AN APPLICATION OF A DYNAMICAL MODEL WITH ECOLOGICAL PREDATOR-PREY APPROACH TO EXTENSIVE LIVESTOCK FARMING IN URUGUAY: ECONOMICAL ASSESSMENT ON FORAGE DEFICIENCY

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Abstract. Extensive livestock farmers have to manage climate risk. Therefore, there is a need to generate quantitative tools to evaluate the biophysical and economic impacts on extensive farming based on native grasslands. We present an ecological model based on the predator-prey approach, used to simulate the effect of forage deficiency on the farm’s economic performance. Different scenarios of animal stocking rate and carrying capacity of grassland are considered to assess the impact of forage deficiency in spring. Results suggest a cubic response of Gross product per hectare as function of Gross margin, according Mott’s theoretical model for meat production on grassland systems in response to stocking rate. The maximum value of this cubic response function strongly depends on the initial grass height and climate scenarios. The initial grass height is critical to maximize secondary productivity and farm economic results. Scenarios including grass reserves can buffer the deficiency on grass growth rates and pasture offer, as occurs in drought periods at the time when farmers try to make animals gain liveweight. Our analysis reinforces the usefulness of forage assignment adjustment by modulating stocking rate to improve liveweight gain and economic results under climate change conditions.

1. Introduction. Uruguayan livestock farming based on native grasslands presents the particular characteristics of the Pampa biome, where grass utilisation is a support for national economy [11] [23]. 66% of the country surface is devoted to livestock farming, where meat cattle and sheep are managed in extensive grazing farming systems. The average stocking rate of native grasslands is about 0.8 Gross unit/ha (GU/ha), varying from 0.53 to 0.98 GU/ha depending on production systems’ size and scale [7]. Most of the surface devoted to cattle ranching (80%) has the native grassland as main food resource, composed by summer perennial grasses with relatively low biomass yield and nutritional value compared to cultivated prairies. Yet, this forage base is of paramount importance from an economic and ecological point of view [5] [6]. Additionally, it permits the valuable natural labelling.
for international markets. Uruguay exports 77% of the meat that is produced in the country [14]. Livestock farming based on grazing can be considered a complex system [35] [36] i.e. the animal performance (liveweight gain and reproduction) depends on forage availability and, at the same time, the grass dynamics depends on foraging pressure by the animals. Mathematical modeling to simulate productive responses for animal and grass management, including climate effect, is central to evaluate productive scenarios, aiming to understand factors that constitutes the resilience of livestock farming at open sky systems. Given the importance of range-land resources in the provision of both forage for livestock grazing and ecosystem services [29], determining appropriate stocking rates has both economic and environmental consequences. There is a long-standing concept that considers grassland management as a complex system [30]. However, the focus on understanding the grass-livestock dynamics using a systemic approach is relatively recent [21] [22] [23]. Dynamical system modeling is a useful tool to formalize the causal relationship between the two main components of the grazing systems, grass and cattle. Soca et al. [33] proposed a conceptual modeling of livestock farming as a Forrester diagram [12] showing the main status and fluxes variables for Uruguayan extensive livestock systems. However, it is still needed an implementation to build scenarios and to assess the impact of input variation. The predator-prey Lotka-Volterra model [26] seems particularly fit to capture explicitly the co-evolution of grass height (as a proxy of forage biomass) and cattle liveweight variations. This approach, besides its well-established ecological basis, has the potential to answer specific questions, like the liveweight gain as a function of the Stocking rate (farmers main management variable of extensive grazing production systems), or, under severe conditions, like the lack of forage due to drought. In fact, those results are outputs for the model and not a model parameter defined a priori (input). In this paper we present results of the application of a predator-prey simulation model to evaluate the climate effect and the stocking rate on economic performance of Uruguayan extensive farming systems.

2. Predator-prey model description. The predator-prey model hereby presented has some improvements of its previous version [8]. Particularly, it includes a digestibility coefficient, function of pasture biomass availability (Grass height). The equation 1 shows the Ordinary differential equation system (ODE) [26] including the digestibility parameter D(x) mentioned above:

\[
\frac{dx}{dt} = r x \left(1 - \frac{x}{K(t) \text{coeffClima}} \right) - \left\{ c \frac{x^2}{H^2 + x^2} \right\} y^{3/4} S
\]

\[
\frac{dy}{dt} = b D(x) \left[ c \frac{x^2}{H^2 + x^2} - I_m \right] y^{3/4}
\]  

(1)

Where:
x: Grass height (cm)
y: Animal liveweight (kg/animal)
r: Logistic grass growth rate (day-1)
K: Carrying capacity of logistic grass (cm)
H: Grass intake half saturation parameter (cm)
c: Grass intake saturation constant (cm/kg/d)
I_m: Maintenance Grass intake (cm/kg/d)
b: Grass-liveweight conversion efficiency (kg/cm/d)
S: Stocking rate (animal/ha)
D(x): Grass digestibility expressed as function of grass height Eq. 2, described as:
\[
0 < x \leq 12 \text{ cm } : D(x) = 0.65 \\
x > 12 \text{ cm } : D(x) = -0.01667x + 0.85
\]  
(2)

The digestibility function described by Eq. 2 is such that it takes a maximum value of 65% between 0 and 12 cm of grass height as it was empirically measured [15]. From that height, the grass digestibility declines linearly. The line slope and the intercept where adjusted by empirical information from technicians and farmers in the development of a “traffic light” ruler generated in the framework of the Uruguayan family farm improvement project, conceived as decision making tool on grazing management [27]. Implementation of the ODE equation can be held on several platforms. One of them is the path diagram (stock and flow) at System dynamics modeller on NetLogo [25] software, that allows to include the ODE equations to run simulations.

![Screen capture of the predator-prey livestock model causal diagram (stocks and flow) implemented on NetLogo [25].](image)

As shown in Figure 1, the status variables of the system are liveweight and grass height related in-between by the grass intake. On one side the animals liveweight variation is affected by the liveweight itself and by the grass height. At the same time the grass height is affected by its growth rate and by the grass height itself. Regarding the climate, models considers a climatic coefficient (the coefClima parameter) that affects the actual growth rate varying the carrying capacity of the logistic growth of the pasture (K parameter; see Eq. 1 and Figure 1). The coefClima represents the monthly regulator for the average growth rate of native grasslands for the ecological regions of Uruguay. It can be considered as a stress factor (reducer or booster) of the grass growth rate slope, depending on its values. E.g., a coefClima = 0.5 implies a reduction of 50%, whereas a coefClima = 1.5 has the effect of an enhancing of 50% of the average grass growth. In that example, a scenario of a forage crisis or a forage surplus are built, respectively. Figure 2 presents a frequency histogram of the coefClima calculated as a monthly value of grass growth rate divided by the historical average for this month [9] for the Uruguayan basaltic region, where extensive family livestock farms are located, being a sensitive region to drought episodes [21] [32]. The histogram is made based on 43.953 hectares monitored in this country region by the Remote sensing pasture monitoring program for the Laboratorio regional de teledeteccion [18] from Buenos Aires University.
Figure 2. Frequency histogram for the climatic coefficient (coefClima) occurrence for Uruguayan basaltic region (serie 2000–2018 [17]).

It is important to remark that the results presented on Figure 2 are from almost 44,000 hectares. For smaller areas, increased variation of the results would be expected. In general terms, it can be stated that there is a direct but non-linear effect of the coefClima value on K parameter for logistic grass growth (affecting the net aerial primary productivity). In addition, the Stocking rate level may lead to an increase or decrease of liveweight daily gain (secondary productivity of the grasslands). The coefClima is then a modulating factor of meat production via grass allowance regulation [9].

3. Productive scenarios and economic considerations. Simulation scenarios were built varying two main key parameters: the stocking rate -as an internal regulator of the system dynamics by farmers- and other external forcing factor, the climate stress, by modifying the coefClima with values less than 1. Likewise, a third parameter was considered in simulations with different initialization values of the Grass height. A detail of scenarios is described below. Scenarios building:

1. Environment: variation of coefClima. In simulations we considered a scenario of grass lack to attain animals feed needs. The forage stress was applied on spring. That season is crucial due to calving in seasonal mating systems. Calving involves lactation and then an enhancement on animal requirements. In that season is expected to have the highest grass growth rate on native grasslands [1] [18] [31]. Likewise, that season is important for rearing animals (prepuberal animals) and for fattening/finishing systems also. From a technical point of view, it is expected that cattle recover body condition and gains liveweight in spring, after a normal weight loss after winter season, and before the summer mating season [28] [33]. Then, the standard scenarios we consider a control value of coefClima = 1, and three scenarios with values of 0.5, 0.25 and 0.125 to force a forage deficiency for the three months of southern spring (September, October and November).
2. **Animal management**: variation on stocking rate. We consider the interaction with the external forcing forage stress with different values of Stocking rate. This parameter (expressed as GU/ha) varying from 0.43 to 1.33 in ten steps of 0.1 GU/ha each time. The average carrying capacity of native grassland is estimated in a yearly average near 0.8 GU/ha \[20\] \[21\]. For simulations here, the initial cattle liveweight was set at 380 kg/animal, then in our scenarios Stocking rate can be expressed in animals/ha also, due to the 1:1 ratio with liveweight of a GU \[16\].

3. **Initial forage allowance**: grass height values. Finally, for scenarios we consider three values of initial Grass height being 3, 5 or 7 cm. These heights correspond to an equivalent of 900, 1500 and 2100 kg of Dry Matter/ha, respectively \[10\].

Considering the combinations explained above, 120 scenarios where hold. No repetitions where made due that predator-prey herein utilized is a deterministic model. All simulations started at the beginning of autumn, on march 21th (Julian day = 80). This season is also important because in recommended technical herd management \[21\] the weaning is implemented and herd is facing the winter with lower grass growth rates \[21\] \[33\]. On the other hand, the economic assumptions where based on information of the Economic monitoring of livestock enterprises of the Instituto Plan Agropecuario (IPA \[16\]) the official country extension agency. For the economical year 2016–2017 according with the information, farmers received in average an amount of 1.44 USD/kg of liveweight sold. That value is an average for the whole regions of the country monitored by this institution. Considering the production costs, it was assumed also an average of main items of livestock farming of the IPA \[16\] monitoring program. Table 1 presents annual cost information (in USD per hectare) for the economical year 2016–2017.

| Item                                           | USD/ha/year |
|------------------------------------------------|-------------|
| Workforce expenses                             | 29.00       |
| Infrastructure conservation                    | 3.50        |
| Equipment, tools and vehicle devaluation and expenses | 13.00     |
| Taxes                                          | 12.25       |
| Miscellaneous system expenses                  | 18.00       |
| Pasture conservation*                          | 9.50        |
| Direct cattle expenses (health)*                | 7.00        |
| Nutrition expenses*                            | 3.50        |
| **Total cost**                                 | **95.75**   |

In order to estimate costs per animal, they were categorized as variable and fixed costs, as a way to assign individual cost affected by the variation on Stocking rate parameter (one of the three variables for the scenario building). The criteria to classify variable cost was mainly expenses on animal health and nutrition. According to May et al. \[19\] fixed costs do not change with the level of production. Examples of typical fixed costs include interest, insurance, and depreciation. Variable costs change with the level of production. Typical variable costs in a livestock operation...
include feed, veterinary care, animal care, and other costs that change with the number of heads.

On the other hand, for individual cost per animal, a conversion of GU was made considering an average equivalence factor of 0.79 GU/animal for a complete cycle system (breeder, rearing and finishing system), assuming 53%, 32% and 16% of the cattle with 1.0 (cows), 0.7 (heifers and steers) and 0.2 (calves) GU/animal respectively. Table 2 shows average economic-productive results published by IPA [16] for complete cycle systems for all country regions monitored for the same economic year (2016–2017).

Table 2. Economic-productive indicators result for economic year 2016–2017 from IPA [16] monitoring program.

| Indicator                  | Value |
|----------------------------|-------|
| Meat production (kg/ha)    | 113   |
| Stocking rate (GU/ha)      | 0.79  |
| Surface (ha)               | 1374  |
| Herd size (total GU)       | 1073  |
| Gross margin (USD/ha)      | 58    |
| Gross production (USD/ha)  | 154   |

It is worthy to mention that in this work the Gross production by hectare (GP/ha in USD/ha) definition is the yearly total meat production (liveweight per hectare) valued with the price received by farmers. The Gross margin per hectare (GM/ha) is the difference between GP/ha and yearly Total cost (in USD/ha). The next section presents the results of simulation considering the scenarios described above for the GP/ha, Gross production per animal (GP/animal in USD/animal), and the GM/ha outputs.

4. Results and discussion. Yearly results of Gross production by hectare and by animal (GP/ha and GP/animal, respectively) and Gross margin (GM/ha) are presented in Figure 3, considering the scenarios for ten steps increasing for the Stocking rate parameter, three initial Grass height and four values of coefClima affecting the grass growth rate on spring season.

Results of GP/ha in Figure 3 showing a cubic response as a function of the Stocking rate. This behavior matches the theoretical model of Mott[24] for animal liveweight gain. This behavior of animal performance (in kg/animal and kg/ha) for Pampa biome grassland systems was reported by Maraschin et al. [18] and FAO [11] with a maximum response value depending on Stocking rate and forage allowance. Carvalho et al. [3] and Soca et al. [33] also report maximum curves response for native pastures of Rio Grande do Sul (Brazil) and for Uruguay grasslands, but with a quadratic dependence on the Stocking rate. As well as the Gross production is a valued expression of the animals liveweight gain, it is logical to think that both can be represented by the same response curves, but with different ordinate axes (USD/ha or kg/ha, respectively). Considering GM/ha, Booysen [2] states that the Gross production response is a parallel curve of meat yield (kg liveweight gain/ha) multiplied by its value using a quadratic model. In that sense, Daza and Martin [4] assumed in their model a quadratic response for GM/ha and stocking rate for extensive grazing systems at the Dehesa ecosystems in Spain. In the same way,
Figure 3. Gross product (USD per head and per hectare; top) and Gross margin (USD per hectare) (down) for scenarios varying Stocking rate (GU/ha) and initial Grass height (cm) for three values (coeffClima) parameter (1.0, 0.5, 0.25 and 0.125).

May et al. [19] also considers a quadratic response for general modeling of effects of stocking rate on economic results at farm level. These authors concluded that the GM/ha is directly related with grass at farm level. At the present work, GM/ha presents a cubic behavior, being the maximum value of the curve strongly influenced by coeffClima and initial Grass height. Table 3 shows GM/ha values (in USD/ha) for four values of coeffClima and three initial Grass heights considered for different scenarios. This table also includes the maximum GM/ha and the corresponding Stocking rate for which this maximum is attained.

Table 3. Maximal GM/ha per hectare and Stocking rate that its value is reached (IGH: initial Grass height; R2: Coefficient of determination; S: Stocking rate).

| IGH (cm) | coeffClima | R2   | Maximum GM (USD/ha) | S (GU/ha) |
|----------|------------|------|---------------------|-----------|
| 3        | 1          | 0.99 | 31.35               | 0.82      |
| 3        | 0.5        | 1.00 | 12.46               | 0.72      |
| 3        | 0.25       | 1.00 | -29.86              | 0.52      |
| 3        | 0.125      | 1.00 | -79.75              | 0.24      |
| 5        | 1          | 0.99 | 107.78              | 1.03      |
| 5        | 0.5        | 0.99 | 71.58               | 0.9       |
| 5        | 0.25       | 1.00 | 1.90                | 0.64      |
| 5        | 0.125      | 1.00 | -68.62              | 0.32      |
| 7        | 1          | 0.99 | 146.27              | 1.13      |
| 7        | 0.5        | 0.99 | 99.82               | 0.97      |
| 7        | 0.25       | 1.00 | 16.30               | 0.69      |
| 7        | 0.125      | 1.00 | -63.85              | 0.35      |
As shown on Table 3, there is a non-linear decrease on Stocking rate of the maximum GM/ha when coefClima decreases, for all scenarios of initial Grass height. Systems support higher values of Stocking rate as the initial forage allowances increases, even for annual simulations. For each level of coefClima it is observed that, even if there is a linear difference in values of the initial Grass height value, GM/ha between steps is reduced by the half. E.g., for simulations with a coefClima = 1, differential results of GM/ha are 38.21 and 19.25 USD/ha for the variation from 3 to 5 cm and from 5 to 7 cm, respectively. On the other hand, for the extreme scenario with coefClima = 0.125 marginal results between the same initial Grass height are about 5.56 and 2.39 USD/ha. Considering the initial Grass height, when this parameter is set on 7 cm, and without forcing the system to reduce grass allowance (coefClima = 1), evidently the higher values of GM/ha are attained. With this initial Grass height for all coefClima scenarios is also when the highest GM/ha is achieved. At the lowest initial Grass height (3 cm) it is observed that, even if in average grass growth condition (coefClima = 1) the GM/ha attained is one third and one fifth of the results for 5 and 7 cm, respectively. The initial Grass height of pasture is then a crucial factor for the yearly economic performance. The result suggests that from a coefClima lower than 0.5 there is an accelerated decrease of the maximum GM/ha and also the Stocking rate that maximum GM/ha is achieved, for all scenarios of initial Grass height. These results agree with Ritten et al. [29], who published that returns per hectare are most responsive to changes in the forage growth parameter. In our study, the coefClima modulates the actual pasture growth rate. Authors concluded that land with more forage production potential can carry more animals over the season to the same ending weights, resulting in much higher return. When comparing simulation with actual data from the economic monitoring of IPA [16] for the economical year 2016–2017, with an average value of 58 USD/ha and a Stocking rate = 0.79 GU/ha, even if no initial Grass height is mentioned, the results are within the simulation range. Even without knowing the farms’ coefClima monitored, it was calculated for basaltic region, using LART [17] data for 2016 spring, at an average value of 0.716. Its results show a reduction of 71.6% of the average grass growth. Figure 4 presents the coefClima of the economic year 2016–2017 calculated from LART [17] (n = 43.953 ha monitored).

![Figure 4](image-url)

**Figure 4.** Monthly evolution of coefClima parameter for the basaltic region of Uruguay, economic year 2016–2017.
Running a simulation with the predator-prey model with the economical year 2016–2017 coefClima presented on Figure 4, for the Stocking rate set on 0.79 GU/ha, the initial Grass height to achieve 58 USD/ha of GM/ha results is 3.7 cm. For the same scenario of coefClima and Stocking rate, the result of initialize the simulation with 5 and 7 cm are 94 and 120 USD/ha. Results shows the importance of having enough Grass height and to improve the economic results at farm level. Livestock farming with a reserve of unharvested Grass results in higher incomes and can be a buffer for possible grass deficiency over the year, mainly in spring season. This Grass height is attained with an adjusted Stocking rate being a good insurance to generate more resilient systems to the variability and climate change, that affects directly the grass allowance in extensive livestock farming systems in Uruguay. With this model we try to have a KISS (Keep it simple and stupid) and KILT (Keep it as learning tool) approach, where simplification without losing touch with the reality essentials is key [34]. As a learning tool, a simple model can be effective to understand and share the basics of dynamical complex systems such as livestock farming under the open sky is.

5. Conclusions. Initial Grass height is the main factor to achieve liveweight gains in rearing or fattening systems, or at least to maintain liveweight throughout the year (in breeding farms). With a Grass height of 5 cm on autumn the cattle can pass through winter and can have more possibilities to improve the liveweight gains on spring season, even with Stocking rate greater than 0.8 GU/ha, and for grass growth rate 50% of the historical average (coefClima = 0.5). At spring, even if is expected to have an increase on grass growth rate and an increase on animal requirements, the initial Grass height still conditions the whole year results of liveweight gain. This result indicates that to have a grass stash at the beginning of any season is important for buffering the possible lack of forage due to drought episodes. Simulations with the predator-prey model confirm some concepts of extensive livestock farming in Uruguay as the safe Stocking rate, adjusting the grass allowance to modulate de liveweight gain. The predator-prey model presented in this work, can capture a productive reality with a pair of simple equations and few parameters. This proposal helps to go from a conceptual model to a dynamical simulation model able to produce quantitative results on optimal use of grassland resources. Our model also includes a climatic coefficient to explore the question of building more resilient systems to climate change and variability. Finally, we want to stress that this lex parsimoniae (Occam razor) strategy, involving simple and stylized ecological modeling, has demonstrated its usefulness in other domains, like predicting species yields in different ecological communities [13].

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