Can intensification of cattle ranching reduce deforestation in the Amazon? Insights from an agent-based social-ecological model

Finn Müller-Hansen[a,b,*], Jobst Heitzig[a], Jonathan F. Donges[a,c], Manoel F. Cardoso[d], Eloi L. Dalla-Nora[e], Pedro Andrade[d], Jürgen Kurths[a,b], Kirsten Thonicke[a]

[a] *Potsdam Institute for Climate Impact Research, Telegrafenberg A31, 14473 Potsdam, Germany*
[b] *Department of Physics, Humboldt University Berlin, Newtonstraße 15, 12489 Berlin, Germany*
[c] *Stockholm Resilience Center, Stockholm University, Kräftriket 2B, 114 19 Stockholm, Sweden*
[d] *Center for Earth System Science, National Institute for Space Research, Av. dos Astronautas 1758, 12227-010 São José dos Campos, SP, Brazil*
[e] *Department of Research and Applied Technology, TerraSAT Company, Rua Pietro Cescon 1938, 99560-000, Sarandi, RS, Brazil*

Abstract

Deforestation in the Amazon with its vast consequences for the ecosystem and climate is largely related to subsequent land use for cattle ranching. In addition to conservation policies, proposals to reduce deforestation include measures to intensify cattle ranching. However, the effects of land-use intensification on deforestation are debated in the literature. This paper introduces the *abacra* model, a stylized agent-based model to study the interplay of deforestation and the intensification of cattle ranching in the Brazilian Amazon. The model combines social learning and ecological processes with market dynamics. In the model, agents adopt either an extensive or semi-intensive strategy of cattle ranching based on the success of their neighbors. They earn their income by selling cattle on a stylized market. We present a comprehensive analysis of the model with statistical methods and find that it produces highly non-linear transient outcomes in dependence on key parameters like the rate of social interaction and elasticity of the cattle price. We show that under many environmental and economic conditions, intensification does not reduce deforestation rates and sometimes even has a detrimental effect on deforestation. Anti-deforestation policies incentivizing fast intensification can only lower deforestation rates under conditions in which the local cattle market saturates.

Keywords: Amazon deforestation, land-use intensification, pasture management, social-ecological systems, agent-based modeling

1. Introduction

Can intensification of agricultural land use help us preserve threatened ecosystems such as the Amazon rain forest? If land is easily accessible, low-productivity land use often results in a high demand for land, putting pressure on ecologically important areas. Therefore, a common proposition is to increase yields per area to ease this pressure. In the economic literature, this proposition is often referred to as the Borlaug hypothesis (Angelsen & Kaimowitz, 2001, p.3). The discussion mainly focuses on crop production, but livestock is equally important.

In the Amazon, livestock production, especially beef cattle ranching, drives expansion of pastures into the rainforest (Barona et al., 2010; Pacheco & Poccard-Chapuis, 2012). While more than 60% of the deforested area in the Brazilian legal Amazon was used as pasture by 2008, only about 5% was used for crop production (Almeida et al., 2016). In the last decades, the opening of the region for national and international markets has led to a shift from extractive land-use activities to cattle ranching and increased the activities of agribusiness including the development of a supply chain for meat processing (Salisbury & Schmink, 2007; Pacheco & Poccard-Chapuis, 2012). This increased the demand for agricultural land in the Amazon basin considerably, also via indirect effects (Richards et al., 2014). The expansion of pasture leads to large-scale deforestation with strong adverse impacts on biodiversity and local climate, for example, reduced precipitation as a result of lower evapotranspiration from deforested areas (Zemp et al., 2017). Lower precipitation in turn affects agricultural productivity (Oliveira et al., 2013) and may constitute a tipping element with relevance for global climate (Lenton et al., 2008).

On average, cattle ranching in the Amazon is characterized by extensive production systems with low stocking rates compared to other regions (Pacheco & Poccard-Chapuis, 2012). Many extensive production techniques can be linked to environmental degradation in the region. Slash-and-burn methods are used to fertilize the land and may spark unintended forest fires (Cano-Crespo et al., 2015). In many areas, nutrient-poor soils lead to fast

*Corresponding author
Email address: `mhansen@pik-potsdam.de` (Finn Müller-Hansen)

run-down of pasture fertility (Serrão et al., 1979; Myers & Robbins, 1991). Additionally, weed invasion, pests, compaction, and erosion further promote pasture run-down (Landers, 2007). The exhausted pastures are often abandoned and secondary vegetation starts to regrow on them (Perz & Skole, 2003b,a). However, this forces the ranchers to replace them with pastures on newly deforested areas and move the frontier further into pristine forest.

Since the 2000s, there have been various efforts to reduce deforestation in the Brazilian Amazon (Nepstad et al., 2014). This includes the enforcement of environmental laws, which entails considerable costs and requires careful monitoring. As the current stagnation of deforestation rates shows, the present policy measures have their limitations (Azevedo et al., 2017). For example, Richards et al. (2017) show that agents react to the current monitoring system by deforesting smaller patches to avoid detection. Besides, current environmental legislation, the Brazilian Forest Code, allows land-owners to deforest 20% of their private lands (Soares-Filho et al., 2014). Cutting only the legally available areas will already lead to large losses in biodiversity and considerable amounts of greenhouse gases released into the atmosphere (Aguiar et al., 2016).

For these reasons, policies that promote the intensification of cattle ranching have been suggested as a viable option to reduce deforestation (Cohn et al., 2014). Intensification could help ranchers use the already deforested land more efficiently and detain them from deforesting more. These proposals are heavily criticized, arguing that higher profits from intensified land use may even increase deforestation rates (Angelsen & Kaimowitz, 1999; Kaimowitz & Angelsen, 2008). Other authors note that the success of intensification policies cannot be determined a priori but highly depends on the political, economic, and environmental circumstances (Latawiec et al., 2014).

Empirical evidence to support the effectiveness of intensification as a means to reduce deforestation in the Amazon is hard to assess and at most mixed. Cohn et al. (2011) review some of the cattle ranching intensification programs in Brazil that aim at the adoption of yield-increasing technology. They argue that due to a lack of data, the implementation of policies should proceed very carefully as it might result in unintended consequences. Soler et al. (2014) find that land-use developments in the federal states of Mato Grosso and Rondônia are strongly linked to market accessibility and the land distribution structure. They cannot uncover clear mechanisms that link land-use intensification to expansion of the deforestation frontier. Barretto et al. (2013) argue that land-use intensification in frontier regions coincides with the expansion of agriculture. An analysis of deforestation drivers also shows that intensified land use is associated with higher incomes, which in turn can be linked to higher deforestation (Busch & Ferretti-Gallon, 2017). After all, huge data gaps make the comparison of different management techniques of livestock systems difficult (Erb et al., 2016). A big challenge is to disentangle the effect of intensification from other influences and drivers (e. g., enforcement of legal protection) in empirical data. This also makes assessments of the impact of intensification policies difficult, mostly because of the huge heterogeneity of agents and their changing importance and roles in the deforestation process (Pacheco, 2012; Godar et al., 2014).

This paper investigates the interdependencies of intensification and deforestation using a theoretical modeling approach. Modeling has been used in the literature to investigate these interdependencies. For example, Bowman et al. (2012) use a spatial land rent model to find that intensification policies have to be complemented by improvements in conservation policies that disencourage land speculation to decrease deforestation. Many land-use models apply a procedure that determines demands for different types of land and then allocates them geographically. They use empirically derived statistics and economic criteria that indicating suitability of areas for different land uses. Then, conversion elasticities determine how changing demands translate into changes in spatial land-use patterns (e. g., Verburg et al., 2002; Michetti, 2012; Aguiar et al., 2012).

To intensify their production, ranchers have to adopt new management practices and production technologies. Such decisions are not only based on economic considerations, but are also determined by the diffusion of knowledge and successful management practices via social networks (Feder & Umali, 1993). This has been demonstrated and modeled for example for the adoption of new agricultural technologies (Berger, 2001; Maertens & Barrett, 2012). Therefore, it is important to consider the social and cultural context of cattle ranching intensification. For example, there are not only strong economic incentives but also cultural drivers, such as the dissemination and adoption of values that make the current practice of cattle ranching attractive in comparison with more sustainable land uses ("cowboy culture", Hoelle, 2011).

Agent-based approaches can capture such influences on land-use change. They model the decisions of heterogeneous agents and their social and environmental interactions to explain emergent patterns and dynamics at the system level. They can therefore describe how social interactions and incentive structures influence the decisions of ranchers to use the land in a specific way. Agent-based models (ABMs) are widely applied to describe social-ecological systems (for reviews see Schlüter et al., 2012; An, 2012; Groeneveld et al., 2017; Parker et al., 2003; Matthews et al., 2007; Heppenstall et al., 2012). In the land-use context, social-ecological ABMs are mostly developed for small study regions, taking into account local specificities and fitting behavioral patterns to data acquired in the field (Parker et al., 2008). There are several ABMs in the literature explicitly developed to study the influence of socio-economic drivers on deforestation dynamics. Many of these models use profit or utility maximization approaches to describe land-use decisions. For example, Andersen et al. (2017) provide a model of households in

a small Bolivian community to explore the consequences of different policy options, including the level of public investment, a deforestation tax, and conservation payments. The model by West et al. (2018) is based on similar principles and focuses on the effects of direct REDD+ payments to agricultural households. Other models use heuristic approaches to land-use decisions, focusing for example on colonist households (Deadman et al., 2004) and on deforestation outcomes under different institutional settings (Costa, 2012) in frontier regions of the Brazilian Amazon. Some models also take local interactions between individual agents into account. For example, Mena et al. (2011) use socioeconomic surveys and demographic data to calibrate complex heuristic decision making modules in a model that describes households in the Ecuadorian Amazon. Manson & Evans (2007) combine different decision-making approaches in a genetic programming framework to model deforestation in Mexico. However, none of these models integrates social influence processes and their role for land-management decisions.

This paper presents the *abacra* (agent-based amazonian cattle ranching) model, a stylized ABM to investigate under which circumstances intensification of cattle ranching can reduce deforestation in Amazon frontier regions. The model described in Section 2 of this paper combines simplified representations of the social, economic, and ecological processes that we judge most important for the purpose of this study. It differs from the above-mentioned ABMs by specifying heuristic land-management strategies and capturing how these change as a result of social influence. Such a combination of approaches has been identified as a promising representation of human decision making in social-ecological models (e. g., Müller-Hansen et al., 2017). The model serves as a proof of concept that the combination of non-standard decision-making with local and social interactions can help to understand and explore the emergent system-level outcomes of social-ecological systems. It does not aim at producing concrete numerical predictions or scenarios of future land use in the Amazon.

After introducing the model, Section 3 provides a detailed analysis of the model results to demonstrate its dynamics, using data from the frontier region around Novo Progresso in southern Pará. Sections 4 and 5 discuss broader implications and limitations of the results and conclude the paper.

2. Model description

In this section, we describe the details of the *abacra* model that we use throughout this study. A full description according to the ODD+D protocol (Müller et al., 2013) is provided in the supplementary material.

2.1. Overview

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-ecological systems.

The model comprises a large number N of ranchers with their respective land properties. The ranchers interact with their local environment by decisions to convert forest into pasture and managing this pasture. The land area of every ranch is divided into three different land-cover categories (forest, pasture, secondary vegetation). Furthermore, the pasture productivity and the soil quality of areas with secondary vegetation decribe the environmental quality of the land. Land-cover succession equations trace deforestation, land abandonment, and forest regrowth, while two other dynamic equations describe the evolution of the productivity of pasture and secondary vegetation.

The ranchers are characterized by their savings and their land-management strategy. The decisions of agents are captured by heuristic strategies depending on economic and ecological constraints. Agents can follow either an extensive strategy, corresponding to traditional cattle ranching with fallow periods and slash-and-burn fertilization, or a semi-intensive strategy. In contrast to intensive cattle ranching that relies mostly on externally produced feedstock, semi-intensive cattle ranching increases the productivity of the pasture on which the cattle graze by inputs such as machinery and fertilizers. The choice of the land-management strategy is modeled as a social learning process: Agents are located on a geographic network representing neighborhood and acquaintance relations. They imitate the successful strategies of their neighbors. Key parameters of the model describe the cattle market demand and the time scale of social learning.

The model is discrete in time t and each time step represents one year, thereby abstracting from seasonal variations. The simulation for each time step proceeds in the following sequence:

First, the agents make decisions about their land-use activities, based on the previous state of their environment and their economic situation (Secs. 2.4 to 2.6). Second, based on the previous state and the decisions, the system evolves according to the environmental dynamics (Sec. 2.2). Third, all ranchers receive revenues for the cattle they produced (Secs. 2.3 and 2.8). Finally, ranchers imitate their neighbors' land-management strategies with a probability depending on the difference of the rancher's consumption with its neighbor (Sec. 2.7).

The model is implemented in python, using various packages of the python ecosystem (numpy, scipy, pandas, networkx) to combine the data with the dynamics described above.[1] This language was chosen to allow an easy

[1] The code is available from `www.github.com/fmhansen/abacra`.

parallelization of model runs on the high performance cluster computing infrastructure of the Potsdam Insitute for Climate Impact Research.

In the following, we describe the different parts of the model in detail. Table 2 gives an overview of the variables used for the formalization.

2.2. 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. Land-cover changes such as deforestation and land abandonment are traced by land-cover succession equations (cp., e. g., Satake & 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

$$P_{t+1} = P_t + d_t + r_t - a_t, \qquad (1)$$

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

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

$$S_{t+1} = X - P_{t+1} - F_{t+1} = S_t - r_n v_t S_t + a_t - r_t, \qquad (3)$$

where r_n is a parameter that describes the natural recovery from secondary vegetation to mature forest. The deforestation d_t, abandonment a_t, and reuse r_t are control variables determined in the rancher's decision process. The land-cover dynamics for a single ranch are illustrated in Fig. 1.

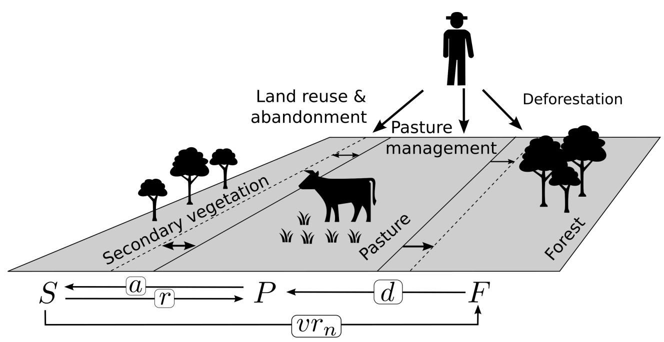

Figure 1: Illustration of the conversion of land for single ranches in the model. The total area of a property is divided into three land-cover types that can be converted by land management with rates d (deforestation), a (abandonment), and r (reuse). Secondary vegetation regenerates with a rate proportional to a natural recovery parameter r_n and the productivity of secondary vegetation v. Cattle raised on the pasture generate revenues for the rancher.

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 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. 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:

$$q_{t+1} = \frac{(1 - \beta(l_t - m_t))q_t(P_t - a_t) + q_d d_t + v_t r_t}{P_t + d_t + r_t - a_t}, \qquad (4)$$

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.

Finally, 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. 4.

$$v_{t+1} = \frac{(v_t + r_S(1 - v_t))(S_t - r_t) + a_t q_t}{S_t - r_t + a_t}. \qquad (5)$$

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

2.3. Economic dynamics

There are five 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:

$$I_t = p_c l_t P_t q_t / T_p - c_D d_t - c_R r_t - c_m m_t P_t, \qquad (6)$$

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 rancher, resulting in the following dynamics for the accumulated savings:

$$k_{t+1} = (1 + \delta)k_t + I_t - C_t, \qquad (7)$$

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 $C_t = (1 - s)I_t$.

2.4. Decision making of agents and land-management strategies

The decision-making functions of agents are the centerpiece of the *abacra* model. They determine the amount of deforestation, abandonment, reuse, stocking rate, and pasture management in every time step. Because the land-use decisions 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 & Gaissmaier, 2011).

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). Because of limited empirical data on actual decision processes in the system under consideration, we made the following simplifying assumptions for the agents' decision functions. We capture the social aspects of land-use decisions in our model by a heuristic land-management strategy that an agent adopts. This strategy determines how an agent makes use of the land. In the model, we implement two idealized strategies, an extensive and a semi-intensive land management strategy. They correspond to typical individual land-use trajectories in the Amazon.

2.5. Extensive strategy

The extensive strategy represents traditional approaches to cattle ranching with fallow periods and slash-and-burn fertilization. It 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 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. For the extensive strategy, the managed pasture cannot exceed a fixed fraction of the total area p_{max} because the rest is set aside as fallow land. 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 profitable, then the option with the higher expected additional income is chosen. The latter depends on the expected cattle price times the expected amount of cattle that can be produced on the new pasture. 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.

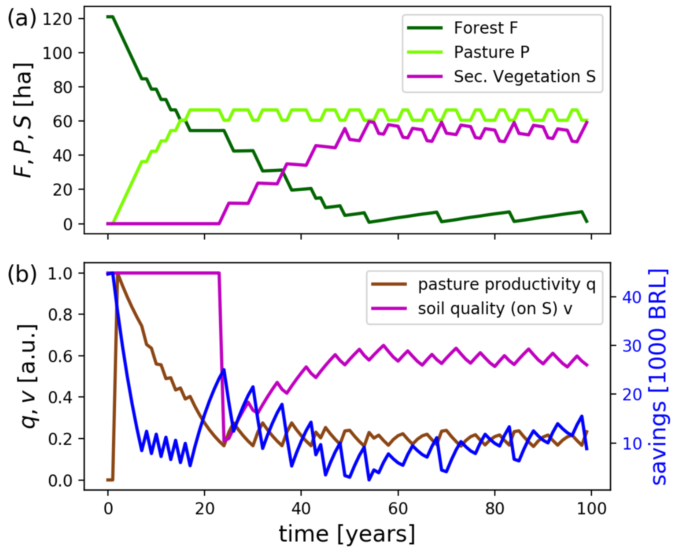

Figure 2: Sample trajectory for illustration of the dynamics of a single ranch with extensive strategy, showing (a) the areas of different land use: pasture (light green), forest (dark green), and secondary vegetation (magenta) and (b) savings (blue), pasture productivity (brown), and secondary vegetation fertility (magenta), which are displayed in arbitrary units (a.u.).

The extensive strategy does not use the pasture management option ($m_t = 0$) and the stocking rate is fixed at a low level $l_t = l_{ext}$. The logic of the decisions are illustrated as two decision trees in Fig. 4. For the implementation of the model, we used Heaviside step-functions. The equations are given in the supplementary material.

Fig. 2 shows a sample trajectory of a single ranch with the extensive strategy. The strong oscillations in the trajectory result from the thresholds in the decision functions. The agent has to reinvest into deforestation and reuse of secondary vegetation in order to improve the pasture productivity every few years.

2.6. 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 evaluates whether it is possible to recover the investment within a certain time period T_{rec}, assuming that the economic circumstances remain constant: The agent compares 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 to the deforestation cost. The agent uses a similar logic to determine whether it is profitable to convert an area of secondary vegetation R back to pasture. 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. An area A of pasture is abandoned if the ranching activity is not profitable anymore.

For the semi-intensive strategy, the deforestation costs are higher by the intensification cost c_I. This also has to be considered in Eq. 6 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. 7. A formulation of these rules in terms of Heaviside functions is provided in the supplementary materials.

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 $l_t = l_{int} > l_{ext}$. A sample trajectory for this strategy is shown in Fig. 3. Here, one can observe that most of the forest is deforested quite fast and the decline of pasture productivity is much slower because of pasture management.

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.

2.7. Local interaction: strategy imitation between agents

In the *abacra* model, we reduce the potentially complex process of adopting a land-management strategy 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). The agents are modeled on a network that represents neighbor relations as illustrated in Fig. 5. This simplifying assumption is motivated by evidence from the literature that neighbor interactions play an important role in deforestation decisions (Robalino & 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 (zu Ermgassen et al., 2018).

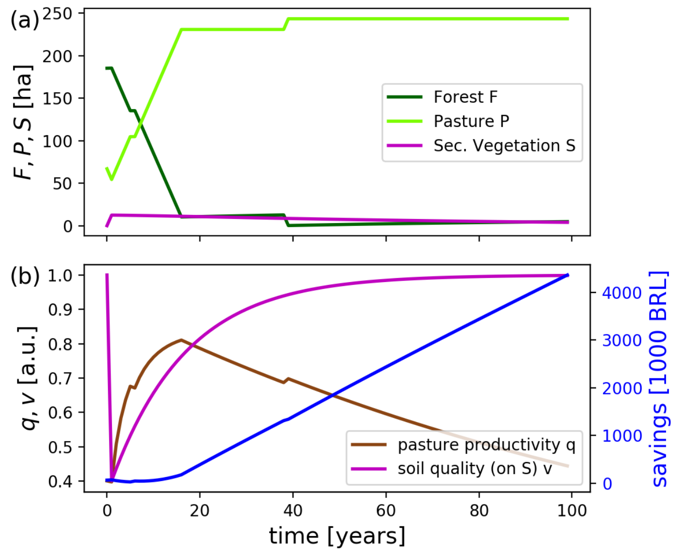

Figure 3: Sample trajectory for illustration of the dynamics of a single ranch with the semi-intensive strategy: (a) areas of different land use: pasture (light green), forest (dark green), and secondary vegetation (magenta). (b) savings (blue), pasture productivity (brown) and secondary vegetation fertility (magenta), which are displayed in arbitrary units (a.u.).

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, i.e., they occur with a constant imitation rate λ. 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 is then given by a random number drawn from a Poisson distribution with rate λ. 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 a hyperbolic tangent function of the difference between the agents' consumption C_t (cp. Wiedermann et al., 2015):

$$P_{ij} = \frac{1}{2}\left(\tanh(\sigma(C_j - C_i)) + 1\right). \tag{8}$$

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}. The imitation process results in a faster spread of production strategies that generate more income.

2.8. 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 demand side of a 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

$$p_c = a_p Y^{-1/\varepsilon}, \tag{9}$$

with price elasticity of demand ε. A high price elasticity means that a slight change in price leads to a high change in demand. Put the other way around, a large change in the quantity leads to a slight change in price. A low elasticity thus implies a strong price reaction to a change in the produced quantity. This relation is illustrated in the upper right of Fig. 5, where the yellow demand curve corresponds to a lower elasticity than the green one.

The price elasticity allows modeling different market settings: 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. 9 gets close to zero such that the dependence on Y becomes negligible and the curve approaches the constant a_p. Instead of studying the case of fixed prices separately, we will look at very high values for the price elasticity.

2.9. Input data and parametrization

We use different data sources to estimate parameters of the *abacra* model. The details are given in Table 1. Some of the parameters, especially those related to decision making, cannot be determined from the data. We analyse the sensitivity of model outcomes on such input parameters further in Sec. 3.2.

The model uses the following input data for initial conditions and set-up of the network: Initial values for pasture areas are approximated from deforestation data from PRODES, using the data from 2000 as initial conditions. For comparison with other initial conditions, we also test initial conditions corresponding to the deforestation extent in 2016. The initial conditions for secondary vegetation are set to zero. Initial values for the soil productivity q are randomly drawn from a uniform distribution of values between 0 and 1. Furthermore, 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.

We apply the model framework on the study region around Novo Progresso in the Brazilian Amazon. We choose the region because it is characterized by strong deforestation in recent years and a high share of cattle ranching on deforested areas. However, the model should be easily adapted to other regions and could be scaled to larger regions.

We use property data from the Rural Environmental Registry (Cadastro Ambiental Rural, CAR, 2018), a geoinformation tool that helps the administration to monitor land owners' compliance with the Forest Code (Azevedo et al., 2017). Between 2000 and 2016, average deforestation on CAR-registered properties in the Novo Progresso region was 9.5 ha/year with an average property size of 563 ha. In total, about 28% of the forest area on registered properties has been cleared by 2016 (own calculations using PRODES and CAR).

We use the CAR data to get a representative heterogeneity of property sizes and construct different neighborhood networks. However, the CAR data is incomplete and contains unsettled land claims, which leads to overlapping properties. To avoid inconsistencies, we remove properties with large overlap by via visual inspection of the data set in a GIS program. Like this, we remove properties that overlapped with more than a small part of their total area. Figure 6(a) shows the municipality of Novo Progresso and its adjacent municipalities as well as the limits of properties in the CAR data.

To construct the network, we apply a function on the distance between properties (nodes) determining whether they are connected or not. The simplest method connects all properties closer than a specific threshold. We test the model with networks for different thresholds and chose 10 km because this results in a good balance between overall connectivity of the network and an average degree that is in a reasonable range for social contacts. This network has 4012 nodes and an average degree of about 81.

We also test probabilistic methods for constructing neighborhood networks, for which the probability of being connected decays exponentially with the distance between properties. Furthermore, we constructed geographic networks that have a proportion α of links replaced by random links. We call these links teleconnections because they are independent of the spatial embedding of the network and therefore represent social interactions over distance. Figure 6 (b) shows the network constructed from the property data without teleconnections. For the model simulations, the initial strategies are set as follows: all properties start with the extensive strategy except the ones within a range of 10 km from the major cities, which start with a 50% probability with the semi-intensive strategy. The colors of the network nodes in the figure indicate initial conditions for the agents' strategies.

3. Model analysis and results

After introducing the model design in the previous section, this section discusses system-level outcomes of model simulations with interacting agents.

Table 1: Description, symbols, and values of parameters in the presented ABM. Where applicable, ranges in the literature for the parameterization with the corresponding sources or own calculations are indicated.

parameter	symbol	default value	range	unit	sources and comments
deforestation cost	c_D	1500	1000 - 3000	BRL/ha*	difference in land prices between pasture and forest from FGVIBRE
reuse cost	c_R	500	500 - 2000	BRL/ha	
pasture maintenance cost	c_m	150	150 - 300	BRL/ha	estimated using IMEA
intensification cost	c_I	500	300 - 1000	BRL/ha	zu Ermgassen et al. (2018)
live cattle price		5	3.4 - 6.4	BRL/kg	SEAB
slaughter age	T_p	3	2.5 - 3	years	Tab. 4 in Pacheco & Poccard-Chapuis (2012)
cattle weight at slaughter (3 years)		500	470 - 520	kg	Tab. 4 in Pacheco & Poccard-Chapuis (2012)
initial life cattle price	$p_c(0)$	2500	1600 - 3330	BRL/head	live cattle price × weight at slaughter
average stocking rate	l_{ext}, l_{int}	0.8, 1.6	0.5 - 2.0	head/ha	Tab. 3 & 4 in Pacheco & Poccard-Chapuis (2012)
saving rate	s	0.25	0.15 - 0.3		gross domestic savings (The World Bank)
natural recovery parameter	r_n	0.013		1/year	corresponding to a half-life of about 50 years (Poorter et al., 2016)
regeneration of soil quality of secondary vegetation	r_S	0.06		1/year	corresponding to a half-life of about 10 years (Davidson et al., 2007)
parameter of pasture degradation	β	0.15		1/head/year	corresponding to a half-life of 3 - 4 years for degradation (Costa, 2012)
productivity of pasture after deforestation	q_d	1		arbitrary units (a.u.)	determines scale
threshold on q for abandonment	$q_{\theta a}$	0.2		a.u.	
relative deforested, abandoned and reused areas	D/X, R/X, A/X	0.05	0.02 - 0.1	relative area	for deforestation, estimations with PRODES yield 0.08
maximum relative pasture for extensive strategy	p_{max}	0.5		relative area	
timeperiod for investment decisions	T_{rec}	7		years	information from personal interviews: 5 - 8 years
management effort	M	1.5		a.u.	
maximal credit for intensification	k_{min}	200		BRL/ha	
imitation rate	λ	1	0.001 - 10	1/year	
price elasticity of demand	ε	10	0.1 - 1000		
share of teleconnections	α	0.02	0 - 0.1		

* Prices are in 2010 Brazilian Real (BRL), areas are in hectare (10,000 m^2)

3.1. System-level dynamics

For parameter settings with a high imitation rate λ and high elasticity of demand ε, the initially small number of agents with a semi-intensive strategy increases over time until almost all agents use this strategy. This happens because the increase in produced cattle does not decrease the revenue per area significantly. Further deforestation allows more cattle to be raised and thus increases overall income, which can be reinvested to deforest more.

Fig. 7 shows the key variables of an ensemble of model runs with such a parameter setting (the other parameters are given in Table 1). The shaded ranges indicate the variation of variables due to different realizations of the stochastic processes in the model. The figure shows that most of the forest is already deforested and converted to pasture in the first 30 to 40 years of the simulation (panel a). Panel 7(b) shows that after an initial peak in pasture productivity stemming from newly deforested pastures with a high initial productivity, q drops because of ongoing pasture degradation. Later, it increases as more and more agents use pasture management to improve their pasture productivity. The productivity of secondary vegetation is initially low, but increases as the soil regenerates. The agents' savings are low at the beginning and accumulate at the end of the simulation as many agents have already deforested all of their area and cannot invest in more pasture. The fraction of ranchers that adopted the semi-intensive strategy in panel 7(c) increases rapidly, because they have the possibility to borrow money for intensification. In a scenarios in which this option is not available, they first have to accumulate the savings to cover intensification costs, which slows down the increase. For higher imitation rates and higher cattle prices, this fraction increases more rapidly. Panel 7(d) finally shows how the produced cattle quantity Y increases rapidly in the first 40 years. After all forest has been converted to pasture, there is a slow decay due to pasture degradation. The cattle price p_c hardly changes because of the high price elasticity.

For comparison, Fig. 8 displays the results of model simulations with similar parameterization except for a lower imitation rate and lower elasticity. Here, one can observe that because of the low imitation rate, the number of ranchers with a semi-intensive strategy increases only slowly (Fig. 8c). This leads to the abandonment of degraded pasture and an increase in secondary vegetation (Fig. 8a). Furthermore, the low price elasticity of demand leads to a strong reaction of prices to increasing production at the beginning of the simulation, as a comparison of Figs. 7 and 8 in panels (d) illustrates. As the pastures degrade and production goes down, the price recovers towards the middle of the displayed simulation time. At the end of the simulation, prices decrease again because intensification sets in and cattle production increases. In the long run, the lower revenues lead to less savings (Fig. 8b) and thus slow down deforestation, as Panel 8(a) illustrates.

A formal analysis of the asymptotic dynamics of the model is difficult because the system is very heterogeneous and stochastic. Long-term simulation results suggest that there are (quasi) stable states and cyclic asymptotic dynamics, depending on the parameter regime. They are only reached after long transients (several hundred years) as an effect of the slow forest recovery dynamics. We do not analyze them in detail, because we are interested in deforestation, which is mainly a transient phenomenon.

3.2. Sensitivity analysis

Here, we present an analysis of how model results depend on specific model parameters. Several parameters are difficult to estimate due to a lack of data and therefore a sensitivity analysis is crucial. Parameters may also change over time and an analysis of the dependence of model outcomes can illustrate how trends in external drivers of the system might influence model outcomes. We focus our analysis on six parameters describing costs and prices as well as the imitation process. An exploration of further results indicates that variations of other parameters do not lead to qualitatively different model behavior.

Price elasticity of demand and deforestation cost are crucial for the revenues and production costs of ranchers. They have a direct influence on the production of cattle and the rate of deforestation. A lower elasticity inhibits the expansion of cattle production and deforestation (Fig. 9), while higher deforestation costs slow down deforestation (see Fig. S1). The former is due to a saturation of the local cattle market. The effect of both parameters on intensification is limited.

The four parameters imitation rate, intensification cost, limitations to intensification credit, and teleconnection share influence the imitation of strategies and therefore directly impact the speed of the spread of the semi-intensive pasture management strategy. Fig. 10 shows how a lower imitation rate leads to a considerably slower spread of the semi-intensive strategy. This also leads to a lower cattle production and deforestation. A higher intensification cost inhibits fast intensification and thus the expansion of pasture and cattle production (Fig. S2). The same applies for low limits to credit that a rancher can access (parameter k_{min}). If ranchers cannot access credit at all ($k_{min} = 0$), the intensification process is considerably slowed down (Fig. S3). Finally, the share of teleconnections has only limited influence on the speed of intensification. However, if we do not add teleconnections to the network of neighboring ranches, some of the ranches are isolated. Therefore, they cannot adopt the semi-intensive strategy at all. This leads to a saturation of the intensification share below 1 (Fig. S4).

To make it more systematic, we extended the analysis to aggregate measures of the transient model behavior. Because this study analyzes on the interaction between intensification and deforestation, we focus on the impact of different parameter combinations on the average deforestation. Figures 11 and 12 show the mean over the first

50 years after model initialization, because this is the period in which most of the deforestation happens (compare Figs. 7 and 8).

In Fig. 11, the average deforestation is plotted depending on the elasticity of the cattle demand function as well as the imitation rate (both on a log-scale). The results match with observed mean deforestation rates on properties ranging between 3 and 20 ha/year (own calculations using PRODES and CAR). The figure shows that for low imitation rates and elasticities, the average deforestation is in the medium range of 3-4 ha/year. For low elasticity, this decreases with a higher imitation rate, which is associated to faster intensification. For a high elasticity of demand, this relationship is reversed: A higher imitation rate increases the higher deforestation rate even further.

If there are high intensification costs and agents do not have access to credit, the intensification under high imitation rates is hampered. Therefore, such conditions will not result in an increase of deforestation under high imitation rates (see Fig. S5).

We also test other parameter ranges indicated in Table 1 and find that even though they may influence the results quantitatively, they do not change the model outcomes in a relevant way. For instance, variation of the parameter determining the relative areas that agents can deforest preserves our main findings(see Fig. S6).

The results presented here are properties of the transient dynamics of the system, not equilibrium or asymptotic states. Therefore, they depend on the initial conditions of the system, especially on the initial pasture areas, pasture productivity, and savings. We test the dynamics for different settings of initial conditions and find for all of them that an increase in imitation rate does not reduce deforestation rates if elasticity is high.

3.3. Network effects

Apart from the influence that certain parameters and initial conditions have on the model outcome, we also investigate the influence of the topology of the underlying neighborhood network. To account for long-range social ties (i. e., family and friendship relations independent of geographic distance), we test how the spreading of land-management strategies on the social network changes. For this we replace a fraction of local links by teleconnections, i.e., random links that are independent of the spatial embedding (cp. Sect. 2.9).

For random initial conditions with a spatially uniform distribution, the spreading does not change strongly when replacing a fraction α of local connections with teleconnections. With initial conditions for which ranches with semi-intensive strategies are spatially concentrated (e. g., around local cities or main roads), the additional teleconnections accelerate the spreading of the strategies considerably. Under parameter settings where the semi-intensive strategy is favored, the intensification process is therefore accelerated by the introduction of teleconnections.

Figure 12 displays the average deforestation rate depending on the share of teleconnections in the network and the imitation rate. For medium imitation rates, the influence of the teleconnection share on the deforestation outcome is small compared to other effects in the model. The figure suggests that adding teleconnections has the same effect as slightly rescaling the imitation rate.

In addition to the network construction as described in Sect. 2.9, we also test a method for network construction that links nodes with a probability that decays exponentially with distance (Waxman, 1988). This results in changes in the network structure because the threshold on the distance is replaced by a characteristic length for the decay. It has only very limited effect on model outcomes and does not change them in a relevant way.

4. Discussion

The model analysis above showed that already a stylized model including a few feedbacks and representing the heterogeneity of agents yields rich non-linear dynamics. The model design implies that only price effects, limited access to credit, high costs for investments, and constraints on decision making impede total deforestation in the *abacra* model. For these assumptions, we find that deforestation can only be curbed by intensification if price elasticity of demand in the model is high and the cattle market saturates at some point.

The elasticity in the model can be interpreted as a measure of integration of the local cattle market into national or international markets. With ongoing globalization and building of infrastructure in the Amazon (de Toledo et al., 2017), the elasticity of demand for local markets rises such that markets will not easily saturate.

Especially with the pavement of the BR-163 highway, our example region around Novo Progresso is increasingly well accessible and connected to the rest of Brazil (Fearnside, 2007). Therefore, a high degree of integration of the local cattle market into national and international markets is probable (Gollnow et al., 2018). In our model, this is represented by a high elasticity of demand approximating a purely price-taking supply side. However, there may be differences also within the region, for example regarding the accessibility of properties far away from the highway (Weinhold & Reis, 2008).

We can similarly interpret the share of teleconnections in the network: with ongoing technical progress, the interaction between ranchers that are not located in the same neighborhood will increase. The model results suggest that this only has a minor effect on the deforestation outcomes. Furthermore, if the costs for intensification are high, limitations on credit hamper the increase of deforestation in the model. This may reflect the success of policies limiting access to agricultural credits in municipalities with high deforestation rates (Assunção et al., 2013).

The model analysis indicated that the exact trajectories depend on the parameterization of the implemented

decision processes and initial conditions. The decision rules used in this model are derived from a survey of the literature and are tuned to reproduce observed land-use patterns in the region. However, there are no empirical studies on the motives, goals and decision procedures of agents, which makes it difficult to construct sound decision functions. Further research in this direction is needed to improve the validity of model results, especially the collection of evidence on how agents in frontier regions make decisions about land use. Furthermore, there often remain many indeterminacies when deriving decision rules from empirical observations even if plenty of data is available. This gap can be bridged by comparing different decision making strategies of agents in a model with empirical data, for instance using inter-temporal or myopic optimization, satisficing, and individual learning approaches. Separating between single intensification practices and techniques would furthermore result in a characterization of intensification as a continuous process, helping to answer for instance the question which level of intensification would be individually and socially optimal.

To date, intensification of cattle ranching in the Amazon is slow (Sparovek et al., 2018). Especially in remote areas, there is limited access to transportation infrastructure, energy, and labor. Furthermore, the land tenure system and land market play an important role for deforestation dynamics because deforestation is a means for agents to lay claim to land and later get land titles through regularization processes (Barretto et al., 2013; Sparovek et al., 2015). This can make deforestation a speculative investment. We did not account for these factors in the *abacra* model, but future extensions focusing on any of these issues could be used to investigate their interplay with intensification further.

The adoption of intensification techniques for cattle production also generates new environmental problems not captured in our model. Intensified systems are associated with heavy nitrogen pollution, water usage, and soil depletion (Tilman et al., 2011). Including such impacts into the model would allow analyzing the environmental trade-offs between intensified and extensive cattle production further. The aim of such modeling could be to identify agricultural practices that are both economically viable and sustainable over long time scales.

In the past, Brazilian conservation policies like the extension of legal reserves from 50 to 80% of private lands in 1996 (Alston & Mueller, 2007) and the monitoring and sanctioning of deforestation activities have reduced deforestation considerably (Nepstad et al., 2014). But current legislation provides low incentives for full compliance with the law, especially regarding reforestation (Azevedo et al., 2017). The internationalization of agricultural commodity markets increased pressure on producers to comply with environmental legislation (Nepstad et al., 2006). This resulted in industry initiatives to monitor compliance such as the zero-deforestation agreement from 2009 (Gibbs et al., 2016). However, recent research shows that the positive effect of the zero-deforestation agreement is undermined by leakage effects ("cattle laundering" Alix-Garcia & Gibbs, 2017; Klingler et al., 2018). To effectively exclude violators of environmental law from the beef supply chain, monitoring of the entire life cycle of cattle would be necessary.

Measures to foster land-use intensification have been debated as an alternative anti-deforestation policy. However, as Merry & Soares-Filho (2017) convincingly argued, intensification policies alone will not lead to better conservation outcomes, i.e., less deforestation. Intensification is rather the result of effective conservation policies. This is consistent with our model results for well integrated markets. Given the model results in this study and despite the limitations of our model, we conclude that anti-deforestation policies only aiming at intensification of cattle ranching will not have the desired result if they are not accompanied by measures that limit the agents' access to new land. Policies aiming to increase intensification cannot replace conservation policies.

An important issue for the design of future anti-deforestation policies is the huge heterogeneity of actors in frontier development. The roles of various types of agents with respect to deforestation outcomes changes as a response to new policy implementations and their effectiveness. Recent studies comparing the contributions of small-holders and large land-owners found opposing trends, depending on the time and location they focused on (Godar et al., 2012, 2014; Richards & VanWey, 2015). For example, large-scale ranchers, who drive land concentration in more consolidated areas, are susceptible to other incentives than small-holders in remote areas, mainly involved in subsistence farming. To investigate the different effect of intensification policies and economic drivers on this heterogeneity of agents is a challenge for future modeling studies.

In general, development and environmental policies for the Amazon have to face the various trade-offs between social and environmental issues (de Toledo et al., 2017). Cattle ranching remains an important source of income for land holders in the Amazon. As the demand for cattle products is increasing world-wide (Thornton, 2010), ranching provides an economic perspective for the region. Policies have to guarantee that local incomes are maintained or increased while conserving the ecosystems. Therefore, it is essential that they can anticipate the multiple feedbacks in the system that could undermine the effectiveness of policies. It remains an open question how cattle ranching in the Amazon will become an environmentally and socially sustainable economic activity in the long term, with or without intensification.

5. Conclusion

This study presents and analyzes a new agent-based model that conceptualizes the intensification of cattle ranching as a socially mediated process. With this approach, we shed light on the interplay between ecological dynamics,

economic conditions, decision making of agents, and interactions on a social network. We show how even from very stylized assumptions about these dynamics, a rich non-linear behavior arises at the system level, which can be explained by the various feedback loops between them. We use recent data sets on land properties (CAR) and deforestation (PRODES) in a frontier region to demonstrate the model dynamics for specific initializations and parameterizations.

In particular, we highlight the effect of the imitation rate and price elasticity of demand for cattle. We show that higher imitation rates, which lead to faster intensification, can only reduce deforestation in a market that saturates. On the other hand, under conditions of less responsive prices, faster intensification can even lead to higher deforestation. Our model shows these effects on a regional scale but similar rebound effects have been discussed for the global food system (Lambin & Meyfroidt, 2011).

The model presented here is only a first step towards including local social interaction into models of land-use change in the context of tropical deforestation. Future work with agent-based models could focus on evaluating the effectiveness and resilience of anti-deforestation policies accounting for heterogeneities of actors in the deforestation process (Godar et al., 2014). Agent-based models are a powerful tool for such analyses because they can represent heterogeneities and account for the various feedbacks in the system. Thereby, they might help developing an economic perspective for the region that provides improvements in livelihoods and at the same time reduce deforestation.

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Declaration of interest The authors declare that they have no conflict of interest.

Code and data availability The model code is available from `github.com/fmhansen/abacra`. The data used for this study is available online and referenced accordingly.

Appendix

Table 2: Overview of variables, symbols, and units in the model.

variable	symbol	unit
pasture area	P_t	ha
forest area	F_t	ha
secondary vegetation area	S_t	ha
pasture productivity	q_t	a.u.
secondary vegetation productivity	v_t	a.u.
savings of rancher	k_t	BRL
income	I_t	BRL
consumption	C_t	BRL
deforestation	d_t	ha/year
abandonment	a_t	ha/year
reuse	r_t	ha/year
management effort	m_t	a.u.
stocking rate for pasture	l_t	head/ha

References

Aguiar, A. P. D., Ometto, J. P., Nobre, C., Lapola, D. M., Almeida, C., Vieira, I. C., Soares, J. V., Alvala, R., Saatchi, S., Valeriano, D., & Castilla-Rubio, J. C. (2012). Modeling the spatial and temporal heterogeneity of deforestation-driven carbon emissions: the INPE-EM framework applied to the Brazilian Amazon. *Global Change Biology*, *18*, 3346–3366. doi:`10.1111/j.1365-2486.2012.02782.x`.

Aguiar, A. P. D., Vieira, I. C. G., Assis, T. O., Dalla-Nora, E. L., Toledo, P. M., Santos-Junior, R. A. O., Batistella, M., Coelho, A. S., Savaget, E. K., Aragão, L. E. O. C., Nobre, C. A., & Ometto, J. P. H. (2016). Land use change emission scenarios: anticipating a forest transition process in the Brazilian Amazon? *Global Change Biology*, *22*, 1821–1840. doi:`10.1111/gcb.13134`.

Alix-Garcia, J., & Gibbs, H. K. (2017). Forest conservation effects of Brazil's zero deforestation cattle agreements undermined by leakage. *Global Environmental Change*, *47*, 201–217. doi:`10.1016/j.gloenvcha.2017.08.009`.

Almeida, C. A., Coutinho, A. C., Esquerdo, J. C. D. M., Adami, M., Venturieri, A., Diniz, C. G., Dessay, N., Durieux, L., & Gomes, A. R. (2016). High spatial resolution land use and land cover mapping of the Brazilian Legal Amazon in 2008 using Landsat-5/TM and MODIS data. *Acta Amazonica*, *46*, 291–302. doi:`10.1590/1809-4392201505504`.

Alston, L. J., & Mueller, B. (2007). Legal Reserve Requirements in Brazilian Forests: Path Dependent Evolution of De Facto Legislation. *Revista Economia*, *8*, 25–53.

An, L. (2012). Modeling human decisions in coupled human and natural systems: Review of agent-based models. *Ecological Modelling*, *229*, 25–36. doi:10.1016/j.ecolmodel.2011.07.010.

Andersen, L. E., Groom, B., Killick, E., Ledezma, J. C., Palmer, C., & Weinhold, D. (2017). Modelling Land Use, Deforestation, and Policy: A Hybrid Optimisation-Heterogeneous Agent Model with Application to the Bolivian Amazon. *Ecological Economics*, *135*, 76–90. doi:10.1016/j.ecolecon.2016.12.033.

Angelsen, A., & Kaimowitz, D. (1999). Rethinking the causes of deforestation: lessons from economic models. *The World Bank research observer*, *14*, 73–98. doi:10.1093/wbro/14.1.73.

Angelsen, A., & Kaimowitz, D. (2001). Introduction: the role of agricultural technologies in tropical deforestation. In A. Angelsen, & D. Kaimowitz (Eds.), *Agricultural Technologies and Tropical Deforestation* (pp. 1–17). Oxon, UK, and New York: CABI Publishing. doi:10.1079/9780851994512.0001.

Assunção, J., Gandour, C., Rocha, R., & Rocha, R. (2013). *Does Credit Affect Deforestation? Evidence from a Rural Credit Policy in the Brazilian Amazon*. Technical Report Climate Policy Initiative. URL: www.climatepolicyinitiative.org.

Azevedo, A. A., Rajão, R., Costa, M. A., Stabile, M. C. C., Macedo, M. N., dos Reis, T. N. P., Alencar, A., Soares-Filho, B. S., & Pacheco, R. (2017). Limits of Brazil's Forest Code as a means to end illegal deforestation. *Proceedings of the National Academy of Sciences of the United States of America*, *114*, 7653–7658. doi:10.1073/pnas.1604768114.

Barona, E., Ramankutty, N., Hyman, G., & Coomes, O. T. (2010). The role of pasture and soybean in deforestation of the Brazilian Amazon. *Environmental Research Letters*, *5*, 024002. doi:10.1088/1748-9326/5/2/024002.

Barretto, A. G., Berndes, G., Sparovek, G., & Wirsenius, S. (2013). Agricultural intensification in Brazil and its effects on land-use patterns: An analysis of the 1975-2006 period. *Global Change Biology*, *19*, 1804–1815. doi:10.1111/gcb.12174.

Berger, T. (2001). Agent-based spatial models applied to agriculture: a simulation tool for technology diffusion, resource use changes and policy analysis. *Agricultural Economics*, *25*, 245–260. doi:10.1111/j.1574-0862.2001.tb00205.x.

Bowman, M. S., Soares-Filho, B. S., Merry, F. D., Nepstad, D. C., Rodrigues, H., & Almeida, O. T. (2012). Persistence of cattle ranching in the Brazilian Amazon: A spatial analysis of the rationale for beef production. *Land Use Policy*, *29*, 558–568. doi:10.1016/j.landusepol.2011.09.009.

Busch, J., & Ferretti-Gallon, K. (2017). What drives deforestation and what stops it? A meta-analysis. *Review of Environmental Economics and Policy*, *11*, 3–23. doi:10.1093/reep/rew013.

Cano-Crespo, A., Oliveira, P. J., Boit, A., Cardoso, M., & Thonicke, K. (2015). Forest edge burning in the Brazilian Amazon promoted by escaping fires from managed pastures. *Journal of Geophysical Research: Biogeosciences*, *120*, 2095–2107. doi:10.1002/2015JG002914.

CAR (2018). Sistema Nacional de Cadastro Ambiental Rural - Base de Downloads. URL: http://www.car.gov.br/publico/municipios/downloads.

Cohn, A., Bowman, M., Zilberman, D., & O'Neill, K. (2011). The Viability of Cattle Ranching Intensification in Brazil as a Strategy to Spare Land and Mitigate Greenhouse Gas Emissions. *CCAFS Working Paper No. 11*, . URL: http://hdl.handle.net/10568/10722.

Cohn, A. S., Mosnier, A., Havlík, P., Valin, H., Herrero, M., Schmid, E., O'Hare, M., & Obersteiner, M. (2014). Cattle ranching intensification in Brazil can reduce global greenhouse gas emissions by sparing land from deforestation. *Proceedings of the National Academy of Sciences of the United States of America*, *111*, 7236–7241. doi:10.1073/pnas.1307163111.

Costa, S. S. (2012). *Regional Scale Agent-Based Modelling Of Land Change: Evolving Institutional Arrangements In Frontier Areas*. Ph.D. thesis INPE, São José dos Campos.

Currarini, S., Marchiori, C., & Tavoni, A. (2016). Network Economics and the Environment: Insights and Perspectives. *Environmental and Resource Economics*, *65*, 159–189. doi:10.1007/s10640-015-9953-6.

Davidson, E. A., De Carvalho, C. J., Figueira, A. M., Ishida, F. Y., Ometto, J. P. H., Nardoto, G. B., Sabá, R. T., Hayashi, S. N., Leal, E. C., Vieira, I. C. G., & Martinelli, L. A. (2007). Recuperation of nitrogen cycling in Amazonian forests following agricultural abandonment. *Nature*, *447*, 995–998. doi:10.1038/nature05900.

Deadman, P., Robinson, D., Moran, E., & Brondizio, E. (2004). Colonist household decisionmaking and land-use change in the Amazon Rainforest: An agent-based simulation. *Environment and Planning B: Planning and Design*, *31*, 693–709. doi:10.1068/b3098.

Erb, K.-H., Fetzel, T., Kastner, T., Kroisleitner, C., Lauk, C., Mayer, A., & Niedertscheider, M. (2016). Livestock Grazing, the Neglected Land Use. In *Social Ecology* (pp. 295–310). doi:10.1007/978-3-319-33326-7_13.

zu Ermgassen, E. K., de Alcântara, M. P., Balmford, A., Barioni, L., Neto, F. B., Bettarello, M. M., de Brito, G., Carrero, G. C., Florence, E. d. A., Garcia, E., Gonçalves, E. T., da Luz, C. T., Mallman, G. M., Strassburg, B. B., Valentim, J. F., & Latawiec, A. (2018). Results from on-the-ground efforts to promote sustainable cattle ranching in the Brazilian Amazon. *Sustainability*, *10*, 1301. doi:10.3390/su10041301.

Fearnside, P. M. (2007). Brazil's Cuiabá- Santarém (BR-163) Highway: The environmental cost of paving a soybean corridor through the Amazon. *Environmental Management*, *39*, 601–614. doi:10.1007/s00267-006-0149-2.

Feder, G., & Umali, D. L. (1993). The adoption of agricultural innovations. A review. *Technological Forecasting and Social Change*, *43*, 215–239. doi:10.1016/0040-1625(93)90053-A.

FGVIBRE (). FGVDados. URL: http://portalibre.fgv.br/main.jsp?lumChannelId=402880811D8E34B9011D92C493F131B2.

Garrett, R. D., Gardner, T. A., Morello, T. F., Marchand, S., Barlow, J., de Blas, D. E., Ferreira, J., Lees, A. C., & Parry, L. (2017). Explaining the persistence of low income and environmentally degrading land uses in the Brazilian Amazon Explaining the persistence of low income and environmentally degrading land uses in the Brazilian Amazon. *Ecology and Society*, *22*, 27. doi:10.5751/ES-09364-220327.

Gibbs, H. K., Munger, J., L'Roe, J., Barreto, P., Pereira, R., Christie, M., Amaral, T., & Walker, N. F. (2016). Did Ranchers and Slaughterhouses Respond to Zero-Deforestation Agreements in the Brazilian Amazon? *Conservation Letters*, *9*, 32–42. doi:10.1111/conl.12175.

Gigerenzer, G., & Gaissmaier, W. (2011). Heuristic decision making. *Annual review of psychology*, *62*, 451–482. doi:10.1146/annurev-psych-120709-145346.

Godar, J., Gardner, T. A., Tizado, E. J., & Pacheco, P. (2014). Actor-specific contributions to the deforestation slowdown in the Brazilian Amazon. *Proceedings of the National Academy of Sciences of the United States of America*, *111*, 15591–15596. doi:10.1073/pnas.1322825111.

Godar, J., Tizado, E. J., & Pokorny, B. (2012). Who is responsible for deforestation in the Amazon? A spatially explicit analysis along the Transamazon Highway in Brazil. *Forest Ecology and Management*, *267*, 58–73. doi:10.1016/j.foreco.2011.11.046.

Gollnow, F., Göpel, J., deBarros Viana Hissa, L., Schaldach, R., & Lakes, T. (2018). Scenarios of land-use change in a deforestation corridor in the Brazilian Amazon: combining two scales of analysis. *Regional Environmental Change*, *18*, 143–159. doi:10.1007/s10113-017-1129-1.

Groeneveld, J., Müller, B., Buchmann, C., Dressler, G., Guo, C., Hase, N., Hoffmann, F., John, F., Klassert, C., Lauf, T., Liebelt, V., Nolzen, H., Pannicke, N., Schulze, J., Weise, H., & Schwarz, N. (2017). Theoretical foundations of human decision-making in agent-based land use models A review. *Environmental Modelling & Software*, *87*, 39–48. doi:10.1016/j.envsoft.2016.10.008.

Heppenstall, A. J., Crooks, A. T., See, L. M., & Batty, M. (Eds.) (2012). *Agent-Based Models of Geographical Systems*. Dordrecht: Springer. doi:10.1007/978-90-481-8927-4.

Hoelle, J. (2011). Convergence on Cattle: Political Ecology, Social Group Perceptions, and Socioeconomic Relationships in Acre,

Brazil. *Culture, Agriculture, Food and Environment*, *33*, 95–106. doi:10.1111/j.2153-9561.2011.01053.x.

IMEA (). Custo de Produção da Bovinocultura de Corte. URL: http://www.imea.com.br/imea-site/relatorios-mercado.

Kaimowitz, D., & Angelsen, A. (2008). Will Livestock Intensification Help Save Latin America's Tropical Forests? *Journal of Sustainable Forestry*, *27*, 6–24. doi:10.1080/10549810802225168.

Klingler, M., Richards, P. D., & Ossner, R. (2018). Cattle vaccination records question the impact of recent zero-deforestation agreements in the Amazon. *Regional Environmental Change*, *18*, 33–46. doi:10.1007/s10113-017-1234-1.

Lambin, E. F., & Meyfroidt, P. (2011). Global land use change, economic globalization, and the looming land scarcity. *Proceedings of the National Academy of Sciences of the United States of America*, *108*, 3465–3472. doi:10.1073/pnas.1100480108.

Landers, J. N. (2007). *Tropical crop-livestock systems in conservation agriculture: the Brazilian experience*. Integrated Crop Management Vol. 5-2007. Rome: Food and Agriculture Organization of the United Nations. URL: http://www.fao.org/3/a-a1083e.pdf.

Latawiec, A. E., Strassburg, B. B., Valentim, J. F., Ramos, F., & Alves-Pinto, H. (2014). Intensification of cattle ranching production systems: socioeconomic and environmental synergies and risks in Brazil. *Animal*, *8*, 1255–1263. doi:10.1017/S1751731114001566.

Lenton, T. M., Held, H., Kriegler, E., Hall, J. W., Lucht, W., Rahmstorf, S., & Schellnhuber, H. J. (2008). Tipping elements in the Earth's climate system. *Proceedings of the National Academy of Sciences of the United States of America*, *105*, 1786–1793. doi:10.1073/pnas.0705414105.

Maertens, A., & Barrett, C. B. (2012). Measuring social networks' effects on agricultural technology adoption. *American Journal of Agricultural Economics*, *95*, 353–359. doi:10.1093/ajae/aas049.

Manson, S. M., & Evans, T. (2007). Agent-based modeling of deforestation in southern Yucatan, Mexico, and reforestation in the Midwest United States. *Proceedings of the National Academy of Sciences of the United States of America*, *104*, 20678–20683. doi:10.1073/pnas.0705802104.

Matthews, R. B., Gilbert, N. G., Roach, A., Polhill, J. G., & Gotts, N. M. (2007). Agent-based land-use models: a review of applications. *Landscape Ecology*, *22*, 1447–1459. doi:10.1007/s10980-007-9135-1.

Mena, C. F., Walsh, S. J., Frizzelle, B. G., Xiaozheng, Y., & Malanson, G. P. (2011). Land use change on household farms in the Ecuadorian Amazon: Design and implementation of an agent-based model. *Applied Geography*, *31*, 210–222. doi:10.1016/j.apgeog.2010.04.005.

Merry, F., & Soares-Filho, B. (2017). Will intensification of beef production deliver conservation outcomes in the Brazilian Amazon? *Elementa: Science of the Anthropocene*, *5*, 24. doi:10.1525/elementa.224.

Michetti, M. (2012). Modelling Land Use, Land-Use Change, and Forestry in Climate Change: A Review of Major Approaches. *FEEM Working Paper No. 46.2012*, . doi:10.2139/ssrn.2122298.

Müller, B., Bohn, F., Dreßler, G., Groeneveld, J., Klassert, C., Martin, R., Schlüter, M., Schulze, J., Weise, H., & Schwarz, N. (2013). Describing human decisions in agent based models - ODD + D, an extension of the ODD protocol. *Environmental Modelling & Software*, *48*, 37–48. doi:http://dx.doi.org/10.1016/j.envsoft.2013.06.003.

Müller-Hansen, F., Schlüter, M., Mäs, M., Donges, J. F., Kolb, J. J., Thonicke, K., & Heitzig, J. (2017). Towards representing human behavior and decision making in Earth system models an overview of techniques and approaches. *Earth System Dynamics*, *8*, 977–1007. doi:10.5194/esd-8-977-2017.

Myers, R. J. K., & Robbins, G. B. (1991). Sustaining Productive Pasture in the Tropics - 5. Maintaining productive sown grass pastures. *Tropical Grasslands*, *25*, 104–110.

Nepstad, D., McGrath, D., Stickler, C., Alencar, A., Azevedo, A., Swette, B., Bezerra, T., DiGiano, M., Shimada, J., Seroa da Motta, R., Armijo, E., Castello, L., Brando, P., Hansen, M. C., McGrath-Horn, M., Carvalho, O., & Hess, L. (2014). Slowing Amazon deforestation through public policy and interventions in beef and soy supply chains. *Science*, *344*, 1118–23. doi:10.1126/science.1248525.

Nepstad, D. C., Stickler, C. M., & Almeida, O. T. (2006). Globalization of the Amazon soy and beef industries: Opportunities for conservation. *Conservation Biology*, *20*, 1595–1603. doi:10.1111/j.1523-1739.2006.00510.x.

Oliveira, L. J. C., Costa, M. H., Soares-Filho, B. S., & Coe, M. T. (2013). Large-scale expansion of agriculture in Amazonia may be a no-win scenario. *Environmental Research Letters*, *8*, 024021. doi:10.1088/1748-9326/8/2/024021.

Pacheco, P. (2012). Actor and frontier types in the Brazilian Amazon: Assessing interactions and outcomes associated with frontier expansion. *Geoforum*, *43*, 864–874. doi:10.1016/j.geoforum.2012.02.003.

Pacheco, P., & Poccard-Chapuis, R. (2012). The Complex Evolution of Cattle Ranching Development Amid Market Integration and Policy Shifts in the Brazilian Amazon. *Annals of the Association of American Geographers*, *102*, 1366–1390. doi:10.1080/00045608.2012.678040.

Parker, D. C., Entwisle, B., Rindfuss, R. R., Vanwey, L. K., Manson, S. M., Moran, E., An, L., Deadman, P., Evans, T. P., Linderman, M., Mussavi Rizi, S. M., & Malanson, G. (2008). Case studies, cross-site comparisons, and the challenge of generalization: comparing agent-based models of land-use change in frontier regions. *Journal of Land Use Science*, *3*, 41–72. doi:10.1080/17474230802048151.

Parker, D. C., Manson, S. M., Janssen, M. A., Hoffmann, M. J., & Deadman, P. (2003). Multi-Agent Systems for the Simulation of Land-Use and Land-Cover Change: A Review. *Annals of the Association of American Geographers*, *93*, 314–337. doi:10.1111/1467-8306.9302004.

Perz, S., & Skole, D. (2003a). Secondary forest expansion in the Brazilian Amazon and the refinement of forest transition theory. *Society & Natural Resources*, *16*, 277–294. doi:10.1080/08941920390178856.

Perz, S., & Skole, D. L. (2003b). Social determinants of secondary forests in the Brazilian Amazon. *Social Science Research*, *32*, 25–60. doi:10.1016/s0049-089x(02)00012-1.

Poorter, L., Bongers, F., Aide, T. M., Almeyda Zambrano, A. M., Balvanera, P., Becknell, J. M., Boukili, V., Brancalion, P. H., Broadbent, E. N., Chazdon, R. L., Craven, D., De Almeida-Cortez, J. S., Cabral, G. A., De Jong, B. H., Denslow, J. S., Dent, D. H., DeWalt, S. J., Dupuy, J. M., Durán, S. M., Espírito-Santo, M. M., Fandino, M. C., César, R. G., Hall, J. S., Hernandez-Stefanoni, J. L., Jakovac, C. C., Junqueira, A. B., Kennard, D., Letcher, S. G., Licona, J. C., Lohbeck, M., Marín-Spiotta, E., Martínez-Ramos, M., Massoca, P., Meave, J. A., Mesquita, R., Mora, F., Munõz, R., Muscarella, R., Nunes, Y. R., Ochoa-Gaona, S., De Oliveira, A. A., Orihuela-Belmonte, E., Penã-Claros, M., Pérez-Garciá, E. A., Piotto, D., Powers, J. S., Rodríguez-Velázquez, J., Romero-Pérez, I. E., Ruíz, J., Saldarriaga, J. G., Sanchez-Azofeifa, A., Schwartz, N. B., Steininger, M. K., Swenson, N. G., Toledo, M., Uriarte, M., Van Breugel, M., Van Der Wal, H., Veloso, M. D., Vester, H. F., Vicentini, A., Vieira, I. C., Bentos, T. V., Williamson, G. B., & Rozendaal, D. M. (2016). Biomass resilience of Neotropical secondary forests. *Nature*, *530*, 211–214. doi:10.1038/nature16512.

PRODES (). Projeto de Monitoramento da Floresta Amazônica Brasileira por Satélite. URL: http://www.obt.inpe.br/OBT/assuntos/programas/amazonia/prodes.

Quaas, M. F., Baumgärtner, S., Becker, C., Frank, K., & Müller, B. (2007). Uncertainty and sustainability in the management of rangelands. *Ecological Economics*, *62*, 251–266. doi:10.1016/j.ecolecon.2006.03.028.

Richards, P., Arima, E., Vanwey, L., Cohn, A., & Bhattarai, N. (2017). Are Brazil's Deforesters Avoiding Detection? *Conservation Letters*, *10*, 470–476. doi:10.1111/conl.12310.

Richards, P. D., & VanWey, L. (2015). Farm-scale distribution of deforestation and remaining forest cover in Mato Grosso. *Nature*

Climate Change, *6*, 418–425. doi:10.1038/nclimate2854.

Richards, P. D., Walker, R. T., & Arima, E. Y. (2014). Spatially complex land change: The indirect effect of Brazil's agricultural sector on land use in Amazonia. *Global Environmental Change*, *29*, 1–9. doi:10.1016/j.gloenvcha.2014.06.011.

Robalino, J. A., & Pfaff, A. (2012). Contagious development: Neighbor interactions in deforestation. *Journal of Development Economics*, *97*, 427–436. doi:10.1016/j.jdeveco.2011.06.003.

Salisbury, D. S., & Schmink, M. (2007). Cows versus rubber: Changing livelihoods among Amazonian extractivists. *Geoforum*, *38*, 1233–1249. doi:10.1016/j.geoforum.2007.03.005.

Satake, A., & Rudel, T. K. (2007). Modeling the Forest Transition: Forest Scarcity and Ecosystem Service Hypotheses. *Ecological Applications*, *17*, 2024–2036. doi:10.1890/07-0283.1.

Schlüter, M., Mcallister, R. R. J., Arlinghaus, R., Bunnefeld, N., Eisenack, K., Hölker, F., Milner-Gulland, E. J., Müller, B., Nicholson, E., Quaas, M., & Stöven, M. (2012). New Horizons for Managing the Environment: A Review of Coupled Social-Ecological Systems Modeling. *Natural Resource Modeling*, *25*, 219–272. doi:10.1111/j.1939-7445.2011.00108.x.

SEAB (). Preços médios nominais mensais recibidos polos produtores - boi gordo. URL: http://www.agricultura.pr.gov.br/modules/conteudo/conteudo.php?conteudo=195.

Serrão, E. A. S., Toledo, J. M., Falesi, I. C., de Veiga, J. B., & Teixeira Neto, J. F. (1979). Productivity of cultivated pasture on the the low-fertility soils in the Amazon of Brazil. In *Pasture Production in Acid Soils of the Tropics* (pp. 195–226). CIAT.

Soares-Filho, B., Rajão, R., Macedo, M., Carneiro, A., Costa, W., Coe, M., Rodrigues, H., & Alencar, A. (2014). Cracking Brazil's Forest Code. *Science*, *344*, 363–364. doi:10.1126/science.1246663.

Soler, L. S., Verburg, P. H., & Alves, D. S. (2014). Evolution of Land Use in the Brazilian Amazon: From Frontier Expansion to Market Chain Dynamics. *Land*, *3*, 981–1014. doi:10.3390/land3030981.

Sparovek, G., Barretto, A. G. D. O. P., Matsumoto, M., & Berndes, G. (2015). Effects of Governance on Availability of Land for Agriculture and Conservation in Brazil. *Environmental Science and Technology*, *49*, 10285–10293. doi:10.1021/acs.est.5b01300.

Sparovek, G., Guidotti, V., Pinto, L. F. G., Berndes, G., Barretto, A., & Cerignoni, F. (2018). Asymmetries of cattle and crop productivity and efficiency during Brazil's agricultural expansion from 1975 to 2006. *Elem Sci Anth*, *6*, 25. doi:10.1525/elementa.187.

The World Bank (). Gross Domestic Savings. URL: https://data.worldbank.org/indicator/NY.GDS.TOTL.ZS.

Thornton, P. K. (2010). Livestock production: recent trends, future prospects. *Philosophical Transactions of the Royal Society B: Biological Sciences*, *365*, 2853–2867. doi:10.1098/rstb.2010.0134.

Tilman, D., Balzer, C., Hill, J., & Befort, B. L. (2011). Global food demand and the sustainable intensification of agriculture. *Proceedings of the National Academy of Sciences*, *108*, 20260–20264. doi:10.1073/pnas.1116437108.

de Toledo, P. M., Dalla-Nora, E., Vieira, I. C. G., Aguiar, A. P. D., & Araújo, R. (2017). Development paradigms contributing to the transformation of the Brazilian Amazon: do people matter? *Current Opinion in Environmental Sustainability*, *26-27*, 77–83. doi:10.1016/j.cosust.2017.01.009.

Traulsen, A., Semmann, D., Sommerfeld, R. D., Krambeck, H.-J., & Milinski, M. (2010). Human strategy updating in evolutionary games. *Proceedings of the National Academy of Sciences of the United States of America*, *107*, 2962–2966. doi:10.1073/pnas.0912515107.

Van Kampen, N. G. (2007). *Stochastic processes in physics and chemistry*. (3rd ed.). Amsterdam: North Holland.

Verburg, P. H., Soepboer, W., Veldkamp, A., Limpiada, R., Espaldon, V., & Mastura, S. S. A. (2002). Modeling the Spatial Dynamics of Regional Land Use: The CLUE-S Model. *Environmental Management*, *30*, 391–405. doi:10.1007/s00267-002-2630-x.

Waxman, B. M. (1988). Routing of Multipoint Connections. *IEEE Journal on Selected Areas in Communications*, *6*, 1617–1622. doi:10.1109/49.12889.

Weinhold, D., & Reis, E. (2008). Transportation costs and the spatial distribution of land use in the Brazilian Amazon. *Global Environmental Change*, *18*, 54–68. doi:10.1016/j.gloenvcha.2007.06.004.

West, T. A., Grogan, K. A., Swisher, M. E., Caviglia-Harris, J. L., Sills, E., Harris, D., Roberts, D., & Putz, F. E. (2018). A hybrid optimization-agent-based model of REDD+ payments to households on an old deforestation frontier in the Brazilian Amazon. *Environmental Modelling and Software*, *100*, 159–174. doi:10.1016/j.envsoft.2017.11.007.

Wiedermann, M., Donges, J. F., Heitzig, J., Lucht, W., & Kurths, J. (2015). Macroscopic description of complex adaptive networks coevolving with dynamic node states. *Physical Review E*, *91*, 052801. doi:10.1103/PhysRevE.91.052801.

Zemp, D. C., Schleussner, C. F., Barbosa, H. M., & Rammig, A. (2017). Deforestation effects on Amazon forest resilience. *Geophysical Research Letters*, *44*, 6182–6190. doi:10.1002/2017GL072955.

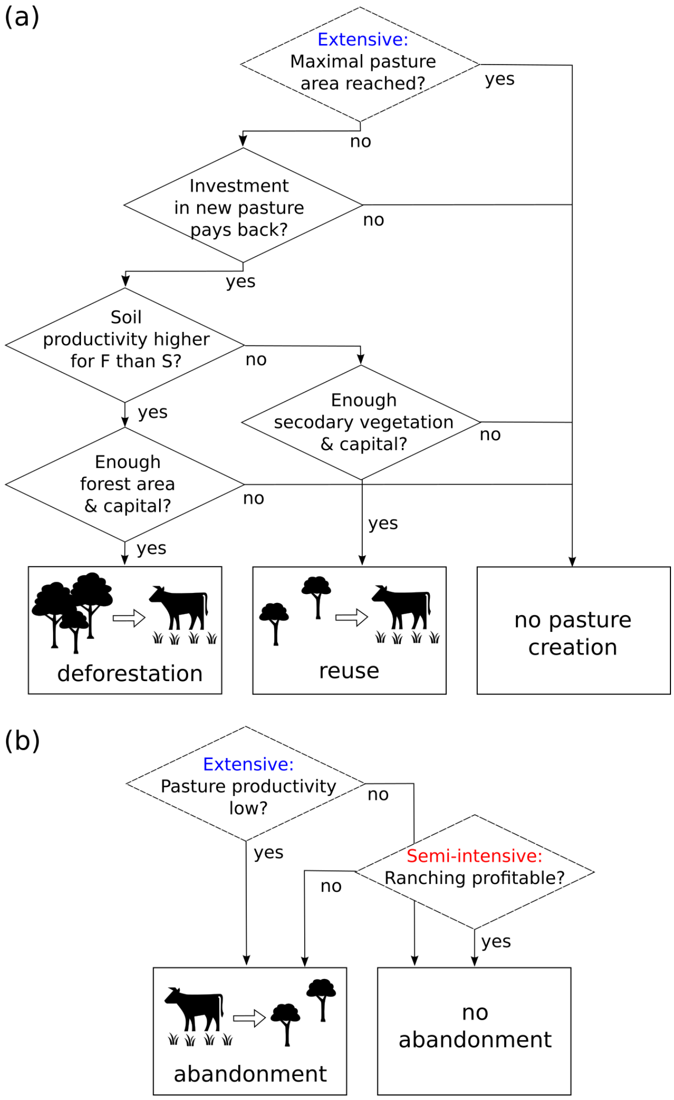

Figure 4: Decision trees illustrating the decision heuristics used by the agents in the model (a) for deforestation and reuse and (b) for abandonment. Differences between the extensive and the semi-intensive strategy are marked as dashed boxes. The differences regarding the stocking rate and the use of pasture management are not displayed.

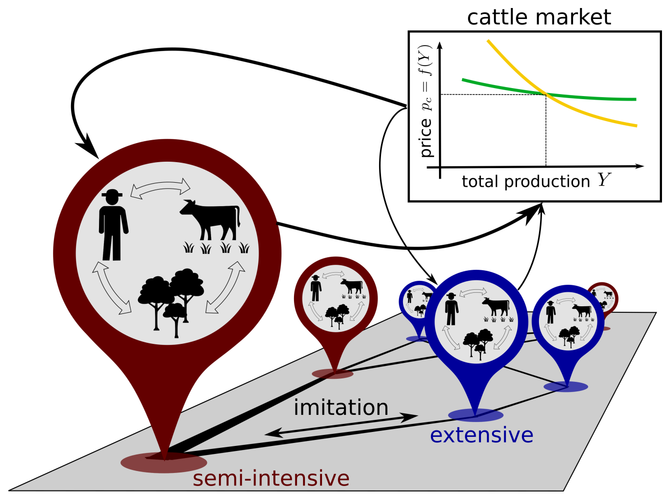

Figure 5: Illustration of the local and system-wide interactions between agents: Agents can imitate their strategies (extensive, blue, or semi-intensive, red) if they are connected on a geographically embedded social network. They sell their cattle on a market that determines the cattle price and thus their income, depending on the price elasticity of demand (yellow curve: low price elasticity, green curve: high price elasticity).

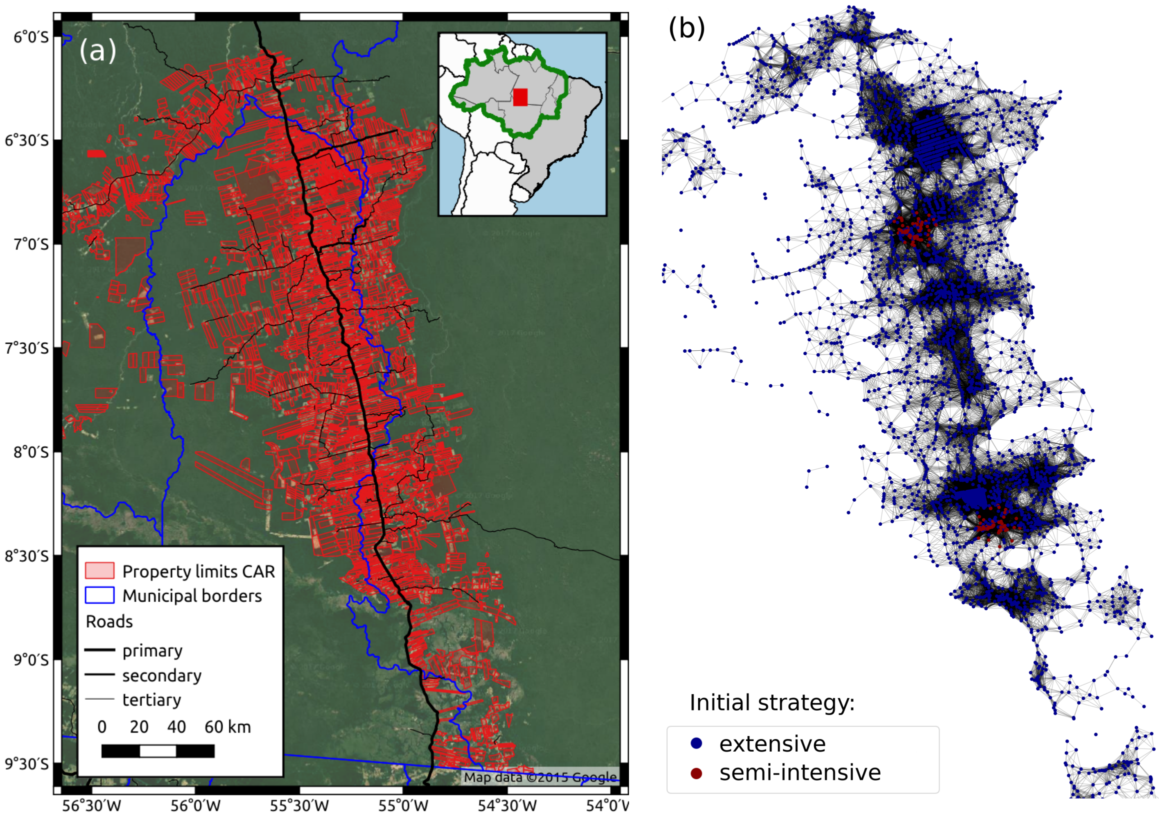

Figure 6: (a) Map of the study region with property limits from the environmental registry (CAR; red), municipality borders (blue) and roads (black). The data is plotted over a satellite image of the region. The inset shows the location in Brazil (grey) and the Brazilian legal Amazon (green line). (b) Geographic neighborhood network without teleconnections ($\alpha = 0$) derived from this data. Each node represents a property. The color of the nodes depicts the distribution of initial strategies.

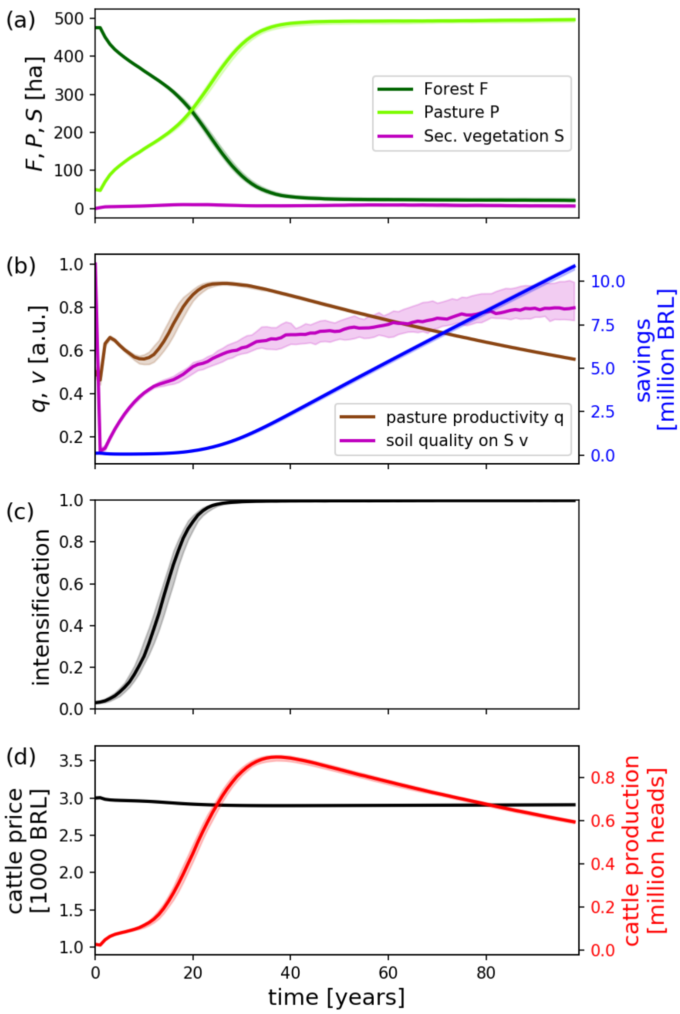

Figure 7: Mean state variables of agents on the geographic network depicted in Fig. 6 with high imitation rate ($\lambda = 1$), high elasticity ($\varepsilon = 100$), and some teleconnections in the social network ($\alpha = 0.02$): (a) mean areas (forest, pasture, secondary vegetation), (b) mean pasture productivity, soil quality on secondary vegetation areas, and savings, (c) intensification: ratio of ranches with the semi-intensive strategy (red nodes in Fig. 6), and (d) price and quantity of produced cattle. The thick lines are the respective ensemble median of a sample of 1000 model runs with different realizations of the stochastic processes in the model and the shaded areas around them indicate the 5th to 95th percentile of the distribution of model outcomes.

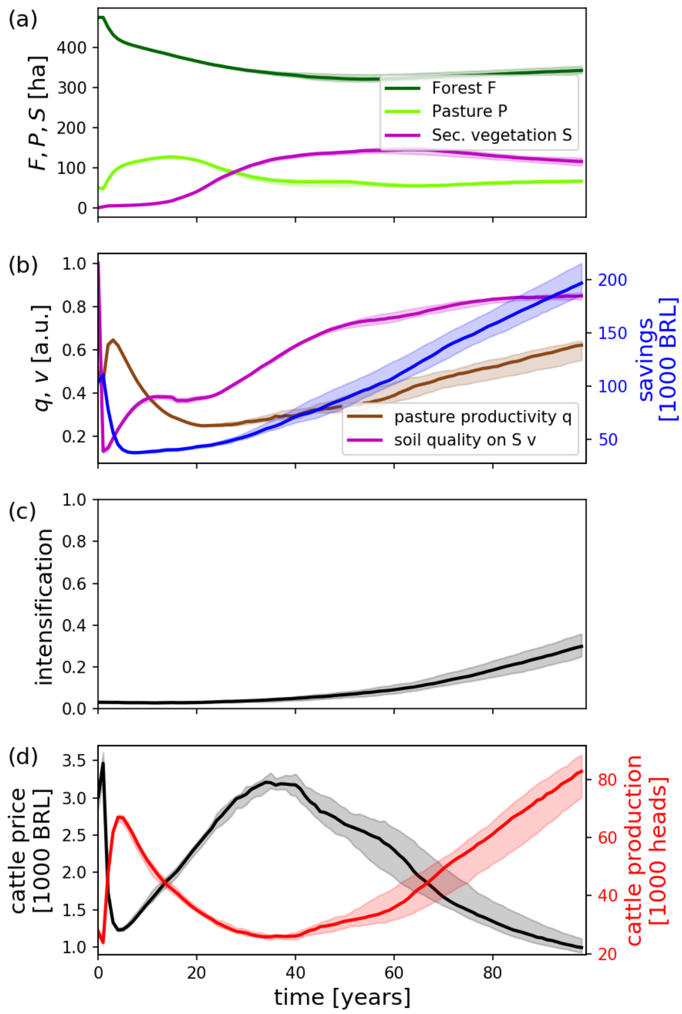

Figure 8: Mean state variables of agents on the geographic network (Fig. 6) but with lower imitation rate ($\lambda = 0.1$) and elasticity ($\varepsilon = 1$). The shown variables are the same as in Fig. 7.

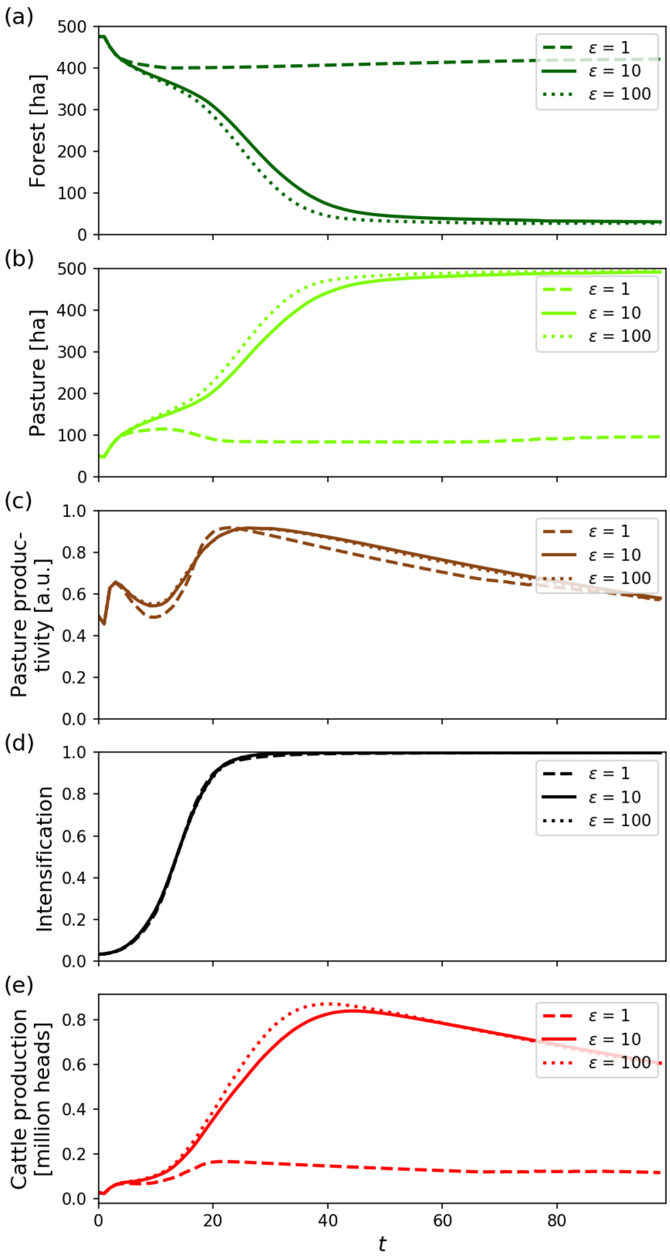

Figure 9: Sensitivities for variations of the price elasticity of demand ε.

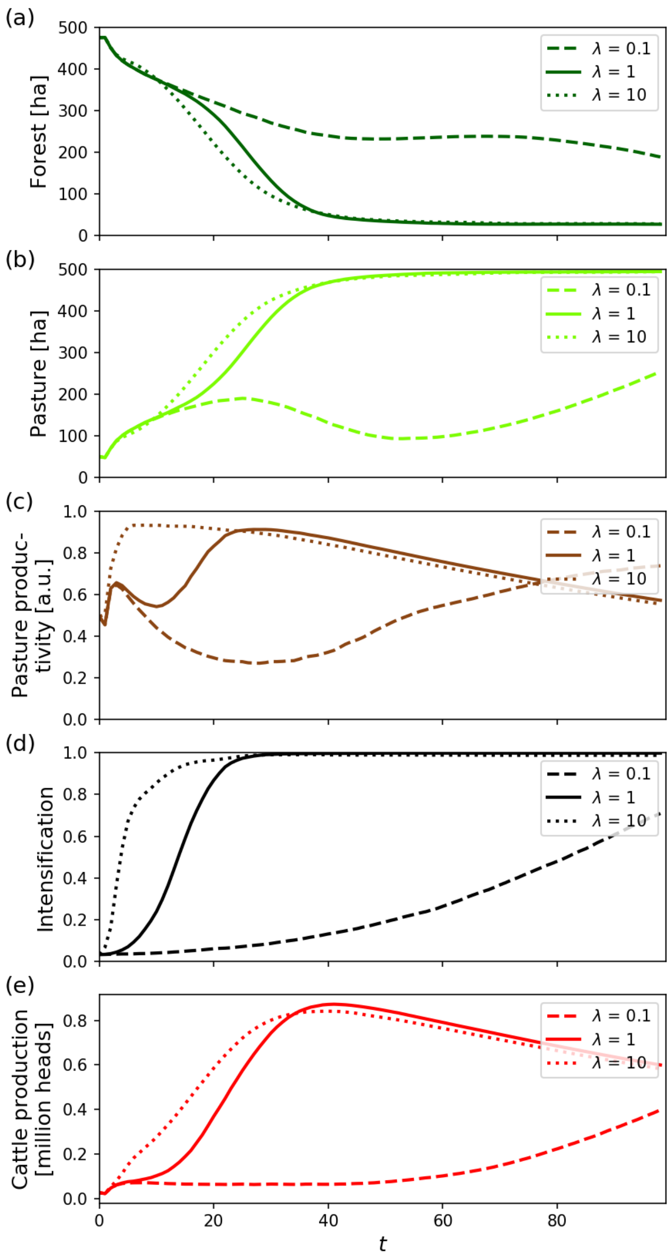

Figure 10: Sensitivities for variations of the imitation rate λ.

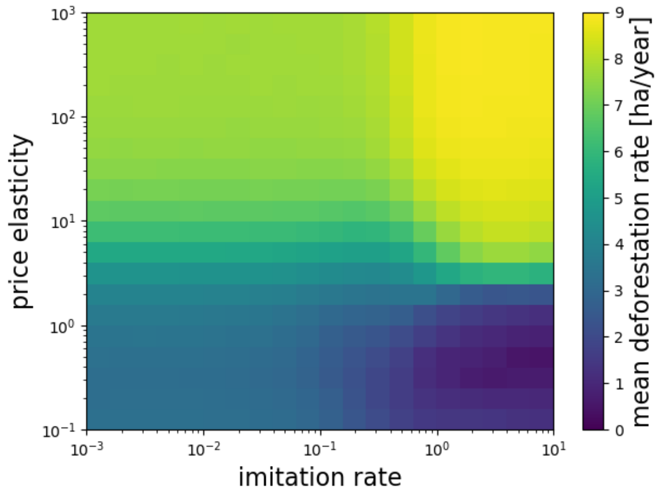

Figure 11: Average deforestation per year and property in dependence on price elasticity and imitation rate. Parameters are given in Table 1 and the initial conditions are based on deforested areas in the study area by 2000. The displayed values are the ensemble median over 100 runs.

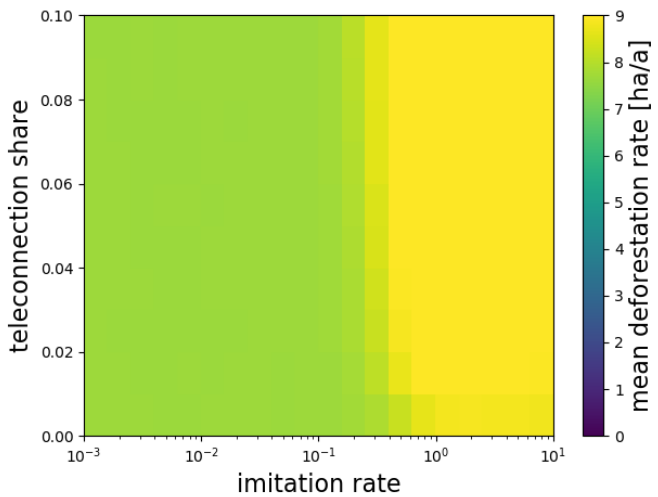

Figure 12: Average deforestation per year and property in dependence on teleconnection share α and imitation rate λ. Parameters as in Table 1 with $\varepsilon = 100$.