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# Participatory Agent-Based Modeling of Grazing Management: Comparing Rotational vs Continuous Grazing Systems

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## Abstract

In the current context of cattle-farming intensification, improving understanding of ecosystem functioning is essential to increase productivity without raising external inputs, while also enhancing adaptability to climate change. This study presents a first implementation of a dynamic predator-prey approach using an agent-based modelling (ABM) platform (NetLogo), which enables separate yet interacting representations of cattle and pasture paddocks governed by management decisions. The objective was to develop, through a participatory process, an ABM that captures the key components and dynamics of grazing systems, and to evaluate its response to spring drought conditions by comparing rotational (ROT) and continuous (CON) grazing strategies. Both systems were simulated within the same platform, differing only in spatial cattle management. Four climate scenarios representing spring droughts were tested under varying initial grass heights and stocking rates to assess productive and economic outcomes. Across all scenarios, ROT improved per-hectare productivity by an average of 18% with lower forage allowance, compared with CON. Animal performance was strongly influenced by initial grass height and drought severity, with ROT consistently supporting higher stocking rates and achieving up to 10% greater economic performance. However, under very low stocking rates or severe drought, CON outperformed ROT economically. This shift was associated with cost structure: ROT systems carried higher fixed costs related to infrastructure, which could be diluted under conditions of higher productivity. The model illustrates how grazing management, climate variability, and system structure interact to shape physical and economic performance, highlighting the potential benefits and context-dependence of rotational grazing.

**Keywords:** multiagent modelling, economic evaluation, livestock management, optimal stocking rate, Voisin rotational grazing

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## Modelado participativo multiagente de la gestión del pastoreo: Comparación entre sistemas de pastoreo rotacional y continuo

### Resumen

En el contexto actual de intensificación de la producción ganadera, comprender el funcionamiento de los ecosistemas es fundamental para aumentar la productividad sin incrementar el uso de insumos externos y mejorar la adaptación al cambio climático. Este estudio presenta una primera implementación de un enfoque dinámico presa-predador mediante una plataforma de modelado multiagente (ABM) en NetLogo, que representa de manera separada pero interactuante a los animales y potreros, integrando reglas de decisiones de manejo. El objetivo fue desarrollar un ABM participativo que reprodujera los componentes y las dinámicas de sistemas de pastoreo y evaluar su respuesta ante condiciones de sequía primaveral comparando dos estrategias: pastoreo rotativo (ROT) y pastoreo continuo (CON). Ambos sistemas fueron simulados en la misma plataforma, diferenciándose solo en la gestión espacial del rodeo. Se analizaron cuatro escenarios climáticos que representaron sequías primaverales, combinados con distintas alturas de pasto y cargas para evaluar el desempeño productivo y económico. En todos los casos, ROT mostró 18% más de productividad por hectárea que CON, con menor oferta de forraje. El desempeño animal dependió de la altura inicial del pasto y la severidad de la sequía, observándose que ROT sostuvo cargas más altas y alcanzó 10% más de rendimiento económico. Sin embargo, con cargas muy bajas o sequías severas, CON presentó mejores resultados económicos, pudiendo explicarse porque presentaba costos fijos más bajos que ROT. El modelo muestra cómo el manejo del pastoreo, la variabilidad climática y la estructura del sistema interactúan para determinar el desempeño físico y económico.

**Palabras clave:** ABM, evaluación económica, manejo de ganado, carga óptima, pastoreo racional Voisin

## Modelagem participativa baseada em agentes do manejo do pastoreio: Comparação entre sistemas de pastejo rotativo e contínuo

### Resumo

No atual contexto de intensificação da pecuária bovina, aprofundar o entendimento dos ecossistemas é essencial para aumentar a produtividade sem ampliar o uso de insumos externos e fortalecer a adaptação às mudanças climáticas. Este estudo apresenta uma primeira implementação de um enfoque dinâmico predador–presa por meio de um modelo baseado em agentes (ABM) no NetLogo, que representa separadamente, mas de forma interativa, o gado e os piquetes, integrando regras de manejo. O objetivo foi desenvolver, de maneira participativa, um ABM que reproduzisse os principais componentes de sistemas de pastejo e avaliar sua resposta a condições de seca na primavera, comparando pastejo rotativo (ROT) e contínuo (CON). Os sistemas foram simulados na mesma plataforma, diferindo pelo manejo espacial do rebanho. Quatro cenários de seca primaveril, combinados com diferentes alturas iniciais de pasto e lotações, foram analisados para avaliar resultados produtivos e econômicos. Em todos os cenários, ROT apresentou em média 18% mais produtividade por hectare, mesmo com menor oferta de forragem. O desempenho animal foi influenciado pela altura inicial do pasto e pela severidade da seca, com ROT sustentando maiores lotações e alcançando até 10% mais retorno econômico. No entanto, sob lotações muito baixas ou secas severas, CON superou ROT economicamente devido à estrutura de custos, apresentaram custos fixos mais baixos. O modelo evidencia como o manejo do pastejo, variabilidade climática e a estrutura do sistema interagem para determinar o desempenho físico e econômico, destacando os benefícios e a dependência das condições para o sucesso do pastejo rotativo.

**Palavras-chave:** ABM, avaliação económica, manejo de ganado, tasa de carga óptima, pastoreio racional Voisin

## 1. Introduction

Extensive livestock production systems are currently challenged by the global increasing demand for animal protein (Godfray et al., 2010). This pushes landowners to increase productivity while reducing ecological impacts and improving resource-use efficiency. The concept of ecological intensification (Modernel et al., 2016) naturally emerges in this context under different forms. For instance, by lowering system inputs (e.g. chemical fertilizers

or supplemented feed), through more efficient use of the resources, and adopting precision livestock production practices (Laca, 2009). For extensive native grassland livestock farming systems, the main challenge and first steps of intensification are to improve spatial-temporal cattle management (Picasso et al., 2014; Soca et al., 2013), considering the climate change scenarios where drought episodes have large impact on primary and secondary system productivity (Cruz et al., 2021).

Uruguay is a traditional beef producer, exporting approximately 80% of its production to international markets (Oficina de Estadísticas Agropecuarias, 2021). Livestock extensive cattle systems are located at the Pampa biome, where native grassland is constituted mainly by sub-tropical C4 species (Royo Pallarés et al., 2005). In Uruguay, according to a recent local survey (Favaro Sapriza, 2022), rotational grazing systems have gained relevance in association with agroecological practices that reduce chemical inputs while prioritizing human, environmental, and animal welfare. Some methods, such as Voisin's rational grazing (Machado Filho et al., 2021), have re-emerged in this context (López-Pérez et al., 2022). For extensive rangelands systems, the Instituto Plan Agropecuario (IPA), Uruguay's national livestock extension agency, encourages process-based technologies, including paddock management, suckling control, shade shelters, and cattle trough for beef cattle farmers (Saravia et al., 2011). These practices are not contradictory with rotationally grazed systems. Nevertheless, the main difference is the frequency of animal movement, which varies from one or two days for intense rotational systems to once a month or even once a season cattle paddock assignment for extensive ranching. The size of paddocks also shows a wide variation, going from ≤ 1 hectare for rotational systems to tens to hundreds of hectares for extensive ranching systems with few paddocks. Grazing management is a key aspect of livestock production over which farmers can exercise control by determining the pasture area allocated to a given number of animals, of one or more species and categories, for a specific period (Allen et al., 2011; Royo Pallarés et al., 2005).

Historically, there has been controversy about rotational vs continuous grazing, and there is no categorical evidence to declare which one is the best management practice (Allen et al., 2011). Indeed, Briske et al. (2011) remark that a human perspective must be incorporated into the discussion, and they propose that grazed rangelands must be conceived as complex and adaptive systems.

Moreover, Machado Filho et al. (2021) state that more ecological knowledge is needed in livestock farming, and farmers must be involved in the discussion. In that sense, livestock modeling can be an interesting tool to enhance the knowledge of agroecosystems functionality. According to McKnight and Ibeagha-Awemu (2019), models have had several uses in livestock productive optimization and can be valuable tools for improving resource-use efficiency. Also, modelling within a serious game approach has demonstrated its utility in discussing results with stakeholders, serving as a learning tool in knowledge-exchange processes (Ryschawy et al., 2022; Wedderburn et al., 2013).

A recent approach to modelling complex systems, consistent with that described by Ryschawy et al. (2022), focuses on the carrying capacity of rangelands and conceptualizes them as predator-prey systems (Ungar, 2019). We have shown that the Predator-Prey Grassland Livestock model (PPGL; Dieguez & Fort, 2019) fits empirical data well, for example, in capturing the effects of changes in stocking rate (S), and provides theoretical support for the concept of an optimal S. Nevertheless, a drawback of population models like PPGL is their inability to account for spatial heterogeneity. Additionally, in the case of rotational systems, a central concept of grazing management is the logistic growth harvesting by animals, which involves intense, localized defoliation followed by sufficient rest periods for the grass to recover its leaf area (Machado Filho et al., 2021; Ungar, 2019). In that sense, complexity is added, as different stages of logistic growth must be considered in the modelled space. Agent-based models (ABM) constitute a suitable approach to describe rotational grazing systems because they explicitly include moving agents (animals) and stationary agents (patches) at different pasture stages across space and time (Railsback & Grimm, 2019).

We present an ABM developed in collaboration with a group of Uruguayan farmers who practice rotational grazing, as a tool to support grazing management. The aim of this work was (i) to develop an ABM in collaboration with stakeholders, (ii) to implement the main components and dynamics of a rotational grazing system in an ABM platform, and (iii) to assess the system's response to spring drought scenarios by comparing rotational and continuous grazing management.

## 2. Materials and Methods

### 2.1 Participatory Modelling Process

Three workshops were conducted at the Centro Emmanuel (Nueva Helvecia, Colonia; https://centroemmanuel.org/) between 2019 and 2021 to facilitate the participatory development of the VABM. Since the group of eight farmers used Voisin's rational grazing systems (VRG), the resulting model was called VABM and it was implemented in the NetLogo platform (NetLogo version 6.4.0). The following topics were discussed in the workshops: i) the grass dynamics and basic management rules of a rotational grazing system; ii) animal herd and paddock structure; and iii) VABM model results presentation to stakeholders (farmers and technicians), with a short evaluation of VABM usability and improvements needed. Results of the first two workshops are reflected in item 2.2 (VABM Description), specifically, in the rules that describe the initial conditions of the model and the rotational grazing management. A brief description of the results of the last workshop is presented in item 3.4 (Stakeholders' Evaluation of VABM). Supplementary Material 1 presents more information about this participatory process.

### 2.2 VABM Description

The main structure and dynamics of the VABM model can be summarized as an agent-based application of the PPGL model (Dieguez & Fort, 2019) with a spatial distribution of animals according to some basic management rules discussed with farmers.

The PPGL model involves a system of two coupled equations:

$$dx/dt = r\,x\,(1 - x/K) - c[x^2/(H^2 + x^2)]\,y^{3/4}\,S \qquad (1)$$

$$dy/dt = b\,[c\,x^2/(H^2 + x^2) - Im]\,y^{3/4} \qquad (2)$$

Where x and y are the grass height (cm.ha$^{-1}$) and body weight (kg.animal$^{-1}$), respectively; $y^{3/4}$ is the metabolic live weight; r (day$^{-1}$) is the logistic growth rate constant, and K (cm) is the system's carrying capacity, which is a time-dependent parameter that varies sinusoidally throughout the year (minimal value at winter and maximal value at the summer solstices). These variables describe logistic grass growth. c (cm.kg metabolic live weight-1.day$^{-1}$) and H (cm) are Holling type III intake model parameters (de Boer, 2018); b is the grass to body weight conversion efficiency constant (kg metabolic liveweight.cm$^{-1}$) (Dieguez & Fort, 2019); S is the stocking rate (animals.ha$^{-1}$); and Im is the maintenance intake (cm.kg metabolic live weight-1.day$^{-1}$). The grass height can be converted to kg of Dry Matter (DM) per hectare using a constant of 250 kg DM.cm$^{-1}$.ha$^{-1}$ (Duarte, 2023). The forage allowance (FA; kg DM.kg LW$^{-1}$) is calculated at a system level, as a ratio between grass and body weight biomass present in the system (Soca et al., 2013). More details of logistic growth and PPGL model are presented in Supplementary Material 2, and by Dieguez & Fort (2019).

The VABM implements the system of equations (Equation 1) for each agent (individual animal), with animals explicitly allocated in space. In addition, each paddock in the VABM has its own logistic growth dynamics, based on its respective grass height. The main difference is that the VABM generates populations of individual animals

and paddocks (Figure 1), rather than representing animals and grass as populations of average individuals, as in the PPGL model.

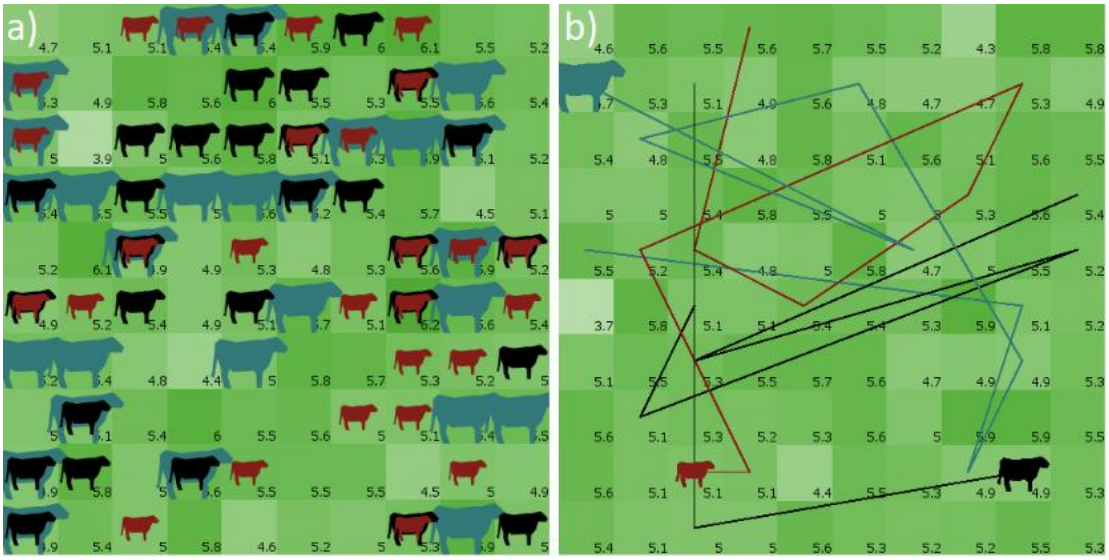


**Figure 1.** NetLogo "world" interface screen capture of CON (left) and ROT (right) simulations at one week of simulation (7 time steps, as example), starting with i-GH = 5 cm.ha$^{-1}$

Number in patches indicates grass height; size and color of cows represent each batch of animals. Lines indicate movement pathway for each batch at ROT treatment.

Based on the workshops with farmers mentioned above (Supplementary Material 1), a consensus emerged that the representative rotational grazing (ROT) management implemented in the first version of the VABM should be structured according to the following rules:

- A grazing surface of 100 ha divided into 100 paddocks (of 1 ha each).
- Three batches of 33 growing animals with different initial liveweight (200, 250, and 300 kg), with no sex specification, corresponding to approximately a S of 1 animals.ha$^{-1}$.
- Grazing on native grass-based pasture.
- Neglecting restrictions of water or shadow shelter.
- Ignoring animal diseases.
- No external supplementary feeding.

In addition, the main simplified rules of animal movement were defined as:

- Each batch of animals is managed separately.
- Animals' batches are moved daily, placed in the three paddocks with the highest grass height.
- Heaviest batch is placed in highest grass paddock, middle batch in the second highest grass paddock, and lightest batch in the third ranked height grass paddock.

To compare results, a continuous grazing (CON) management was also implemented in the VABM, using the same initial values as in ROT, and varying only in its management. In the present work, the decision rules governing herd management were intentionally simplified. Under CON, animals move randomly between paddocks on a daily basis. While initial weight distribution is the same as in ROT (with animals evenly distributed among three different initial liveweight), there are no batches of animals in terms of management, as they all move independently. This management scenario does not include predefined grazing rules or key behavioral factors; instead, it was designed as a neutral baseline against which to benchmark the performance of the ROT setup against a non-structured grazing alternative. Therefore, the CON scenario should not be interpreted as representative of actual cattle management practices on farms.

Figure 1 represents a static snapshot of a dynamic modeling process for CON and ROT management (Figures 1a and 1b, respectively). Specifically, the ROT screen capture displays three batches, each containing a defined number of animals according to the respective scenario. Due to the two-dimensional representation, the silhouettes of animals located within the same patch are superimposed.

The main system response variables considered were the average individual liveweight gain (I-LWG) per year for the three batches and the liveweight gain per hectare (H-LWG) per year, based on 365-day simulations. As for the economic assessment, the economic response variable was gross margin (GM).

Once the core structure of the representative VABM model had been defined, alongside the biological assessment, economic data were incorporated into the model to calculate farm profitability using the GM method. For this analysis, average national steer liveweight prices (Pantalla Uruguay, n.d.), production costs from three farmers who participated in the workshops (López-Pérez et al., 2022), and data reported in the IPA's *Economic Monitoring of Livestock Enterprises* for 2018-2019 (Molina Riccetto, 2019) were considered. These data were later adapted to the specific conditions that were intended to be represented in the model (e.g., supplementation costs were excluded). The GM was calculated based on the following assumptions:

- A fixed price per liveweight kg was used to estimate gross product.

- Costs were classified as fixed (do not vary with the level of production) or variable (change with the level of production, in this case, with the number of animals).

- Fixed costs (FC) included labor, taxes, depreciation, and facility maintenance. ROT incurred higher fixed costs due to the larger number of paddocks.

- Variable costs (VC) included typical animal health costs, such as vaccines and antiparasitic drugs, and assumed no nutritional expenses and no major health issues in the herd. VC per animal were equal for CON and ROT.

With this information, the model generated the GM at the end of each simulation. The GM (USD.ha$^{-1}$.y$^{-1}$) is calculated as presented in Equation 3:

$$GM = S * [(fLW - iLW) * P - VC] - (FC / G) \quad (3)$$

Where iLW and fLW are the initial and final liveweight (kg.animal$^{-1}$), respectively; P is the price of liveweight per kilo; VC are the variable costs per animal; FC are the fixed costs, and G the grazing surface. All monetary values were expressed in American dollars. Values are detailed in section 2.3 (Scenarios), made with the defined representative VABM model.

For the GM calculation, a fixed price of P = 2.15 USD per unit of liveweight was used, based on the mean price of cattle sold at livestock auctions in the country between July 2018 and June 2019 (Pantalla Uruguay, n.d.). FC were calculated using mean per-hectare values multiplied by 100 (the number of hectares of the vABM). For CON, FC amounted to 7,300 USD, in accordance with the mean costs reported by the IPA for 2018-2019 in the North, Northwest, and North-Central regions (Molina Riccetto, 2019), excluding nutritional supplementation and animal health costs. In order to maintain a common criterion, ROT FC were the same for CON, plus the mean per-hectare depreciation and maintenance costs of the VRG facilities reported for three farms belonging to farmers who participated in the workshops (López-Pérez et al., 2022), multiplied by 100. Thus, total FC amounted to 9,966 USD for ROT. On the other hand, VC were set at 7 USD.animal$^{-1}$ for both systems, an intermediate value between the mean reported by Molina Riccetto (2019) and that for the farms that participated in the study (López-Pérez et al., 2022).

A summarized version of the ODD (Overview, Design Concepts, and Details) protocol is presented below following the suggestions by Grimm et al. (2020):

*Purpose* - The overall objective of the VABM is to evaluate rotational grazing management in comparison with continuous grazing under similar structural and environmental conditions (within a *ceteris paribus* approach), in collaboration with stakeholders. Specifically, the model was designed to: (i) determine whether rotational grazing is simultaneously more productive and economically viable than continuous grazing; (ii) identify the optimal S for both management systems; and (iii) assess the effects of a spring drought episode on system productivity and resistance (Ingrisch & Bahn, 2018).

*Entities and state variables* - The model includes two entities: Patch and Cow. Cows are grouped into batches. The state variables are grass height for each Patch and liveweight for each Cow. Cows also have a batch identification (1, 2, or 3), according to its initial liveweight. Regarding spatial and temporal resolution and extent, each time step in the model represents one day, and simulations run over a year (365 days). VABM is spatially explicit and is defined over the area of the grazing farm case study. The landscape, or "world", consists of a 10 × 10 grid of patches, each covering 1 ha, resulting in a total area (G) of 100 ha.

*Process overview and scheduling* - The core process of the VABM is the daily movement of animals across the world's grid, considering the grass height. For each time step, patches are sorted according to their grass height, and the three patches with the highest grass are selected and assigned to the animal batches (the heavier the animals, the greater the grass height of the patches to which they are assigned). Grass growths daily and is harvested by animals, implementing its variation expressed in the *dx/dt* term of Equation 1. Changes in animal liveweight correspond to the *dy/dt* term in Equation 2.

The animal liveweight change is used to calculate the GM at the end of the simulation, considering a fixed price per kg.

*Design concepts* - The most important design concepts of the model are:

*Objective* - The design model objective is to represent a Voisin's rational grazing system as a communication tool with stakeholders.

*Observation* - Monitors display the actual number of Cows in each batch during simulations, the average liveweight gain per animal for each batch, and the average, minimum, and maximum grass heights. These variables are plotted daily in the model interface.

*Communication* - The main communication variables are displayed in the model interface. Grass height is represented by a color scale, with each Patch assigned a color according to its grass height, facilitating visualization

of the model's state. The interface also displays the grass height of the patches in each paddock. In the CON scenarios (see Section 2.3), the different batches are represented by Cows with different shapes, sizes, and colors (Figure 1). In the ROT scenarios, Cows are not assigned to batches; instead, they graze together across the paddock. A monitor displays the gross margin (GM) at the end of each simulation (365 days).

*Interaction* - The interaction between Cows and Patches is the grass intake operation.

*Stochasticity* - By default, there is no stochasticity in the evolution rules. During initialization, the only random variable is the initial grass height, that has a normal distribution with a mean specified by the user and a coefficient of variation of 10%. To make comparable simulations, a random seed was fixed for all simulations. In the CON simulations, with a fixed seed, the system moves animals randomly at each time step. No human-defined grazing rules are implemented.

*Adaptation* - There are no adaptation processes. Cows change their liveweight as a function of grass height, with the PPGL model equations (Dieguez & Fort, 2019) applied individually, based on the assigned paddock by the system and according to the defined scenarios.

*Initialization* - The VABM is initialized with information provided by the user: the mean grass height in the paddocks and the number of animals per batch. The user can also set the initial liveweight of Cows, the liveweight price, and the production costs; however, these parameters were fixed in the scenarios tested. All simulations started at the beginning of southern autumn (March 21).

*Input data* - The model has no external input data. Only set information at initialization is considered.

### 2.3 Scenarios

The scenarios comparing ROT and CON grazing management had identical initial conditions. The default initial conditions were a mean of 5 cm.ha$^{-1}$ and CC 1. These conditions were varied as follows to assess their effects on the system. The value of S is expressed as animal.batch$^{-1}$. In ROT, this corresponds to the number of animals in each batch, whereas in both CON and ROT, it represents the number of animals with the same initial liveweight. As the number of batches does not change (and ROT and CON scenarios always have the same number of animals), the total number of Cows is three times the number of animals per batch.

Considering that resistance to drought episodes is one of the main problems in extensive livestock grassland systems (Cruz et al., 2021; Dieguez & Pereira, 2020), climate stress is induced at the most sensitive period of the fattening cycle. Previous research with satellite remote sensing in Uruguay (Dieguez & Pereira, 2020) has shown that southern spring months –especially October– are the more stable and favorable to native grass growth. Since pastures are mainly composed of C4 species, the growth rate is maximum in spring and summer, altough summer presents a higher risk of drought episodes (Royo Pallarés et al., 2005). This creates an opportunity to simulate a highly vulnerable system by affecting grass growth dynamics in spring. The standing deferred forage accumulated during spring could help offset a potential forage shortage in summer. The objective of that management strategy is to take advantage of the stability and high rates of spring grass growth to mitigate the impact of a summer drought.

The K parameter of the logistic growth (Supplementary Material 2) is affected by a climate coefficient (CC) that is a stress factor that multiplies the grassland carrying capacity, as described in PPGL model development (Dieguez & Fort, 2019). Then, the K parameter (Equation 1) can be rewritten as K = K.CC. To build a climate scenario, the grass growth can be modulated through increases or decreases in the K parameter. Accordingly, the climate scenarios we use for spring are then: CC = 1, 0.75, 0.50, and 0.25, in October and November, to simulate four levels of grass growing rate in the spring season. The CC = 1 treatment represents the control condition, with no spring drought episode.

To explore the system maximal stocking rate a parameter sweep was conducted by varying the number of animals per batch from 20 to 50 in increments of 1 (being 60 to 150 total animals at grazing surface), for all climate scenarios. This sensitivity analysis is performed for CON or ROT systems. To understand the system reaction to drought and stocking rate variation for different initial conditions, three different levels of initial grass height (i-GH) were considered: 4, 5, and 6 cm.ha$^{-1}$. For economic assessment, scenarios were made varying stocking rate at the same range as previously described and for the same four CC values, for both grazing management systems (considered here as treatments), but only with I-GH = 5 cm.

In total, 12 scenarios were generated by combining the three i-GH levels with the four CC levels. The GM in all scenarios was analyzed as a function of S. Quadratic and cubic regression models were fitted, and their goodness of fit was compared using the Akaike's Information Criterion (AIC) and the Bayesian Information Criterion (BIC), implemented in RStudio software (version 4.4.3).

## 3. Results

### 3.1 Simulations at Control Climate Scenario

Figure 2 shows I-Lwg and H-Lwg under the control climate scenario (CC = 1), with no simulated spring drought episode, for both CON and ROT systems.

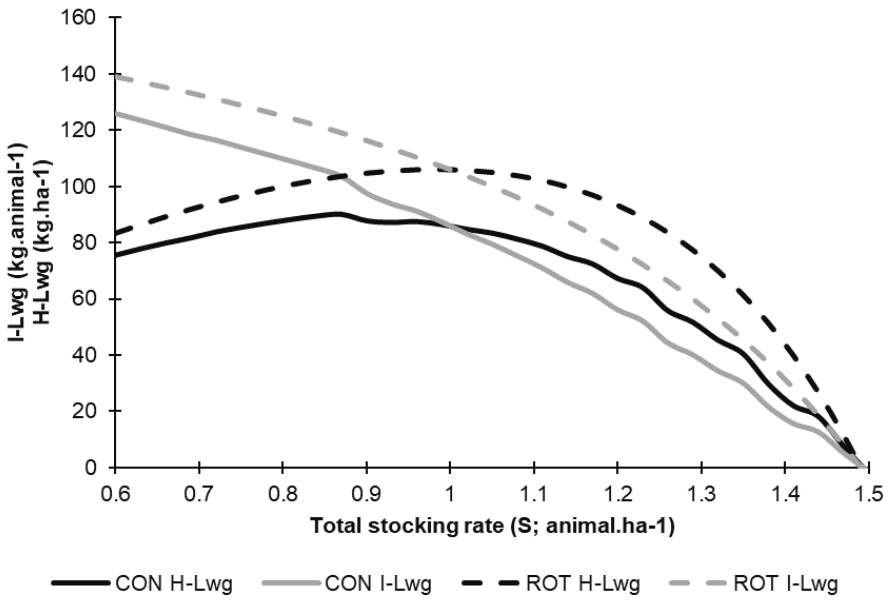


**Figure 2.** Individual and per-hectare liveweight gain (I-Lwg and H-Lwg, respectively) for CON and ROT treatments varying S, without spring drought episodes (CC = 1), and with an initial grass height of 5 cm.ha$^{-1}$

The effect of ROT treatments is clear, producing higher I-Lwg for the S considered range. This difference affects the H-Lwg, producing a quadratic behaviour. The maximal H-Lwg is achieved at the control situation presented in Figure 2 (CC = 1; initial grass height = 5 cm.ha$^{-1}$), with 29 and 33 animals/batch for CON and ROT treatments, respectively (being a total S of 87 and 99 animals in 100 ha, respectively).

Regarding grass intake, all ROT scenarios showed higher annual DM intake than CON scenarios, with an average difference of 7%. For instance, the sum of grass intake was 3,871 vs 3,590 kg DM.year$^{-1}$ for ROT and CON management, respectively. Additionally, for low S simulations (with 60 animals in total) this difference was maintained (4,400 vs 4,211 kg DM.year$^{-1}$ for ROT and CON, respectively). Moreover, for high S simulations (with 150 animals in total) the same tendency was observed, with 2,801 vs 3,037 kg DM.year$^{-1}$ for ROT and CON, respectively.

Considering the FA, it was similar between ROT and CON 6.6 (kg DM.kg LW$^{-1}$) with a SR = 1 animal.ha$^{-1}$. The ROT management produced heavier animals with more grass intake, but with more forage production in CON.

### 3.2 Simulations with Variation of Initial Grass Height and Spring CC

Table 1 presents the maximum H-Lwg and FA results across all scenarios, with combinations of initial grass height and spring CC.

**Table 1.** Maximum H-Lwg, FA, and S (animal.batch$^{-1}$) achieved, obtained at the different scenarios of i-GH(cm.ha$^{-1}$) and spring CC for CON and ROT treatments

| *i-GH (cm.ha$^{-1}$)* | *Spring CC* | *CON max H-Lwg* | *CON S max* | *CON FA S max* | *ROT max H-Lwg* | *ROT S max* | *ROT FA S max* |
|---|---|---|---|---|---|---|---|
| **4** | 1 | 72 | 24 | 9.68 | 85 | 30 | 7.38 |
| **4** | 0.75 | 68 | 24 | 9.27 | 81 | 29 | 7.03 |
| **4** | 0.5 | 61 | 24 | 8.56 | 72 | 28 | 6.82 |
| **4** | 0.25 | 37 | 21 | 8.60 | 46 | 23 | 7.43 |
| **5** | 1 | 90 | 29 | 7.65 | 106 | 33 | 6.41 |
| **5** | 0.75 | 86 | 29 | 7.32 | 101 | 32 | 6.12 |
| **5** | 0.5 | 76 | 28 | 7.12 | 91 | 30 | 6.21 |
| **5** | 0.25 | 46 | 24 | 7.37 | 59 | 25 | 6.72 |
| **6** | 1 | 104 | 33 | 6.47 | 121 | 35 | 6.00 |
| **6** | 0.75 | 98 | 32 | 6.48 | 115 | 34 | 5.89 |
| **6** | 0.5 | 87 | 31 | 6.29 | 104 | 32 | 5.73 |
| **6** | 0.25 | 54 | 25 | 7.09 | 67 | 27 | 6.17 |

Increasing the initial grass height (i-GH) from 4 to 5 cm resulted in a 25% increase in maximum H-Lwg for both CON and ROT. Similarly, increasing i-GH from 5 to 6 cm led to a 15% increase in maximum H-Lwg in both treatments. Under progressively more adverse climate scenarios, the main results for CON and ROT can be summarized as follows:

- The ROT treatment showed an 18% higher maximum H-Lwg for CC values ranging between 1 and 0.5.
- For the worst considered climate scenario, CC = 0.25, the ROT treatment exhibited 25% higher maximum H-Lwg than the CON treatment.
- At spring, the worst climate scenario (CC = 0.25) reduced by half the maximum H-Lwg in all situations.

The number of animals per batch specified by the stakeholders during the workshops in which the VABM was designed coincides exactly with the S that produces maximum H-Lwg in the case of the control or normal situation (Table 1; i-GH=5 cm.ha$^{-1}$ and no climate effect on grass growth rate, with spring CC = 1). Specifically, this corresponds to three batches of 33 animals each. That situation is stressed or relaxed depending on whether less or more grass is available at the beginning of simulations. The reduction in S at maximum H-Lwg for both CON and ROT treatments reflects the reduction in CC, and consequently the decreasing forage availability for grazing.

In all instances ROT grazing management represents a higher animal performance than CON. This improvement of productivity is an emergent property of the management of the whole system. The average FA results at max S was sensitive to i-GH and CC. The CON management had higher FA than ROT in all scenarios, but since S max is higher in ROT in all situations, the maximal H-Lwg is achieved in ROT with more animals, with relative less FA per animal.

### 3.3 Economic Performance

Economic results, expressed as gross margin (GM; USD ha$^{-1}$ year$^{-1}$), are presented in Figure 3.

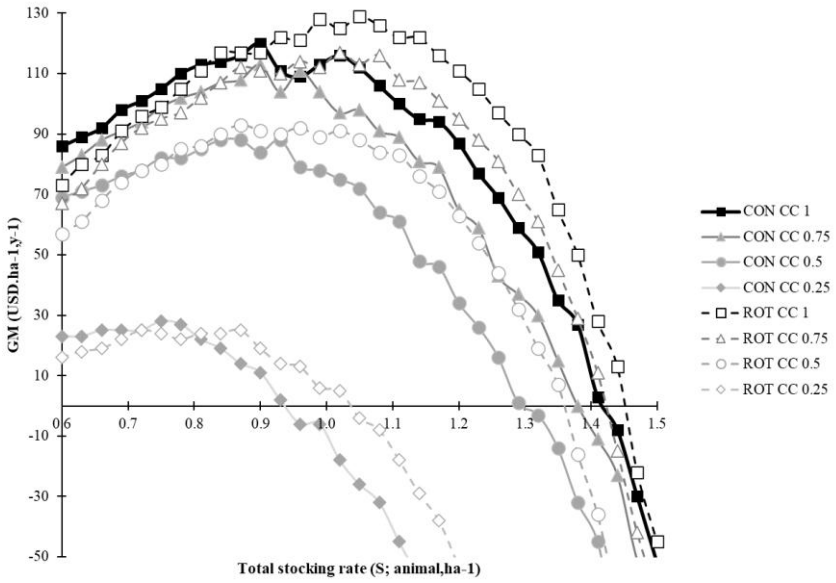


**Figure 3.** Gross margin for CON and ROT treatments at different stocking rates (S), under four spring climate scenarios (CC = 1, 0.75, 0.50, and 0.25), with initial grass height of 5 cm.ha$^{-1}$

GM showed a cubic relationship with S, according to the best-fit model selected based on AIC and BIC. For example, under the control climate scenario (CC = 1), the response equations are:

GMROT = −613.1 S3 + 1387.7 S2 – 892.4 S + 245.5 (4)

GMCON = −294.1 S3 + 472.3 S2 + 108.9 S – 44.8 (5)

This result is unsurprising, since GM depends on liveweight gain per hectare (Figure 2) and was therefore expected to show a similar pattern (Figure 3).

Regarding treatments, once again, clear differences between CON and ROT were observed. ROT was able to withstand higher S than CON in all climate scenarios. With a CC of 0.25, despite holding a lower S, CON had higher GM than ROT, with the highest values at 26.3 and 22.8 USD.ha$^{-1}$, respectively. For scenarios with higher CC, ROT had higher GM values than CON: the maximum GM was 10% higher for scenario of CC = 0.5, 9% higher for CC = 0.75, and 11% higher for 1. In the best scenario (CC = 1 and maximum liveweight gain per ha), GM was 128.7 USD.ha$^{-1}$ for ROT and 115.5 USD.ha$^{-1}$ for CON, with this last value being very similar to ROT results on CC = 0.75.

In situations of low S, CON had a higher GM than ROT management. This relation is inverted when managing scenarios with high S (from 0.86 onwards), in which ROT obtains a better economic result. This difference increases with higher S, as is observed in scenarios with CC = 0.75 and 1.

### 3.4 Stakeholders' Evaluation of VABM

Farmers were presented with the final version of the model and a range of scenarios involving different ROT management strategies. They first discussed the model and scenarios as a group and then completed a short individual questionnaire to evaluate the model's realism, usefulness, and potential areas for improvement (Supplementary Material 1).

The evaluation of the VABM was generally positive. The group expressed that the model captured the essence of a VRG system and that the simulation results were consistent with their expectations. Visualization was considered useful for "grasping the system at a glance." Farmers highlighted the ability to project stocking rates, rapidly test multiple scenarios, and use the tool for decision-making and training. Limitations mentioned included the simplification of real-world complexity and the need for further calibration using empirical data. Suggestions for further model development included adapting the model to real farms; representing systems with lower implementation of VRG (such as not having water or shade in all paddocks); adding decision-making points (such as deferred grazing or supplementation), and incorporating animal inflows/outflows. The group also emphasized the value of running multi-year simulations to reflect improvements in pasture productivity and diversity over time, and the potential of mobile applications for practical use.

## 4. Discussion

A preliminary examination of the results shows that the system's behavior is consistent with Mott's theoretical model (Mott, 1960) for extensive grassland systems, in terms of both individual (I-Lwg) and per-hectare (H-Lwg) productive performance. Responses to S have been previously discussed by Ungar (2019) using a predator-prey approach, reflecting the dynamic interaction between grass growth and cattle grazing (de Boer, 2018). The responses of animal performance, on an individual and per-hectare basis, in Pampa biome grasslands have been reported by Royo Pallarés et al. (2005) and Soca et al. (2013), who showed that maximum productivity depends on S and forage availability. Likewise, the concept of an "optimal" stocking rate and its relationship with carrying capacity in grazing-based livestock systems have been widely discussed (Ungar, 2019).

The logistic growth-harvesting framework is a key factor in improving system performance through grazing management control (de Boer, 2018; Machado Filho et al., 2021; Ungar, 2019), regardless of the grazing method used. Voisin's rotational grazing rules (Machado Filho et al., 2021) emphasize harvesting forage near the optimal stage of logistic growth (e.g., immediately after the inflection point of the growth curve), while also ensuring adequate post-grazing recovery time, a principle also highlighted by Teague et al. (2013). These principles are broadly applicable across grazing systems. In the present study, rest periods arise naturally in the ROT treatment as a result of daily herd movement.

In our VAMB model, ROT management consistently outperformed CON management, in both individual and per hectare liveweight gain. This outcome stands in contrast to major historical reviews, such as Briske et al. (2008) and Rouquette et al. (2023), who concluded that rotational grazing rarely yields superior productive outcomes when compared to continuous grazing. Reconciling these divergent outcomes requires a careful examination of differences in management practices, taking into account the variations among systems labeled as rotational grazing, as well as the limitations of our current model.

A key issue concerns selective grazing by cattle and its implications for paddock biodiversity and vertical vegetation structure, including effects on nutritional quality and herbage availability (Enri et al., 2017). These processes can be affected by the grazing system (Enri et al., 2017; Modernel et al., 2016; Moojen et al., 2022; Picasso et al., 2014), but are not explicitly represented in VABM –partly because they were not prioritized by stakeholders during early model development–, which limits the depth of discussion of these topics. Nonetheless, they should be incorporated in future model extensions.

Another factor to consider is the extent of variation among rotational grazing systems and how these differences could impact comparisons with continuous grazing systems. Briske et al. (2023) highlight the difficulties of evaluating rotational grazing due to the wide range of terms used, which do not always have clearly defined meanings. As such, *rotational grazing* or *rotational system* can be considered umbrella terms including both rigid

rotational management, which have a predetermined sequence for grazing, and adaptative systems, with different criteria. The aim of our VABM model was to represent the specific management practices used by farmers who were part of the participatory process. As a result, the VABM uses a clear criterion for selecting paddocks, which is grass height, and thus it does not follow a predetermined sequence.

Moojen et al. (2022), comparing continuous and rotational grazing with sheep on fertilized Italian ryegrass pastures, showed that forage allowance is the key determinant of grazing system performance, surpassing the effect of grazing method. Although their study involved a different species and pasture type, the underlying principle remains highly relevant: FA regulates both I-Lwg and H-Lwg outcomes. In their experiment, higher I-Lwg under continuous grazing was associated with greater forage accumulation and related processes, such as enhanced selectivity under high forage allowance, while no differences in H-Lwg were found between treatments. Carmo et al. (2019), in a survey of Uruguayan cattle farms on native pastures, reported that adaptive management systems with fattening steers operate at 5-8 kg DM·kg $LW^{-1}$ in spring (fattening season), rising to ~10 kg DM·kg $LW^{-1}$ in winter.

In the present study, FA emerges as an output of the simulation (unlike Moojen et al., 2022 and Carmo et al., 2019, who use FA as a management target), resulting from the interaction between current grass biomass, cattle biomass, S, and CC. Even though processes such as selectivity, foraging behavior, and patch-scale attributes (e.g., biodiversity, nutritional quality) were not explicitly included, the simulated ROT system reproduces key mechanisms such as forage accumulation during rest periods, increased herbage intake, and higher I-Lwg under favorable forage availability. This availability is regulated globally by S and locally by density-dependent processes (de Boer, 2018; Ungar, 2019) such as the grass intake and the I-Lwg (Equations 1 and 2). Model responses –both I-Lwg and H-Lwg– to S variation and CC scenarios indicate that higher forage availability increases FA for a given animal liveweight and intake, resulting in higher I-Lwg and grass intake at a given S. This effect is particularly pronounced in ROT systems, where rest periods enhance pasture recovery and thereby increase intake potential relative to CON. Although grazing behavior and pasture quality are not formally represented in VABM, the model still reflects a compensation mechanism between daily gain and S on H-Lwg (Moojen et al., 2022). Overall, modeling results align with the conceptual framework identifying forage allowance as a central driver of grazing system performance. Furthermore, they suggest that under favorable climatic conditions or reduced drought stress, rotational grazing can more effectively capitalize on periods of high pasture growth, reinforcing the role of rest periods in enhancing forage availability and improving animal performance.

Regarding economic results, Daza and Martín (2007) assumed a quadratic response between GM·$ha^{-1}$ and S for extensive grazing systems in the Spanish Dehesa. Beck et al. (2020) found a linear increase in net income as S increased from 1.83 to 4.13 animal·$ha^{-1}$ in growing steers. It is noteworthy that these models did not account for climate variability. In contrast, VABM economic and physical outputs are consistent with Dieguez and Fort (2019), where CC affected the stocking rate achieving maximum GM for each initial grass height scenario. In our results, GM behavior is partly explained by ROT supporting higher stocking rates than CON and therefore obtaining higher H-Lwg. Another contributing factor is cost allocation: fixed costs were higher for ROT scenarios due to paddock depreciation and maintenance. Thus, CON requires high stocking rates to dilute these costs. By supporting higher S, ROT presents two advantages: under unfavorable conditions, it can reduce losses by avoiding forced sales or additional nutritional supplementation; under favorable conditions, its higher costs are diluted, increasing profitability.

To compare the modeled GM, the mean values reported in the IPA database of cattle farm economic results for 2018-2019 (Molina Riccetto, 2019) were considered. The mean GMs were USD 53 and USD 90 $ha^{-1}$ for the North-Northwest-North-Central and East-Northeast-East-Central regions, respectively, where cattle ranching is prevalent. These values are higher than those obtained in the VABM under CC = 0.25, but lower than those for

CC = 0.75 and 1, with CC = 0.5 sitting in between. This indicates that model outputs fall within the range observed in real Uruguayan farms. According to Daza and Martín (2007), GM is directly related to forage levels in farms under average conditions. Similarly, in our results, GM followed the same pattern as liveweight gain, both being influenced by CC through its effect on grass growth. Under this framework, ROT remained viable under more scenarios than CON owing to its capacity to support higher stocking rates. According to Paparamborda et al. (2023), management practices that increase forage height, pregnancy rate, and weaned-calf weight per breeding event improve productive, economic, and environmental performance. These results align with Carvalho et al. (2011), who highlight the large potential to improve livestock productivity through better grazing management alone, without external inputs such as fertilizer or supplemental feed.

Finally, regarding the participatory modeling process, VABM reproduced known results and was positively evaluated by participating farmers (Supplementary Material 1). However, more data are needed for full validation. A major challenge is access to detailed records on daily animal movement, cattle weights, and paddock grass height. Farmers typically manage systems based on empirical rules of thumb and intuition (Briske et al., 2011). VABM incorporates several of these rules, and agent-based modeling offers the flexibility to integrate common practices and test them against alternative managements, making it a valuable decision-support tool. This enables farmers to explore counterfactual management options through an accessible simulation platform (Ryschawy et al., 2022; Wedderburn et al., 2013).

Companion modeling (Étienne, 2014) is a useful approach to address ecological aspects of livestock farming (Teague et al., 2013) by involving stakeholders in a participatory manner (Ryschawy et al., 2022). According to Modernel et al. (2016), grassland livestock systems can achieve win-win outcomes between economic and ecological performance, reducing greenhouse gas emission intensity, improving feed efficiency, and preserving biodiversity through ecologically based grazing management (Carvalho et al., 2011; Enri et al., 2017; Paparamborda et al., 2023). Nevertheless, the expansion of rotational grazing depends on infrastructure, water distribution, and labor organization (Machado Filho et al., 2021). The literature indicates that effective grazing strategies exist for both continuous and rotational systems; however, major challenges stem from social constraints and from how grazing research is conducted (Briske et al., 2011; Moojen et al., 2022; Soca et al., 2013). Local participatory initiatives combined with modeling tools are essential to foster learning, discussion, and engagement around the ecological processes underpinning grazing-based systems.

## 5. Conclusions

The VABM model represents a first participatory attempt to simulate a rotational grazing system in Uruguay through a spatially and temporally explicit agent-based approach. Although certain processes (such as grazing selectivity, foraging behavior, or patch-level attributes such as pasture quality) were not included in this initial version, the model successfully reproduces core mechanisms widely documented in grazing ecology and recognized by farmers. In particular, it captures the interplay between pasture logistic growth, forage availability, and animal performance.

Results confirm that FA emerges as a main driver of productive outcomes. FA is regulated by the stocking rate and climatic conditions, which together modulate pasture biomass dynamics and, consequently, individual liveweight gain, per-hectare productivity, and economic performance. The rotational grazing system demonstrated a greater ability to sustain higher stocking rates than continuous grazing, due to forage accumulation enabled by rest periods. This advantage allowed rotational grazing systems to capitalize more effectively on favorable climatic conditions by enhancing forage availability and animal performance, while also reducing economic vulnerability under adverse conditions by avoiding forced sales or additional supplementation.

Even though further empirical data (particularly detailed records of daily animal movements, liveweights, and paddock grass height) are required to strengthen the model, at this first version the participatory modeling process proved valuable for integrating local knowledge, formalizing common management rules, and enabling the exploration of alternative scenarios through a simulation platform. Such approaches contribute to collective learning and to the design of grazing strategies capable of improving productive, economic, and ecological outcomes in pasture-based livestock systems. Future model improvements should incorporate key ecological and behavioral processes not yet represented, including (i) animal foraging behavior with explicit grazing selectivity, (ii) patch-scale biodiversity dynamics, (iii) vertical vegetation structure, and (iv) the nutritional quality of forage. Integrating these components would allow for a more comprehensive representation of grazing-ecosystem feedbacks and enhance the model's capacity to support management decisions.

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## Transparency of Data

The entire data set that supports the results of this study was published in the article itself.

## Author Contribution Statement

| | F Dieguez | MB López-Pérez | H Fort | G Benítez |
|---|---|---|---|---|
| Conceptualization | ■ | ■ | | ■ |
| Data curation | ■ | ■ | | |
| Formal analysis | ■ | ■ | ■ | |
| Funding acquisition | | | | ■ |
| Investigation | ■ | ■ | | ■ |
| Methodology | ■ | ■ | ■ | |
| Project administration | | | | ■ |
| Software | ■ | ■ | | |
| Supervision | ■ | ■ | | ■ |
| Validation | ■ | ■ | | |
| Visualization | ■ | ■ | | |
| Writing – original draft | ■ | ■ | ■ | |
| Writing – review and editing | ■ | ■ | ■ | ■ |

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# Supplementary Material

## 1. Workshops with Farmers

This supplementary material describes the participatory process carried out for the development of the VABM, as well as the main outcomes of the workshops conducted with farmers.

The process was structured in three stages: (i) workshops with farmers, (ii) implementation of the model, and (iii) simulations. These stages were conducted in parallel, since the workshops and model implementation informed each other iteratively. A representative farm model was developed and implemented to share the main scenarios generated by changes in stocking rate (to achieve optimal) under different drought stress intensities (by varying the CC parameter) and to evaluate system behavior. Three workshops were organized with the producers' group from Centro Emmanuel (Nueva Helvecia, Colonia, Uruguay; https://centroemmanuel.org/) between 2019 and 2022 (Figure S2). The group included the farmers who had participated in the previous study, two of whom participated consistently and acted as a "core group" sensu Etienne et al. (2011).

**Workshop I**: The main objective was to discuss the criteria used for determining resting and grazing periods, as well as the factors affecting pasture growth. Farmers first listed individually the entry and exit criteria they applied in paddock management. These criteria were then presented, classified, and consolidated when overlapping. Subsequently, the discussion focused on pasture growth, where the logistic growth curve was introduced as a conceptual framework (Figure S1). The main characteristics of the curve were discussed (maximum height K, inflection point K/2, and the "optimal rest point"). Farmers highlighted several factors affecting the slope of the curve: season of the year, temperature, rainfall, pasture species, soil type, nutrient status, and topography. The consensus emerging from this workshop defined two fundamental assumptions for the model: (i) animals would be moved daily to the paddock with the highest grass height, and (ii) pasture growth would follow a logistic function, with K modulated by a climate coefficient (CC).

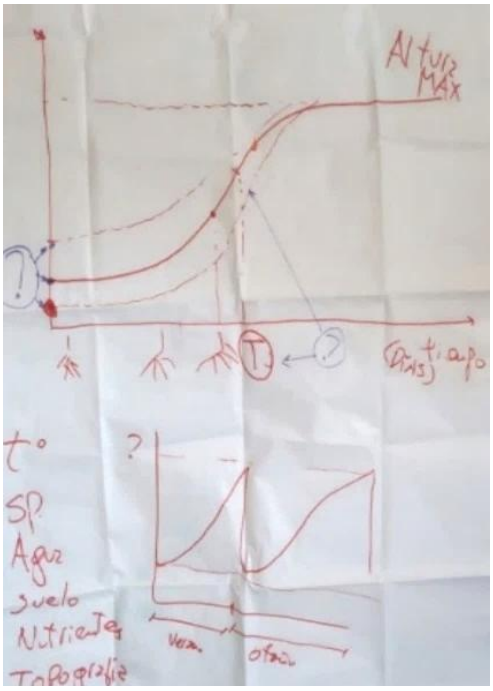


**Figure S1.** Photograph of the flip chart paper used to discuss logistic growth dynamics and harvesting with farmers

**Workshop II**: Conducted during the COVID-19 pandemic via remote conference, the objective was to discuss the elements required for an ABM of a ROT system and to define the characteristics of a "representative farm." Producers were introduced to the basic concepts of the Unified Modeling Language (UML) (Carmo et al., 2019)

and asked two guiding questions: What are the essential structural and management characteristics of a farm system for it to be considered VRG? and What daily management practices must be present in a VRG system? Farmers identified key components, including animals (species, category, batch, number, and health status), decision-making personnel, soil (type, location, and topography), water distribution (pipes, troughs, and sources), pasture (native or sown, species composition), climate factors (temperature, rainfall, and drought), paddocks (number, size, layout, and presence of shade and water), reserves (standing forage, hay, silage, and concentrate), infrastructure, and social areas. For daily management, they emphasized the need for criteria for paddock entry (forage height, quality, and rest days) and exit (short occupation time, typically one day). Based on this exercise, the model's "representative farm" was defined: 100 hectares divided into 100 paddocks of 1 ha each, with native pasture (*campo natural*) and three batches of growing animals with different average initial liveweights.

**Workshop III**: The objective was to present the representative VABM prototype, validate its structure, and discuss potential improvements. Farmers reviewed which elements identified in Workshop II had been implemented and prioritized additional ones for future versions. Suggestions included adapting the model to real farms using NetLogo's GIS extension (incorporating soil heterogeneity, pasture diversity, and topography), representing systems with lower implementation (e.g., paddocks without shade or water), adding decision points such as deferred grazing or supplementation, and incorporating animal inflows/outflows (e.g., sale of animals reaching market weight). The group also emphasized the value of running multi-year simulations to reflect improvements in pasture productivity and diversity over time. At the end of the workshop, farmers completed an individual questionnaire to evaluate the model's realism, usefulness, and areas for improvement.

**Workshop Outcomes**: Farmers converged on the concept of an "optimal grazing point," although they acknowledged the difficulty of determining it precisely. The logistic curve representation helped systematize their empirical knowledge and link their criteria for entry and exit to quantitative growth dynamics.

The definition of the representative farm provided a baseline structure that was simple yet realistic, facilitating its use as a reference for simulations. Farmers agreed that three batches of animals with different initial liveweights reflected common practice.

They expressed that the model captured the essence of a VRG system ("the model minimally reflects a VRG system") and that simulation results were consistent with their expectations (e.g., daily weight gain, seasonal pasture growth). Visualization was considered useful to "grasp the system at a glance."

Farmers highlighted as strengths the ability to project stocking rates, rapidly test multiple scenarios, and use the tool for decision-making and training. Limitations mentioned included the simplification of real-world complexity and the need for further calibration using empirical data. Farmers also emphasized the potential of mobile applications for practical use.

**Questionnaire Synthesis**: Farmers' evaluations were generally positive. They acknowledged the usefulness of the tool for clarifying concepts, monitoring farm functioning, and supporting decision-making. All respondents recommended continuing the research and development of such models, considering them attractive to younger generations and valuable for planning. Suggested improvements included incorporating additional forage variables (e.g., dry matter mass), simulating deferred grazing, differentiating pastures by season, and adding outputs relevant to farm management.



**Figure S2.** Photographs of workshops with farmers and stakeholders

## 2. Model Parameters and Grass Logistic Growth

Table S1 shows the meaning, values and units of the different model's constants used in the VABM model as well as the PPGL model (Dieguez & Fort, 2019).

**Table S1.** PPGL model constants, values, and units

| Symbol | Meaning | Value | Units |
|---|---|---|---|
| r | Logistic grass growth rate | 0.02 | $day^{-1}$ |
| c | Maximum grass intake | 6.2 × 10-4 | cm·kg metabolic live $weight^{-1}$·$day^{-1}$ |
| H | Half saturation grass intake | 2.3 | cm |
| b | Grass conversion efficiency | 81 | kg metabolic liveweight·$cm^{-1}$ |
| Im | Grass requirements for animal maintenance | 5.1 × 10-4 | cm·kg metabolic $liveweight^{-1}$·$day^{-1}$ |
| Kmax | Maximum grass carrying capacity | 27.7 | cm |
| Kmin | Maximum grass carrying capacity | 5.45 | cm |

*Source*. Dieguez & Fort (2019).

The K value presents a sinusoidal behavior, using the equation:

$$K(t) = [(Kmax - Kmin)/2 \cdot \cos((2.\pi.t)/365) + (Kmax + Kmin)/2]$$

Figure S3 shows logistic growth after an intense defoliation episode (e.g. i-GH = 2 cm), expressed as grass height (primary axe) and as kg $DM.ha^{-1}$, using a conversion constant of 250 kg $DM.cm^{-1}.ha^{-1}$ (Duarte, 2023).

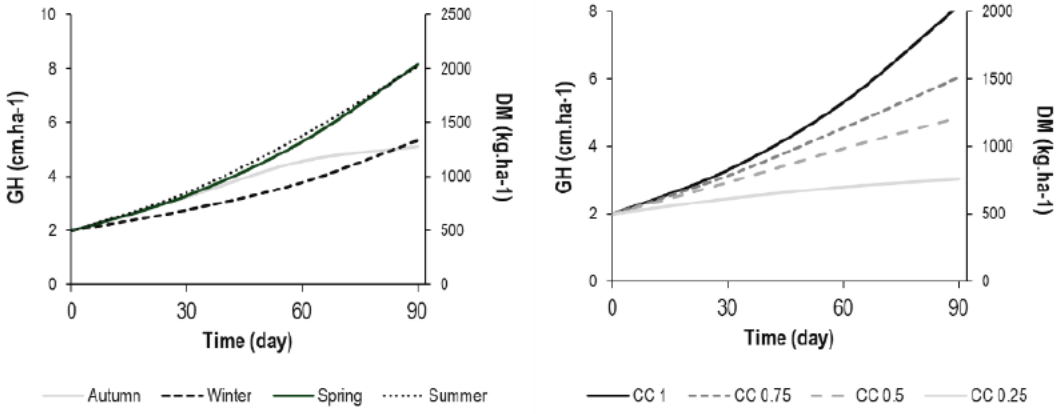


**Figure S3.** Logistic grass growth by season (left) and for spring (right) affected by the CC scenarios

Figure S4 presents logistic grass growth by season and Holling type III intake (de Boer, 2018; Dieguez & Fort, 2019) for three levels of S (0.6, 1, and 1.5 animal.ha$^{-1}$), showing the representative model and the extreme (minimum and maximum) values across scenarios.

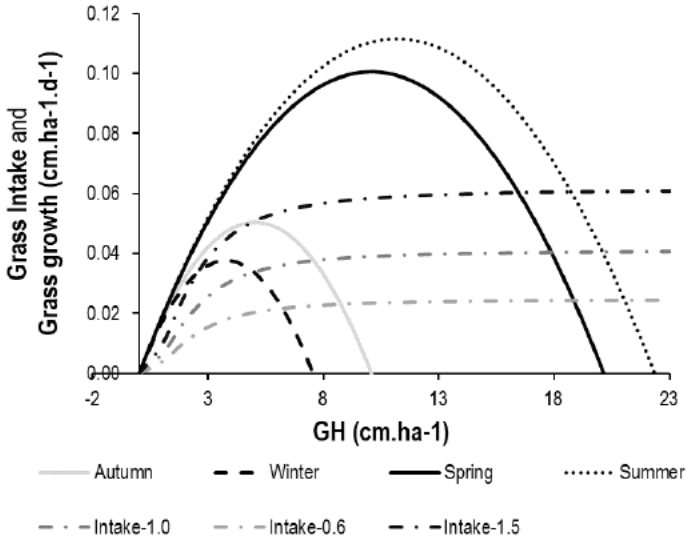


**Figure S4.** Logistic grass growth (by season) and animal's intake with three levels of S (0.6, 1, and 1.5 animals.ha$^{-1}$)