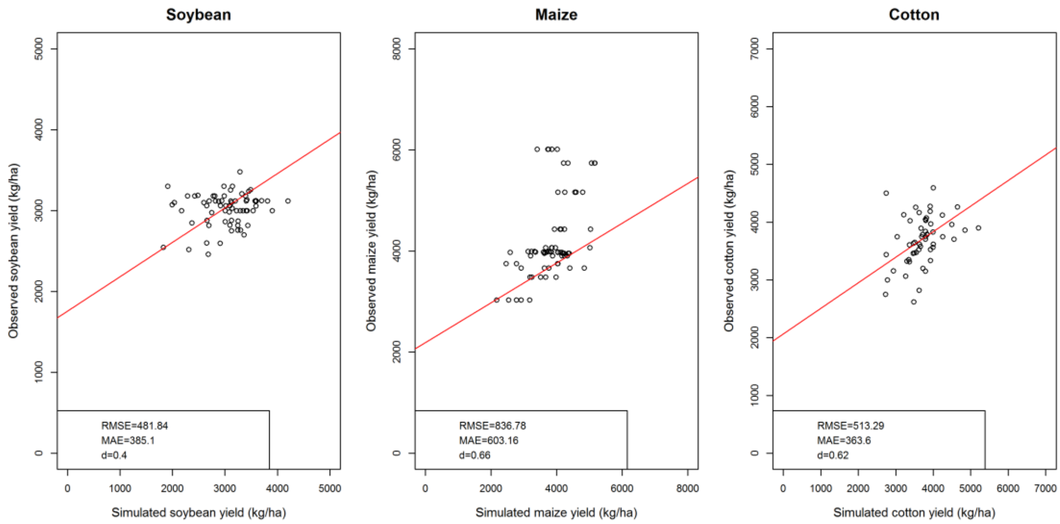

Figure 3. Validation of crop yields simulated with the MONICA model for five survey sites in Mato Grosso, Brazil. The red line indicates a regression line between the simulated and observed crop yields.

The second and third steps are related to the validation of our bio-economic model component, which was done with the MPMAS software. First, we ran a farm-level validation and after that, a municipality-level validation (Figure 4). Those two processes were carried out separately and were necessary because the model simulates both the behavior of individual farms and of the study area as a whole. For the farm-level validation, data from the IMEA (2015) was collected and, for the municipality level, municipality land use data from IBGE (2017). The MPMAS validation of the bio-economic component took into account the different farm profiles for each region, such as land ownership, asset endowments, as well as inter-regional characteristics and constraints.

The model efficiency was estimated following Nash-Sutcliffe (an efficiency of one indicates a perfect match between the simulated and the observed data, while an efficiency smaller than zero indicates that the sample mean is a better predictor than the model). Under the farm-level step, our application has a model efficiency of 0.66, which improved to 0.81 at the municipality-level step. In addition, the fitted no-constant regression lines and their calculated R-squared (0.92 for the farm level and 0.97 for the municipality level) indicate a good fit of the model results (Figure 4). Therefore, the validation outcomes suggest that our MPMAS application is able to simulate land use decisions consistently and accurately both at the farm and municipality level.

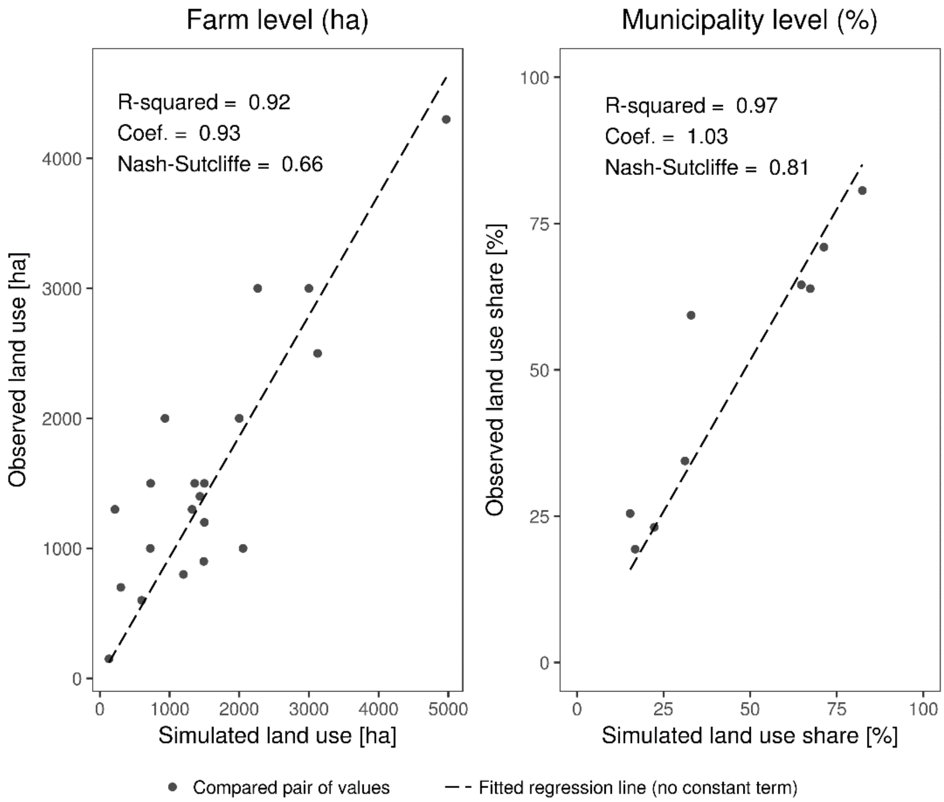

Figure 4. Model validation based on MPMAS simulation. The dashed line indicates a regression line between the simulated and observed land uses. Coef. = coefficient of the regression line with no constant term.

RESULTS AND DISCUSSION

Impact of crop cycle and sowing dates on crop yields

As soybean is usually cultivated in the first season, the sowing date is not such a significant decision variable as it is for crops sown in the second season, such as maize and cotton. However, soybean yields are significantly influenced by the length of its growing cycle and according to maturity groups. As shown in the previous section, a longer maturity cycle requires additional application of pesticides, as crop exposure to pests is increased. On the other hand, a longer growing cycle has the potential to achieve higher yields (approximately six additional bags when compared to the shortest maturity group, Figure 5). Despite its lower yields, soybean varieties with a shorter maturity cycle allow for maize and cotton in the second season to be sown earlier, which might increase the rotation system gross margin. This result converges with Cohn et al. (2016) findings, showing that shorter-cycle soybeans facilitate second-crop production, but reduce first-crop yields. Therefore, an agent's decision regarding crop rotation should take into consideration the trade-off between crops yields and its relative price levels.

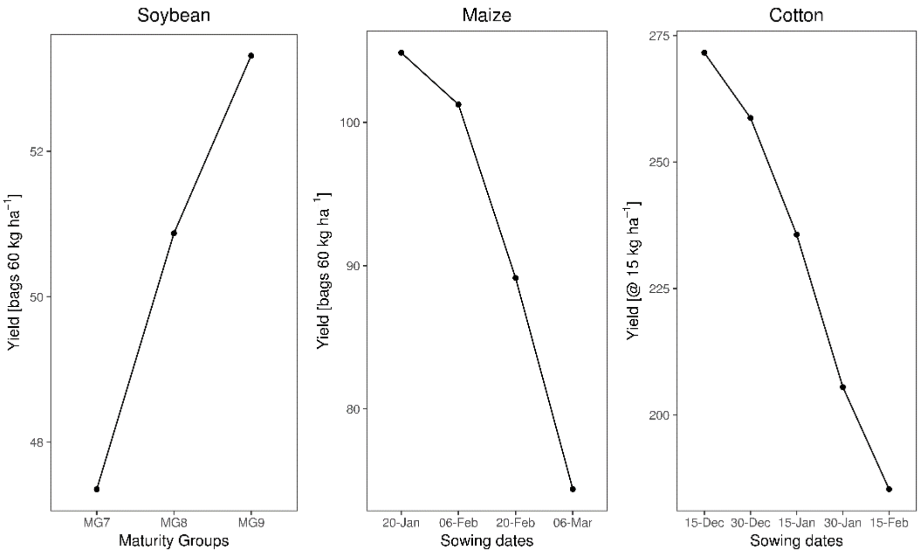

Figure 5. Simulated crop yields for different maturity group and sowing dates in Mato Grosso, Brazil (average of all survey sites). Soil: Ferrasol Dystrophic; Nitrogen Amount (kg ha^{-1}): 0, 120 and 185, respectively.

For crops sown during the second season (maize and cotton), sowing date is a significant decision variable. On average, the latest sowing date results in a yield reduction of 30 bags for maize and 86 *arrobas* (one *arroba* is approximately 15kg) for cotton when compared to the earliest sowing date (Figure 5). This can be explained by a lower supply of rainfall during the crop development phase and an increasing transpiration deficit that limits crop growth. The coefficient of variation for that decision variable was 15% for both crops. Thus, our simulation results suggest that both maturity group and sowing date are important to a farm agent's decision-making process.

As pointed out by Arvor et al. (2014), double cropping system adoption is related to high annual rainfall, a long rainy season and a low variability of the onset of the rainy season. Our simulation results additionally show that those variables are also related to the adoption of medium to late soybean varieties (such as MG8 and MG9). On the other cases, a higher share of shorter maturity cycle is observed, since it favors early sowing dates at the second season.

Economic outcome of different crop management practices

In order to assess the impact of all decision variables in each production system, we estimated the gross margin (in Brazilian Reais per hectare) of all crop management practices. Figure 6 shows that all crop practices related to soybean production presented positive gross margin.

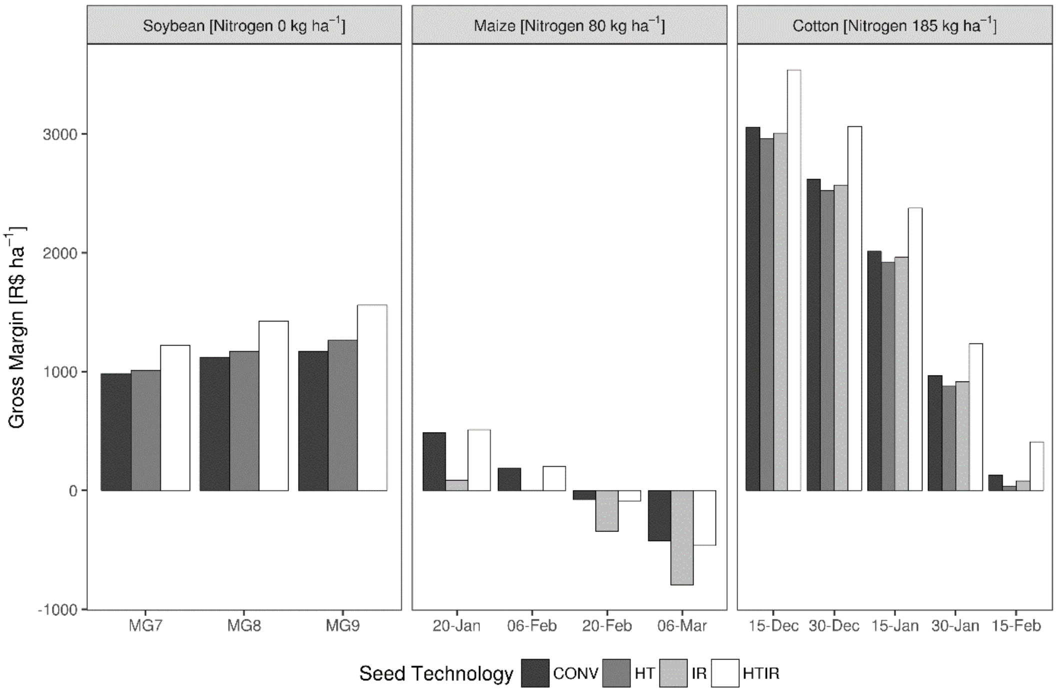

Figure 6. Gross margin per hectare for Mato Grosso (average of all survey sites). Seed technology: conventional (CONV), herbicide tolerant (HT), insect resistance (IR) and herbicide tolerant and insect resistance (HTIR). Soybean Maturity Group (MG)

On average, soybean varieties of MG8 and MG9 achieve a higher gross margin when compared to varieties of MG7, which can be explained by the higher yields these varieties achieve (Figure 5). The best soybean economic performance was observed in treatments with HTIR seeds, as those seeds presented, on average, an increase of 11,4% in yields in our econometric analysis from Céleres database. Soybean HT varieties achieve a higher economic performance when compared to conventional ones, due to cost reduction in herbicide application.

Due to macroeconomic conditions related to the crop season 2015/2016, maize production show, on average, negative gross margin. There are several factors which can explain this result. The first one is that yields tend to decrease with late sowing dates (Figure 5), which makes it very risky to grow maize with a high level of investment in technology on a later sowing date. The second reason is the current economic crisis in Brazil, which increased the inflation rate over the recent years and, consequently, production costs. Production costs were also affected by depreciation in exchange rates, as a large share of inputs (mainly pesticides and fertilizers) is imported from abroad. As pointed out by Bennet, Ismael, Morse (2005), high seed prices for transgenic maize varieties increased the production cost, which led farmers to avoid adopting these technologies.

It is important to note that maize is also grown for technical reasons since it increases organic matter, keeps the soil covered during the dry season, reduces soil compaction and improves water infiltration in the soil (ALVARENGA et al., 2001). Another reason is that maize is easily tradable in Mato Grosso, while for others crops, such as millet, sorghum, and crotalaria this is not true. Therefore, it still makes sense to produce maize under low price conditions, but farmers will probably reduce the technology level with a combination of lower nitrogen amount and cheaper seeds.

In this study, cotton showed the highest gross margin among all crops. Crop production is more profitable when cultivated in the first season (15-Dec and 30-Dec) compared to late sowing dates. However, the crop rotation in the first case consists of growing millet, which is not sold on the market, as a cover crop from October to December. On the other hand, second season cotton is cultivated after soybean, providing an alternative source of income to the production system. It is important to note that cotton production is very complex and requires experience, expertise and a high level of investment. Therefore, despite its higher gross margin, there is still a higher share of maize adoption since cotton production requires: (1) specific soil and climatic conditions, (2) high capital/liquidity requirements (due to high production cost), (3) high machinery requirements (due to its high frequency of field operations) and (4) high investment costs (due to the use of specialized machinery, such as cotton harvester).

In regard to seed technology, our simulation suggests that the economic benefit of lower production cost from fewer herbicide and insecticide applications for HTIR seeds more than compensate the investment on those seeds, pushing the adoption of those varieties.

Simulated land use of optimal agricultural practices

Our simulation experiment shows that the optimal agricultural practice changes significantly according to each region. The key factor is the yield variation through all regions, which can be explained by changes in climatic and soil conditions. Mato Grosso state has nine hundred thousand square kilometers, the third largest state in area, and holds a large variety of biomes and biodiversity, which directly influences rainfall pattern, soil conditions, temperature, and solar radiation (ARVOR et al., 2014; PIRES et al., 2016). Therefore, despite all the agricultural practices available for each farm holding, the optimal set chosen in our simulation experiment is mostly influenced by climatic conditions. This highlights the fact that it is important to conduct an IA that integrates all key decision variables in order to properly assess the complexity of production systems. As an example, double cropping in Mato Grosso is more prevalent in areas with a longer period of rainy season and a higher annual mean rainfall (ARVOR et al., 2014). Results from Figure 7 converge with the aforementioned literature, showing that areas with a longer rainy season such as Mid-North and West show higher land use share with maize and cotton.

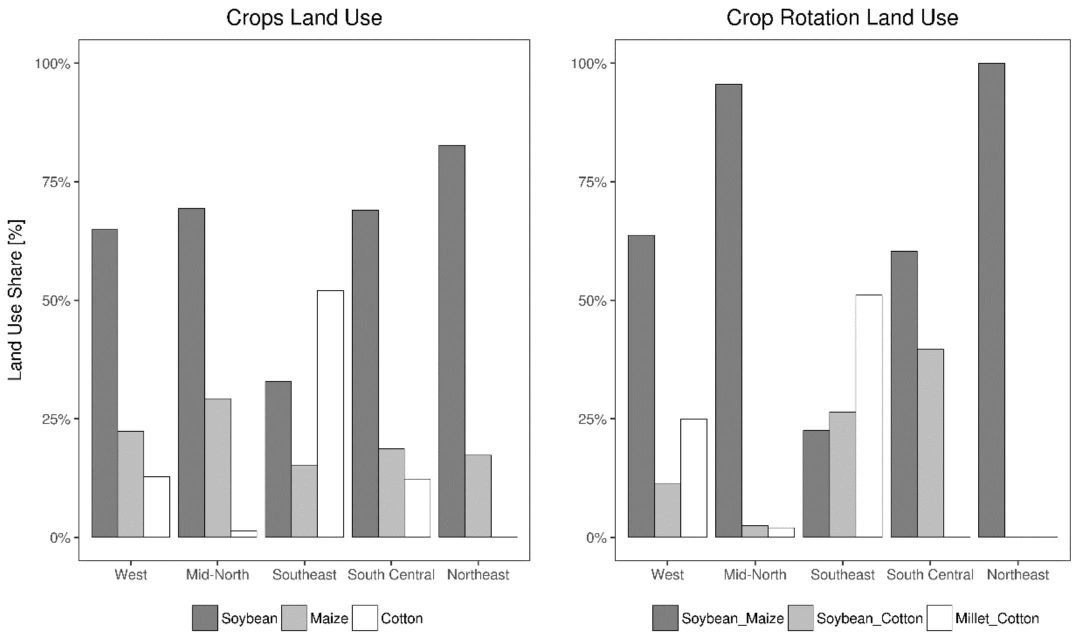

Figure 7. Simulated land use of optimal agricultural practices in Mato Grosso, Brazil (upscaled to regional level using IBGE sampling weights for land use).

Simulated land use share for Southeast shows high level of double cropping even though rainfall levels are lower compared to other regions. This divergence show that rainfall may not be the only deciding factor of whether farmers adopt double cropping or not. Even though the average precipitation in the Southeast region is smaller, there are still favorable climatic conditions to produce cotton in this region, since there cotton lint is less exposed to rain, which improves its quality. Although Northeast region had the second highest mean rainfall, Arvor et al. (2014) indicate that this region had the lowest double cropping systems and Figure 7 confirms this with Northeast region displaying the highest level of land use share for soybean production (or the lowest level of land use share for maize and cotton combined). Figure 7 shows that cotton production systems were more concentrated in the Southeast and West regions, while soybean and maize were more evenly applied across the state.

Figure 8 shows an example of a simulated optimal land use by our MPMAS application for one typical farm in the South Central region that implements both soybean-cotton and soybean-maize rotation systems. The farm cropland area comprises 2500 hectares, which are completely used for soybean cultivation in the first season. Due to machinery and labor constraints, it is not possible to cultivate the whole area on the same sowing date; therefore, our simulation shows that this agent should sow part on the first sowing date (01-Oct) and the remaining on the following dates (15-Oct and 01-Nov).

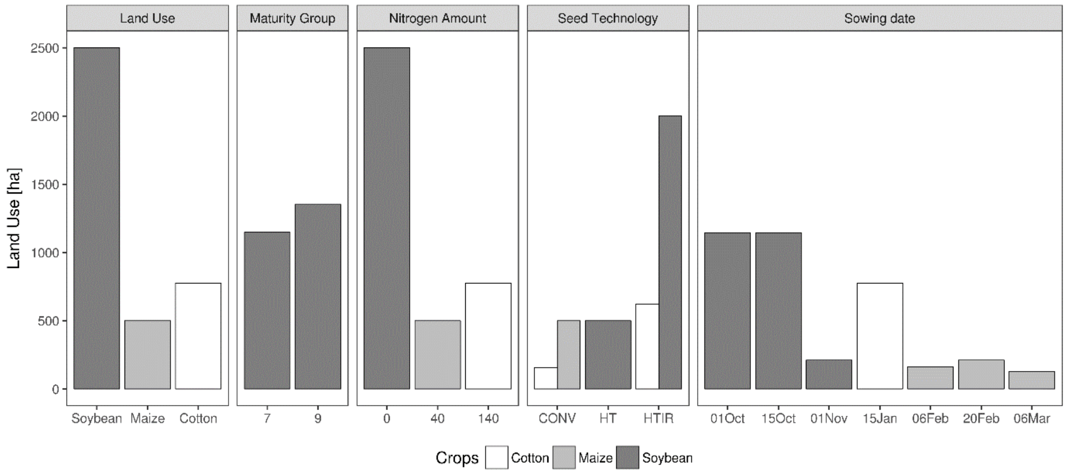

Figure 8. Optimal land use simulated by MPMAS for a typical farm in South Central region. Seed technology: conventional (CONV), herbicide tolerant (HT), herbicide tolerant and insect resistance (HTIR).

In order to sow maize and cotton in the second season, the agent shall start by sowing soybean MG7 to achieve higher yields on the second season. Afterwards, the agent can sow soybean MG9, as soybean with a longer maturity cycle achieves higher yields (Figure 5). Other decision variables, such as nitrogen amount and seed technology are also simulated for each crop and represented in Figure 8.

Despite the fact that soybean MG9 achieves higher yields, one should consider the trade-off between yields and sowing dates for the second season crops, as those combinations are intrinsically linked to the length of the soybean's maturity cycle. In this way, the yield difference from shorter maturity cycles shall be offset by a yield gain in the second season. These results confirm the findings of Allen and Lueck (1998), where the authors argue that the steps of linking the production cycle and field activities are a key element to technology diffusion. It is important to note that each farm will have its own optimal solution, as it is subject to environmental conditions and production factor endowments (such as land, machinery, labor and capital). Therefore, Figure 8 represents the optimal solution for only one specific farm holding and, therefore, should not be considered in a different context.

CONCLUSIONS

The results of our simulation suggest that climatic conditions play a major role in Mato Grosso's agricultural production, and there is a wide range of variation in crop yields across the state. Early sowing dates are an important variable for achieving higher yields in the second season and our simulation experiment fully captures the yield difference between those sowing dates on maize and cotton production, providing key elements and insights to a farmer's decision-making process. The closer a crop is sown to the beginning of the rainy season, the higher the probability to achieve greater yields, as the crop is exposed to less water deficit, which can be decisive, especially in years of low price levels or higher production costs. Furthermore, high levels of incoming solar radiation at the beginning of the year (Jan-Feb) favor carbon assimilation and hence yield formation.

As soybean is sown at the beginning of the rainy season, sowing date is not such a decisive decision variable as for second season maize and cotton. However, sowing dates are closely linked to the choice of suitable soybean maturity groups. A longer growing cycle means a higher yield because the crop has more time to develop. However, adopting a longer maturity cycle reduces farmer's second season options and, as discussed above, the short cycle soybeans that are sown first allow a higher yield during the second season cropping system. In this context, the interdependence between the elements which define the production system also determines a certain level of rigidity. Therefore, the flexibility that soybean MG7 produces in the cropping system is a key element to those farm holdings.

In conclusion, we argue that the introduction of short maturing soybean varieties increased farmers' flexibility in second season crop planning, but at the same time also increased the production system's complexity as well as trade-offs in crop yields, corroborating the use of an Integrated Assessment approach. We showed that our simulation experiment has the full potential of assessing region-specific decision variables which farmers have to deal with in Mato Grosso. Our model provided key information to farmer's decision-making process, stressing the most important decisions and its implication to the whole system, as well for its economic performance. Our simulation experiment showed that all decision variables are somehow connected and pointed out the importance of evaluating site-specific and/or region-specific variables.

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