Cultivating System Dynamics Skills via Facilitated Learning with a Generic Livestock Grazing Management Model

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System dynamics modeling field offers a diverse inventory of small, off-the-shelf models that facilitates discussions on the structure and behavior of complex systems. These models serve both for educational purposes in skill building for system dynamics modeling and communicating purposes to convey complex systems principles to audiences with varying backgrounds and without prior experience in system dynamics. While these resources (e.g., Goodman, 1974; Sterman, 2000; Fisher, 2005; Ford, 2009; Haefher, 2005) provide invaluable support in teaching system dynamics modeling in diverse fields, similar teaching materials, and supporting models are not widely available in agriculture and animal science contexts (Turner et al., 2016), although individual applications or case studies (Turner et al., 2013; Tinsley et al., 2019; Aderinto et al., 2020; Taylor et al., 2022) may be useful depending on the learning objectives.

In this study, we build a simple starter model, called Herd-and-Pasture, with the purpose of skill building in system dynamics for an audience with a background in agriculture and animal sciences. Our study presents the step-by-step model-building process that can be followed during a training session, the model structure and behavior, the cover story that can accompany the model, the skill-building and discussion topics that can be elaborated during a training session, and possible scenario analysis that can be conducted with the participants.

This study was initiated by the requirement of a simple yet insightful model for a four-hour satellite course (Atzori et al., 2022) as a part of an animal science conference. The main objective of the satellite course was to introduce the fundamental principles of system dynamics modeling to an audience with an agricultural and animal science background without prior knowledge of system dynamics. To achieve this aim, the authors conducted a series of meetings and model-building sessions, as well as offline and asynchronized model-building activities, prior to the event. The initial structure of the model was inspired by the well-known generic predator-and-prey structure (Swart, 1990) and evolved based on the mental models and subject matter experience of the authors on farm management and livestock production principles. The model was subsequently parametrized, tested, and documented. Following its use in the corresponding satellite course event, additional pilot applications were conducted in educational activities in the Department of Agricultural Sciences of the University of Sassari and the College of Agriculture and Natural Resources in Texas A&M University in Kingsville. We believe that the presentation and documentation of this model, along with its accompanying information, will contribute to the inventory of simple system dynamics models that can be used in agriculture and animal science contexts.

The primary purposes of Herd-and-Pasture model are to expose participants to system dynamics and allow them to gain hands-on experience with the iterative modeling process, convey how the model structure influences behavior, demonstrate that predicting the future behavior of nonlinear systems is not straightforward even with small structures, and illustrate the use of these small models in managerial decision-making processes in the agricultural context.

Here, we present the model-building steps in a manner similar to that used in our sessions: the process begins with a simple initial structure (i.e., two independent stock-and-flow structures, one for pasture and for the herd, which are decoupled), which is expanded step-by-step to endogenize a set of essential feedback loops. With each subsequent step, the structure and behavior evolve, becoming more dynamic and interdependent as additional information links and feedback loops are added. In each step, the target system dynamics modeling skills are presented with possible discussion topics to elaborate on with the participants.

- Introduction: Storyline for the Herd-and-Pasture model: Before the hands-on modeling activity starts, a cover story to accompany the model is presented to the audience. The storyline presented in our pilot studies can be summarized as follows: the participants are given the objective of managing a small-scale farm that focuses on sustainability and ecologically sound production. As the manager of the enterprise, the primary responsibility of the participants is to maintain a balanced ecosystem while expanding the herd, requiring utilizing systems thinking and modeling to better understand and manage the processes and constraints of the farm. Depending on the type of training activity, this storyline can be shared with the participants through a presentation or written text.

- Initial model – Model 0: Independent stocks: After the storyline of the model is presented to the participants, the hands-on training starts with an initial model, called Model 0. The structure of Model 0 (Figure 1) comprises two stocks, each having a single inflow and two outflows. In the *Herd Population*, all flows are mainly determined by the population size itself. Different than the natural processes of *animal births* and *animal deaths*, *animal sales* are subject to managerial decision making, with a constant fraction defined for the initial version of the model. On the *Pasture* side, pasture growth depends on both the available pasture stock and precipitation, while the *pasture senescence loss* varies with the time of the year. In Model 0, *grazing consumption* is 0, as there exists no connection between the two stocks.

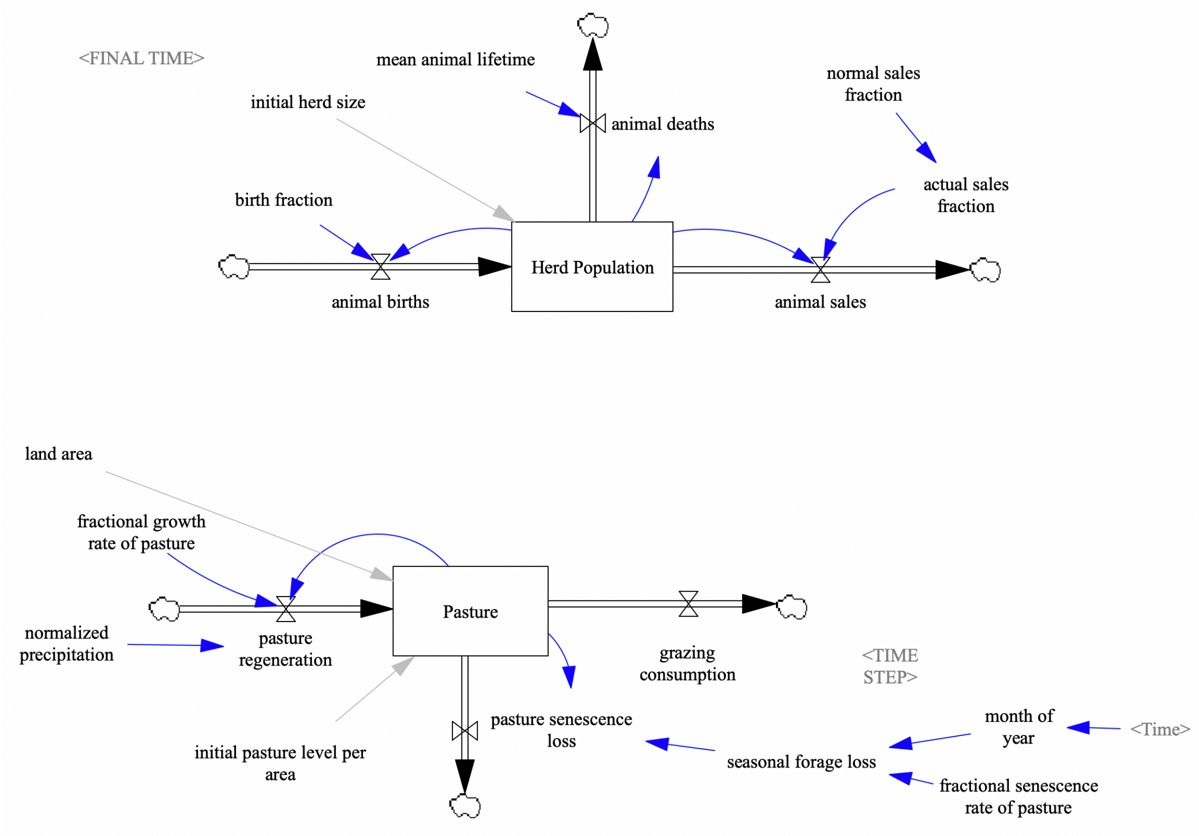

Figure 1 – Stock-and-Flow Diagram for the Initial Model, Model 0

The target learning objectives in this initial model are (i) when the variables are not connected, the behavior of one variable does not affect the other, (ii) stocks change with their net flow, and (iii) stocks can increase, decrease or stay constant based on the sign of their net flow.

The expected behavior of the model exhibits fluctuations in the *Pasture* stock due to seasonality in *pasture senescence loss* outflow. Meanwhile, the *Herd Population* is expected to remain constant since the net flow for the *Herd Population* stock balances out to zero.

- Model 1: Connected stocks with one directional effect: In Model 1, a one-directional causal relationship between the *Herd Population* and the *grazing consumption* is built, indicating that the herd consumes the available pasture on land and the *Herd Population* determines the magnitude of the consumption rate. To build this connection, two new variables, *expected consumption per animal* and *expected consumption of herd*, are added to the model, and *grazing consumption* variable is adjusted as follows:

grazing consumption = MIN ((Pasture/TIME STEP-pasture senescence loss), expected consumption of herd)

In this iteration, the target learning objectives are (i) building stock and flow relationships considering the conservation of material, and (ii) anticipating the behavior of a stock (i.e., Pasture stock), by accounting for the change in its net flow without requiring a simulation run.

As a result of Model 1, the expected behavior of *Herd Population* is to remain constant as in Model 0, while the *Pasture* stock is expected to diminish and approach zero in a year due to a high *grazing consumption* rate.

- Model 2: Feedback for the adjustment of pasture growth: In Model 2, a small balancing feedback loop for the adjustment of pasture growth is added. In the starting model, *pasture regeneration* is driven by a constant fraction, *fractional growth rate of pasture*, multiplied by the *Pasture* stock. The dynamic hypothesis is, the pasture growth rate is not a constant fraction but is adjusted depending on the density of pasture on land. In line with this, *pasture per land area* variable is added to the model and the *fractional growth rate of pasture* is modified as a table function.

The target learning objectives in this iteration are (i) creating a feedback loop representing the capacity of an agricultural resource, and (ii) defining a variable with a table function.

As the result of Model 2, the *Pasture* stock again fluctuates due to the seasonality of the *pasture senescence loss* yet presents a more stationary trend compared to the results in Model 0 since the pasture growth rate regulates itself in Model 2. The *Herd Population*, on the other hand, still remains constant. Following the examination of the behavior in Model 2, a brief discussion can be conducted to identify other types of feedback loops required in the model.

- Model 3: Feedback for the animal behavior: In Model 3, a feedback loop explaining a common practice in animal behavior is added to the model: when there is ample food available, the animals tend to consume at their normal, expected levels. However, when they experience a shortage and struggle to find enough food, they tend to eat less on average. Therefore, grazing consumption is regulated by food availability. To build that structure, *food available per animal* is added to the model, and *expected consumption of herd* is adjusted as follows:

*expected consumption of herd = expected consumption per animal * ((MIN (food available per animal/TIME STEP/expected consumption per animal, 1))) * Herd Population*

Along with enhancing the practice of incorporating new feedback loops into an existing model, the main target learning objective here is to elucidate the distinction between the expected level and actual level of a variable (i.e., grazing consumption flow here), where the actual level sometimes can be influenced by the availability of reserves (i.e., availability of *Pasture* stock).

For the parameter set provided used in the pilot studies, Model 3 produces the same behavior as Model 2 since the food availability does not fall below 1 for this base scenario. One possible discussion point that can be held with the participants is the reason for this result.

- Model 4: Feedback for managerial decision making to regulate the herd size: In Model 4, the feedback loop representing the managerial decision-making process of adjusting the *Herd Population* is added to the model. The stock-and-flow diagram for Model 4 is given in Figure 2, where the relationships added in Models 1, 2, 3, and 4 are shown with green, orange, red, and purple arrows, respectively. This final feedback loop completes the interconnected relationship between herd and pasture stock in two directions (i.e., both herd size impacts *grazing consumption* and the available pasture stock impacts the *animal sales*), which results in oscillating *Herd Population* behavior along with the seasonally fluctuating *Pasture* stock behavior (Figure 3).

To build that structure, three new variables, *relative pasture stress*, *adjustment time for sales based on food availability*, and *effect of food availability on sales* are added to the model and the *actual sales fraction* is reformulated as a first-order information delay.

The target learning objectives in this iteration are (i) getting familiar with the idea of delays, specifically first-order information delay with exponential smoothing, and (ii) understanding the impact of closing the loop between two stocks. To achieve the first learning objective, it may be necessary to provide the participants with theoretical and mathematical information regarding the interpretation and formulation of delays. For this specific example, the equation of first-order exponential smoothing can be presented, and the adaptive processes involved in human perception and decision-making can be briefly explained. The second learning objective can be elaborated via a discussion prior to the simulation run: the final behavior of the Pasture stock can be provided to the participants, and they can be asked to anticipate the behavior of the Herd Population.

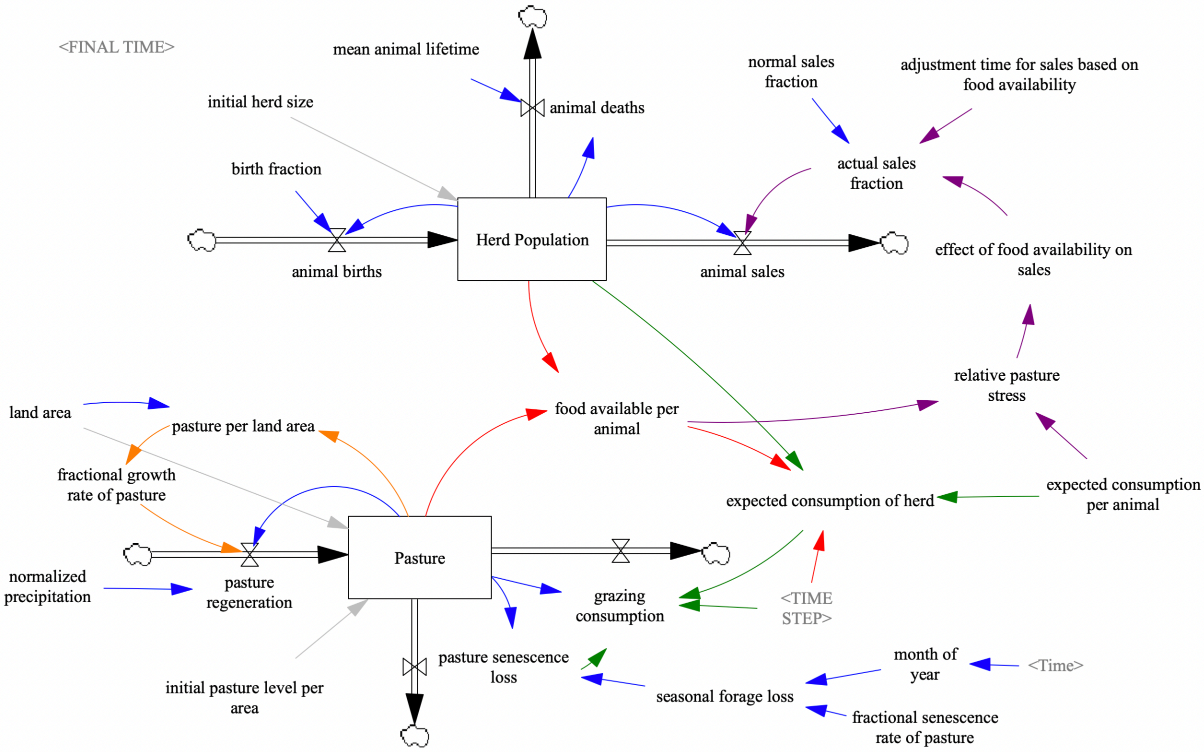

Figure 2 - Stock-and-Flow Diagram for Model 4

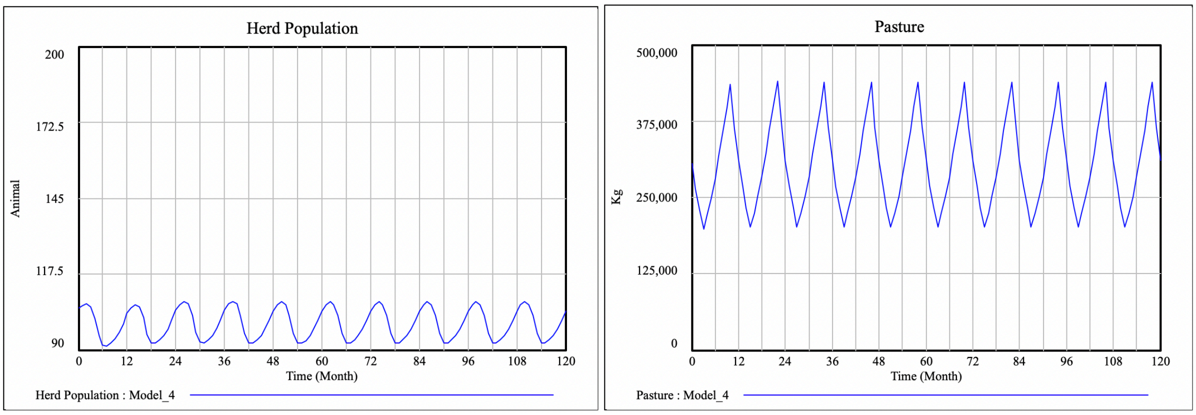

Figure 3 – Herd Population and Pasture behavior in Model 4

In this study, we present a simple starter model, named Herd-and-Pasture, built for training and skill-building purposes, intended for an audience with a background in agriculture and animal sciences. This study presents the model and outlines its use with subsequent model-building iterations, along with the learning objectives and discussion topics that can be elaborated in each iteration. Since the building of the model for a satellite course event in September 2022, several pilot applications have been conducted, involving different participants and students, and the model and its accompanying materials are still being improved.

Following the completion of model building steps, as described in the previous section, a useful application of the model is to subject it into a series of tests encompassing various scenarios that may arise during farm management practices. These tests can be designed to facilitate understanding the behavior of nonlinear systems and practice decision making for corrective actions. The test scenarios that have been used in our training sessions up to now are a) the impact of drought, b) the impact of management responsiveness, and c) the impact of animal performance. These scenarios lead to cases where the sustainability of the grazing system is threatened: for instance, droughts lead to reduced pasture regeneration, causing a severe decline in pasture stocks and leading to an increase in animal sales. If the farm management's response time is high and they cannot respond quickly, the pasture stocks can deplete faster, causing the grazing system to collapse. Overall, the goal of these tests is for the participants to properly interpret the model modifications and to preserve their intuitions or predictions about what happens to behavior patterns over time.

This study contributes to the collection of simple system dynamics models that can be used for facilitating model-building skills in agricultural and animal science contexts. In all, the model and its accompanying material with iterative model-building steps, target learning objectives, and possible discussion topics aim to help the instructors, researchers, and practitioners in the system dynamics community.

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