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Hybrid Simulation Model For Economic-Financial Evaluation In Integrated Crop-Livestock Systems

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Abstract

Mixed or integrated Crop-Livestock Systems (iCLS) have been in focus for the potential benefits they can provide concerning environmental, social, and economic directions, as compared with those of monoculture systems; however, iCLS practices demand more processes, management, and organization to implement. The number of studies that used Hybrid Simulation Models (HSM) applied to the iCLS are narrow. In this study, we used Discrete Event (DES) and Agent-Based (ABS) Simulation methods to develop models in a top-down analysis with a more general view that examined the individual agents. The objective of this study was to create an HSM based on agentes for iCLS and to evaluate the productive and economic indicators of these Productions with monoculture systems. The model was developed to represent the behavior of corn production and grazing cattle and the integration between them, and the model was parameterized using real data from an experiment carried out in the field in the state of São Paulo, Brazil. The development of the HSM was implemented in AnyLogic® software. All information on the parameters used in the HSM came from spreadsheets, which were processed in the model (in AnyLogic®) and transcribed into text files. Results from the model evaluation found the total cost in Beef Cattle Monoculture (BCM) was about 58% higher than the results found in iCLS treatments for livestock production. Financial profitability for Net Margin (NM) was viable for corn monoculture (CM) and unviable for BCM. In the integrated systems, NM was viable for all treatments. These results were then represented by the Internal Rate of Return. The economic-financial gains depended in part on the productive arrangement in iCLS, and therefore the simulated (in silico) models gained importance by allowing researchers to test hypotheses in advance. ABS and DES methods with stochastic variables have demonstrated their utility for HSM in the context of iCLS. The increases in the operational capacity of computers and big data have allowed the programming models to be more complex, so the HSM developed in this study may be able to predict more precise outcomes. AnyLogic® allows interface with spreadsheets, which facilitates the modeler's work about changes in parameter values during the simulation run and gives the HSM more usability and supports the decision-making process. The HSM has the potential to serve other animal and plant production systems and is therefore worthy of the further studies needed to evaluate these systems more thoroughly.

Keywords: agent-based simulation, crop-livestock systems, decision-making, modelling and simulation, livestock production systems

1. Introduction

Agricultural and livestock practices have followed the evolution of the human species for thousands of years, and the development and maintenance of this system have always been fundamentally important. Crop production and productivity have increased over the last few decades, with estimates of a significant increase for the next 10 years, according to a report by the Brazilian Ministry of Agriculture, Livestock and Supply (MAPA, 2020). Modern production techniques face challenges to maintain the sustainability of these systems from such threats as soil degradation, changes in the global cycles of nitrogen, phosphorus etc., as well as signs of depletion of some essential resources for life (Gerber et al., 2013; Steffen et al., 2015).

Mixed or integrated Crop-Livestock Systems (iCLS) adopt more supposedly sustainable production practices (Gerber et al., 2013; Herrero et al., 2015; King & Hofmockel, 2017; Ryschawy et al., 2017; Schiere et al., 2017; Schiere et al., 2017; 2002) that minimize climate and market risks (Paut et al., 2019). This integrated approach to agricultural and livestock activities, however, demands the knowledge of more technical expertise by managers, a broader infrastructure, and access to specialized technical assistance (Gil et al., 2016; Russelle et al., 2007). As the quantity of production processes increases, management and organizations have commensurate challenges to implement the detailed planning required for iCLS systems.

Due to the numerous variables that affect the productive and economic-financial performance in iCLS, simulation models are requisite tools that facilitate modeling and conducting experiments in silico. These are Operations Research (OR) methods suitable for understanding broad systems by directing future research and integrating disparate parts to assist in the decision-making process (Black, 2014). The increases in the operational capacity of computers and the abundance of data have driven the programming models to be more complex (Saltelli et al., 2019). This has allowed Discrete Event (DES) and Agent-Based (ABS) Simulation methods to become more common due to the possibility of including stochastic variables, probability distributions, risk analysis and individual characteristics by providing behavioral autonomy and interactivity to agents (Borodin et al., 2016; Borshchev, 2013; Laengle et al., 2017; Macal, 2016).

In agriculture, applications of these methods have been proposed by Carauta et al. (2018), Hampf et al. (2018) and Müller-Hansen et al. (2019). Van der Linden et al. (2020) found a significant number of models that considered the economic aspect in their analyses. In this study, we used DES (events) and ABS (agents) methods to develop models in a top-down analysis with a more general view that examines the individual agents. Given this approach, the objectives of this study were to develop and describe a hybrid simulation model that is based on agents and discrete events and that also features stochastic components to evaluate integrated agricultural production systems and compare the productive and economic-financial indicators of iCLS systems with those of monoculture systems.

2. Method

2.1 Conceptual Modeling

The Hybrid Simulation computer Model (HSM) was developed to represent the integrated behavior between corn and cattle grazing production and to emulate and calculate technical and economic-financial indicators in silico. The HSM used discrete event and agent-based simulation methods from Operations Research (OR) to assist the implementation of the HSM in the simulation software, and a conceptual model diagram was developed, as shown in Fig. 1.

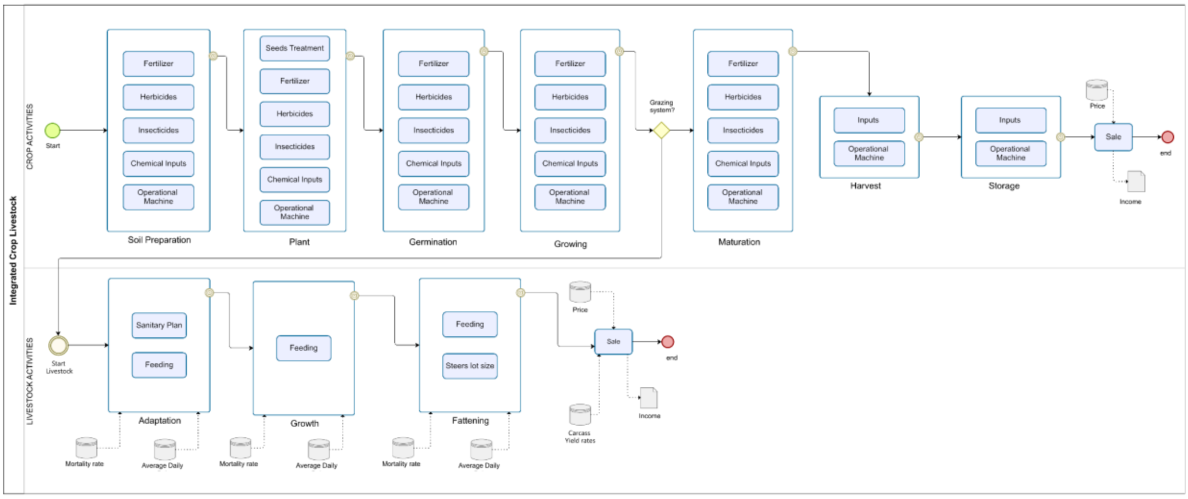

Figure 1. Conceptual Hybrid Simulation computer Model (HSM) of integrated corn and beef production activities

2.2 Computational Modeling

To develop the HSM, the conceptual model (Fig. 1) was implemented in AnyLogic® software (The AnyLogic Company) version 7.1.2 (Educational). The programming language used by the software was Java, which is object-oriented. The HSM took advantage of the resources available in the agent-based (ABS) and discrete-event (DES) computer programming libraries. The hybridization between the ABS and DES methods was of the integration type, in which the methods used in Operations Research complemented each other. The unit of time in the HSM was defined in days.

In the HSM, it was defined that the animals would function as the agents that moved through the “adaptation”, “growth”, “fattening” and “sold” states. The transition of animals across these states was dependent on the production strategy used, and this was defined by grazing days, which simplified HSM development. In each of the states, mortality parameters, daily Body Weight Gain (BWGd), and Nutritional supplement intake (NS) were determined and individually attributed to the agents.

The HSM was developed to assess the characteristics of agricultural production of corn in monoculture (CM) or in integration systems in conjunction with the production of cattle. Their states were defined as: “soil preparation”, “plant”, “germination”, “growing”, “maturation”, “harvest” and “storage”. All and any management carried out in each of these states were inputs that tracked the use of fertilizers, pesticides, seeds, and the operation of machines. These inputs were duly recorded as soon as the information became available. The soil preparation, planting, and germination states were designed to be similar between agricultural and livestock production in order to share activity items.

The HSM was developed to obtain all data from a previously defined and formatted spreadsheet; later the HSM processed the information and returned the outputs in a new text file, and a new spreadsheet was prepared to receive these outputs. The allocation of all HSM inputs in a spreadsheet allowed two main differentials, among others: 1) Any spreadsheet user could contribute their data to be inserted in the HSM without the need to install the simulation software on their computer, 2) When designing the computational experiments, the researchers would have no difficulties in looking for which parameters to change and where they would be among the existing programming codes. This was an innovation in relation to the work developed by Ojeda-Rojas et al. (2021) and Reijers et al. (2019). Details that were developed in HSM have been described in the Appendix A.

2.3 Economic-financial Analyzes

All cost items from productive activities were considered and followed the concepts of the Neoclassical Theory of Economics. The cost items were allocated according to the volume produced, in fixed, variable, and income of production factors. This last item considered remuneration for working capital which is a variable cost item, and remuneration for land and fixed capital which are items of fixed cost.

Depreciation costs were classified as fixed costs and calculated using the straight-line method, which assumes a constant rate over the asset's useful life (Croitoru et al., 2015; Sartorello et al., 2018). The method uses acquisition value, residual value, useful life, and proportional use for each activity, as informed in the spreadsheet inputs. Full formulas and treatment of pasture formation and exhaustion are detailed in Appendix A (Charts A.2 and A.3).

The item “Remuneration factors” are income from factors of production that considered variable and fixed costs, and they were separated from the other items to allow the elaboration of different cost indicators: Effective Operating Cost (EOC), Total Operating Cost (TOC) and the Total Cost (TC); the equations and the respective acronyms were described in Appendix A.

The determination of income was performed by the HSM, while profitability indicators such as Gross Margin (GM), Net Operating Margin (NOM), and Net Margin (NM) were calculated in the output spreadsheet. Definitions and formulas for all economic indicators are available in Appendix A (Charts A.2 and A.3).

The investment analysis used the Discounted Cash Flow (DCF) method, comprising fixed capital investments and operational expenses over time. All financial inflows and outflows simulated by the HSM are available in Appendix C, where the full cash flow tables for each treatment are shown (Tables C.1–C.6).

The economic-financial analysis developed with the HSM allowed for the apportionment of the use of capital goods and inputs at any stage for the activities of corn and cattle production in monoculture or integrated operations. This was another novelty of this work, since the sharing of some items raises doubts among managers; therefore, the decision, whether there should be an apportionment and at what rate, was free to be considered in the HSM according to the filling of the data in the inputs.

2.4 Computational Study (in Silico)

The Hybrid Simulation Model (HSM) was used to calculate the technical and economic-financial performance in iCLS from data from a field experiment carried out between 2015 and 2017, as documented in the dissertation by Mendonça (2018) and later published as Mendonça et al. (2020).

The field experiment was carried out at the Beef Cattle Research Center, Instituto de Zootecnia/APTA/SAA, Sertãozinho, SP, Brazil (21°8'16" S and 47°59'25" W). The average local altitude is 548 meters. The regional climate, according to the Köppen classification, is Aw, as humid tropical, with a rainy season in the summer and a dry season in the winter. The soil of the experimental area was classified as clayey dystrophic Red Latosol (Santos et al., 2018).

2.4.1 Experimental Design

A representative property of 75 hectares was delineated from the experimental data, as described by Mendonça et al. (2020). The objectives of the computational experiment, which followed what was carried out in the field, were to calculate the costs of agricultural and livestock production in the monoculture systems and in the integrated systems and to evaluate the economy of scope that the strategies provide.

Six treatments were structured (as shown below in Fig. 2) to take into account the following factors: Monocultures of corn and beef cattle production and the integrated crop-livestock systems (iCLSs 1, 2, 3 and 4).

In the monoculture system for corn (CM), plants were sown with a spacing of 75 cm between rows at a density of 70,000 plants/ha. At this sowing, the First Fertilization (FF) was carried out with 32 kg/ha of Nitrogen (N, in the form of urea), 112 kg/ha of simple superphosphate (P2O5) and 64 kg/ha of potassium chloride (K2Cl). In addition, 80 kg/ha of N and 80 kg/ha of K2Cl were applied to the corn twenty days after sowing, which was defined as the Second Fertilization (SF). The field was left fallow between the harvest and the next planting, which was considered as annual production. In the monoculture system for beef cattle production (BCM), the pasture cultivar used was *Urochloa brizantha* cv. Marandu (syn. *Brachiaria brizantha* cv. Marandu), known as “marandu grass”, which was sown with a spacing of 37.5

cm between rows, seeding density of 5 kg/ha (76% of cultural value). The marandu grass seeds were mixed with the FF fertilizer (the same composition as the above corn treatment). In addition, maintenance fertilization (MF) was applied using 40 kg/ha of N, 10 kg/ha of P2O5 and 40 kg/ha of K2Cl; these applications were made annually in October from planting. Ninety days after planting the pasture was ready for grazing. Three continuous grazing cycles were carried out: The first cycle was between March and April (30 days), the second between August and October (78 days) and the third between November and October (348 days).

In the integrated systems, the same parameters and procedures were used as in the monoculture in relation to cultivars, spacing between rows, sowing density and fertilizers, and planting was as follows: iCLS1 - Marandu grass was sown simultaneously with corn in the same row; iCLS2 - The sowing was simultaneous, with the difference that 20 days after planting the corn, the herbicide Nicosulfuron *Nortox* 40 SC (8 g/ha of active ingredient) was applied; iCLS3 - The pasture seed was planted 20 days after corn planting (delayed sowing), and for this the grass seed was mixed with the fertilizer during the second fertilization, and the sowing between rows was carried out in a cultivator, and iCLS4 – The corn and pasture seeds were sown simultaneously, but with grass seed sown in the furrows between the corn rows, resulting in a spacing of 37.5 cm. Additionally, Nicosulfuron was applied, as in the iCLS2 treatment. In iCLSs, corn and cattle production were biennial, i.e., it was carried out every two years and, consequently, there were costs with the formation of pastures, while in beef cattle production (BCM) there were costs with the depletion of pastures. The experimental design scheme was described in detail in Fig. 2.

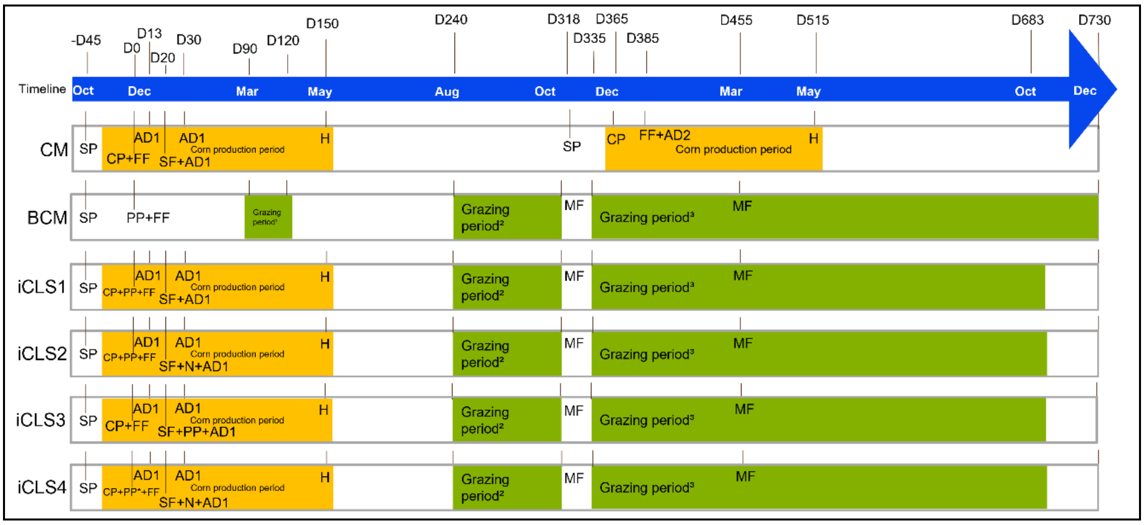

Figure 2. Experimental design of the treatments used

Note: SP: soil preparation; CP: corn planting; PP: pasture planting; PP*: pasture planting in and between corn rows; FF: first fertilization; SF: second fertilization; MF: maintenance fertilization; AD1: agricultural defensive (year 1); AD2: pesticides (year 2); H: harvest; N: herbicide of action on grasses, Nicosulfuron Nortox 40 SC; Grazing period: ¹30 days; ²78 days; ³348 days. CM: Corn Monoculture; BCM: Beef Cattle Monoculture; iCLS: integrated Crop-Livestock Systems; iCLS1: with simultaneous planting of pasture and corn; iCLS2:

with simultaneous planting with herbicide application 20 days after planting; iCLS3: with planting during the second corn fertilization (delayed sowing) and; iCLS4: with simultaneous sowing, with seed from pastures in and between corn rows and more herbicide application 20 days after planting.

All these experimental treatments were designed to be suitable in terms of machinery and equipment, constructions, and installations for the representative property size of 75 ha. The unit value, useful life, residual value, and utilization rate of each item (proration) was assigned by the field experiment, which was used in this HSM, as shown below in Table B.1 (Appendix B).

The rate used to remunerate working capital and fixed assets was set at 4.34% per year – the average rate of Brazil's Special System for Settlement and Custody (Selic) for the years 2019 and 2020 (Brasil, 2021). This same rate was used as the discount rate and in the calculations of present value and future value (Equation A.9., Appendix A) in the financial analysis. The exchange rate of US\$ 0.3119 = R\$1.00 was suggested for the base year of the study (2019). The value of land remuneration was set at US\$ 374.28/ha.year^{-1}, based on the local leasing rate for sugarcane production in the region of the representative property. In the iCLS scenarios, this cost was split equally between agricultural and livestock activities.

The prices for cattle (US\$1.366/kg BW) and corn (US\$0.17/kg) were based on historical averages from July 2007 to August 2017 (IEA, 2021), adjusted to August 2017 values using Brazil's General Price Index (IGP-DI/FGV). Taxes on production (Funrural) were accounted for at a 1.5% rate.

The prices of other production factors – such as seeds, fertilizers, pesticides, fuel, and feed supplements – were sourced from regional suppliers in Sertãozinho/SP and compiled into simulation spreadsheets. These values were applied across treatments according to their activity needs. Full unit prices and quantities can be found in Appendix B (Tables B.1 and B.2).

The price of fuel (diesel) used by the machines was US\$ 1.21 per liter, and the quantity consumed was 51, 47 and 70 liters for the treatments Corn (CM) and Beef Cattle (BCM) and iCLS, respectively. In iCLS, that quantity was apportioned as 32 liters for agricultural and 38 liters for livestock use.

The cost for labor for production activities were for 3 days allotted to Cattle, 50 days to Corn, and 56 days to iCLS at a cost of US\$37.43/day. Fixed labor was remunerated at US\$ 648.75 per month (including taxes, vacations and Brazil's required bonus salary). Although iCLS had two employees, these were apportioned by 50% to each productive activity, which was equivalent to one employee considered in monocultures.

The cost of nutritional supplementation for animals (NS) was established at US\$ 1.82/kg, and the sanitary protocol was set at US\$ 3.12 per animal. The protocol consisted of anthelmintic and prophylaxis for Botulism, symptomatic anthrax, Clostridiosis and other diseases.

The animals used in the field experiment were of the Caracu breed with 14 months of initial age. This breed chosen was according to the availability of the Research Center. The number of animals in the treatments averaged 3.7 animal units/ha (AU = 450 kg of body weight). The weight gain performance of these agents was according to the distribution function presented in Table 1. There was no animal mortality in the experimental period for any of the production phases; however, this parameter could be included in the HSM.

In the agricultural crop of corn, the parameters used in the HSM were those of the results of the field experiment, and only the weights of the cob were considered stochastic for that population.

Table 1. Parameters in the hybrid simulation model used by the proposed treatments for agents

Parameters	Distribution function	CM[1]	BCM[2]	iCLS[3]1	iCLS2	iCLS3	iCLS4
Cattle, units	N/A	N/A	292	255	255	250	248
Body Weight initial, kilos	Uniform kg (Min. and Max.)	N/A	347.00; 356.40	342.80; 350.30	343.60; 348.70	338.40; 341.70	335.60; 345.40
BWGd[4] Adaptation state, kilos	Uniform kg (Min. and Max.)	N/A	0.217; 0.223	-	-	-	-
BWGd Growing state, kilos	Uniform kg (Min. and Max.)	N/A	0.216; 0.593	0.563; 0.660	0.510; 0.510	0.330; 0.330	0.219; 0.722
BWGd Finishing state, kilos	Uniform kg (Min. and Max.)	N/A	0.215; 0.255	0.232; 0.437	0.298; 0.401	0.447; 0.457	0.338; 0.480
Intake Mineral Salt	N/A	N/A	22.72 g/100 quilos BW				
Carcass yield	N/A	N/A	50%	50%	50%	50%	50%
Grazing start	N/A	N/A	March 3rd	August 8th			
Grazing end	N/A	N/A	May 5th	October 10th			
Body Weight minimum output, kilos	N/A	N/A	461	461			
Corn cob weight	Uniform kg (Min. and Max.)	0.122; 0.238	N/A	0.156; 0.204	0.178; 0.230	0.145; 0.241	0.158; 0.240
Corn cobs, plant	N/A	1	N/A	1	1	1	1
Grain moisture at harvest	N/A	14.88%	N/A	14.88%	14.88%	14.88%	14.88%
Plant-to-pickup, days	N/A	150	N/A	150	150	150	150
Corn plants, hectare	N/A	70,000	N/A	70,000	70,000	70,000	70,000

Note: [1]CM: Corn Monoculture; [2]BCM: Beef Cattle Monoculture; [3]iCLS: integrated Crop-Livestock Systems; iCLS1: with simultaneous planting of pasture and corn; iCLS2: with simultaneous planting with herbicide application 20 days after planting; iCLS3: with planting during the second corn fertilization (delayed sowing) and; iCLS4: with simultaneous sowing, with seed from pastures in and between corn rows and more herbicide application 20 days after planting; 4BWGd: body weight gain per day; N/A: not applicable;

The HSM parameters were entered from a structured MS Excel® spreadsheet, and the outputs were compared to those reported by Mendonça et al. (2020). This process served as the empirical basis for model calibration and cross-validation. The model was iteratively adjusted until its outputs closely reproduced the observed results in both technical and economic dimensions. For parameters not directly measured in the field (e.g., individual supplement intake, mortality rates), expert elicitation was employed through consultations with specialists experienced in integrated crop-livestock systems. This two-pronged approach – empirical replication and expert validation – ensured the reliability of the HSM for simulating iCLS performance. The analysis time in the HSM simulations was 3,285 days (nine years).

The experiment was carried out using a computer with a 4-core processor and 8 gigabytes of Random Access Memory (RAM) (Intel Core i7-4790 CPU 3.60 GHz, 8.0 GB RAM, NVIDIA GeForce GT 740).

3. Results

3.1 Technical-economic Performance of Beef Cattle Production

The technical and economic results of beef cattle and corn production refer to the first cycle of computational production, which was equivalent to the actual field experiment from 2015 to 2017. This was chosen for better visualization and understanding and therefore does not represent the nine years of simulation that was made and used in financial analyses.

The animals were kept on continuous grazing with a variable stocking rate in the treatments. The stocking rate in iCLS was 3.3 AU/ha, while in monoculture cattle (BCM) production was 3.5 AU/ha. The grazing areas had similar productive capacity, and the maintenance fertilization management adopted was the same.

The average productivity in kilograms of body weight per hectare (kg ha-1) of the treatments for cattle was: 330, 499, 493, 551 and 534 for, BCM, iCLS1, iCLS2, iCLS3 and iCLS4, respectively. The simultaneous planting of pasture seeds with corn (iCLS1 and iCLS2) or delayed (iCLS3) resulted in differences in the performance of animals that produced, on average, 43,653 kg, 43,115 and 48,200 kg of body weight in the first production cycle (426 days of grazing). The strategy of sowing pasture in and between corn rows increased the productivity of the animals, which in the iCLS4 produced 46,747 kg of body weight in the period, a result superior to the iCLS2. In the treatments iCLS2 and iCLS4, the herbicide application was made to control the development of pastures in the initial stages so as not to harm the development of corn plants; however, this application management increased the costs of pasture formation. All production costs related to beef cattle production are in Fig. 3, following the proposed cost allocation.

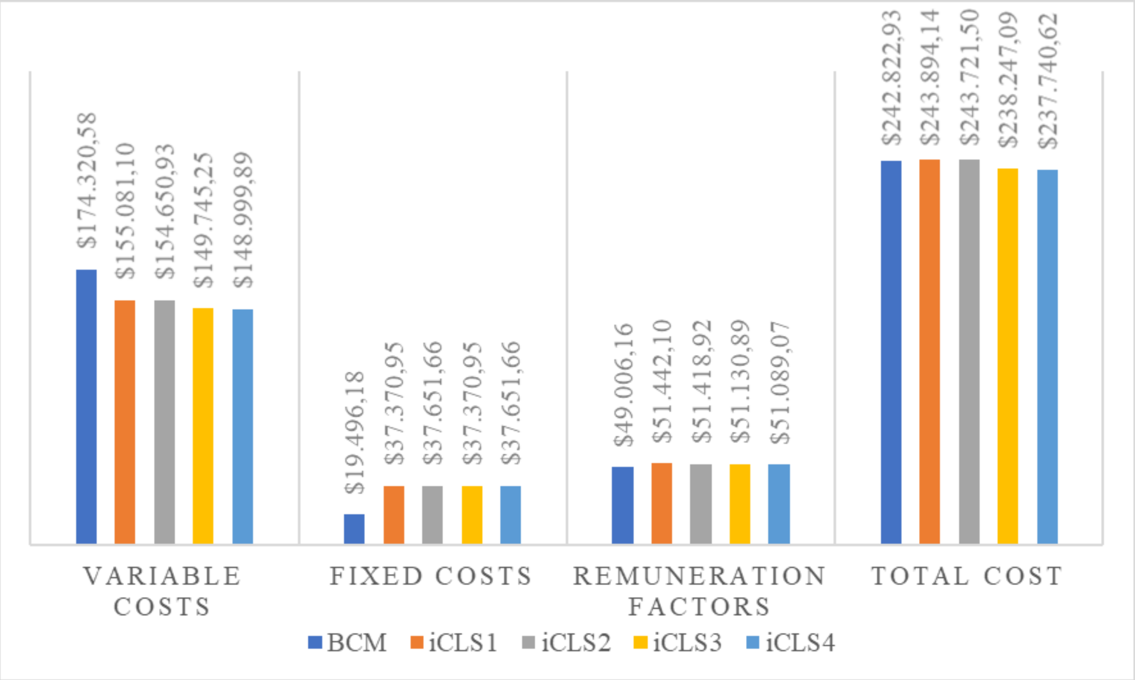

Figure 3. Production costs of cattle for beef cattle monoculture and cattle in integrated agricultural production systems

Note. BCM: Production system in a beef cattle monoculture system; iCLS1: Integrated crop-livestock systems with simultaneous planting of pasture and corn; iCLS2: with simultaneous planting with herbicide application 20 days after planting; iCLS3: with pasture planting during the second corn fertilization (delayed sowing) and; iCLS4: with simultaneous sowing, with seed from pastures in and between corn rows and more herbicide application 20 days after planting.

The cost of acquiring the animals was allocated in VC and represented, on average, 58% in Beef Cattle monoculture (BCM) and 49% in iCLS. The feed cost was calculated using a hybrid simulation model (HSM) function, which estimated the daily body weight (BW) of individual animals; therefore, the costs represented what the animals actually consumed. Financial expenditures for purchasing animals and food were the two main cost items in cattle production.

Maintenance of pasture fertilization represented 6.7% of variable costs in this study. In the BCM treatment, pastures were fertilized annually from the year they were formed, whereas in iCLS, despite having made corn production every two years in the interval between agriculture and livestock, the pastures were fertilized, and this cost was allocated to animal production.

In iCLS there was sharing of use of permanent labor and capital goods; therefore, temporary labor and depreciation were divided between the agricultural production of corn and cattle, although these costs were the same between all treatments. This occurred due to the biennial results of productions, as demonstrated in the experimental design (Fig. 2). Thus, as they are fixed cost items, they occurred regardless of the number of kilograms of products produced (corn in grain and/or cattle body weight). The costs of remuneration of factors of production with fixed assets and land were considered fixed cost items, although they have been classified in the item “Remuneration of Factors”.

In the cost analysis, “Pasture formation” was considered as production inputs in iCLS and this implied paying this cost in each production cycle, US$ 14,391.02 for iCLS1 and iCLS3 (without application of Nicosulfuron herbicide at planting) and of $14,671.73 for iCLS2 and iCLS4. BCM cost analysis differed in that the formation of pastures was considered as a fixed capital asset (with a theoretical useful life of 20 years); therefore, this cost was allocated annually in “Pasture exhaustion” US$ 1,235.18. The total of these costs were divided by the kilos of production of corn or beef, which were represented in the Fig. 4 below.

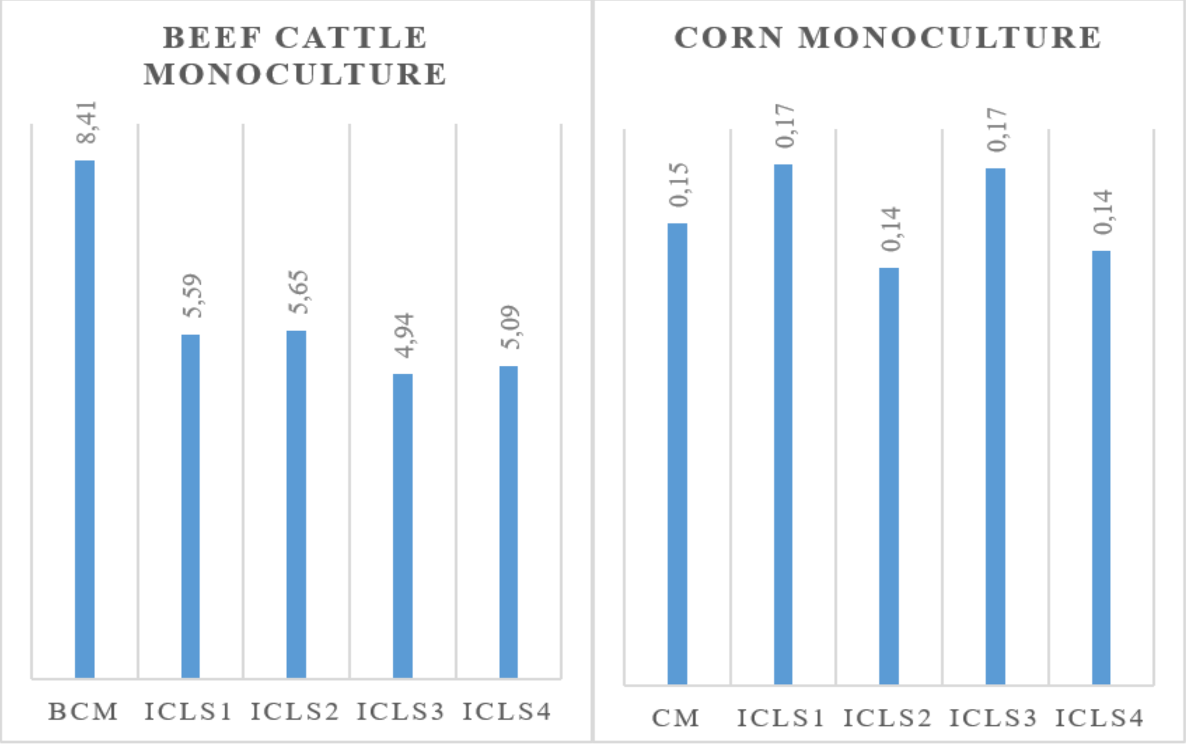

Figure 4. Total cost of cattle and corn production in monoculture and integrated systems

In the corn production, costs among treatments in iCLS differed only in the taxation of sales on the crop. The other cost items did not differ among them, and this behavior was expected since the corn production parameters were the same. The costs for fertilizers, herbicides and machine operation, were lower in iCLS than in Corn monoculture (CM), this was due to the apportionment of use between corn and cattle production in the planting of pastures. Costs with “Productive Inputs” included the outsourcing costs of harvesting.

In FC, integrated activities shared the use of resources such as permanent labor and some capital goods and facilities, but as corn production in iCLS was biennial, fixed costs were attributed, even in years without corn production. This also applied for remuneration of fixed assets and land, including the remuneration of fixed assets in iCLS, which was 18.5% higher than that of CM.

The VC per kilo averaged US$0.08 for iCLS, while for Corn monoculture (CM) it was US$0.09. FCs were quite similar between treatments. In iCLS2 and iCLS4, the TC was lower than in CM. The economic advantage of sharing resources became more evident when analyzed from the point of view of unitary fixed cost.

The average Unit Fixed Cost (UFC) of productive activities showed the cost of producing one kilo of the product of interest (corn grain and/or beef cattle body weight). These data were organized in Fig. 5, below. UFC was higher in iCLS when compared to monoculture Corn (CM) and Cattle (BCM) treatments. When considering the UFC, the results in iCLS were lower than those observed in the production of BCM.

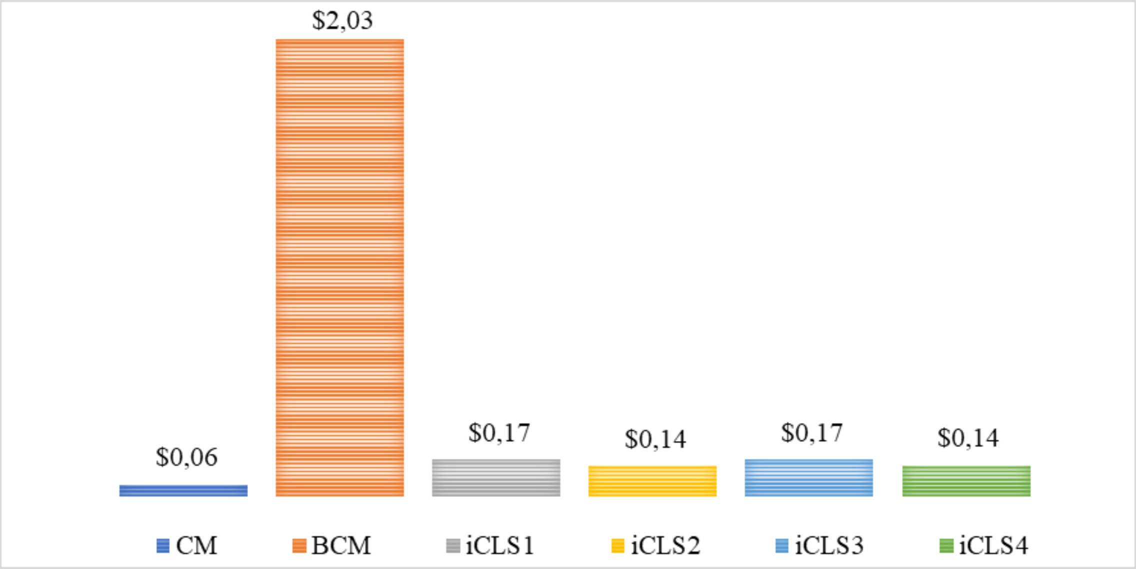

Figure 5. Fixed unit cost of beef cattle and corn production activities in monoculture and integrated systems 1)

3.2 Financial Viability of Production Systems

The results of the financial profitability of the treatments performed showed positive gross margins, except for the beef cattle monoculture (BCM) treatment. The lowest net margin results in livestock production were -US$67,752.31 and -US$67,957.47 for iCLS1 and iCLS2, respectively. While in corn production, the only treatments with negative NM were in iCLS1 (-US$ 2,369.70) and iCLS3 (-US$ 1,435.14). The treatments iCLS2 and iCLS4 were the most profitable when analyzing corn as a product.

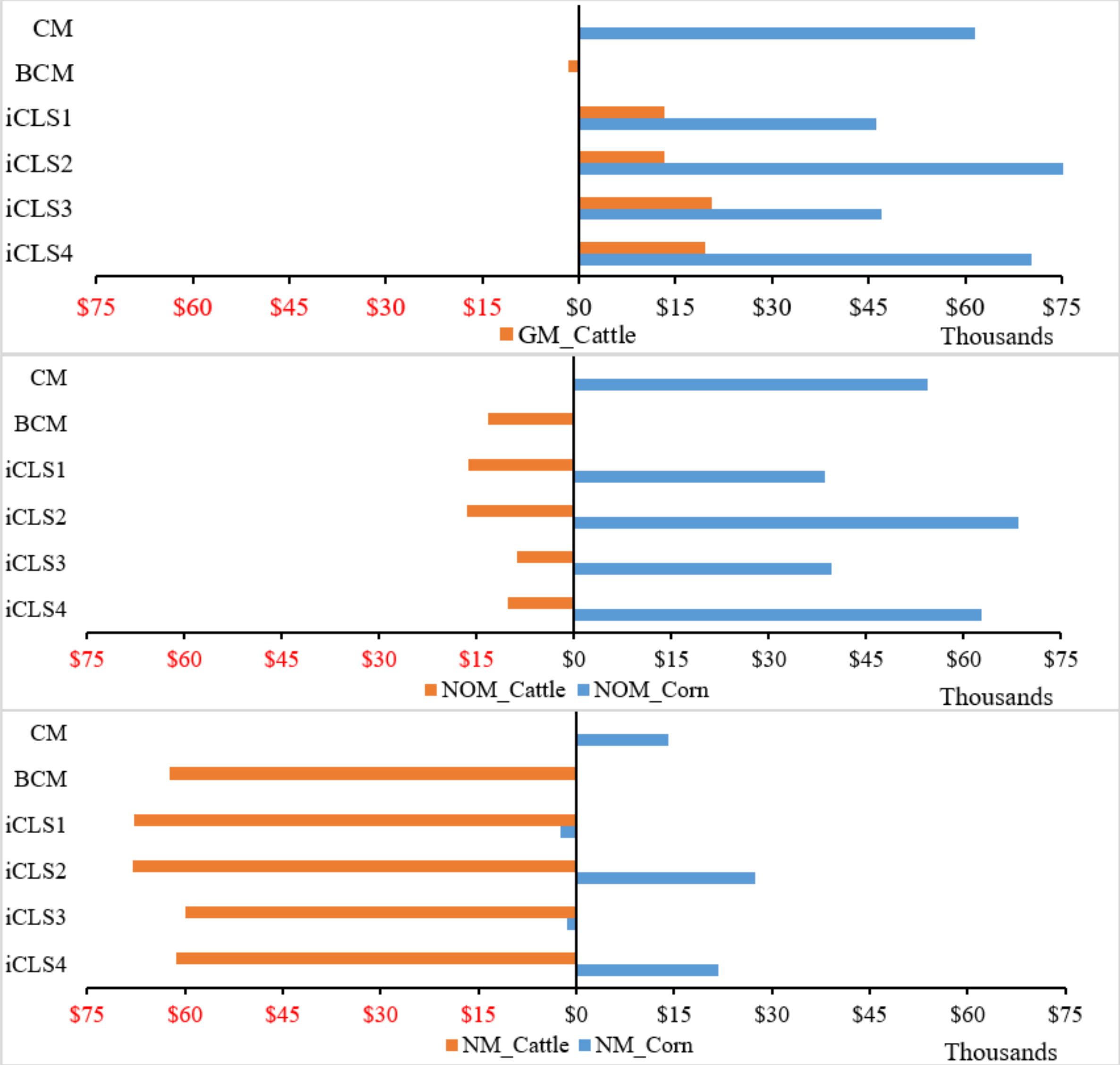

Figure 6. Financial profitability of the production of corn (CM) and cattle (BCM) in monoculture and in integrated crop-livestock systems (iCLS)

Note. GM: Gross Margin, NOM: Net Operating Margin, NM: Net Margin.

When all treatments were analyzed together and in a more holistic way, it was verified that the worst results of financial viability occurred in the production of cattle in monoculture. The results were a negative Net Present Value (NPV) of -US$ 169,909.66 and a negative Internal Rate of Return (IRR), as shown in Fig. 7. The detailed data that best demonstrates how these results were obtained can be found in the Appendix C of this paper.

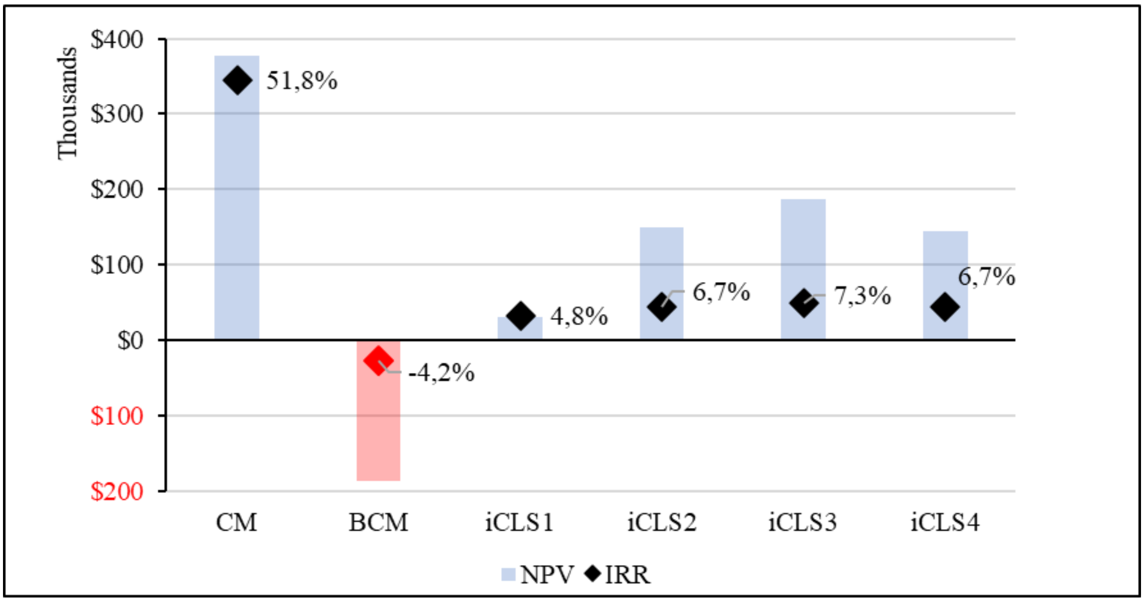

Figure 7. Financial viability of corn and cattle production in monoculture and in integrated crop-livestock sysytems (iCLS)

Note. NPV Net Present Value (in Dollars), IRR – Internal Rate of Return (in percent).

The most favorable scenario occurred with the production of corn in monoculture, with a NPV of US$ 377,832.57 and an IRR of 51.8%. Among the iCLS, the iCLS3 treatment had the best performance in terms of financial viability. iCLS2 and iCLS4 presented very similar financial viabilities. The only project with negative financial results was the production of cattle in monoculture, which, in theory, suggests the rejection of the adoption of the project with those technical parameters used. The tables in the Cash Flow Statement in the Appendix C help to elucidate these results in greater detail.

4. Discussion

4.1 Capacity Rate and Productivity by Area

The animal productivity per area was 57% higher in the treatments of the integrated systems compared to the Cattle monoculture (BCM). The differences found in this study were more modest than those reported by Reis et al. (2020), who found five times the difference between integrated systems with pasture monoculture systems (331 kg ha-1 vs. 63 kg ha-1, respectively).

Although the animal productivity per area was similar among the iCLS treatments, it is possible that the treatments with application of Nicosulfuron Nortox (iCLS 2 and 4) had lower carbon biomass; in iCLS4, the management of planting pasture seeds in and between rows may have mitigated this effect. The soil microbiological aspects of this study were extensively discussed by Maia et al. (2021).

The herbicide application strategy in the iCLS2 and iCLS4 treatments to control forage growth, in addition to having reduced productivity per area, resulted in greater financial expenditure for its formation. Pasture formation costs were US$ 14,391.02 vs. $14,671.73 for iCLS1 and iCLS3 compared to iCLS2 and iCLS4 respectively.

Pasture formation costs were considered as investments for BCM treatment and as productive inputs in iCLS. It is understood as an investment for those resources that generate value for a longer period and, in this regard, there are costs with the depletion of pastures. The depletion of pastures, by definition, is a loss of value resulting from the exploitation of exhaustible natural resources, and it is known that in practice the perenniality of pastures depends on the management adopted (Oliveira Neto et al., 2008). The formation of pastures was considered productive inputs (consumed in the same production cycle to generate value in the short term) for the integrated systems, because, after a cycle of cattle production, the pastures were replaced by the new agricultural crop. These methodological definitions of cost allocation implied differences in economic and financial costs. This increased the fixed costs (FC) for the integrated systems that presented the costs with the formation of pastures biannually.

Depreciation corresponds to the financial reserve necessary to acquire goods with the same characteristics at the end of their useful life, thus avoiding the decapitalization of productive activities. Determining the most suitable time is something that raises doubts; therefore, in this HSM the user can propose the time and residual value that are most appropriate for their reality, and if it is understood that pasture formation costs must be assumed in any situation as investment or productive inputs, distinctive methods can be proposed.

The experimental design as proposed, Fig. 2, increased the idleness of capital goods in iCLS as the production cycle alternated annually between grain and meat production. This indicated that there was a reduction in the unit fixed cost (UFC) to what is expected in terms of economy of scope. This was due to the combination of the production of different products (corn grains and beef carcasses), so the UFC were lower in integrated systems than in BCM (Panzar & Willig, 1981). The economy of scope effect was also identified by Gameiro; Rocco and Caixeta Filho (2016), Mendonça et al. (2020) and Reis et al. (2020).

Despite the benefits of economy of scope, the HSM did not consider the effects of soil microbiological quality and its effect over time. These variables could be modeled and imputed in the HSM, making it more dynamic and robust. The financial results found in this study were more favorable to the execution of agricultural activity in monoculture, as shown in Fig. 7. In the experimental design proposed by Reis et al. (2020), Internal Rate of Return (IRR) results were 11%, 22% and 10% for agriculture, iCLS and livestock, respectively. Additionally, Mendonça (2018) reported IRR of 40%, 5% and 23% for agricultural production of corn, cattle and ICLS, respectively. Ryschawy et al. (2012), when evaluating the environmental and economic dimensions of production systems in agricultural and livestock monoculture and in integrated systems, did not find the best economic results in iCLS.

iCLSs demand less natural resources such as fertilizers and fuel when compared to monoculture production systems (SCHIERE; IBRAHIM; VAN KEULEN, 2002): e.g. they minimize GHG emissions (GERBER et al., 2013) and have the potential to mitigate these gases (HERRERO et al., 2015); increase the bioavailability of nitrogen (N) of soil organic matter, in relation to microbial biomass (KING; HOFMOCKEL, 2017); maximize property autonomy through production diversification (RYSCHAWY et al., 2017), and minimize climate and market risks (PAUT; SABATIER; TCHAMITCHIAN, 2019). However, the environmental aspect was not considered in the HSM.

In addition to the methodological contributions and economic findings, the HSM structure presents promising conditions for adaptation to other contexts. Since the model was developed based on a clear mapping of key technical and economic variables – and structured through a modular spreadsheet interface – it can be recalibrated to simulate alternative agricultural settings. This includes different crops, such as soy or wheat, or even other livestock chains like dairy cattle or poultry. While further refinements would be necessary to expand the model's robustness in these new contexts, this study represents a foundational step toward a transferable hybrid modeling framework for integrated agricultural systems.

4.2 Hybrid Simulation Model

The hybrid simulation model (HSM) was developed using the AnyLogic® simulation software, which uses Java as a language, object-oriented programming. This software, according to a bibliometric review by Brailsford et al. (2019), was the most used among the studies and found in 34% of the cases. The differential of this software is regarding the consideration of the three simulation methods (dynamic systems - DS, discrete events - DES, and agent-based - ABS) and the possibility of mixing the methods from the components of the modeling library that comes as standard feature. Brailsford et al. (2019) identified that less than 20% of the models found used a mixture of ABS and DES methods. The hybridization, in this study, was of the integration type and happened automatically between DES and ABS.

DES has become more popular with the advancement of computational capacity, which allows the consideration of random variables. Models with stochastic variables that included probability components made the decision-making process more applicable. In ABS, the main advantage is that it provides the most adequate and natural representation to describe an agents (individual, machine, people, among others) and the behaviors that can affect the actions of the agents themselves, including other agents and the environment in which they are inserted (Borshchev, 2013; Macal, 2016).

In this study, the agents were cattle and the corn production area (hectares). The corn plants could have been elected as agents in the HSM; however, this would require greater hardware operational capacity to run the simulations. Another aspect is that the relevance of the agents must be considered to avoid unnecessary complications, since the level of abstraction is modeler-dependent (Jakeman et al., 2006).

The functions of forming batches of animals for output from the system and the definition of nutritional supplement consumption justify and represent the differential in the use of these methods in the HSM. From the definition of specific rules and having the agent as the center of the process, the developed HSM that defined the day as a unit, assigned nutritional supplement intake by the agent's weight and by the pre-established weight grouped itself with other individuals to then leave the system in a single event. This cyclical, daily event is another differential of the HSM, because other models, despite considering randomness, do not consider the individuality of the agents and are not able to accurately estimate such parameters.

Agent-based simulation models in crop-livestock have been developed. Carauta et al. in 2018, used a Mathematical Programming-based Multi-Agent Systems (MPMAS) software package to simulate farm behavior and human-environment interactions in agriculture. MPMAS was also used to simulate potential crop yields under different climatic conditions, soil types, planting dates, crop rotation schemes and fertilization rates in micro regions of Mato Grosso, Brazil, by Hampf et al. (2018). The MPMAS was a model developed in a broad work carried out by Schreinemachers and Berger (2011). An agent-based model was also developed by Müller-Hansen et al. (2019), who wanted to understand whether the intensification of cattle production could reduce deforestation in the border region with the Amazon rainforest.

AnyLogic® also allows data to be imported (inputs) and exported (outputs) to files external to the HSM (text files, Microsoft Excel® and others). This feature was explored in the developed HSM and is an advance in relation to the studies carried out by Reijers et al. (2019) and Ojeda-Rojas et al. (2021). All information on the parameters used in the HSM came from Excel® spreadsheets, which, when processed in the model (in AnyLogic® software), were transcribed into text files (txt.csv). This functionality facilitates the modeler's work in relation to changes in parameter values during the simulation run; gives the HSM more usability because the spreadsheets are accessible by a large number of users, and, if filled in with the respective data, they can also be processed to create new scenarios and support the decision-making process.

AnyLogic® converts flowcharts used for modeling into animations to understand the modeled system and even to make the project more attractive, enabling the creation of more comprehensive management dashboards.

5. Conclusions

Regarding the findings of this experiment, the economic-financial gains depended in part on the productive arrangement in iCLS and, therefore, simulated (in silico) models gain importance by allowing researchers to test hypotheses in advance. In this way, Operations Research (OR) methods demonstrated their usefulness for hybrid computational simulation models that are based on agents and discrete events with stochastic variables in the context of integrated crop-livestock systems.

The HSM did not consider the environmental (nutrient flow N, P and K) or social aspects, nor did it monetize them, which would be of interest when including other variables that make up the integrated systems of agricultural production. The HSM could become more useful when considering the effects that occur over time in iCLS.

The HSM has the potential to serve other animal and plant production systems and is therefore worthy of the further studies needed to evaluate these systems more thoroughly.

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Authors contributions

Dr. Flavia F. Simili designed the field study and provided the field data. Dr. Joslayne Cyrillo supplied the dataset used for model calibration. Dr. Oscar A. Ojeda-Rojas and Dr. Thayla S. S. S. Reijers contributed to the development of the methodology and assisted with model testing. Professor Dr. Augusto H. Gameiro supervised the overall project. All authors read and approved the final manuscript. There were no special agreements concerning authorship. All authors contributed in accordance with their roles and responsibilities in the project.

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Competing interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Obtained.

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The Publication Ethics Committee of the Macrothink Institute.

The journal’s policies adhere to the Core Practices established by the Committee on Publication Ethics (COPE).

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The data that support the findings of this study are available on request from the corresponding author. The data are not publicly available due to privacy or ethical restrictions.

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No additional data are available.

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