On-Farm trade-offs for optimal agricultural practices in Mato Grosso, Brazil

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Abstract: Agricultural production in Mato Grosso (in mid-western Brazil) has been increasing strongly over the past years, producing a quarter of the national grain production. In order to keep that path, farmers have been adopting several technological innovations with the major share of this production gain coming from yield advances. However, the agricultural production system in Brazil has become complex and dynamic and it has experienced a large increase in decision variables which farmers need to tackle every year. Moreover, as those 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 a farmer's decision-making process. Therefore, we developed an Integrated Assessment simulation experiment with a region-specific bio-economic component in order to assess the trade-offs between different agricultural practices and production systems in Mato Grosso. We implemented our simulation in MPMAS, a multi-agent software package developed for simulating farm-based economic behavior and human-environment interactions in agriculture. The crop yields were simulated with the Model of Nitrogen and Carbon dynamics in Agro-ecosystems (MONICA). Our simulation results captured both regional difference between farms and between climate conditions, providing key insights into farmers' decision-making process and comprehension about the interaction of those decision variables. We show that climate conditions are still a key variable to decision-making process and that farmers should assess those variables together in order to fully optimize their production and economic results.

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

Resumo: A produção agrícola em Mato Grosso (em meados de oeste do Brasil) vem crescendo significantemente nos últimos anos, produzindo um quarto da produção nacional de grãos. Produtores rurais de Mato Grosso têm adotado várias inovações tecnológicas a fim de manter o crescimento da produção, onde a maior parte deste ganho tem sido proveniente de avanços na produtividade em detrimento à avanços da área cultivada. 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. Além disso, a multidisciplinariedade destas variáveis tem gerado um maior nível de complexidade à tomada de decisão. 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 capturaram tanto da diferença regional entre fazendas bem como as diferenças de condições climáticas que condicionam os sistemas de produção, fornecendo informações importantes sobre processo de tomada de decisão dos agricultores bem como uma maior compreensão sobre as interações dessas variáveis de decisão. Nosso estudo mostra que as condições climáticas ainda são variáveis chave para o processo de tomada de decisão e que os agricultores devem avaliar essas variáveis em conjunto de forma a otimizar a sua produção bem como seus resultados econômicos.

Palavras-Chave: Avaliação Integrada; Modelo Multi-Agentes; Simulação

1. INTRODUCTION

Agricultural production places Brazil amongst the most important worldwide economies. For over 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, Brazil is the second largest producer of soybean, the third largest producer of maize, and the fifth largest producer of cotton lint (FAOSTAT, 2016).

Located in the center-western region, the State of Mato Grosso is a key player in producing agricultural commodities. It leads the production of soybean, maize, cotton, sunflower, and holds the largest cattle herd in the country (CONAB, 2016). The state is also known for its biodiversity, holding three different biomes: Cerrado (Brazilian Savannas), Pantanal and Amazon Rainforest. Despite being a large agricultural producer, the state still preserves approximately 60% of its native forest (IMEA, 2016).

The key factor which distinguishes this region from others is the possibility of growing crops in a second season, the so called “safrinha” (in English, second season). This provides producers new revenues possibilities, intensifies the use of production factors (land, input, machinery and labor) as well as the possibility to draw different strategies to overcome market fluctuations and climate instabilities. Second season maize is responsible for 66% of the national production while it was 11% two decades ago.

Brazilian agriculture has intensified production, enabling 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, 2016). The state of Mato Grosso has intensified production and expanded the agricultural frontier into the savannas. Expanding the agricultural frontier partly explains the increase in yield, but technological innovation in agriculture is the main element spurring production.

The development of new seeds is the foremost innovation enabling adaptation of varieties into different climate and soil conditions (VIEIRA FILHO; SILVEIRA, 2011). Technological advances in GMOs (Genetically modified organisms) and short maturity cycle seeds designed to overcome natural instabilities, pests and to provide a higher productivity 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, producers access a wide range of varieties with specific genetic characteristics that, by interacting with the environment, 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 takes place in a modular (FRENKEN, 2006) and heterogeneous (ROGERS, 1995, 2003) way, which influences adoption criteria by farmers. This process is revealed to be a complex issue because it leads farmers to face more combinations of production practices, drastically increasing the number of decision variables related to farmer`s decision making process.

The agricultural system in Mato Grosso consists of producing soy, maize and cotton, which are sown in different crop rotation set ups during the rainy season. Each crop presents differences in maturity and seed technology (conventional seeds, herbicide tolerance and/or insect resistance), which can be combined with a large range of sowing dates and fertilization requirements. In turn, producers have a wider range of possibilities when deciding which crop rotation combination would achieve the highest yield given market and environmental conditions.

Hence, the objective of this work is to analyze the trade-offs of different agricultural practices on agricultural production systems in Mato Grosso, Brazil. In this way, this article aims to address the decision variables farmers need to take into consideration and their impact on system gross margins and on the production scheme. 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 those 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 developed a region specific bio-economic micro-simulation model which is able to capture the interregional differences between farms, farm-based economic behavior and human-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 producers to better manage and foresee production. The results of this article provide a full understanding on economic and natural aspects of different combinations of agricultural systems in Mato Grosso.

2. LITERATURE REVIEW

The agricultural sector is immersed in a series of risk and uncertainties when it comes to the decision-making process of which cropping systems and varieties to choose. This is because a wide range of decision variables is involved in agricultural activities. Moreover, producers are confronted with economic uncertainties as well as natural risks such as severe weather, pests, seasonality and climate impacts. In order to avoid or reduce these impacts, 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 heterogeneity of adopters, who follow different criteria when adopting a certain technology (DOSI, 1982; ROGERS, 1995).

Advances in biotechnology on crop production are a key factor in the development of agricultural production. According to Valois (2001), genetically modified plants can provide an increase in production and yields, a reduction in production costs and improved pest management control. The main transgenic traits are insect resistance, herbicides tolerance, and more recently, a combination of those. The impacts of transgenic varieties are diverse and vary across countries especially due to differences of environmental pressures and pest control management. While in some countries genetically modified organism (GMOs) reduced production costs, in others it decreased production itself due to weak agricultural practices (FINGER et al., 2011).

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

As for herbicide tolerant cotton in Brazil, it demands less cultural practices and weed control when compared to conventional varieties (ALVES et al., 2012). Additionally, it demands less herbicide, mechanic and manual operations, thus reducing costs and environmental impacts. On the other hand, when it comes to herbicide tolerant soybean, Seixas and Silveira (2014) found an increase in environmental impacts. Oliveira Duarte et al. (2006) found evidence that insect resistant maize varieties presented agricultural and economic advantages such as lower demand of labor and pesticides. Additionally, it achieved higher yield, when compared to conventional varieties.

Sowing date is also an important decision variable as it allows producers to draw different production strategies by combining crop rotation, seed varieties as well as sowing dates. The sowing date directly effects crop yields due to different rainfall regimes, temperature and incoming solar radiation (CRUZ; PEIXOTO; MARTINS, 2010). These authors observed that maize and cotton varieties sown by the end of the rainy season in the Brazilian savannah presented lower production than those planted 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 a decrease of 25%, 17% and 41% 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 influence water supply for the second season. Therefore, this result highlights the importance of drawing production strategies for sowing cotton as soon as possible (FERREIRA et al., 2015).

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

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

3. METHODS AND DATA

3.1 Methodology

The methodology applied in this work follows the same steps of Moraes et al., 2016. 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).

Micro and macroeconomic analysis are suitable tools to analyze agricultural production systems. However, IA presents 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.

To simulate a farm decision-making process in agricultural system, MPMAS uses the constrained optimization approach (SCHREINEMACHERS; BERGER, 2011). MPMAS has been applied in a range of studies of IA of farm-level agricultural production system and on innovation diffusion in agriculture (MAROHN et al., 2013; QUANG; SCHREINEMACHERS; BERGER, 2014; SCHREINEMACHERS et al., 2010; TROOST; WALTER; BERGER, 2015; WOSSEN; BERGER, 2015).

MPMAS combines the economic component of a farm level decision-making problem with a crop growth model, simulating the crop yield response to changes in inputs. Crop yields are simulated with the MONICA model, a dynamic, process-based simulator that describes transport and bio-chemical turnover of carbon, nitrogen and water in agro-ecosystems (MONICA, 2016; NENDEL et al., 2011). Both models are linked to an online database stored in a MySQL server. The crop yields are simulated for all climate 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 is 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 real world harvest 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 larger number of choices in regard to the crop production system, crop management, crop rotation and production factor requirements (acquisition of inputs, labor and machineries). 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 climate conditions, which is 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 in 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 on 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, therefore, correctly simulate the agent 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 according to technical recommendation for each cropping system included in the model. 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 related with daily climate data.

3.2 Model Parameterization

The MPMAS model was parameterized for five municipalities in Mato Grosso: Sapezal, Sorriso, Campo Verde, Tangará da Serra and Canarana. IMEA considers these municipalities as representative for the following regions: West, Mid-North, Southeast, South Central and Northeast. The agent population includes all crop-production 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 corresponds 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).

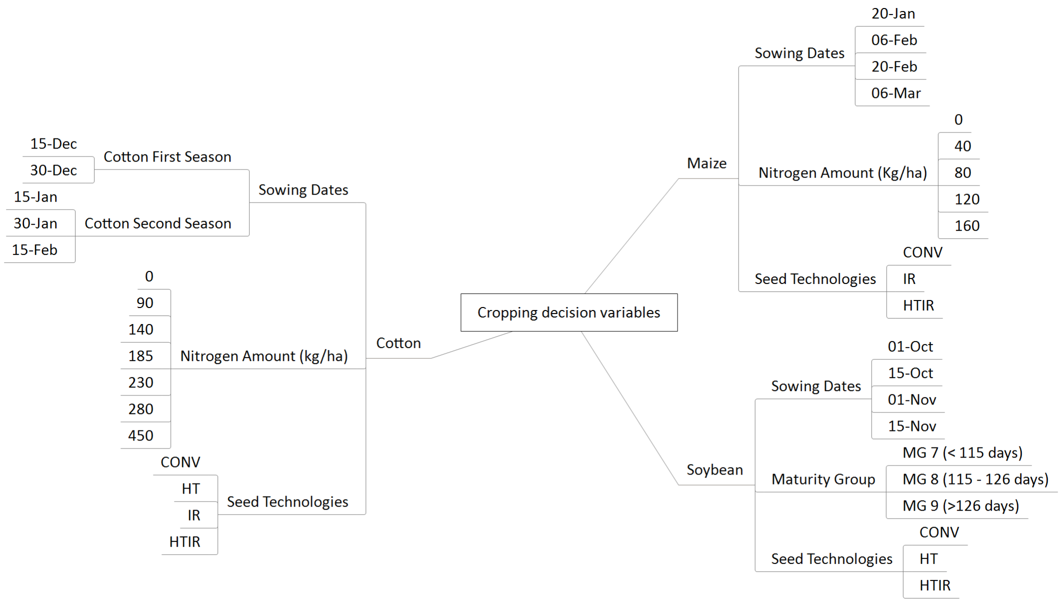

Figure 1: Decision variables of simulated agricultural practices

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 combinations considering those municipalities. Soil classes in each municipality were also linked with MONICA in order to simulate crop yields. We further implemented a weather data set from 1999 to 2013 for each of the five model regions. These data were taken from the website of the Brazilian Meteorological Institute (INMET, 2014) and contain the following weather data in daily resolution: maximum and minimum air temperature, sun duration, 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. Our simulation models MPMAS and MONICA also include region-specific production practices (for example, agents in different regions employ different types of pesticides and they choose different intensity of machinery use, etc.). For soybean, we considered three maturity cycles (MG7, MG8 and MG9 corresponding to less than 115, between 115 and 126 and greater than 126 days of maturity, respectively); four planting 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). For maize and cotton, instead of maturity cycle, we introduced nitrogen application (kilograms per hectare) as a decision variable. In this sense, four planting dates for maize were considered (20-Jan, 06-Feb, 20-Feb and 06-Mar); five nitrogen applications (0, 40, 80, 120 and 160 kg/ha) and three technologies (CONV, IR and HTIR). Finally, for cotton, five planting 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 can be combined with specific soil fertility constraints for each region, resulting into 1990 possible set ups that each farm agent deals with in every year. The complexity in agent decision making increases even further as favorable climate conditions allow a double cropping system, resulting in 40 feasible double crop combinations.

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 less insecticides applications; Herbicide Tolerant (HT) crops require herbicides with different active ingredients and, in case of soybean HTIR, the longer the maturity cycle is, greater is the substitution effect between the insecticide application and the genetically modified (GM) Bt toxin. Different crop technology requires different inputs quantities (Figure 2), but also the active ingredients changes according to each chosen technology. The crop management options for MPMAS were estimated with a farm level survey from Céleres – local agribusiness consulting enterprise – database (CÉLERES, 2013), including 157, 299 and 303 observations for soybean, maize and cotton, respectively, as well as technical advice from local experts.

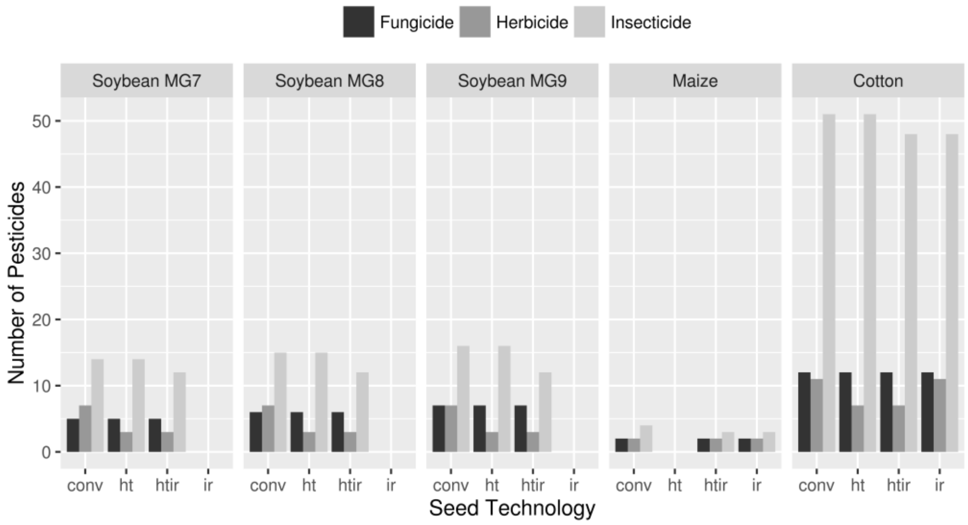

Figure 2: Pesticide application based on different crop management practices dates for Mato Grosso (average of all regions)

The estimation of production costs for each crop and region is done by IMEA in a yearly time interval (IMEA, 2015a). Together with farmers and experts from all stages of the production chain (i.e.: input sellers, machinery dealers, rural union), the production cost is estimated using a collaborative approach in which the concept of “modal farms” is used - a productive unit with characteristics that approximate the local reality profile to the regional (CONAB, 2010). From the modal production cost we estimated a production cost for each crop, seed cycle, seed technology (CONV, HT, IR and HTIR) and region based on local expert technical advice. Besides the production cost, 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, 2015b).

3.2 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 an economic micro simulation model is compared with the corresponding statistics from the real world (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 municipal crop yield estimations from the IBGE (2015). The observed yield data were compared to the simulated yield data from MONICA (and later integrated into MPMAS). Due to lack of farm-level information on individual crop yield 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.

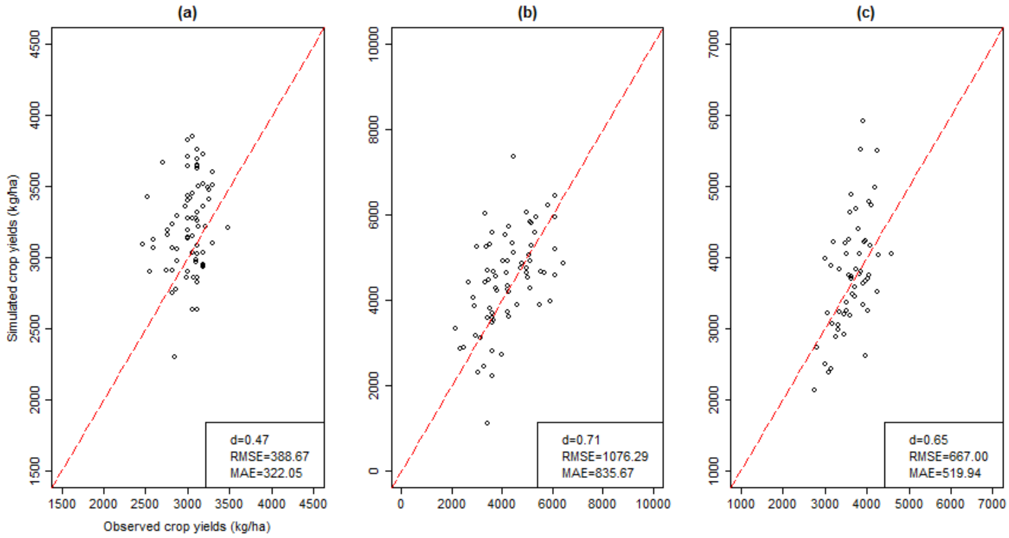

Figure 3: Validation of crop yield simulated from MONICA software

We used three different statistical indices to assess the crop model´s performance: Mean absolute error (MAE), root mean square error (RMSE) and the 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 322.05; 835.67; 519.94; RMSE of 388.67; 1076.29; 667; d of 0.47; 0.71; 0.65, respectively for soybean, maize and cotton).

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. 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 Mato Grossense

Institute of Agricultural Economics (IMEA, 2016) was collected and, for the municipality level, municipality land use data from IBGE (IBGE, 2015). 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 the inter-regional characteristics and constraints.

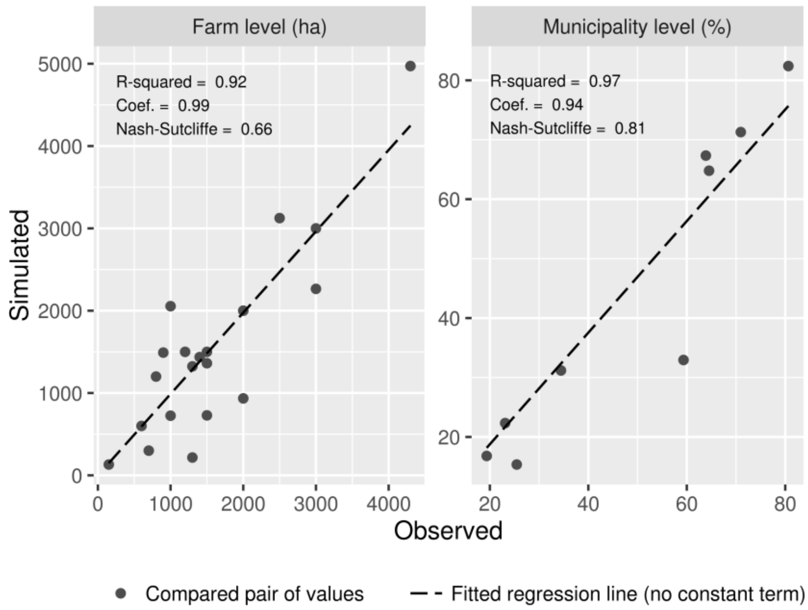

Figure 4: Model Validation based on MPMAS simulation

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 in 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. Therefore, the validation outcomes suggest that our MPMAS application is able to simulate land use decisions consistently and accurately both at farm-level and municipality level.

4. RESULTS

4.1 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 its cycle (or maturity groups). As it was shown in the previous section, a longer growing cycle requires a higher application of pesticides, as crop exposure to pests is increased. On the other hand, a longer maturity cycle has the potential to achieve higher yields (approximately 6 begs when compared to the shortest maturity group), as it is shown in the Figure 5. Despite its yield reduction, a soybean with shorter cycle allows an early sowing of maize and cotton in second season, which might increase the rotation system gross margin. Therefore, agent decision regarding crop rotation should take into consideration the trade-off between crops yeilds and its relative price levels.

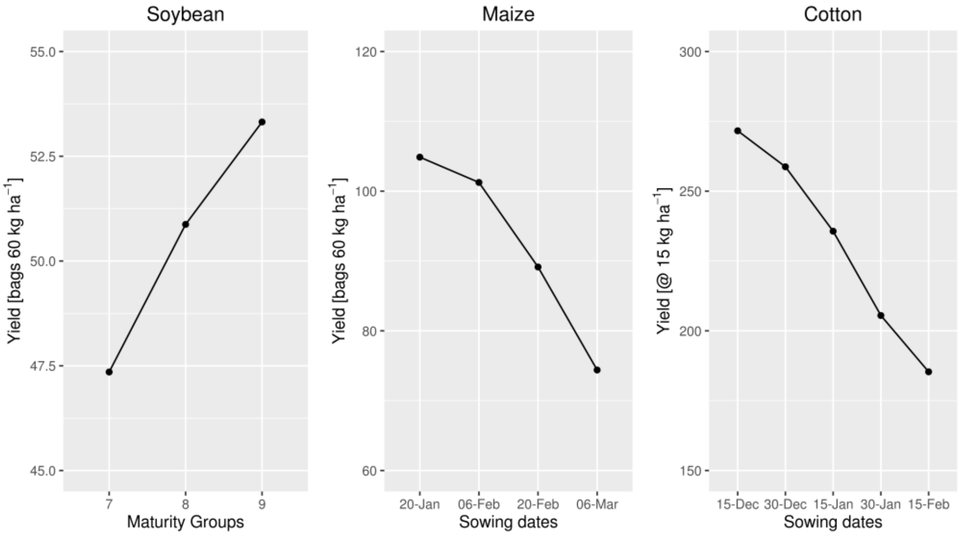

Figure 5: Simulated crop yields for different maturity group and sowing dates for Mato Grosso (average of all regions)

For those crops sown during the second season (maize and cotton), the sowing date is a significant decision variable. It presents a range of 30 bags for maize and 86 *arrobas* (one *arroba* is approximately 15kg) for cotton. This can be explained by a lower supply of rainfall during the crop development phase for those sowing dates which are more distant to the beginning of raining season (usually around mid-September or beginning of October). 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 farm agent decision making process.

4.2 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) for all crop management practices. Figure 6 shows that all crop practices related to soybean production presented positive gross margin. On average, longer maturity groups achieve a higher gross margin when compared to shorter MG, which can be explained by the yield effect explained above (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 on herbicide application.

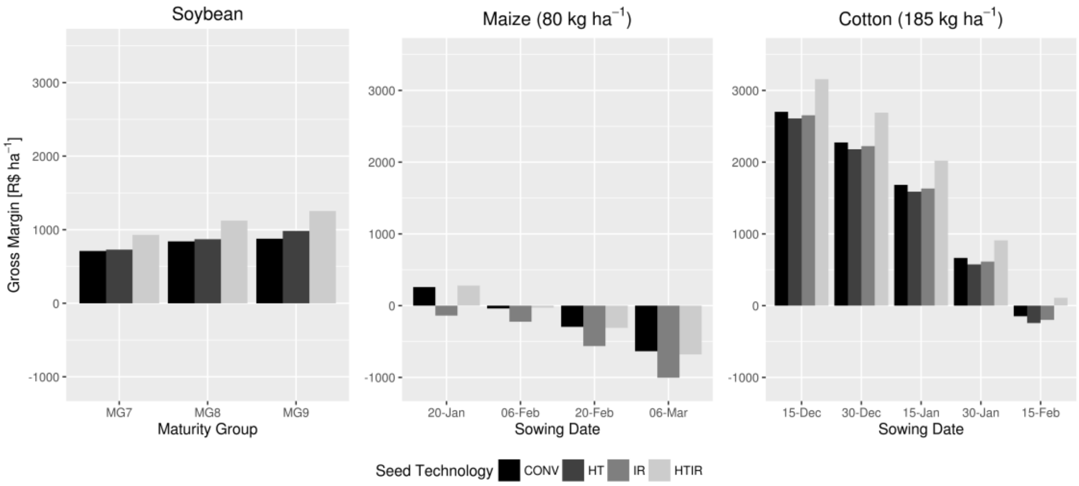

Figure 6: Gross Margin per hectare for Mato Grosso (average of all regions)

Due to macroeconomic conditions related to the crop season 2015/2016, maize production practices exhibit, on average, negative gross margin. There are several factors which can explain this result. The first one is the decreased yield effect on sowing date (Figure 5), which makes it very risky to grow maize with high level of investment in technology on a late sowing date. The second reason is the current economic crisis in Brazil, which increased the inflation rate over the recent years and, consequently, the costs of production. Production costs were also impacted by depreciation in exchange rates, as a large share of inputs (mainly pesticides and fertilizers) is imported from abroad. As point out by Morse at al. (2005), high seed prices for transgenic maize varieties increased the production cost, avoiding the adoption of these technologies.

It is important to note that maize is also grown for technical reasons (it increase organic matter, keeps the soil covered during the dry season, reduces soil compaction and improves water infiltration into the soil. 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, however, farmers will probably reduce the technology level with a combination of lower nitrogen amount and cheaper seeds.

Cotton showed the highest gross margin among all crops in this study. Crop production is more profitable when cultivated in the first season (15-Dec and 30-Dec) when compared with later sowing dates. However, the crop rotation in the first case consists in growing millets as a cover crop during October-December, which is not sold on the market. 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 system is a very complex system which requires experience, expertise and a high level of investment. In regard to seed technology, our simulation suggest that the economic benefit of lower production cost due to herbicides and insecticides applications for HTIR seeds more than compensate the investment on those seeds, pushing the adoption of those varieties.

4.3 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, it is the third largest state in area and holds a large variety of biomes and biodiversity, which directly influences rainfall pattern, soil conditions, temperature and radiation. Therefore, despite all the agricultural practices available for each farm holding, the optimal set chosen in our simulation experiment is mostly influenced by climate conditions, which highlights the fact that it is important to conduct an IA that integrates all key decision variables in order to properly assess production system complexities. 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.

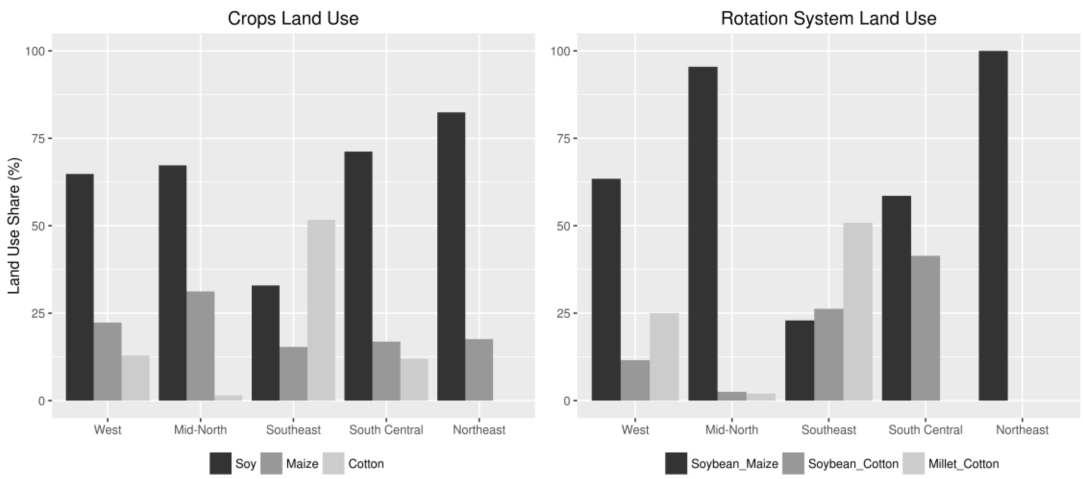

Figure 7: Simulated land use of optimal agricultural practices by crop and rotation system

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

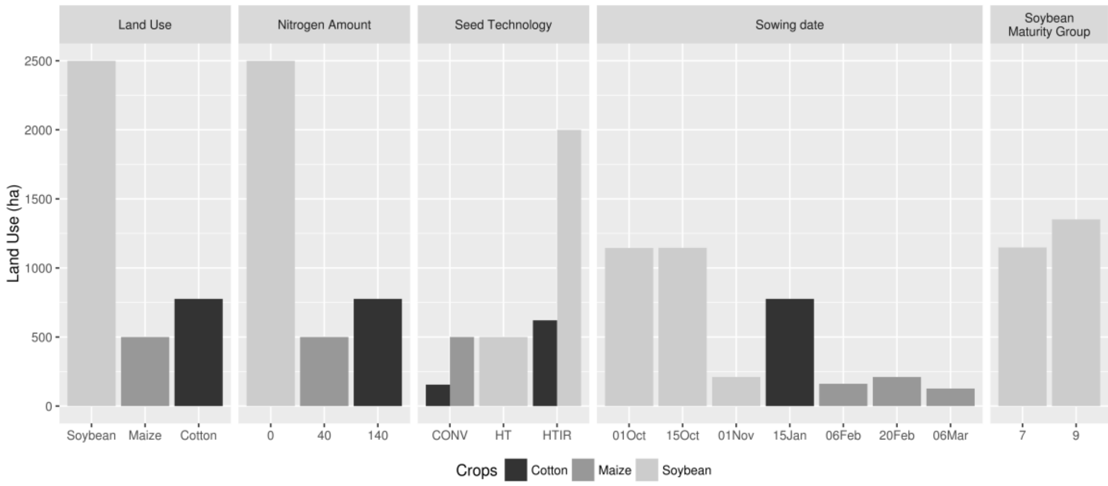

Figure 8: MPMAS simulated optimal land use by cropping decision variable (typical farm on South Central region)

In order to sow maize and cotton in the second season, the agent shall start by sowing soybean MG7, in order to achieve higher yields on second season and, afterwards, sow soybean MG9, as soybean with a longer growing 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 a higher yield, one should consider the trade-off between yield and sowing dates for the second season crops, as those combinations are intrinsically linked with soybean cycle. In this way, the yield difference from those soybean cycles shall be offset by a yield gain on 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 its subjected to regional condition 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 into a different context.

5. DISCUSSION AND CONCLUSIONS

The results of our simulation suggest that climate conditions play a major role in Mato Grosso agricultural production, and there is a wide range of variation on crop yields across the state. The sowing date is a key variable in achieving higher yields on second season cropping systems and our simulation experiment fully capture the yield difference between those sowing dates on maize and cotton agricultural production, providing key elements and insights to farmer's decision-making process. The closer to the beginning of raining season a crop is sown, the higher the probability to achieve greater yields, as the crop will receive more water supply, which can be decisive, especially in years of low price levels or higher production costs.

As soybean is sown at the beginning of the rainy season, sowing date is not a decisive decision variable as for second season maize and cotton. However, it does suffer an impact on its maturity group. A larger production cycle means a higher yield because the crop has more time to develop. However, choosing a longer cycle reduces farmer's second season options and, as discussed above, the first sowing dates are those which achieve a higher yield during the second season. In this context, the interdependence between the elements which define the production system also determine a certain level of rigidity. Therefore, the flexibility that soybean MG7 produces into the crop rotation system is a key element to those farm holdings.

In conclusion, we argue that agricultural production in Mato Grosso has become a complex and dynamic system, corroborating the hypothesis for an Integrated Assessment approach. We showed that our simulation experiment has the full potential of assessing those specific decision variables which farmers face 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 they are site-specific and/or region-specific.

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