Supplementary material for the article: "Can intensification of cattle ranching reduce deforestation in the Amazon? Insights from an agent-based social-ecological model"

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1 Additional figures

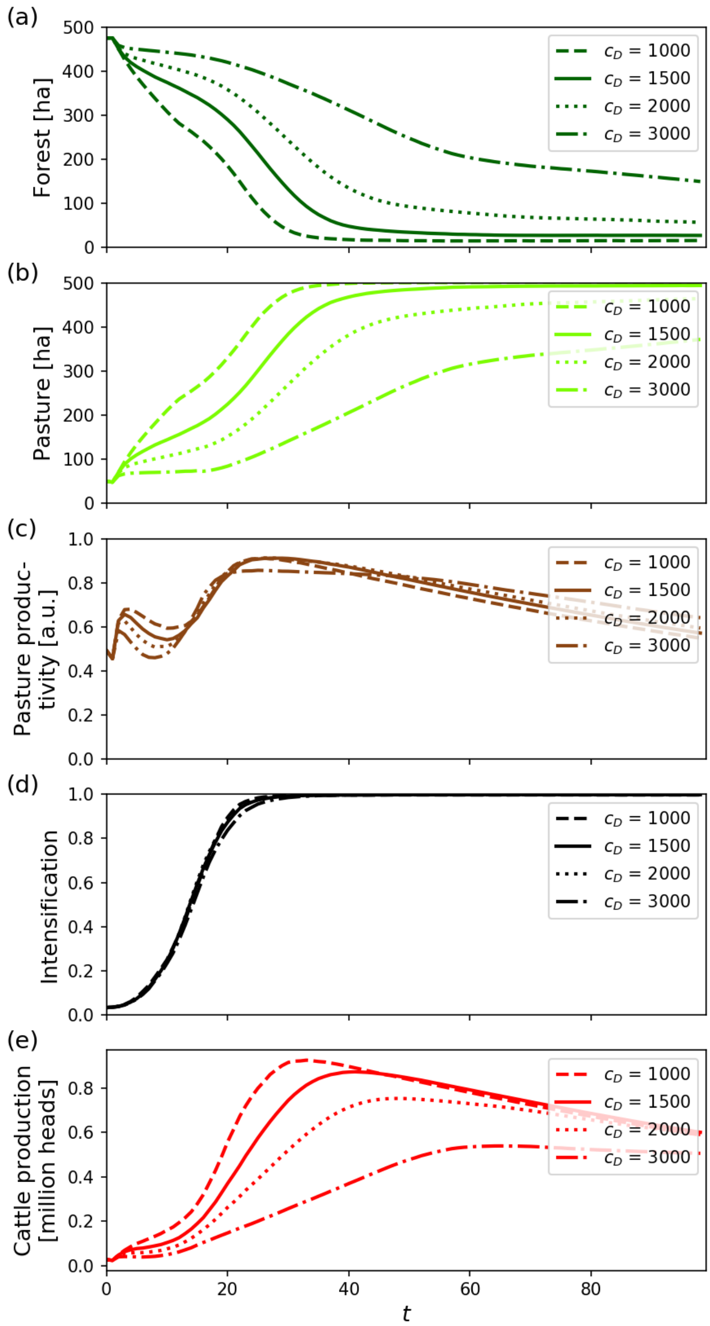

Figure S1: Sensitivities for variations of the deforestation cost c_D.

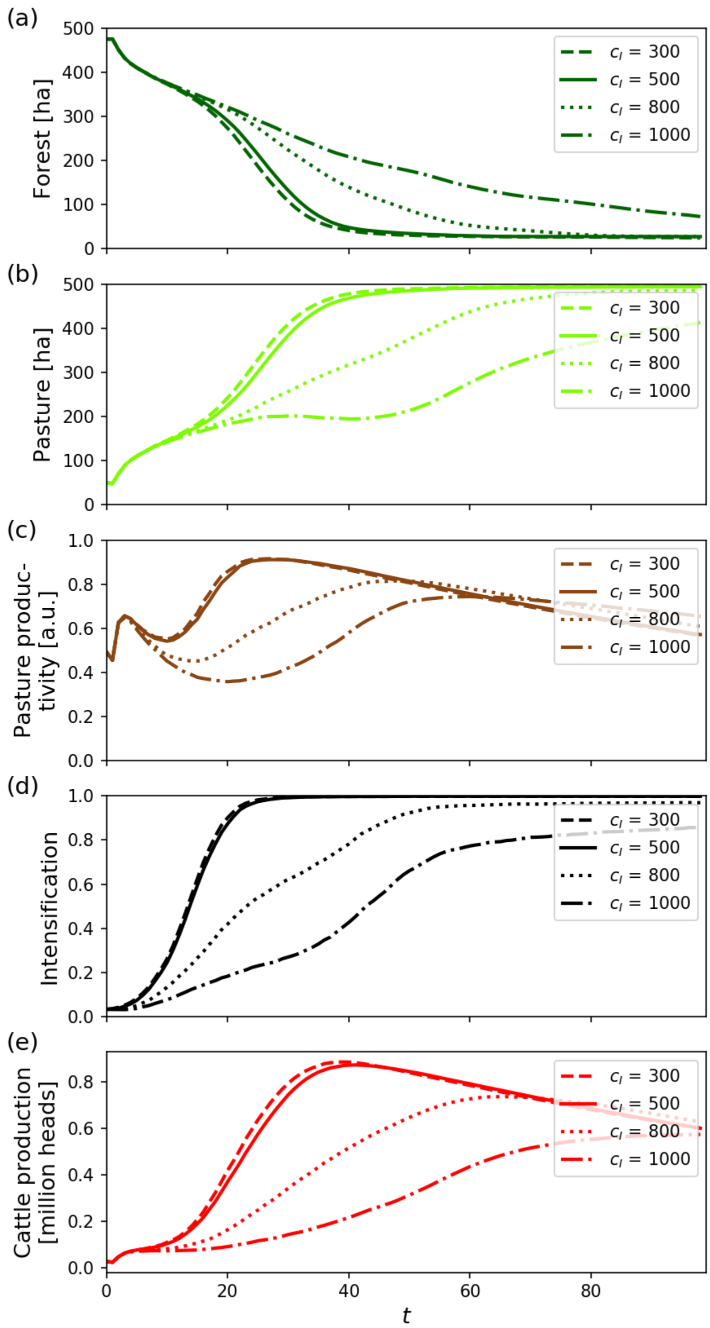

Figure S2: Sensitivities for variations of the intensification cost c_I.

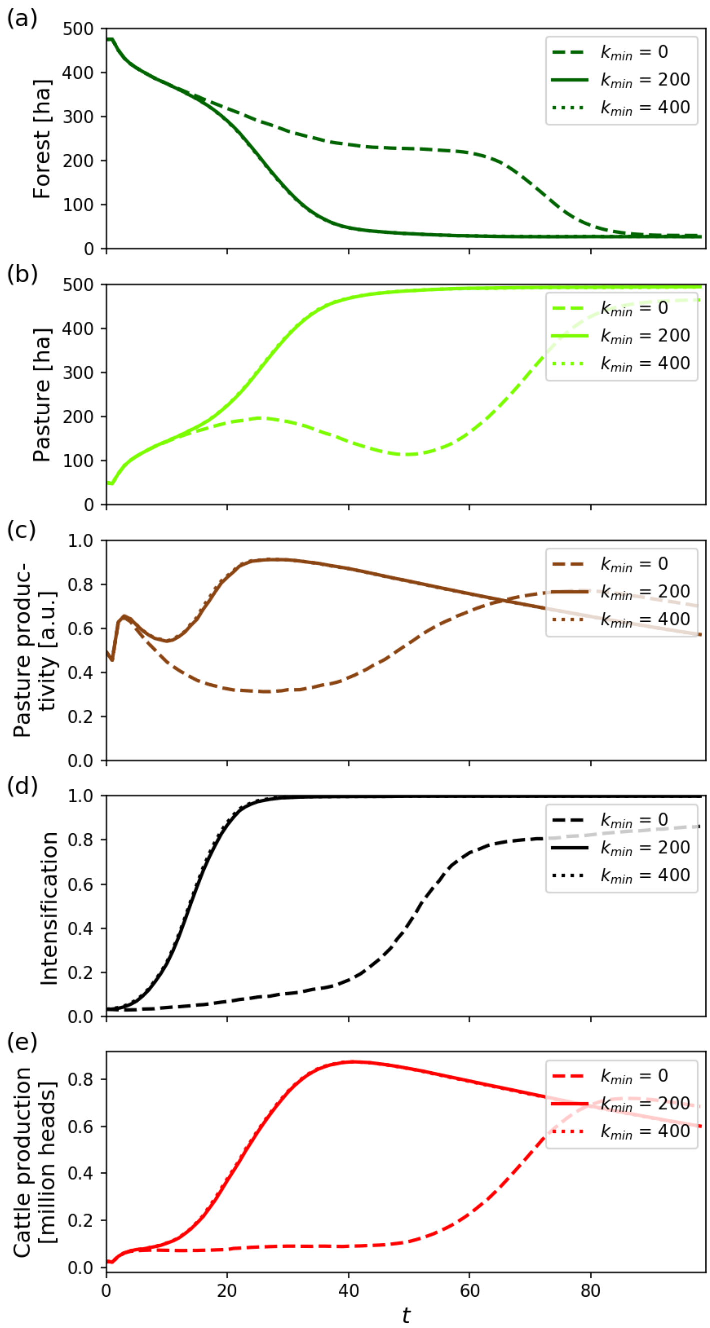

Figure S3: Sensitivities for variations of the limit for intensification credit k_{min}.

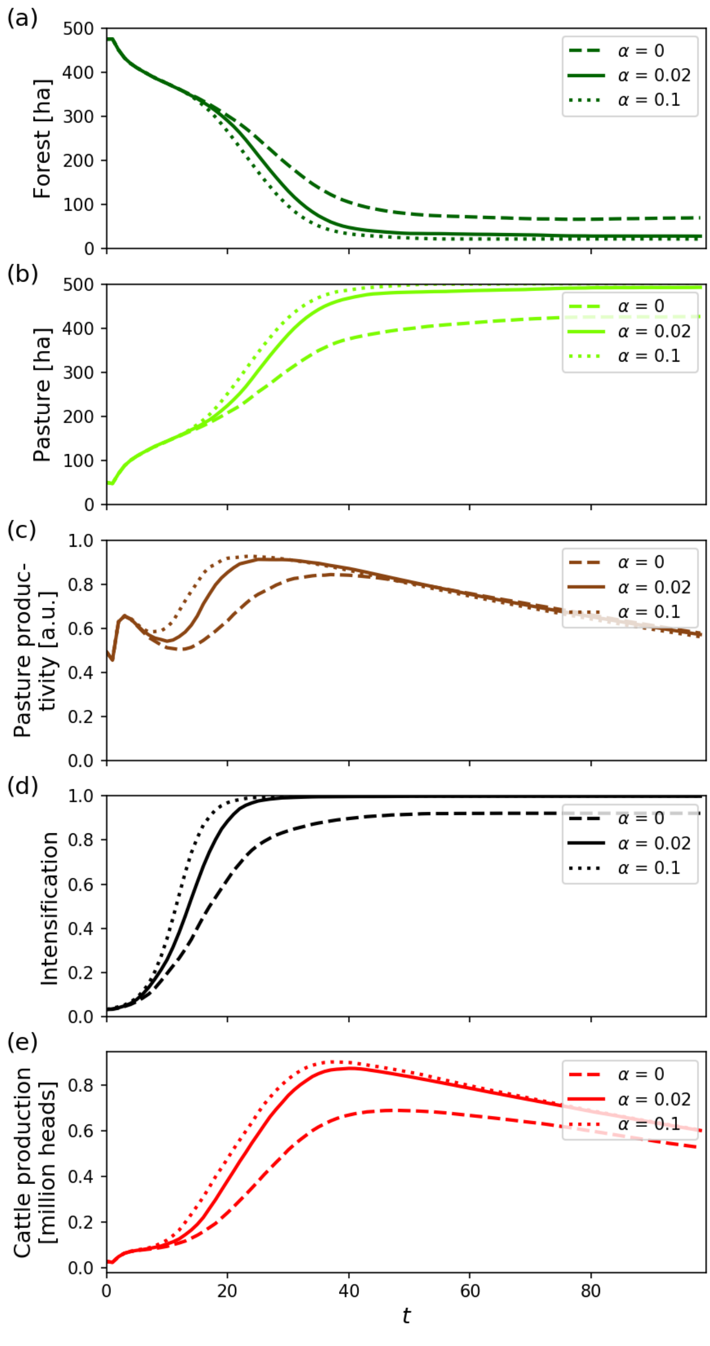

Figure S4: Sensitivities for variations of the teleconnection share α.

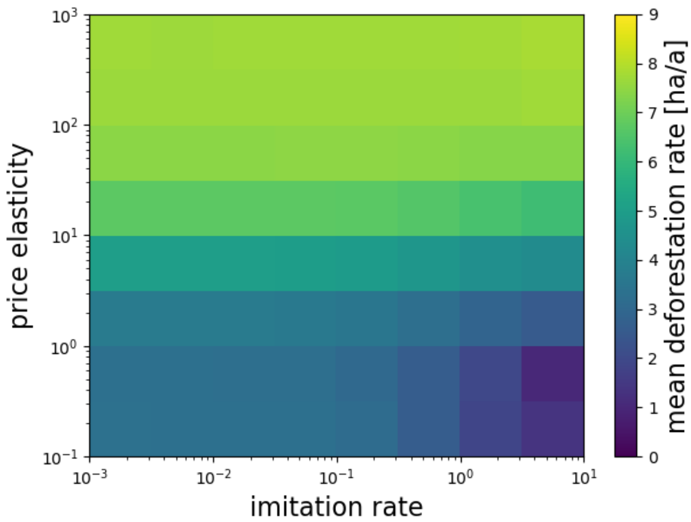

Figure S5: Average deforestation per year and property in dependence on price elasticity and imitation rate without the possibility for agents to access credit for intensification. Parameters as in Table 1.

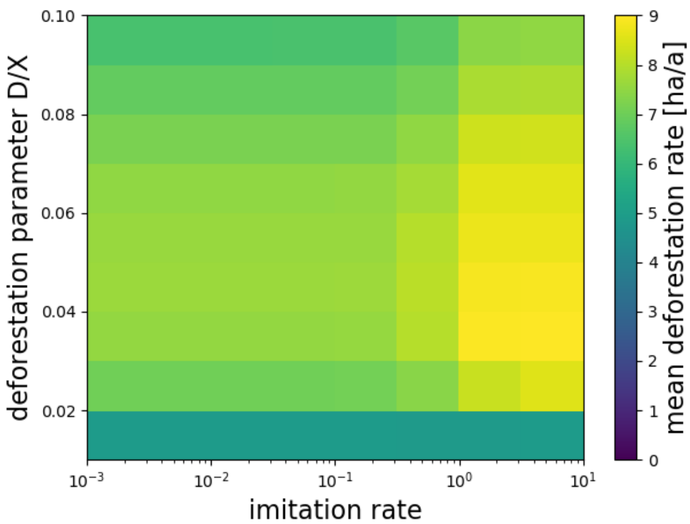

Figure S6: Average deforestation per year and property in dependence on the relative area that can be deforested in one year (D/X) and imitation rate λ. Parameters as in Table 1 with $\varepsilon = 100$.

2 Model description according to the ODD+D protocol

In the following, we provide a description of the model according to the ODD+D protocol described in Müller et al. (2013).

I Overview

I.i Purpose

The model is designed to investigate the interrelation between intensification of cattle ranching and deforestation in an Amazon frontier region. Furthermore, it demonstrates how social learning dynamics can be combined with heuristic land-management strategies and market dynamics to integrate social, economic and ecological dynamics. The model is designed for researchers interested in tropical deforestation, land modeling and complex social systems.

I.ii Entities, state variables and scales

The model comprises a large number of ranchers (or ranching households) with their respective land properties in a region of the Amazon. The ranches are described by the areas in three different land-cover categories (forest, pasture, secondary vegetation), the pasture productivity, and the soil quality of areas with secondary vegetation. The households are characterizes by their savings and their land-management strategy. Key parameters of the model describe the cattle market demand and time scale of social learning. Space is included only implicitly as a network of neighboring ranches. The spatial scale spans from single ranches to the extent of the region (several hundred kilometers) while the temporal resolution of the model is one year.

I.iii Process overview and scheduling

The modeling procedure for each time step representing one year is as follows: First, the decision model determines the decisions of all ranchers on their land-use change activities, pasture management and investments. Second, the environmental dynamics determine the new environmental state of each ranch. In a third step all ranchers receive a revenue for the cattle they produced which is determined by the total production and the demand curve of the cattle market. Finally, ranchers imitate their neighbors land-management strategies with a certain probability.

II Design Concepts

II.i Theoretical and Empirical Background

The model was designed to investigate whether intensification of cattle ranching is able to reduce deforestation – and if so under which circumstances. The hypothesis that land-use intensification can spare land from deforestation is also known as the Borlaug hypothesis and the model is therefore used to test the special case of the Borlaug hypothesis for cattle ranching in tropical forest regions. Furthermore, the model wants to shed light on the interaction of social, environmental and economic processes: How do social learning of management strategies interact with dynamics such as pasture degradation and price formation? The decision model describing the agents is based on bounded rationality theory, particularly heuristic decision making. This particular decision model was chosen because ranchers in the Amazon are observed to follow traditionally learned land-management practices and the literature suggests that the intensification and adoption of new agricultural technology is a socially mediated process and agents often do not engage in economically optimal behavior. The choice for the functional forms of the submodels were based on three different sources: 1) The existing literature on land-use change, 2) on data about deforestation in the the region, 3) on qualitative evidence from field surveys in Amazon frontier regions. The property and deforestation data used to initialize the model was available for single properties, while data to estimate model parameters was often only available for the aggregate level.

II.ii Individual Decision-Making

The subjects of the decisions in the model are ranchers (or ranching households) that use a specific land property. They decide on the land conversion between different land-cover types, the number of cattle on their pasture and thus influence the environmental states of their property. The agents are modeled individually. Agents have the goal to generate income from cattle ranching and use this for consumption and reinvestment into their productive capacities. The specific decisions are modeled as heuristic threshold functions. The agents adapt their behavior to the environmental state of their properties and the situation on the cattle market from which their generate their revenues. For example, they only invest in deforestation for new pastures if this generates sufficient revenues. This is also where temporal aspects play a role in the decision process: Agents only invest if they can regain the investment within a certain time period. However, the agents do not use dynamic optimization to make their decisions. Spatial aspects only play an indirect role in the decision process through the social learning from neighboring ranches. This is also where uncertainty plays a role in the decision model: the imitation of land-use strategies is a realization of a stochastic process in which the imitation probabilities depend on the difference of the consumption between ranchers.

II.iii Learning

While individual learning is not modeled explicitly, the imitation process is a social learning mechanisms that favors land-management strategies with higher revenues.

II.iv Individual Sensing

The agents in the model are assumed to know the environmental state of their property, their savings as well as the price of cattle from the previous year. Furthermore, agents can observe the land-management strategy and consumption of their interaction partners on the neighborhood network. The mechanisms why which agents obtain this information and the spatial aspects of information retrieval are not explicitly modeled. Furthermore, there are no explicit costs assumed for gathering information.

II.v Individual Prediction

Ranchers are assumed to make predictions about the future development of their environment and the economic situation based on past experience. They do not use explicit internal models to predict and can therefore be wrong about the future if there are deviations from the past.

II.vi Interaction

There are two types of interactions in the model: The first is through the cattle market, in which interactions are indirect through the price formation mechanism. It depends on the parameters of the demand curve and the total production of cattle by all agents. The second type of interaction is the imitation process, which is direct and depends most crucially on the imitation rate and the difference in the consumption between interacting ranchers. These interactions can only happen on an imposed network of neighborhood relations. The implementation of these processes is stylized and does not include explicit representations of communication.

II.vii Collectives

There are no explicit aggregations of single agents and therefore no distinction between collectives.

II.viii Heterogeneity

The ranchers are heterogeneous regarding different properties. First, the property size of the ranches differs considerably. The sizes are taken from data of registered properties in a frontier region. Second, the initial conditions for initial pasture on the properties and the savings are heterogeneous. And lastly, the decision-making is heterogeneous because agents can make decisions according to one of two possible land-management strategies (extensive or semi-intensive). These two different strategies differ in the average stocking rate on pasture and the use of land and other inputs.

II.ix Stochasticity

The imitation process is modeled as a stochastic process. Furthermore, the initial conditions for savings and initial pasture productivity are drawn randomly from log-normal and uniform distributions, respectively.

II.x Observation

We recorded the trajectories for individual ranches, statistics of the distributions of state variables over the ranches (mean, median, standard deviation, gini coefficient) as well as temporally average measures for example for average deforestation. One of the main findings of the analysis was that intensification can only lower deforestation in situations in which the cattle market saturates fast enough. Otherwise it may even increase deforestation.

III Details

III.i Implementation Details

The model was implemented using the multi-purpose python programming language, making use of a variety of packages for including networks and plotting results. The model code is available at www.github.com/fmhanse/abacra.

III.ii Initialisation

The model uses the following initial conditions, which can be described in three different categories:

1. Individually set parameters: The property sizes are set individually using data from CAR (2018). Initial pasture extent was estimated using PRODES (2018) deforestation data from the year 2000 by default and from 2016 for comparison.

2. Uniform initial values: Using estimates from aggregate data (see Table 1), the initial values of some state variables are set uniformly. For example, secondary vegetation was set to zero initially for all properties.

3. Randomized initial values: Randomization is used to generate and reflect heterogeneity in important variable for which no individual data is available. For example, we allocate initial savings to the ranchers drawn from a log-normal distribution with mean 200 and standard deviation 100 BRL per ha of property area. The initial values for the soil productivity q is drawn from a random distribution of values between 0 and 1.

III.iii Input Data

The model does not use additional data from other models.

III.iv Submodels

Ecological dynamics

Each agent i has a ranch with a constant area X that is covered by forest F_t, pasture P_t, and secondary vegetation S_t. Thus, $F_t + P_t + S_t = X$, where we dropped the index i indicating the rancher. This implies that there are two degrees of freedom in dynamic variables describing the different areas. The model is discrete in time t and each time step represents one year, thereby abstracting from seasonal variations. Land-cover changes such as deforestation and land abandonment are traced by simple land-cover succession equations (cp., e. g., Satake and Rudel, 2007). At each time step, pasture land can be created through deforestation d_t or reuse of land previously covered by secondary vegetation r_t. Pasture with area a_t can also be abandoned, leading to secondary vegetation regrowth. The change in pasture land is given by

$$P_{t+1} = P_t + d_t + r_t - a_t, \tag{1}$$

where d_t, r_t, and a_t are rates per year in units of area. The dynamics of forest and secondary vegetation are given by

$$F_{t+1} = F_t + r_n v_t S_t - d_t \quad \text{and} \tag{2}$$

$$\begin{aligned} S_{t+1} &= X - P_{t+1} - F_{t+1} \\ &= S_t - r_n v_t S_t + a_t - r_t, \end{aligned} \tag{3}$$

where r_n is a parameter that describes the natural recovery from secondary vegetation to mature forest proportional to the productivity of secondary vegetation v_t, the dynamic of which is explained below. The deforestation d_t, abandonment a_t, and reuse r_t are control variables chosen by the rancher and are determined as part of the decision process.

The pasture land is furthermore characterized by an average productivity q_t. The agent can decide how much cattle to place on the pasture. Pasture productivity is decreasing if the stocking rate $l_t = L_t/P_t$ is high, i. e., there is a high number of cattle L_t per area on the pasture. The model formulation implicitly assumes here that the herd size of ranchers is variable through acquisition and sale of calves and the ranchers adjust it to their requirements (cp. Quaas et al., 2007). The decay of pasture productivity nevertheless can be reduced by a management effort m_t, which subsumes various processes like fertilization, adoption of new grass species, fencing, and maintenance work.

For describing the dynamics of the pasture productivity, we chose the simplest decreasing dynamics with a lower zero bound, i. e., an exponential decay. This dynamics ensures that the averaging over different land areas with different initial productivities is valid.[1] Deforestation and reuse add land area to the pasture with productivities q_d and v_t, respectively. Furthermore, abandonment lets the pasture area shrink. Averaging over all these changes and weighting with the respective areas gives the following dynamics for pasture productivity:

$$q_{t+1} = \frac{(1 - \beta(l_t - m_t))q_t(P_t - a_t) + q_d d_t + v_t r_t}{P_t + d_t + r_t - a_t}, \tag{5}$$

where β is the rate of degradation, l_t is the stocking rate of the pasture, and m_t is a management effort that can counteract pasture degradation.

To complete the ecological dynamics, the variable v_t tracks the productivity and regrowth on land areas with secondary vegetation. It follows a similar dynamics as the pasture productivity, but with an exponential approach to the natural relative productivity $v^* = 1$ with rate r_S. The other terms stem from weighting and averaging for additional and outgoing areas, similar to Eq. 5.

$$v_{t+1} = \frac{(v_t + r_S(1 - v_t))(S_t - r_t) + a_t q_t}{S_t - r_t + a_t}. \tag{6}$$

In summary, the ecological state of each ranch has four degrees of freedom (P_t, F_t, q_t, and v_t).

[1] Assume that each ranch consists of separate land patches indexed by j with pasture productivity q_t^j. Only this type of dynamics makes the averaging before applying the dynamic equivalent to averaging after applying the dynamic:

$$\left\langle q_{t+1}^j \right\rangle = \left\langle (1 - \beta l_t) q_t^j \right\rangle = (1 - \beta l_t) \left\langle q_t^j \right\rangle. \tag{4}$$

q_t describes this average and thus can account for different initial productivities of the underlying land patches.

Economic dynamics

d_t, r_t, a_t, l_t and m_t constitute the control variables of the ecological dynamics, representing the possible decisions for the rancher. The management m_t, deforestation d_t and reuse r_t are associated with a cost per area. The income of the agent is realized from selling cattle $y_t = l_t P_t q_t / T_p$ at a price of p_c (per head), where T_p is the average time that cattle have to spend on the pasture until they can be slaughtered. Thus the income of the agent is given by:

$$I_t = p_c l_t P_t q_t / T_p - c_D d_t - c_R r_t - c_m m_t P_t, \tag{7}$$

where c_D and c_R are the cost of deforestation and reuse (per area) and c_m the cost of management (per area and effort).

This income can either be consumed or saved by the ranch, resulting in the following dynamics for the accumulated savings:

$$k_{t+1} = (1 + \delta)k_t + I_t - C_t, \tag{8}$$

with an interest rate δ. The income spent for consumption C_t also comprises a control in the model. Note that the savings can also be negative, such that they effectively represent the debt of the rancher. For reasons of simplicity, we assume here a fixed saving rate s, such that $C_t = (1 - s)I_t$.

Decision making of agents and land-management strategies

The decision-making functions of agents are the centerpiece of the *abacra* model. They determine the control variables in every time step. Because the decision to deforest may depend on many factors such as location, available resources, weather, beliefs about future prices and policies, and the choices of other agents, it is especially challenging to capture them appropriately in a stylized model.

Here, we use a heuristic decision approach for modeling the decisions of the ranchers. Heuristics are rules of thumb, often formalized as decision trees, that help agents to evaluate available information and choose actions that lead to more desirable outcome over less desirable ones (for a recent review, see Gigerenzer and Gaissmaier, 2011). Heuristics are related to bounded rationality theory, which deals with constraints of cognitive capabilities of decision makers and decisions under incomplete information (Simon, 1956; Tversky and Kahneman, 1974). Many heuristics are satisficing strategies: An agent makes a decision as soon as a specific criterion is satisfied rather than optimizing over all possible actions. Heuristics have been used to model land-use decision, for example in the models by Deadman et al. (2004) and Salvini et al. (2016).

Because of limited empirical data on actual decision processes in the system under consideration, we made simplifying assumptions for the decision functions of agents, which we will discuss in the following. As evidence from surveys suggests, land use decisions are not only based on monetary incentives but strongly influenced by social preferences (Garrett et al., 2017). We capture this in our model by the land-management strategy that an agent adopts, which determines the specific decision process of an agent. We identified two idealized strategies, an extensive and a semi-intensive land management strategy, which correspond to typical individual land-use trajectories in the Amazon. The decisions to deforest, manage the pasture, or abandon parts of it as well as to decide for a stocking rate depend on the management strategy that the agent has adopted.

Extensive strategy

The extensive strategy represents traditional approaches to cattle ranching with fallow periods and slash-and-burn fertilization and is characterized by low stocking densities. The pasture productivity decreases over time and has to be renewed by fallow periods and slash-and-burn practices. The choice of control variables in the *abacra* model follows simple threshold heuristics that can be written using the Heaviside function

$$\theta(x) = \begin{cases} 0 & \text{if } x < 0 \\ 1 & \text{if } x \geq 0 \end{cases} \tag{9}$$

as a compact notation.

The decisions to deforest or reuse (i. e., slash-and-burn) an area D or R are determined as follows. First, the respective savings for covering the conversion costs c_D or c_R have to be available. The conversion can only take place, if there is enough forest F_t or secondary vegetation S_t, respectively. For the extensive strategy, the managed pasture cannot exceed a fixed fraction p_{max}. Finally, the expected additional income $I^d_{exp} = p_c l_t D q_d / T_p$ (or $I^r_{exp} = p_c l_t R v_t / T_p$ for reuse) from the additional pasture is compared to the cost. If the investment is paying back within a time period T_{rec}, the investment is made. If both deforestation and reuse are paying back, then the option with the higher expected additional income is taken. This is determined by the expected amount of cattle that can be produced on the new pasture, which depends on the pasture productivity q_d after deforestation compared to after reuse v_t as well as the difference in the cost for deforestation and reuse. With the notation of Heaviside functions, the decision procedure can be written as

$$\begin{aligned} d_t =& D\ \theta(k_t - c_D D)\ \theta(F_t - D)\ \theta(p_{max} X - P_t) \\ & \times \theta(I^d_{exp} T_{rec} - c_D D)\ \theta(I^d_{exp} - I^r_{exp}), \end{aligned} \tag{10}$$

$$\begin{aligned} r_t =& R\ \theta(k_t - c_R R)\ \theta(S_t - R)\ \theta(p_{max} X - P_t) \\ & \times \theta(I^r_{exp} T_{rec} - c_R R)\ \theta(I^r_{exp} - I^d_{exp}). \end{aligned} \tag{11}$$

An area A of land is abandoned if pasture productivity falls below a certain threshold $q_{\theta a}$ and this land was used as pasture before:

$$a_t = A\ \theta(q_t - q_{\theta a})\ \theta(P_t - A). \tag{12}$$

The extensive strategy does not use the pasture management option ($m_t = 0$) and the stocking rate is fixed at a low level $l_t = l_{ext}$.

Semi-intensive strategy

The semi-intensive strategy, corresponding to cattle ranching with various industrial inputs and pasture improvement techniques, has higher stocking densities but also higher costs for inputs. Agents invest in inputs for pasture maintenance such as fertilizers and fencing for pasture rotation, but also in measures such as better adapted grass and cattle species, improved pasture seeding with legumes, or additional concentrated feed to improve pasture and livestock productivity.

The semi-intensive strategy is implemented in the following way: Deforestation D occurs if there is enough primary forest on the property left and the agent has sufficient savings to cover the deforestation cost. Furthermore, the agent decides whether the investment to be made can be regained within a certain time period T_{rec}, assuming that the economic circumstances remain constant. For this, the expected income $I^d_{exp} = p_c l_t D q_d / T_p - c_m m_t D$ from using a newly deforested area is compared to the deforestation cost. In the case of the semi-intensive strategy, the calculation of income takes the costs for pasture management into account. The decision for reusing an area R is made similarly. As for the extensive strategy, the decision between deforestation or reuse to get new pasture results from a comparison of the expected income increases of both options.

$$\begin{aligned} d_t =& D\ \theta(k_t - (c_D + c_I)D)\ \theta(F_t - D) \\ & \times \theta(I^d_{exp} T_{rec} - (c_D + c_I)D)\ \theta(I^d_{exp} - I^r_{exp}), \qquad (13) \\ r_t =& R\ \theta(k_t - (c_R + c_I)R)\ \theta(S_t - R) \\ & \times \theta(I^r_{exp} T_{rec} - (c_R + c_I)R)\ \theta(I^r_{exp} - I^d_{exp}). \qquad (14) \end{aligned}$$

Note that here the deforestation costs for the semi-intensive strategy are higher by the intensification cost c_I. This also has to be considered in Eq. 7 by subtracting the intensification cost $c_I(d_t + r_t)$ for converted areas. Similarly, when adopting this strategy, the cost for converting existing pasture $c_I P_t$ has to be subtracted from the savings stock, Eq. 8.

An area A of pasture is abandoned if the ranching activity is not profitable anymore,

$$a_t = A\ \theta(-I_{exp})\ \theta(P_t - A), \qquad (15)$$

with $I_{exp} = p_c l_t P_t q_t / T_p - c_m m_t P_t$. The semi-intensive strategy uses the pasture management option $m_t = M$, where M is a constant. The stocking rate is higher than in the extensive case $l_t = l_{int} > l_{ext}$.

Evidence for the proposed kind of heuristic behavior was obtained in personal interviews by one of the co-authors (E. D.-N., unpublished fieldwork carried out in 2016 in the states of Pará and Mato Grosso along the highway BR-163). Ranchers tend to invest in new pasture if they can recover their initial investment in a time period below a threshold of about 5-8 years. Furthermore, the valuation of land is an important factor for decision making of ranchers. Because our model does not contain a description of the land market, we do not consider this in our analysis.

Local interaction: strategy imitation between agents

The decision to adopt a certain land-management strategy could in principle take into account the amount of available land and savings, possibilities to move to other areas, and the available information about technologies and environmental factors. In the *abacra* model, we reduce this potentially complex decision to a social imitation process on a geographic network and assume that the adoption of a certain management strategy only depends on the agent's own success and its comparison with the neighbors (cp. Traulsen et al., 2010; Wiedermann et al., 2015).

We model the choice of management strategy as a social updating process: Strategies are transmitted via a network of neighbors and acquaintances. The agents are modeled on a network, which represents neighbor relations. This simplifying assumption is motivated by evidence from the literature that neighbor interactions play an important role in deforestation decisions (Robalino and Pfaff, 2012) and the role of networked social interactions in various environmental contexts (Currarini et al., 2016). Furthermore, word-of-mouth recommendation has been identified as one of the most important determinants for the participation in sustainable ranching programs (Ermgassen et al., 2018).

We implement the neighbor interactions as follows: The simplest assumption for the timing of interaction events is that they are equally probable for every point in time. Such a stochastic process is called Poisson process and is described by a rate λ (Van Kampen, 2007). The number of interaction events K in one time step of the model (one year) is then given by a random number drawn from the Poisson distribution

$$P(K) = e^{-\lambda} \frac{\lambda^K}{K!}. \tag{16}$$

We draw a random number from this distribution for each time step in the model to determine the number of interaction events. For each interaction event, a random node i of the network and a random neighbor j of this node are chosen. Then, i imitates the strategy of j with a probability given by

$$P_{ij} = g(x_i, x_j), \tag{17}$$

where x is a property of the agents that is compared between them and $g\colon \mathbb{R}^2 \to [0, 1]$. For the model implementation presented here, we choose the consumption of agents C_t as the property for comparison and a hyperbolic tangent function to compute the probability (cp. Wiedermann et al., 2015):

$$P_{ij} = \frac{1}{2} \left(\tanh(\sigma(C_j - C_i)) + 1 \right). \tag{18}$$

However, the imitation of the intensive strategy is only possible if an intensification cost per area c_I can be covered. This cost can also be payed by a credit (modeled as negative savings) up to a certain limit k_{min}. This strategy imitation with the imitation rate λ results in the spread of production strategies biased towards the more income generating strategy.

Interaction between all agents: the cattle market

Additionally to the local imitation, the model captures how ranchers interact on a cattle market, which determines the price that ranchers can realize when selling their cattle. We model the price as given by a demand curve that represents the local market for cattle. The price response to changes in cattle quantity $Y = \sum_i q_i P_i l_i$ is modeled by a constant elasticity function

$$p_c = a_p Y^{-1/\varepsilon}, \tag{19}$$

with price elasticity of demand ε.

The exact curve is difficult to estimate from data, which is why we analyze the model for different settings of the price elasticity of demand and base prices (as given by the parameter a_p). However, we can reasonably assume that the price elasticity is lower and thus prices are more sensitive to changes in quantity in regions with a market that is not well integrated into national or international markets. If markets are well connected to bigger markets, the prices will not be affected much by changes in locally produced quantities but rather by external price fluctuations. The special case of fixed prices (ranchers being price takers) is effectively equivalent to very high price elasticities: in this case, the exponent in Eq. 19 gets close to zero such that the dependence on Y becomes negligible. This is why we studied also very high values for this parameter.

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