Jul 11th, 11:10 AM - 11:30 AM

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Marcelo Moraes
Universität Hohenheim, m.carauta@uni-hohenheim.de

Affonso Libera
Instituto Federal de Ciência e Tecnologia de Mato Grosso (IFMT)

Evgeny Latynskiy
Universität Hohenheim

Anna Hampf
Leibniz Centre for Agricultural Landscape Research

José Maria Silveira
Universidade Estadual de Campinas

See next page for additional authors

Presenter/Author Information
Marcelo Moraes, Affonso Libera, Evgeny Latynskiy, Anna Hampf, José Maria Silveira, and Thomas Berger

International Environmental Modelling and Software Society (iEMSs)
8th International Congress on Environmental Modelling and Software
Toulouse, France, Sabine Sauvage, José-Miguel Sánchez-Pérez, Andrea Rizzoli (Eds.)
http://www.iemss.org/society/index.php/iemss-2016-proceedings

Integrated assessment of novel two-season production systems in Mato Grosso, Brazil

Moraes, Marcelo C. M. M.[a]; Libera, Affonso A. D.[b]; Latynskiy, Evgeny[a]; Hampf, Anna[d]; Silveira, José Maria F. J.[c]; Berger, Thomas[a]

(a) Universität Hohenheim, Stuttgart, Germany (m.carauta@uni-hohenheim.de)
(b) Instituto Federal de Ciência e Tecnologia de Mato Grosso (IFMT), Campo Verde, Brazil
(c) Universidade Estadual de Campinas (UNICAMP), Campinas, Brazil
(d) Leibniz Centre for Agricultural Landscape Research (ZALF), Müncheberg, Germany

Abstract: One of the most significant advantages of growing crops in Mato Grosso (in mid-western Brazil) is that farmers can grow two crops (in some specific cases even three) in the same season. From an economic point of view, on the one hand, this provides a strong comparative advantage. On the other hand, this increases the number of decision variables that a decision making agent has to take into account. The agricultural production planning is complex and dynamic and it needs to consider crop rotation/succession in accordance with annual variability of climatic conditions. We developed a region-specific bio-economic micro-simulation model in order to assess the trade-offs between soybean, maize and cotton production in that region. The model explicitly accounts for a combination of several variables, such as crop rotation (against season and year), planting dates, fertilizer amount, crop varieties, soybean maturity groups, climatic conditions, and prices. 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). The simulation captured the inter-regional differences between farm holdings, which is one of the key factors in order to assess the land use change between those seasons. The simulation results show that the introduction of soybean varieties of maturity group VII improved farmer flexibility, allowing a greater number of crop rotation possibilities. It exhibits an interchanging effect on maize and cotton cultivation, as both crops compete for area during the second season, changing the production system set-up in that region.

***Keywords**:* farm-level modeling; multi-agent systems; innovation diffusion.

1 INTRODUCTION

Brazil is one of the leading countries on the agricultural world market and the State of Mato Grosso is the most important internal contributor, accounting for 24% of the national grain production (CONAB, 2016). Currently, Mato Grosso leads in the production of soybean, maize, cotton, sunflower and holds the largest cattle herd in the country (CONAB, 2016). According to the Brazilian Institute of Geography and Statistics (IBGE), the state is the third largest in area. It is located in the western part of the country and holds three different ecosystems: Cerrado (Brazilian Savanna`s), Pantanal and Amazon Rainforest.

An important key factor that distinguishes this region from others is the possibility of growing crops in a second season, which starts on mid-January and goes until July-August. It started initially as a practice for land protection, in order to avoid leaving the land unprotected during the dry season. It brought several advantages such as dilution of fixed costs, new revenue possibilities, and an increase use of production factors (i.e.: land, labor and capital). This technological progress completely changed the Brazilian production system. Nowadays, maize production during the second season accounts to 66% of the national maize production, whereas two decades ago it was only 11%. At the present time, the second production season in Mato Grosso is as important as the first.

This double-cropping process lead to a production intensification, allowing farmers to produce more units of agricultural product on the same cultivated area. Over the last ten years, grain production in Brazil has grown by 72% while cultivated area grew by 22%. This production increase was mostly led by gains in productivity, which grew 41% over that period (CONAB, 2016). The economic viability of agricultural enterprises in Mato Grosso is based on technological advances, which provided the proper incentives necessary for the development of those activities. The main technological advances were the establishment of a new technical paradigm (Dosi, 1982) in the local agricultural sector (mainly GMOs - genetically modified organism – and short maturity cycle seeds) combined with the expansion of the agricultural frontier due to the adaptation of new seeds to local conditions. The innovation itself goes through changes over time, receiving incremental improvements, which also determines changes in its performance. This process was later revealed to be a complex issue because it lead farmers to deal with two or three different crops during the same rainy season.

The objective of this study is to investigate how the introduction of soybean varieties with short growing cycles influences the economic organization of farms in the Brazilian Midwest. In this way, this article aims to address the decision variables farmers need to take into consideration in order to tackle the trade-off between first and second production seasons ("*safra"* vs "*safrinha*"). As a research hypothesis, we argue that the main aspect which influences farmers' technology adoption is related to an increase in flexibility in regard to crop management under extreme climate conditions (interaction between climate and pest occurrence).

By conducting a quantitative analysis in a farm level approach of the farm systems in Mato Grosso, we 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 production systems changed with the introduction of a new soybean cultivar as well as the trade-off between *first and second* production season.

2 METHODS AND DATA

2.1 Methodology

We applied an integrated assessment (IA) based on a multi-agent micro-simulation model in order to assess the adoption of soybean cultivar with short growing cycle (maturity group VII) on agricultural production systems in Mato Grosso. IA can be defined as an interdisciplinary process which combines knowledge from diverse scientific disciplines in order to allow a better understanding of a complex system or phenomena (van Ittersum et al., 2008). The IA approach offers several benefits over traditional economic analysis because, first, it takes into consideration the cross scale issue, as the farm-based multi-agent system enables us to simulate heterogeneous population of real world farms. In that way, it is easy to up-scale farm level data into different macro levels (i.e. market, sector, municipalities, states or regions). By reducing the micro-macro gap it enables the assessment of policies, that evolve both the micro and macro level (van Ittersum et al., 2008). Third, the multi-agent micro-simulation component generates mathematical programming problems which take into consideration many operation and investment constraints of individual farm holdings. Because of technical advances in computational processing, it can be easily extended to each farm and agent of the region population, allowing the analysis of different groups of agents and/or farms. Fourth, the interdisciplinary approach connects the socio-economic component with the biophysical component. With a crop growth model one can simulate the effects of soil, climate, crop management and crop rotations on crop yields. Consequently, the bio-economic farm model enables the assessment of policy changes and technological innovations. Last but not least, 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. MPMAS uses the constrained optimization approach in order to simulate a farm decision-making process in agricultural systems (Schreinemachers and Berger, 2011). This software has been applied in a number of studies of IA of farm-level agricultural production system and on innovation diffusion in agriculture (MP-MAS, 2016).

Our IA application combines the economic component of a farm level decision making problem with a crop growth model, which simulates the crop yield response to changes in the crop water supply and changes in soil nutrients. The crop yields were simulated with MONICA model, a dynamic, process-based simulation model which describes transport and bio-chemical turn-over of carbon, nitrogen and water in agro-ecosystems (Nendel et al., 2011). Both software packages are linked through an online database stored in a MySQL server. The crop yields are simulated for all climate conditions and region specific characteristics and stored in the database. Then, the database application MPMASQL accesses all the relevant information in the database and converts it to a MPMAS input. Finally, 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 two decision problems in each simulation period (which corresponds to one real world agricultural year): an investment decision and a production decision. Those problems are converted into a MILP (Mixed Integer Linear Programming model). The full MP-optimization problem for each agent consists of 4023 decision variables (165 integers) and 4002 constraints, which results in a very large number of choices in regard to the crop production system, crop management, crop rotation, production factor requirements (acquisition of inputs, labor and machineries). Agents in MPMAS maximize expected farm income, which needs to be done subjected to a set of constraints (such as land, machinery capacity, labor supply and capital), specified in the form of equations or inequalities.

The interactions between agents was done through the technology diffusion component. All agents interact in the same network into with the technology diffusion is done by sales representatives of the suppliers or raw materials and its partners (resellers). Agents were divided into five categories (innovators, early adopters, early majority, late majority, and laggards) according to the distributions and methods described on Rogers (1995). In order to fully capture the technological diffusion process, the simulations were run for seven years. In our approach, we considered innovation genetically modified soybean, maize and cotton seeds with tolerance to glyphosate (herbicide tolerant - HT) and protection against the major worms (insect resistance - IR).

A crop calendar of agricultural activities was created in order to capture the timing of agricultural activities and, therefore, correctly simulate the agent allocation of machinery and labor over time. The crop calendar was created according to local technical recommendation on which agricultural activities are typically undertaken for each of the crops included in the model. The link between the crop calendar and the data on labor and machinery provides estimates of machinery and labor weekly requirements. The crop calendar is also linked to the crop growth model, in which each agricultural activity is related with daily climate data.

2.2 Model Parameterization

The MPMAS model was parametrized for five municipalities in Mato Grosso: *Sapezal*, *Sorriso*, *Campo Verde*, *Tangará da Serra and Canarana*. These municipalities are considered by IMEA as representative for the following corresponding macro regions: West, Mid-North, Southeast, South Central and Northeast. 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 844 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).

The MONICA model was calibrated using data from different field experiments sites (Aguiar and Guiscem, 2002; Fundação Rio Verde, 2013; Rosolem, 2001). As yields reported on those sites are above the regional average, a field condition modifier (FCM) was used to fit the MONICA model response to average management field conditions found in Mato Grosso. The FCM hinders the photosynthetic activity, in turn diminishing the assimilation of carbon hydrates required for growth and maintenance respiration. Additionally, 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). 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, 2015) and contain the following weather data in daily resolution: maximum and minimum air temperature, sun duration, precipitation, wind speed and relative air humidity.

The estimation of production costs for each crop and region is done by IMEA in a yearly time interval (IMEA, 2013). 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, 2015).

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 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 as first season (15-Dec and 30-Dec) and three as 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).

Different crop management practices for each agricultural production possibility were also taken into account (due to lack of information, the impact of pest and weeds are not considered in MONICA). 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, specifically for soybean HTIR, as longer the maturity group, greater is the substitution effect between the insecticide application and the genetically modified (GM) Bt toxin. The crop management options for MPMAS were estimated with a farm level survey from Céleres – local agribusiness consulting enterprise – database, including 157, 299 and 303 observations for soybean, maize and cotton, respectively, as well as technical advice from local experts.

2.3 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 et al., 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. 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. The validation process considered Mato Grosso`s soil and climatic conditions and used municipal crop yield estimations from the IBGE (2014). We used three different statistical indices to assess the model´s performance: Mean absolute error (MAE), root mean square error (RMSE) and the Willmott´s index of agreement (WIA), 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; WIA 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, 2013) was collected and, for the municipality level, municipality land use data from IBGE (IBGE, 2006). The validation 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.

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 0.72, which improved to 0.78 in the municipality level step. In addition, the fitted no-constant regression lines and their calculated R-squared (0.87 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.

2.4 Experimental Set Up

In order to assess the impact of the introduction of soybean varieties with shorter maturity cycles (MG7) into the agricultural production systems in Mato Grosso, we compared the *Baseline* scenario (reflecting the current conditions) with a counterfactual scenario where no soybean varieties of maturity group VII are available. In this case, farmers face a more restricted set of double crop combinations because a longer soybean cycle reduces the planting date possibilities for maize and cotton. In addition, we also designed four scenarios with alternative market conditions, in which maize and cotton prices were increased by 15 and 30 percent. The idea behind those scenarios is to assess the farmer`s trade-off in regard to with crop to grow during the second season (in which maize and cotton competes by area).

3 RESULTS

3.1 Technology adoption of soybean with shorter maturity cycle

The introduction of a new soybean variety with a shorter maturity cycle enabled farmers to sow cotton and maize at earlier planting dates, increasing the number of crop rotation combinations. Our MONICA simulations suggest that both maize and cotton achieve greater yield with earlier planting dates (Figure 1), which were not available before the introduction of soybean MG7.

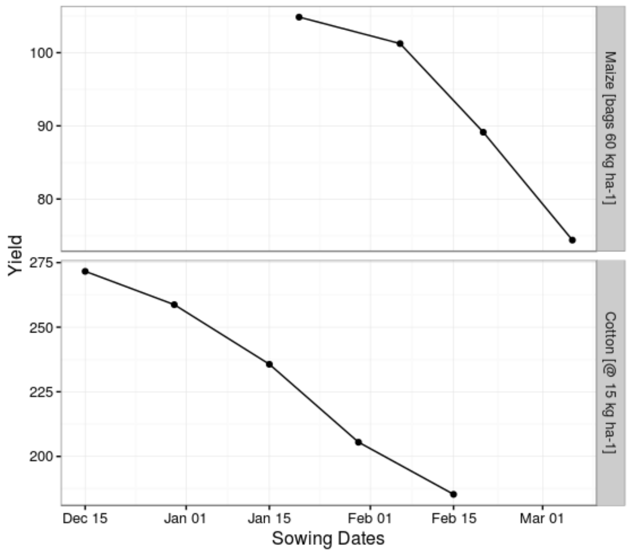

Figure 1: Simulated crop yields for cotton (bags of 15kg/ha) and maize (bags of 60kg/ha) – Mato Grosso average (Ferrasol Dystrophic Soil with 185 kg/ha of nitrogen application for cotton and 120 kg/ha for maize)

Additionally, sowing maize and cotton in an earlier planting date also reduces the risk of facing a *veranico* (drought of one or two weeks which can happen during a critical period of a crop development stage). Before the introduction of soybean MG7, farm agents had five possible combinations in the cover crop – cotton production system and four with the soybean-cotton. The diffusion of this novel technology, however, increased the number of possible combinations to 13 in the soybean-cotton production system, allowing also a new sowing date for cotton in the second season (15-Jan). The adoption of soybean MG7 impacted cotton land use in first (sown on 15-Dec and 30-Dec) and second season (sown on 15-Jan, 30-Jan and 15-Feb). With the possibility to grow more soybean before cotton, farm agents in our model reduced the share of first season cotton from 0.60 to 0.45 while increasing the share of second season cotton from 0.40 to 0.55.

In regard to maize cultivation, our IA simulation suggests that the shortening of soybean cycle lead to a lengthening of the maize second crop planting window, shifting part of the cultivation to January 20th (Figure 2). Moreover, it allowed more flexibility in regard to both crop and farm management, as the production activities can now be distributed over a longer time period, reducing periods of high intensity use of labor and farm machinery. It also reduces drought risk and increases maize yield due to better exposition into the rainy season.

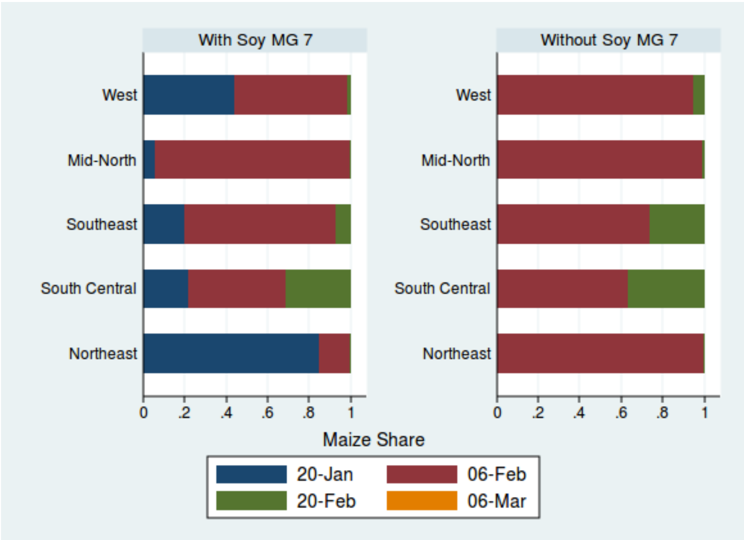

Figure 2: Maize land use by possible planting dates

3.2 Second season (*safrinha*) trade-offs

The introduction of soybean MG7 increased the maize sowing window, letting farm agents achieve higher yields (as shown in Figure 1). Moreover, it favored the soybean-cotton double crop rotation, allowing farm agents to achieve a higher income per hectare. As maize and cotton compete for area in the second season, one might argue that the net effect could be uncertain. Therefore, in order to fully assess the second season trade-off between maize and cotton, we developed a price sensitivity analysis of both crops (Figure 3).

While there was a higher share of second season cotton (55%) against first season cotton (45%) in the baseline scenario, one can observe an inversion of this relationship as soon as the cotton price increases, with a greater share of cotton first season in the last scenario (cotton price increase by 30%). This occurs because agents change from soybean-cotton to cover crop-cotton system, as cotton becomes more profitable. On the other hand, when maize prices increase, agents start to grow more maize, which in turn increases the soybean share. As cotton competes with soybean for area in the first season, a decrease of cotton first season in that scenario is observed.

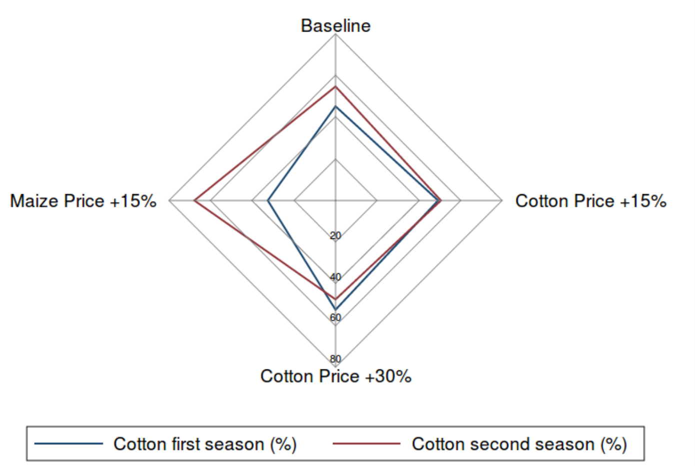

Figure 3: Price sensitivity analysis of maize vs cotton trade-off

4 DISCUSSION AND CONCLUSIONS

The results of our simulations suggest that the adoption of a soybean cultivar with a shorter maturity cycle completely changed the optimal set of double crop rotation systems currently adopted by Mato Grosso farmers. Interestingly, the introduction of the new soybean cultivar in our simulations had a greater impact on the maize and cotton production system than on soybean cultivation itself. This happened because a shorter soybean cycle increased the number of crop rotation possibilities during first and second season. When sown in the first season, soybean usually does not suffer from drought risk. Thereby, the introduction of a new soybean cultivar increased the number of double crop rotation possibilities, generating a trade-off effect on maize and cotton cultivation.

With regard to maize, our simulation showed a split of cultivation between all the planting dates, with a higher share of cultivation on the first two dates (20-Jan and 06-Feb). This can be explained by the fact that farm agents in our models can achieve a higher yield and reduce their risks. For cotton cultivation, it was shown that in the baseline scenario, farm agents switch from cover crop-cotton to soybean-cotton production system, as the second one enables them to achieve a higher income per hectare, as well as diversifying their production. In terms of total cultivated area, the only crop that presented a net increase during the simulation was cotton, while there was an exchange between seed technologies and planting dates for soybean and maize.

In addition, the introduction of this new soybean MG7 also allowed farm agents to produce more. A comparison with the baseline scenario against a counterfactual scenario without the new crop variety allows us to infer that the cultivated area would be 7% lower in absence of that technology. By allowing farm agents to produce more in the second season, a shorter soybean cycle lead to intensified land use and higher production levels using the same cultivate area. The increased number of crop rotation combinations also allowed farm agents to distribute the sowing period over time, reducing the high labor and machinery intensive periods.

Even though soybean with shorter production cycle exhibits, on average, lower yields when compared with the longer ones, they are still preferred by farm agents in our model, because they enable them to increase the second crop maize and cotton cultivation, by extending the maize sowing window and by increasing cultivation possibilities of soybean-cotton rotation systems.

ACKNOWLEDGMENTS

We thankfully acknowledge the scholarships awarded to the authors of this paper by the Brazilian Coordination for the Improvement of Higher Education Personnel (CAPES). We would like to thank Céleres for the field data provided and the partnership established with the Agricultural Economics Center of UNICAMP. We are grateful to Embrapa Agrossilvipastoril and IMEA for the technical materials and knowledge provided. Special thanks to Dr. Austeclínio Farias Neto, Rafael Chen, Otávio Celidônio, Dr. Marcio Júnior, Dr. José Siqueira, Alexandre de Oliveira and Julio Nalin for their expert input and facilitation of information exchange.

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