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Modeling the Impacts of Soil Management on Avoided Deforestation and REDD+ Payments in the Brazilian Amazon: A Systems Approach

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Abstract: An Integrated Assessment Model (IAM) was employed to develop a Narrative Policy Framework (NPF) and a quantitative model to investigate the changes in land use within the Brazilian Amazon. The process began by creating a theoretical NPF using a 'systems thinking' approach. Subsequently, a 'system dynamic model' was built based on an extensive review of the literature and on multiple quantitative datasets to simulate the impacts of the NPF, specifically focusing on the conversion of forests into open land for ranching and the implementation of soil management practices as a macro-level policy aimed at preserving soil quality and ranching yields. Various fallow scenarios were tested to simulate their effects on deforestation patterns. The results indicate that implementing fallow practices as a policy measure could reduce deforestation rates while simultaneously ensuring sustainable long-term agricultural productivity, thus diminishing the necessity to clear new forest land. Moreover, when combined with payments for avoided deforestation, such as REDD+ carbon offsets, the opportunity costs associated with ranching land can be utilized to compensate for the loss of gross income resulting from the policy. A sensitivity analysis was conducted to assess the significance of different model variables, revealing that lower cattle prices require resources for REDD+ payments, and vice-versa. The findings indicate that, at the macro level, payments between USD 2.5 and USD 5.0 per MgC ha^{-1} have the potential to compensate the foregone cattle production from not converting forest into ranching land. This study demonstrates that employing an IAM with a systems approach facilitates the participation of various stakeholders, including farmers and landowners, in policy discussions. It also enables the establishment of effective land use and management policies that mitigate deforestation and soil degradation, making it a robust initiative to address environmental, climate change, and economic sustainability issues.

Keywords: systems thinking; systems modeling; soil conservation; REDD+; Amazon deforestation

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1. Introduction

Most of the soils in the Amazon region are fragile and prone to rapid fertility depletion. As the productivity of agricultural and ranching land declines with use, farmers and ranchers are prompted to move to new land and clearcut native tropical forests to maintain land production [1]. Soil management practices can be used to reduce the rate of deforestation because they maintain soil quality and biomass production of cleared areas [1–4]. Many studies have emphasized that fallow regimes can greatly reduce the 'deforestation trajectory' in tropical regions by maintaining the productivity of cleared land and consequently reducing the need to clear new forest lands [5–10]. Nepstad et al. [11,12], Stabile et al. [13], and Koch et al. [14] recognized that incentive-based mechanisms have an important role in slowing Amazon deforestation, but they have not been implemented so far.

Currently, several methodologies are being used to estimate Verified Carbon Units (VCUs) to promote or propose payments for Reduced Emissions from Deforestation and Degradation (REDD+) [15] (Verra methodologies: for example, (a) VM0007—REDD+ Methodology Framework (REDD + MF) v1.6, (b) VM0011 Methodology for Calculating GHG Benefits from Preventing Planned Degradation v1.0, (c) VM0015—Methodology for avoided unplanned deforestation v1.1, (d) VM0017—Adoption of sustainable agricultural land management v1.0). These and other methods (TREES—The REDD+ Environmental Excellence Standard. Available online: www.artredd.org (accessed on 21 June 2023). The Gold Standard. Available online: www.goldstandard.org (accessed on 21 June 2023). Climate Action Reserve. Available online: www.climateactionreserve.org (accessed on 21 June 2023). ACR—American Carbon Registry. Available online: www.americancarbonregistry.org (accessed on 21 June 2023)) are being debated at national, state, or province levels in many countries to customize programs according to their reality and needs, since new methods can be proposed based on a scientific peer review process [14,15]. REDD+-oriented initiatives can provide payments for poor countries that lack the resources to conserve forests and implement sustainable management programs. REDD+ could also serve to compensate or complement opportunity costs that would accrue from the conversion of forests to agricultural land [12,16–20]. As a trade-off, the emission of greenhouse gases (GHG) to the atmosphere could be reduced. This initiative could help countries such as Brazil to achieve their national emission commitments and other conservation goals and to advance towards a jurisdictional REDD+ program (J-REDD+).

Brazil has advanced in that direction by approving the Federal Law #14,119/21, which establishes the National Policy for Payment of Environmental Services, and by resuming the National Plan for Prevention and Control in the Legal Amazon—PPCDAm. There is an extensive published literature that explores the main direct and underlying causes of deforestation in the Brazilian Legal Amazon [21–35]. Most of these studies adopt a 'global approach' (for the whole region, state, and municipal levels), and rank as (a) the major correlated drivers: cattle ranching, forest stocks, timber value, road networks, and rural population, and as having (b) a negative correlation: GDP, planted crops, access to rural credit, and delimited Protected Areas. These articles evidence that the more formal, sophisticated, and costly agricultural activities, such as soybeans plantations, are subsequent activities of selective logging, land opening, and ranching. Assunção et al. [23] estimate that deforestation is responsive to agricultural product prices, and that conservation policies and controlling the effects of agriculture prices do have an important role in avoiding deforestation. Barona et al. and Mammadova et al. [28] developed an exercise related to the bovine leather industry in the Brazilian Amazon and reinforced the importance to assess the "systemic trap that cause the production sector to continue with nature's destruction". Barona et al. [27] relate that this debate is complex and the interlinkages between deforestation and policy "need further exploration, in order to make a conclusive case for 'displacement deforestation'". Further, the literature indicates that there is no evidence that there will be a slowdown in the agricultural expansion frontier in the Amazon in the near future.

Several studies have considered a systems approach to analyze the drivers and effects of land utilization in Colombia [28], the Philippines [30], Myanmar [31], Indonesia [32,33], and China [34]. Other studies analyzed the potential effects of REDD+-related policies. West et al. [35] applied a spatial explicit model, with an optimization model to simulate REDD+ and forest degradation combined with forest management and conservation. The study considered a local-level approach, specific to an agriculture settlement, State of Rondônia in the Amazon. Wehkamp et al. [36] analyze the perception of deforestation drivers by African policy makers as a possible response to a REDD+ policy. They relate the importance of developing logical frameworks, with long-term impacts and measurable indicators, to support decision-making activities [35,36]. Hiratsuka et al. [10] studied the potential of fallow vegetation for receiving REDD+ payments in Northern Laos. Certainly, there is a growing literature on these topics, and the given recommendations for future studies have encouraged the development of this article.

Since Brazil needs to develop mechanisms to support decision-making and design policies related to deforestation and conservation in the Amazon, this study had as its general objective the development of an Integrated Assessment Model (IAM) based on a Narrative Policy Framework (NPF). Specifically, the study aimed to estimate: (1) the biological and economic effects of soil management systems, (2) its relationship with avoided deforestation, (3) the identification of possible outcomes for REDD+ payments to compensate the forgone income and opportunity costs of ranching, and (4) alternatives to incentive-based mechanisms for forest and land conservation in Brazil.

2. Methods

2.1. Study Area

The Brazilian Amazon area was taken as the study site (Figure 1). It comprises an area of approximately 5.0 million km^2 of which 75% are covered by tropical rainforest and the remaining 25% by other land uses, including farms, ranches, and mines. It covers nine Brazilian states (States of Acre, Amapá, Amazonas, Mato Grosso, Pará, Tocantins, Maranhão, Rondônia, and Roraima) and 772 municipalities, which have independent governments but abide by the same federal laws. The current population of the region is 28.1 million inhabitants (13% of the Brazilian population), which has grown 243% since 1972 [37].

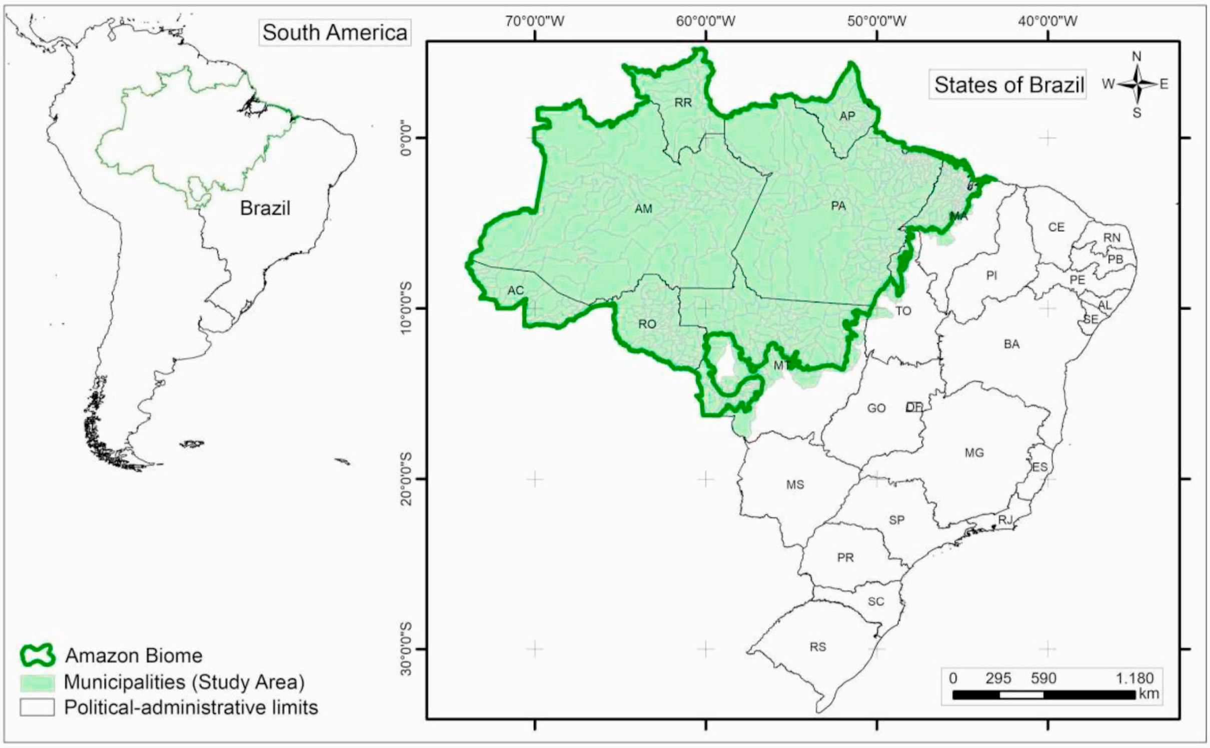

Figure 1. The Brazilian Legal Amazon region used as the case study. Source: [21].

In November 2022, the total area of deforestation amounted to 837,653 km^2, which accounts for 17% of the region [38]. This area is currently experiencing drastic changes and is being subject to close examination, both domestically and internationally. It requires the development and implementation of policies that can reconcile conflicting interests between development and conservation.

2.2. Modeling Approach

In the Integrated Assessment Model (IAM), two methods were applied, namely: (a) systems thinking and (b) systems modeling and simulation. A system is described as "an assemblage of physical objects or components which interact, intercommunicate, or are dependent on each other so as to operate as an integrated whole" [39]. Additionally, in the context of natural resource management, the systems approach provides a basis for the sustainable, multiple use of natural resources by facilitating multidisciplinary planning and the creation of an effective communication interface between scientists and policymakers [40]. IAM has an important role in facilitating the improvement of science-driven policy issues, such as climate change [41]. The systems modeling and simulation approach was used to transform the system thinking model into a quantitative model to simulate the effects of the system. The software STELLA® (V.9.0.3) was used to simulate the demand of forest conversion into new open lands and of ranching productivity rates. A fallow regime was incorporated into the model as a soil management practice to restore soil properties and ranching productivity. Lastly, the effects and sensitivity of gains from ranching expansion and from carbon offsets from avoided deforestation were assessed.

2.3. The System Thinking Concept

The system thinking process employed in this study aimed to explore and develop a theoretical understanding of the fundamental components and interrelationships involved in land-use change processes in the Amazon. It considers the holistic nature of the process of change, incorporating their dynamic complexities [42]. The term "dynamics" suggests that instead of following conventional linear patterns, change processes should be organized into loops of cause–effect relationships [43]. These feedback loops can either reinforce or balance actions, and they involve the active participation of humans who share responsibility for the problems arising from the process and affecting the system. A systems archetype was used to structure a conceptual model of deforestation in the Brazilian Amazon. The method is based on causal loop diagrams, organizing patterns for behavior, and proposing alternative solutions for the problems. The system archetype that best fits the pattern of deforestation in the Amazon is 'shifting the burden' [43] (Figure 2).

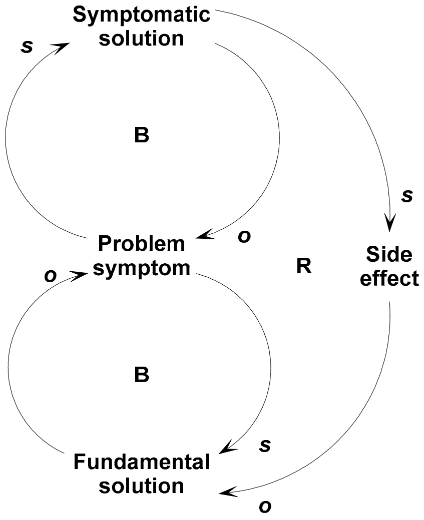

Figure 2. Structure of the systems archetype 'shifting the burden'. Source: [43]. Note: S = same-way effect, O = opposite-way effect, B = balancing loop, R = reinforcing loop.

The archetype is composed of three main parts (circles of causality): The first part theorizes the problem and the adoption of a short-term 'symptomatic solution'; the second part theorizes that even though there are some 'benefits' in using the short-term solution, it brings 'unwanted consequences'; and in the third part a 'fundamental solution' to the problem is sought to induce the sustainable use of resources [43].

The literature indicates this approach can be qualitative, quantitative, or mixed mode [30,31]. In this study, the approach was centered on a quantitative approach only. This decision is supported by the literature, given that quantitative data is considered critical for the model-building exercise [30].

2.4. The Systems Modeling and Simulation of Soil Management on Avoided Deforestation

Following the structure of the *system thinking* concept, a quantitative simulation model was developed as a stock and flow system, using the STELLA$^{®}$ software (V. 9.0.3). Initially, the structure of the model was laid out, followed by the specification of the values of conditions, parameters, and functions. The model was divided into four parts for practical and logical reasons (also, for better understanding the concept, the factors are labeled by numbers (1, 2, 3, etc.). For the system modeling, the model is stratified by parts (A, B, C, and D) and subcomponents labeled in lowercase letters (a, b, c, etc.)):

Part A: population effects on land requirements;
Part B: stock of natural forests and stock of open land;
Part C: the fallow regime;
Part D: the accounting of land use.

The quantitative model description, subdivisions, equations, and data sources are presented and explained in Section 3.2, since it is a result of the systems thinking concept, explained in Section 3.1. Data from the literature [1,44–50] and a statistical database [38,51–55] were used to develop the model. The main outputs (estimates) of the model were: (i) the stocks of natural forests and farmland associated with the soil management practice, (ii) the revenues from ranching expansion and from avoided deforestation, and (iii) the opportunity cost of land. A sensitivity analysis was carried out to assess the significance of the price range of cattle and carbon offsets.

The Opportunity Costs of Land

The economic concept of ‘opportunity cost’ refers to the benefits that are forgone when choosing to use one resource over another, whether in qualitative or quantitative terms. Smallhorn-West and Pressey [56] point out that publications tend to downplay several aspects of opportunity costs, particularly regarding conservation interventions, which can mislead stakeholders’ understanding of land use. In this study, the opportunity cost was analyzed based on two dominant land uses in the study area: (1) cattle ranching and (2) avoided deforestation.

The opportunity cost of cattle ranching was considered because revenues from REDD+ (Reducing Emissions from Deforestation and Forest Degradation) are believed to compensate for potential income arising from ranching if the fallow cycle is not implemented. By avoiding deforestation and thus preventing the release of carbon from forests into the atmosphere, a monetary value can be provided to certain stakeholders. These multiple interests can be aligned, promoting exchanges and fostering behavior change with positive reinforcement. Moreover, this approach can contribute to a more honest and accountable communication of conservation progress, targets, and planning [55]. This article considers the suggestions found in the literature, particularly the notion that income from both ranching and REDD+ can be seen as complementary components of the farm-production portfolio rather than substitutes. This is because REDD+ cannot exist without ranching and forest conservation [15,20,57–60].

2.5. Model Verification and Validation

Model verification was performed to check if: (i) the model was programmed correctly, (ii) data reflected and replicated the correct values, (iii) the algorithms have been implemented properly, (iv) the model did not contain errors, oversights, or bugs, and (v) if the data generated by the model were consistent with the scenarios [61].

Model validation used an ordinary least squares (OLS) regression, evaluating the statistical significance and adjustment of the observed versus the predicted (a) deforestation rates and (b) income from cattle ranching. Also, the results of the estimated opportunity costs were confronted with the results of similar exercises found in the literature (non-parametric analysis).

2.6. Model Limitations

As suggested by Looking-bill et al. [62], "general models have been effective for simulating change over large areas and long timeframes" and they are also ideally suited for characterizing the consequence of climate-induced changes in disturbance regimes that ultimately affect the evolution of landscape pattern over timescales ranging from centuries to millennia". Additionally, Merckx and Pereira [63] argue that modeling exercises and policy considerations should adopt a broad-scale perspective, incorporating less productive lands and protected areas to promote the resilience of functioning ecosystems.

One of the main limitations of general models, including the one used in this study, is that it is lumped (space-independent); therefore, it does not target a specific location in the Brazilian Amazon. So, for its application to field-level management, it needs a higher spatial complexity to account for the spatial heterogeneity of various dynamic factors that lead to variations in model outcomes [64]. This complexity should include considerations of scale and historical behaviors related to land use and biology [63,65]. However, increasing modeling complexity also introduces potential sources of error, particularly when relying on secondary data. For instance, additional factors that could be considered for further improvement in this research are economic, institutional, physical, human, behavioral, and agricultural aspects.

Examples of modeling limitations in the present research include (a) other sources of income beyond ranching and REDD+ abatements, such as timber and grain production; (b) alternative or combined strategies of land management to fallow areas and characteristics at the local level; (c) variation in population size and behavior; (d) factors of production; (e) different types of land tenure [66]; and as suggested by [28], (f) indirect drivers of deforestation, such as trade and consumption, land speculation, and other sources of uncertainty. Including these factors can permit the model application for specific selected regions.

3. Results and Discussion

3.1. The Narrative Policy Framework (NPF)

The Narrative Policy Framework (NPF) and systems thinking design are presented in Figure 3. It starts with the fundamental premise that human beings require food for their subsistence. With the emergence of the market economy, land has become a form of capital where goods and services are produced. Consequently, food and natural resources are exchanged for other goods, addressing the needs of the (1) population, which generates rents that are then transferred to other levels of the economy, (2) rent supplies and demands. In the model, in order to fulfill the population's rent supplies and demands, (3) natural forests must be (4) slashed and burned, resulting in (5) available land for (6) cattle and agriculture production.

This system operates within a balancing feedback process (B1), as the population either grows or declines, leading to a (7) gap between target and actual production. Therefore, as the population increases, this gap also increases. Consequently, a larger area of forest needs to be slashed and burned to produce sufficient food. Conversely, if the population decreases, less deforestation occurs since existing cropland can meet the reduced demands.

The study draws an inference based on the shifting of the burden archetype, suggesting that clearing up more land is a 'symptomatic solution' to the problem, which creates 'undesirable consequences. The consequences of deforestation encompass the loss of forest cover and biodiversity, depletion of water resources, and increased carbon emissions. A critical consequence that falls into a reinforcing feedback process (R) is element (8) in Figure 3, namely, the depletion of production capacity resulting from the loss of soil fertility. Therefore, as land productivity declines, the need for deforestation increases.

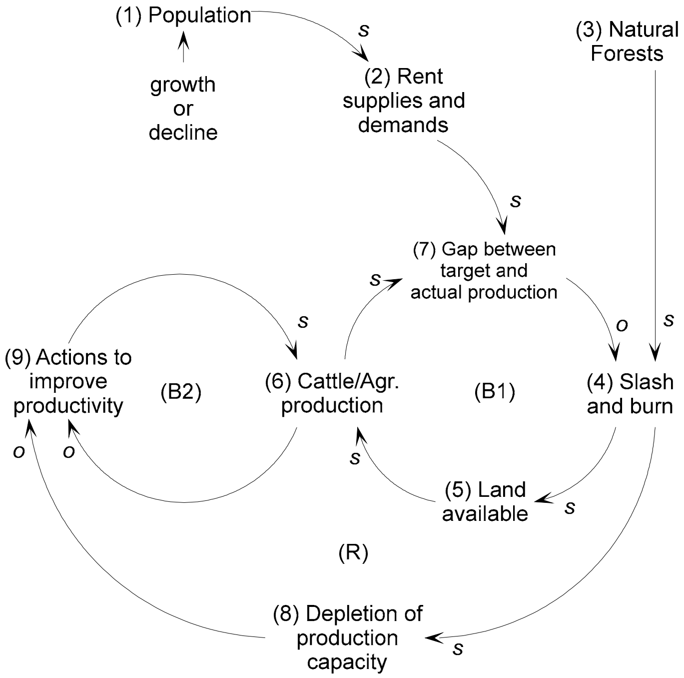

Figure 3. Conceptual system thinking dynamics for land use in the model. Note: S = same-way effect, O = opposite-way effect, B = balancing loop, R = reinforcing loop.

In the Amazon Forest, nutrients are lost through volatilization during burning, exported through timber and crop harvesting, and further depleted due to poor soil management practices, all of which contribute to a rapid decline in soil fertility. As a result, the regrowth potential of vegetation is greatly reduced [47]. Following a clearcut, the region's high-intensity rainfall regime leads to nutrient leaching and runoff, caused by recurrent erosivity [43]. Surprisingly, it has been estimated that only 7% of the land in the Amazon is naturally fertile and free from significant nutrient limitations [50].

Consequently, the third and final loop of the system archetype (B2) focuses on identifying a long-term corrective measure (fundamental solution) to address the reliance on symptomatic solutions (B1) and mitigate the 'unwanted consequences' of soil fertility depletion (R). By implementing another balancing feedback process (9), actions aimed at improving soil productivity should be adopted to sustain or increase cattle production while meeting the population's land demand without resorting to deforestation. Soil management practices offer a potential means to achieve this objective. Several ongoing studies are currently exploring soil management and carbon stocks in the Amazon [50,67–69].

In conclusion, the system thinking diagram above reinforces the notion that soil fertility depletion significantly influences land use and emphasizes the beneficial impact of soil management practices on the conservation of natural forests, thereby reducing pressure on pristine forests.

Figure 4 illustrates an example of the land use dynamics in the municipality of Apuí, located in the State of Amazonas. It demonstrates how overgrazed land (a) leads to the clearing of native forests (b) in the surrounding areas, ultimately resulting in the establishment of new pastures (c). Typically, land clearings progress from more accessible regions to more remote ones as new roads are constructed, expanding the reach into previously inaccessible areas (Figure 4c).

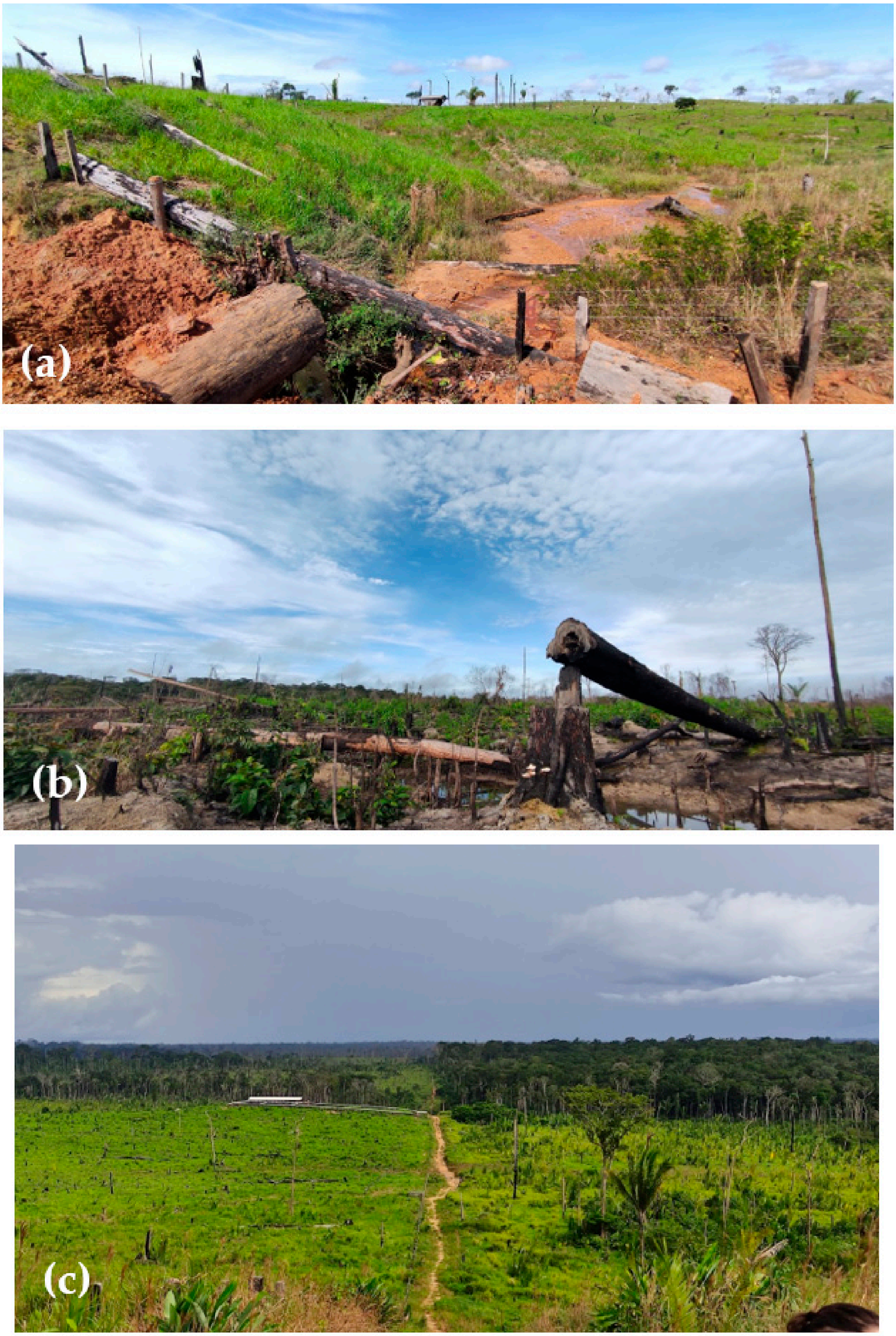

Figure 4. Common field situation of (**a**) overgrazed land, (**b**) clearcut native forest for (**c**) pasture establishment—municipality of Apuí, State of Amazonas. Notes: Author photos.

3.2. *System Modeling of Land Use in the Amazon*

The developed Systems Model is presented in Figures 5 and 6. The model has been divided into Parts A–D and the elements that comprise each part are indicated by lowercase letters. Part D of the model is presented in Figure 6.

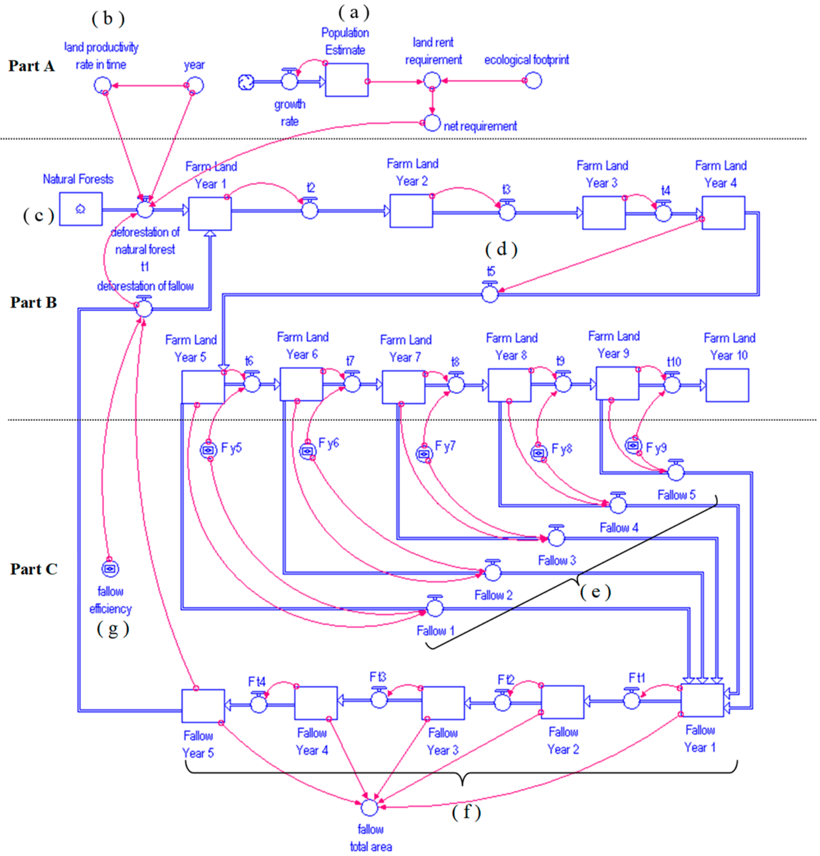

Figure 5. Stock and flow model of the land use in the Brazilian Amazon. Notes: Part A—population effects on land requirements, Part B—natural forests and open land, and Part C—the fallow regime and area.

(a) Part A—Land net requirements and land productivity rate:

In this study, we made certain assumptions about the drivers of deforestation, namely: (a) population growth and its demand for land, limited by (b) the decrease in soil fertility. We estimated the annual population growth rate in Brazil to be 1.4% using data from the Brazilian Institute of Geography and Statistics for the years 1988–2021 [70].

To estimate the individual demand for land, we used a proxy measurement called the ecological footprint, which is assumed to be 10 hectares per person for the Brazilian Amazon [71]. The ecological footprint does not directly influence land use behavior in our model, but it does affect the rate at which land is used as soil fertility declines. Consequently, a higher ecological footprint corresponds to a greater land requirement. In our model, we calculated the net land requirement for a growing population by multiplying the first-order derivative of the population growth rate by the ecological footprint.

Regarding land productivity rates, it is well known that farmland has varying production capacities in different years and that it declines over time, especially when poor soil management practices are employed. In our model, we adopted the principle of soil fertility depletion over time proposed by [44], as illustrated in Figure 7. The authors of that study found that immediately after clearcutting, the carrying capacity of Amazon tropical soils is 0.25 cattle per hectare due to the presence of stumps and slash, which hinder pasture growth. This limitation persists until the second year when the organic matter left by deforestation starts decomposing after the first wet season. During the second year, the carrying capacity increases to 2.0 cattle per hectare. However, the carrying capacity subsequently declines over the following years until the ninth year and beyond, at which point, production stabilizes at a carrying capacity of 0.20 cattle per hectare per year.

Part D

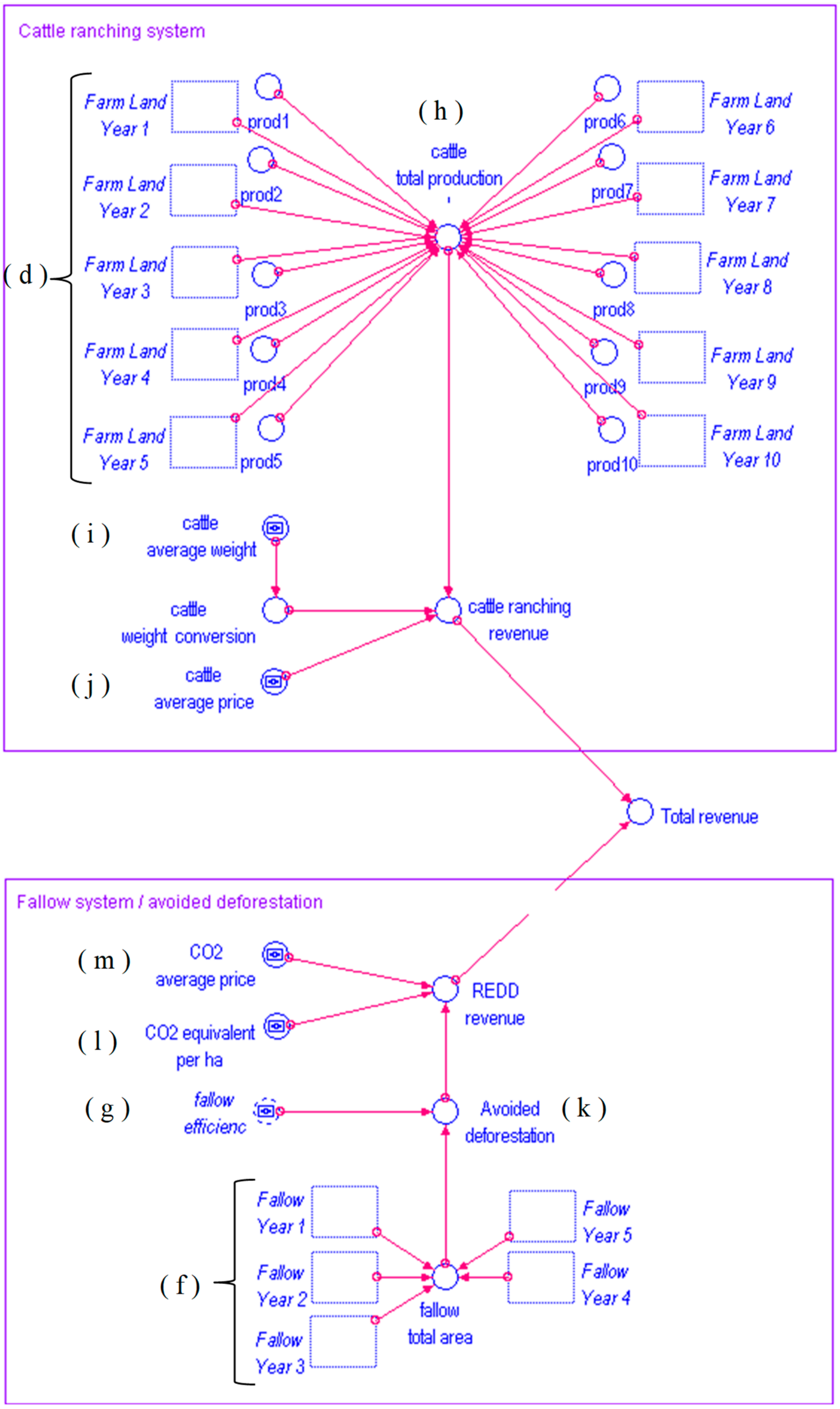

Figure 6. Stock and flow model of the land use in the Brazilian Amazon (continuation). Notes: (1) Part D—accounting of land use (ranching system and its income/revenue, and the fallow system/avoided deforestation and its income/revenues). (2) (f,g) retrieved from Figure 5 (above).

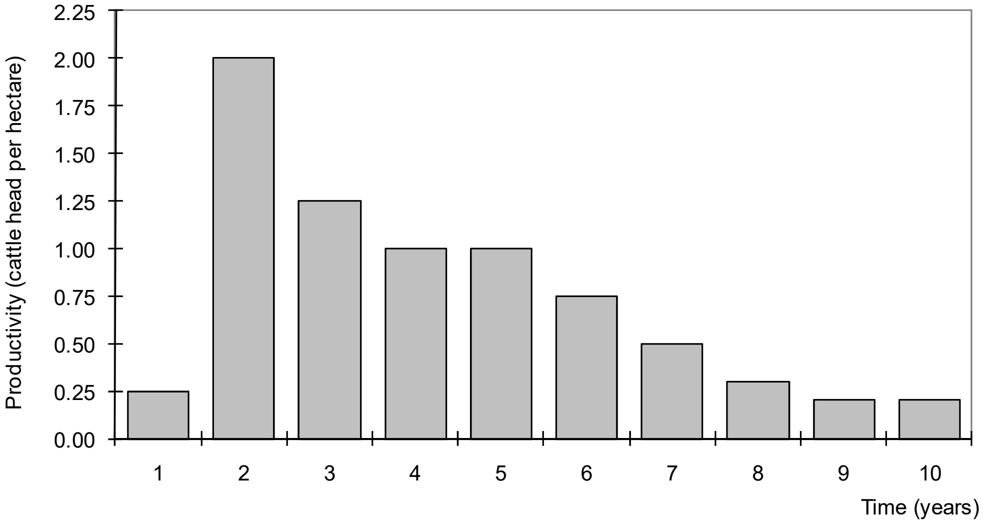

Figure 7. Cattle ranching carrying capacity in the Amazon without soil management. Source: [44].

Due to the non-convex nature of the production function [44], the first year of production was excluded from the analysis. Instead, the production capacity for the second year was calculated as the value for the first year, resulting in a production value of 2.0 cattle heads per hectare. This adjustment was made to obtain a convex function of productivity. The rationale behind this assumption is that in the first year, forest clearcutting does not occur all at once but rather happens throughout the year due to various constraints, such as climate, resources, and access.

Therefore, the net land requirements can be determined by multiplying the population's net requirements for production with the *land productivity rates* over time, as specified in Equation (1).

$$\text{Land net requirement} = \text{population} \times \text{population growth rate} \times \text{ecological footprint} \quad (1)$$

(b) Part B—Stock of natural forests and stocks of farmland:

The second part of the model incorporates the inclusion of the stock of natural forests (c) and how, once the forest is cleared through deforestation, these areas transition into stocks of farmland (d) (Figure 5). In the initial year of agricultural use, the cleared land is referred to as farmland year 1. As time progresses, this stock of land transitions to farmland year 2, and so on (The model design developed is an open view of the function named 'queue' in STELLA. The intent here is to facilitate the understanding of this process, as in its 'closed' modeling form). The extent of deforestation is influenced by the land net requirements (Part A), excluding the fallow land that is allowed to regenerate for future production. Based on these factors, estimates were made for the stocks of natural forest (Equation (2)) and the available farmland for production (Equation (3)).

$$\text{Stock of natural forests } = \sum\nolimits_{i=1}^{n} \text{land net requirements} * \left(\sum\nolimits_{i=1}^{n} \text{deforestation} - \sum\nolimits_{i=1}^{n} \text{land fallow returned to production}\right) \quad (2)$$

$$\text{Farm land } = \sum\nolimits_{i=1}^{n} \text{land deforested} + \sum\nolimits_{i=1}^{n} \text{land fallow returned to production} \quad (3)$$

A dummy variable was included in the model to capture the effect of the National Plan for Prevention and Control in the Legal Amazon—PPCDAm, created in 2004 [72]. The policy effect was considered after 2009, with a reduction of 60% in the deforestation rates.

(c) Part C—The soil management system and total area lie fallow:

As the third part of the model, a fundamental solution to improve soil productivity was pursued in which farmland is subjected to a fallow regime of natural regeneration. The proposed land-use system is plot rotation. A farmer can let varying percentages of land to fallow from year to year (e). For practical reasons, only one level of fallow was tested; this is to allow 100% of the farmland stock in one given year (year 5, 6, 7, 8, or 9).

The model assumed that if land is allowed to (f) lie fallow, land recovers a certain rate of its original productivity; this is the measure of (g) fallow efficiency. In this model, land stays fallow for five years, going back to the system for production at the 6th year and it is assumed that the rate of fallow efficiency is 100%. The model permits adaptation to allow the fallow regime to have a longer or shorter length of time (in years), and to have different rates of fallow efficiency. Those were not reported here given space limitations. Also, other types of additionalities from fallow were not considered for analysis in this study.

The premises above consider the regenerative capacity of tropical secondary forests to sequester carbon and to rebuild the nutrient capital following pasture abandonment [6,73–76]. Styger and Fernandes [77] (p. 425) define fallow as a "resting period for agricultural land between two cropping cycles during which soil fertility is restored, [nevertheless] it has more roles than just fertility restoration". Fallow can also: (a) control weeds and pests, produce wood, fibers, and medicinal plants, (b) produce structural benefits to the soil (physical, biological, organic, and inorganic), and (c) be combined with the natural regeneration or planted trees, shrubs, and herbs, which can generate other associated economic benefits. Nevertheless, they cautioned that "fallowing alone may not be sufficient to achieve a productive sustainable system", noting that other types of supplementations may be necessary [77] (p. 433).

(b) Part D—The accounting of land use:

The final part of the model is where the 'accounting of land use' is measured (Figure 5). Here, the model simulated: cattle ranching revenue, REDD+ revenue (from VCUs), and their sum as the total revenue. For easier understanding, the model is separated into two boxes (Figure 6). The box on the top of the page simulates the cattle ranching system and the box on the lower part simulates the fallow system and avoided deforestation. The total revenue is the sum of the cattle ranching revenue and the REDD+ remuneration.

Here, the accounting of land use excludes the following factors: (a) leakage, (b) VCUs generated from fallow itself, and (c) VCUs from improved land management (VM0042). It is assumed that control and management practices lead to a neutral estimate. Two equations were specified to estimate revenues from ranching and the REDD+ revenues from carbon offsets. They were:

$$\text{Cattle ranching revenue} = \text{total cattle production} \times \text{average cattle carcass weight} \times \text{average price} \tag{4}$$

where (the equation factors are represented in letters (h), (i), and (j) in the STELLA model (Figure 5)):

*Total cattle production = stock of land available in a given year * land productivity rate in time* (variable value)

The land productivity rate is based on Hecht et al. [44].

The average cattle weight of 250 kg (fixed value). Average third quarter 2022 [51].

The average price in 2022 for the cattle arroba (@ = Brazilian weight measurement = 15 kg) at slaughter was ~USD 50 (in Paragominas, Pará ((a) Exchange rate Brazilian Reais (BRL) to US Dollars ~5.0 (minimum rate in 2021 and 2022). (b) Average price for cattle arroba: 2019 = BRL 152~USD30, 2020 = BRL 200~USD 40, 2021 = BRL 300~USD 60, 2022 = BRL 250~USD 50) [52]. The average price USD 30 and USD 40 were used to test the sensitivity.

$$\text{REDD+ revenues} = \text{area of avoided deforestation} * CO_2 \text{ equivalent/ha} * \text{average C price} \tag{5}$$

where (the equation factors are represented in letters (k), (l), and (m) in the STELLA model (Figure 5)):

*Area of avoided deforestation = (total area * fallow efficiency).*

The total area available for abatements is equal to the area fallowed multiplied by the fallow efficiency (variable value). This is the area of forests that will not need to be slashed and burned to maintain cattle production stable. This is a generalized and reduced complexity formula that considers the elements of planned and unplanned deforestation, and forest degradation considered on the VCS VM0007 [14].

The carbon stock equivalent (C/ha) in forests is 200 MgCha^{-1} (fixed value) (Forest Type = Dense forest + Open Forest/simple average = (212 + 188)/2 = 200 MgCha^{-1}. The Project "Canindé Grouped REDD+ Project" registered at Verra = 744.29 tCO$_2$/ha * 0.27 (constant) = ~200 MgCha^{-1}) [53,54].

The average price set for carbon ton equivalent was USD 1.00, USD 2.50, or USD 5.00—variable value (conservative values were considered) [46,54,55].

Since this is a modeling study of a macroscale policy strategy, only the gross revenue was considered, representing the businesses' values, growth potential, and how much money can be earned with each activity. The gross revenue would allow general comparisons to be better comprehended. At the microscale, each farm has its production and cost functions, and net revenue is dependent on each farm administration strategy. This specific analysis goes beyond the scope of the article.

The complete specification of the algorithms used for modeling and the programming syntax are presented in Appendix A.

3.3. Model Verification and Validation

A robust model verification process was developed, to minimize the effects of errors on the results of the simulation. Model validation indicates that the proposed model has good accuracy in interpolations of:

(a) the deforestation pattern in the Brazilian Amazon, from 1988–2022 (Figure 8)—the statistical evaluation based on OLS single regression of the (1) data from the Brazilian Institute of Spatial Research [38], versus the (2) simulated data resulted in a R^2 = 0.93, with no intercept (regression with the intercept, shown no significance on the parameter. R^2 estimates = 0.75, confidence > 99%) (confidence level of 99%, F = 784.1, Durbin Watson = 1.244, no auto correlation with 5% significance (Critical values → n = 35, k′ = 1, dL = 1.402, dU = 1.519), and good fit of residuals).

(b) the income from ranching (Appendix B)—the (1) data from the Ministry of Agriculture, Ranching [78], versus the (2) data produced from simulation resulted in an R^2 = 0.90 for income in USD and R^2 = 0.99 for income in Brazilian Reais (BRL), both with no intercept (confidence level of 99%, F = 94.5 for USD, F = 2190 for BRL).

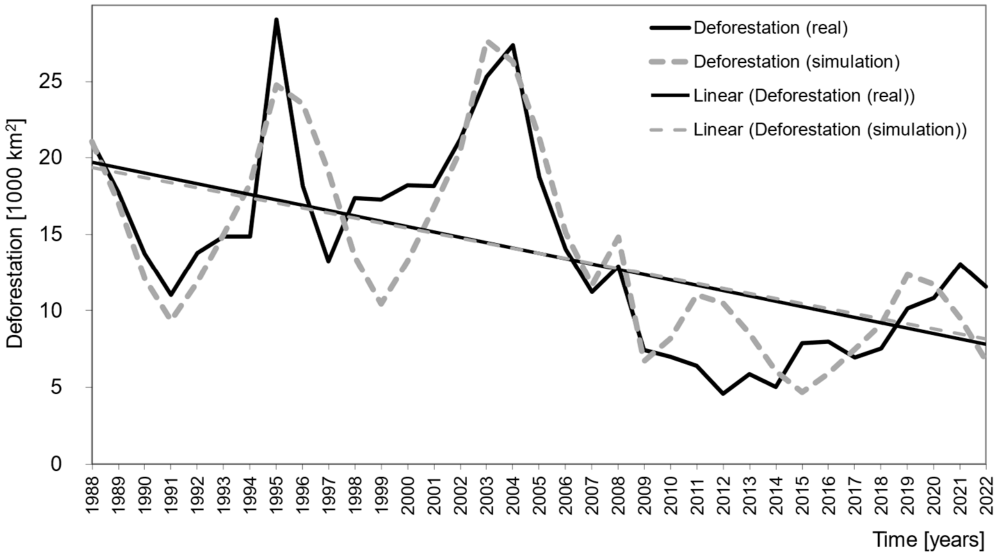

Figure 8. Annual deforestation of the Brazilian Amazon (observed [57] and modeled), 1988–2022.

Figure 9 illustrates the projected impacts of cumulative land deforestation in the Brazilian Amazon forests under a business-as-usual (BAU) scenario, without any fallow periods, as well as the potential effects of different fallow regimes on soil productivity. According to the simulations, natural forests would experience a reduction of 9.8% within a 50 year period. However, implementing fallow periods can help mitigate deforestation. The estimated deforestation rates with fallow range from 2.9% to 3.7%, depending on when the fallow periods begin, with rates increasing from 2.9% for fallow starting in year 5, to 3.7% for fallow starting in year 9. These findings highlight the importance of early implementation of fallow periods to minimize deforestation in the region and preserve soil productivity.

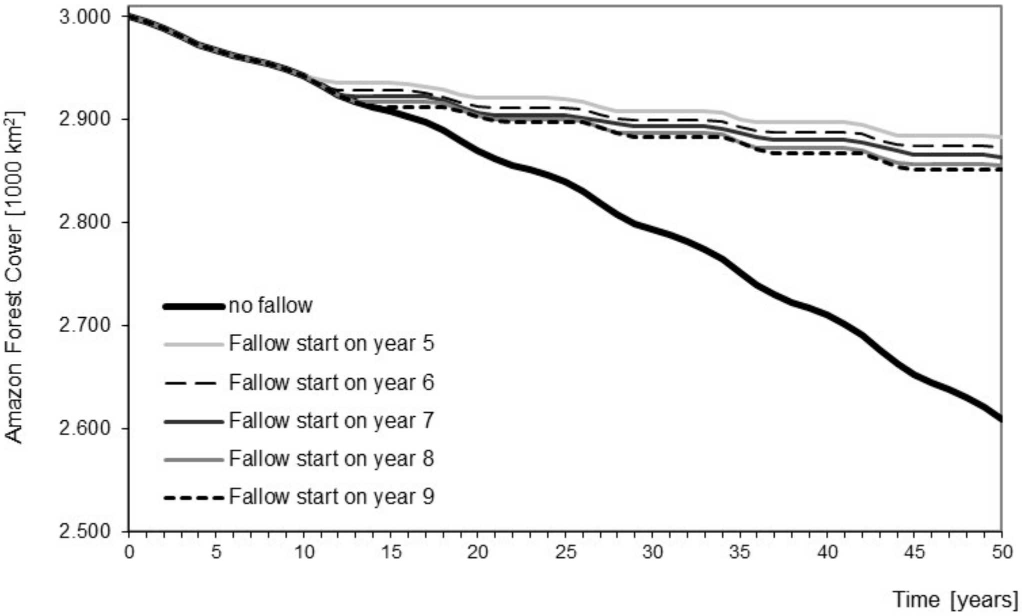

Figure 9. Simulation results—effects of deforestation trends on the Amazon Forest cover, with and without fallow (in 10^3 km^2).

The fallow management regime alone is not able to halt deforestation of natural forests, though it has a significant impact in easing deforestation trends in at least 62% of the cases (with fallow starting in year 9). The earlier the fallow regime starts, the more effective it is in diminishing deforestation. These findings indicate that soil management practices can have a large impact on deforestation and land-use trends.

3.4. Income from Ranching and Fallow

The simulation of cattle production and farmer income shows positive trends with and without the fallow practices (Figure 10). The estimates for cattle heads are equivalent to the income and will not be presented since the results are proportional to income.

Figure 10 indicates that ranching without fallow promotes higher returns and yields, compared to ranching with fallow systems. Specifically, the earlier fallow is started, the lower the returns from ranching if the practice starts at later years (i.e., less in the fifth year, less in the sixth year, and so forth). In conclusion, considering only ranching income, the adoption of fallow could be seen a "loss of returns" for the landowner, and if adopted, it would be better in later years.

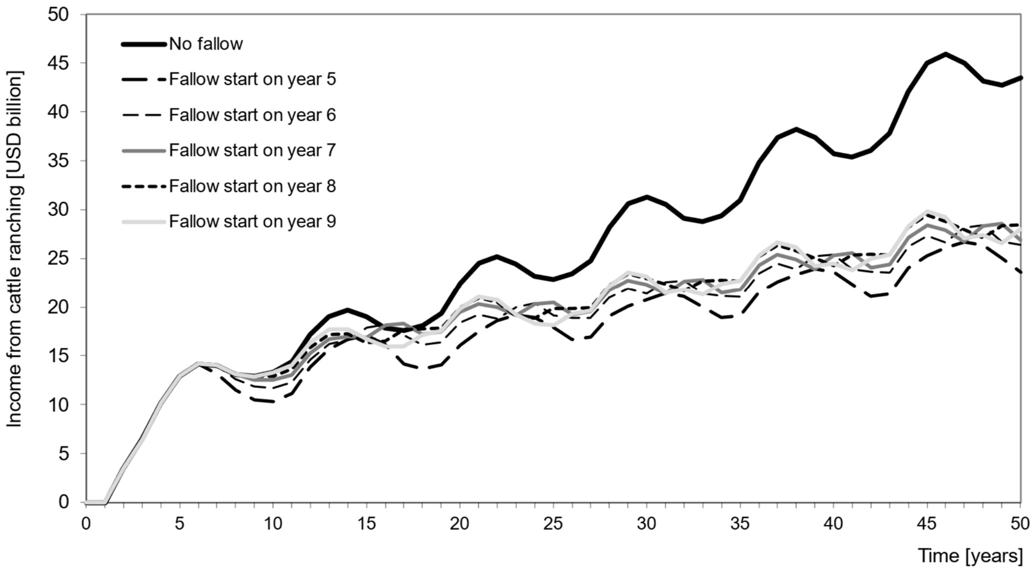

Figure 10. Simulation results—revenue from cattle ranching, with and without fallow (USD billion).

3.5. Income from Avoided Deforestation

Simulation of the income generated from avoided deforestation (REDD+) also shows a positive trend over time (Figure 11). When fallow is not adopted, the accounting of avoided deforestation is not computed, and no income is generated. Conversely, when fallow is adopted, the earlier it starts, the larger the returns from REDD+ if initiated at later years (i.e., greater in the fifth year, greater in the sixth year, and so forth). In conclusion, adopting fallow could be seen as "gain in returns" for the landowner, and if adopted, it would be preferred at later years.

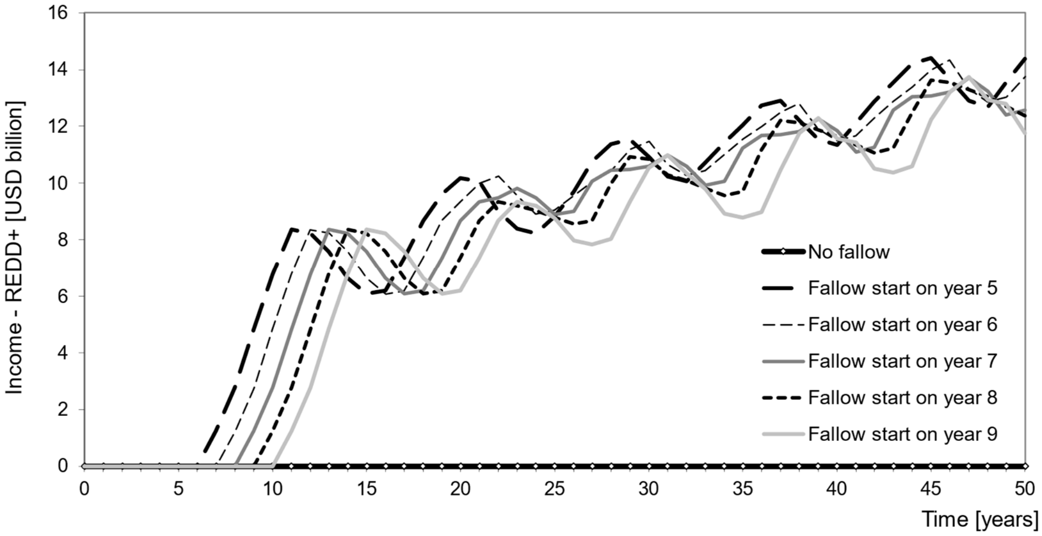

Figure 11. Simulation results—total income from REDD+/avoided deforestation (USD billion).

3.6. Income Sensitivity to Carbon and Cattle Prices

In the general Amazon model, the primary outcome was the estimation of the sensitivity of income generated from ranching and the REDD+ policy. This analysis considered various price scenarios for cattle and carbon, such as cattle prices of USD 30, USD 40, and USD 50 per unit weight (@), and carbon prices of USD 1.00, USD 2.50, and USD 5.00 per metric ton of carbon sequestered ($MgCha^{-1}$).

Figure 12 and Table 1 display the results for a fallow period starting in year 7, which is the midpoint between year 5 and year 9. Comparing the results, it is evident that the profitability of each activity can vary depending on the prevailing market prices. In some cases, one activity may yield higher returns compared to the other, depending on the specific market conditions.

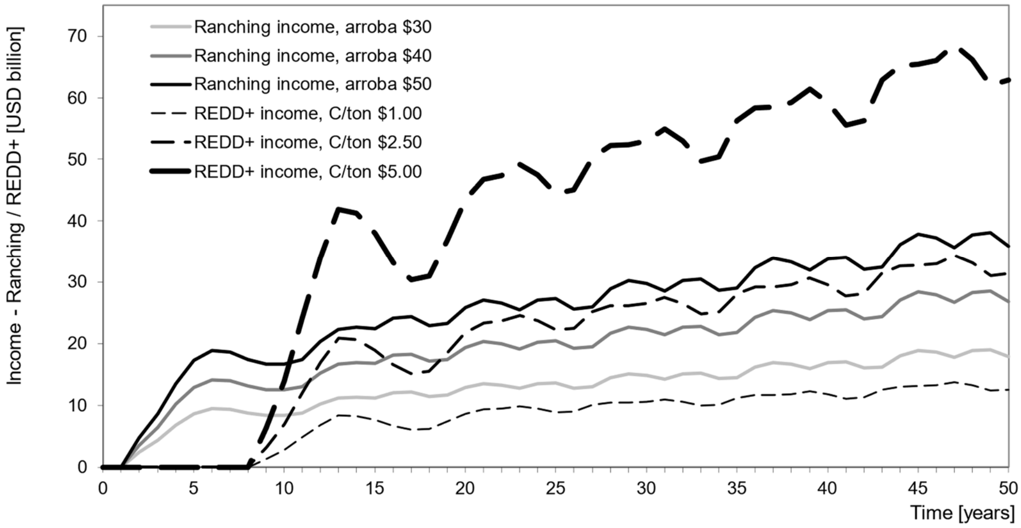

Figure 12. Simulation results—total income variation given different prices for cattle and carbon (Ranching and REDD+, isolated). Note: results for fallow starting at year 7 (USD billions).

Table 1. Total income from cattle ranching and REDD+ activities—year 20 (in USD billion).

Sources of Income		**Ranching Income** [1]			
		USD 0	**USD 30**	**USD 40**	**USD 50**
REDD+ income [2]	**$0.0**	0.0	13.0	19.4	25.9
	$1.0	8.7	21.6	28.1	34.6
	$2.5	21.7	34.6	41.1	47.6
	$5.0	43.4	56.3	62.8	69.3

Note: results for fallow starting at year 7. [1] Arroba price (15 kg). [2] C/ton price.

The simulation indicates that when the carbon price is USD 1.00/MgCha^{-1}, the income accrued from avoided deforestation (USD 8.7 billion) is smaller compared to cattle prices of USD 30/@, USD 40/@ and USD 50/@ (13.0, 19.4, 25.9 billion). But, when the price of carbon is USD 2.50/MgCha^{-1} the revenue from REDD+ can be equivalent to cattle ranching at USD 40/@ (21.7 and 19.4, respectively). Finally, when the price of carbon is USD 5.00 per ton, the income from avoided deforestation is higher than those of cattle ranching with the price USD 50/@ (43.4 and 25.9, respectively). In all, the price paid for carbon can provide a real stimulus to landowners to change land-use behavior and adopt soil management practices to compensate and complement the rents that could accrue from land use.

3.7. Opportunity Cost of Land

In Figure 13 are presented the results from the model simulation of the income from ranching and the impact that fallow regimes have on long-term ranching revenues. Conventionally, the opportunity cost would be thought of as an implication of the result presented in Figure 10, in which fallowing would diminish the opportunity cost of land and of the ranching activity [58,59].

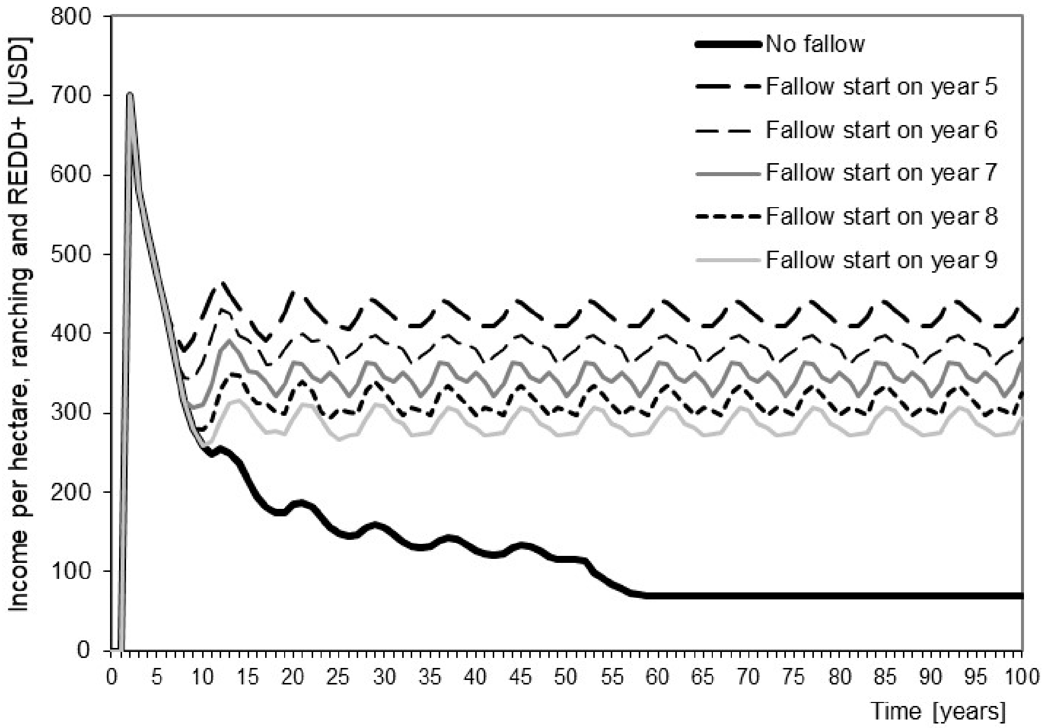

Figure 13. Simulation results—income per hectare from cattle ranching and REDD+, without and with fallow (in USD/hectare).

Figure 13 indicates that the opportunity cost of land for ranching would have a lower value when the fallow regime is not adopted. Thus, with fallow, more value is aggregated to the land, increasing opportunity costs. This was because the environmental services provided by the land starts to be measured and paid (e.g., carbon payments and the promotion of soil conservation, which consequently permits the ranching production with more cattle heads per hectare).

The results of the general model indicate that, in the long run, when fallow is not adopted, the average income will continuously decline until it is stabilized at approximately USD 70 per hectare (after year 55). The income decrease happens because general land productivity is lowered in later years with grazing. So, even when new forests are cleared and incorporated into the system with the intent of maintaining cattle production, the average revenues will continually decline over time until stabilization.

With the fallow regime, cycles of soil fertility are created, which reflects on stabilized (increasing and decreasing) trends of income in the long run. Thus, a stable system is created, so production and income increase.

The estimated opportunity cost of ranching land (per year) over in the long run was: (a) no fallow = USD 138, (b) fallow at year 5 = USD 420, (c) fallow at year 6 = USD 383, (d) fallow at year 7 = USD 348, (e) fallow at year 8 = USD 318, (f) fallow at year 9 = USD 295. So, the opportunity cost of land is higher the earlier the fallow system starts.

Another justification for adopting soil management practices is that agriculture expansion moves into old, consolidated ranching areas, converting them to soybeans farms [71]. Soybean growing is more profitable and promotes more carbon sequestration compared to ranching [69,72], and this would consequently increase the opportunity cost in the future.

The REDD+ income per hectare varies according to the market MgCha^{-1} price. For this model, the carbon stock (C/ha) in forests is fixed at 200 MgCha^{-1} per hectare. The estimated opportunity cost per hectare of preserved forest would be: (a) USD 250 considering USD 1.00/MgCha^{-1}, (b) USD 625 considering USD 2.50/MgCha^{-1}, and (c) USD 1250 considering USD 5.00/MgCha^{-1}. So, the opportunity cost of land tends to be higher with REDD+ at USD 2.50/MgCha^{-1} than with ranching alone, even with the best fallow strategy.

Therefore, here we estimated that the compensation value for the conversion program would be between USD 2.5 and USD 5.0, considering the cattle ranching at a USD 50/@. Nepstad et al. [16] also estimated the Brazilian "national opportunity costs" of the forgone profits from forest-replacing agricultural and livestock production systems to forest maintenance. They indicated that USD 3.0/MgCha^{-1} could be the opportunity cost of avoiding the Amazon Forest emissions, and of USD 5.5/MgCha^{-1} in the best scenario. In the entire Amazon region, they estimated the compensation of USD 450 billion (~15 billion/year/average) for a 30-year program [17]. de Figueiredo Silva [60] estimated an average shadow price to a range of USD 6.76 to USD 16.64/MgCha^{-1} to preserve the Amazon carbon stocks, but without considering the effects of soil fertility depletion, and therefore tending to increase the value of the estimate. They estimated a total cost of USD 257 billion, but with a phase in and phase out strategy [17]. The results obtained by other authors are approximate to the ones generated in the present study, validating the proposed method.

West et al. [35] found that zero gross deforestation was unattainable, but zero net carbon emission could be reached at approximately two-thirds the cost, with reduced impacts on food production. For instance, they found that the revenue transference initiated at USD 5/MgCha^{-1} and increased with the MgCha^{-1} price. They suggest that shifts in food production are directly a consequence of the "optimal bundle" of returns, and households tend to opt out of the program if they perceive that there would be a reduction of revenue, because of the shift in the opportunity cost of land use. These results are also equivalent to those developed in the present study, but here they were obtained with a more generalized and simpler model. This indicates that the proposed method can indeed work as a Narrative Policy Framework (NPF).

Using an integrative approach named "FALLOW model" on an aggregated scale of Upper Konto, Indonesian researchers concluded that a land zoning approach is the most promising way to balance (a) fodder availability, (b) farmers' welfare (total profits gained), and (c) increase ecosystem functions (such as carbon stocks) [9]. Similar factors were used in the present study, including the livestock carrying capacity, soil fertility recovery during fallow, and carbon sequestration, along with manure and livestock dynamics.

Results of the Indonesian authors follow the same findings here, by capturing the dynamics of agricultural expansion, and welfare (income). They recommend the use of results at the mesoscale level of decision-making, subsidizing the debate of GHG emissions. All systems models must be simplified, and should not be used for numerical predictability, but rather should provide an understanding of possible outcomes, and guidance to the type of acceptable application.

The final decision of land allocation (size, period, etc.) for different management strategies is dependent on the optimization state of the income accrued from agriculture and REDD+. As suggested by West et al. [35], the "optimal bundle" is a consequence of implicit returns from land use. We conclude that land-use behavior is based on the *perceived* opportunity cost of the land, so that policy scientists should seek changes in conventional ways of thinking and behavior [56,79].

3.8. Sinergies of the Conservation Policy, Socio-Economic Objectives, and Practical Applications

Brazil already has a National Strategy for Reducing Emissions from Deforestation and Forest Degradation (ENREDD+), which regularly receives incentive-based payments for forest conservation from various international sources, in particular the Green Climate Fund (GCF). The National Strategy aims at fostering sustainable productive activities through the following steps: (a) strengthen the productive chains that constitute alternatives to deforestation; (b) promote good practices in agriculture, including alternatives to the use of fire; (c) increase the production of wood and promote market growth for sustainable forest management; (d) promote environmental compliance and foster sustainable production in agrarian reform settlements and smallholdings; and (e) generate sustainable-development-related science, technology, and innovation in the Amazon [80]. This study is closely related to these objectives.

Recently, on 5 June 2023, the President of Brazil instituted a National Commission to coordinate, monitor, and revise the ENREDD+ (Decree 11548/2023). One of the Commission's mandates is "to issue certificates recognizing the payment for REDD+ results in the country" (Article 9), and to entitle the Brazilian development bank-BNDES to receive the payments of its proceedings (Article 11).

Given this institutional context, the proposed method and its results can be instructive for the government and private stakeholders as a pathway for agreements and for policy implementation related to land conservation. The allocation of resources is necessary, and BNDES could anticipate future payments by covering the expenses of projects, especially in deforestation hot spots.

One of the downsides of Brazil's ENREDD+ policy is that direct payments are made only to Federal and State governments, which invest these resources in local projects (REDD+ for Early Movers—REM). Decentralizing the incentive-based payments at the local level could reinforce the behavior change of peasants and farmers after they perceive the trade-offs and payoffs of their investments in sustainable practices [60]. Torres et al. [81] relate that in the Ecuadorian Amazon, the adoption of financial incentive programs promoted the implementation of livestock best management practices at the household level, and also enabled public–private partnerships to develop REDD+ projects. In the end, most farmers are searching for ways to manage the land and to generate income [10,12,73].

Considering international policies, the EU focus on creating market barriers, such as banning unsustainable products, is considered to "miss out deeper leverage points to address the systemic drivers of deforestation", being considered relevant to put incentives for more sustainable agricultural production and compensations as REDD+ [28].

Some of the alternatives for policy implementation could be the promotion of programs for (a) extension services, (b) property regularization, and (c) environmental compliance. Nevertheless, such programs face many challenges, since illegal and criminal practices are some of the drivers that expand the agriculture frontier. On the other hand, governments lack field capillarity and human resources to implement and keep up with the task. This tends to be a vicious cycle, and tackling this problem is key for governments and citizens.

4. Conclusions

General landscape models are widely recognized as important tools to facilitate debates and decision-making processes for developing improved conservation policies in developing countries [9,36,62,64,65,69,82,83]. However, when increasing complexity arises from the incorporation of factors or drivers into the models, it is essential to exercise caution and prioritize simplicity to effectively induce behavioral changes in conservation-oriented strategies [43,84].

To advance the discussion surrounding REDD+ initiatives, this study applied an Integrated Assessment Model (IAM), using systems thinking and systems modeling and simulation. The objective was the development of a Narrative Policy Framework (NPF) that could assess the behavior of land conversion and trade-offs between fallow regimes in cattle ranching. The general model yielded different outcomes for various management scenarios, considering different cattle and carbon prices, as well as opportunity costs. This facilitated the construction of a theory of change toward sustainable land use in the Amazon.

The findings of this quantitative study reinforce those obtained in previous studies, highlighting the beneficial impact of soil management practices on the conservation of natural forests, making them eligible for payments for environmental services [9,10,82]. In the case of the Brazilian Amazon, where fallow practices are not common and land is often overused, system modeling can serve as a tool to educate farmers and managers about the different outcomes of land use and management.

Additionally, it can enhance dialogue among stakeholders, contributing to the development of a political agenda and the customization of lower-level programs toward sustainable development. These aspects could be incorporated into the current Brazilian policy customization, especially since the National Commission of REDD+ has recently been established, enabling the issuance of certificates for incentive-based payments (RBP).

The proposed model provided a good fit between observed and modeled results, indicating that the fallow management regime alone may not be sufficient to halt deforestation of natural forests, but still has a significant impact in reducing deforestation trends in at least 62% of the cases.

The earlier the fallow practice starts, the more effective it tends to be in diminishing deforestation and increasing income from REDD+. However, from a revenue perspective, starting later is better. Thus, compensation for avoided production plays a crucial role as a trade-off policy. The payments collected for avoided deforestation need to be directly distributed to those implementing the policy, including the landowners. This ensures that landowners can directly benefit from the opportunity cost voided by the ranching production [23,60].

Addressing this gap in public policy is crucial in Brazil, since all local REDD+ RBP payments are currently collected by the Federal and State Governments only. On the other hand, the literature emphasizes the importance of making REDD+ RBP more distributed at the local level [12]. Collecting rents from both sustainable agriculture and avoided deforestation could bring about a change in conventional practices, such as the intensive and exhaustive use of land, and influence land management behavior towards more sustainable practices [10,82].

At the macro level, the proposed model suggests that a payment between USD 2.5 and USD 5.0 per MgCha^{-1} has the potential to compensate for the foregone cattle ranching production, considering a price of USD 50 per 15 kg (@). These results are similar to those of other studies that utilized different methods and data [17,35,60], demonstrating that the model serves as a tool to facilitate multidisciplinary planning and as a communication interface between scientists, policymakers, citizens, and especially peasants and farmers [9,40].

The proposed model has a potential for future research, including the incorporation of additional complexities, such as drivers of deforestation, alternative management strategies, and downscaling to the local level. As suggested by McGregor et al. [64], the combination of different scales can produce 'better solutions' by capturing a pluralistic perspective and improving commitment.

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Data Availability Statement: The datasets generated in this study are available from the corresponding author upon reasonable request.

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Conflicts of Interest: The authors declare no conflict of interest.

Appendix A. Algorithms Specification and Programming Syntax

☐ Fallow_Year_1(t) = Fallow_Year_1(t − dt) + (Fallow_1 + Fallow_2 + Fallow_3 + Fallow_4 + Fallow_5 − F_t1 ×dt

INIT Fallow_Year_1 = 0

INFLOWS:
→ Fallow_1 = Farm_Land_Year_5*F_y5
→ Fallow_2 = Farm_Land_Year_6*F_y6
→ Fallow_3 = arm_Land_Year_7*F_y7
→ Fallow_4 = Farm_Land_Year_8*F_y8
→ Fallow_5 = Farm_Land_Year_9*F_y9
OUTFLOWS:
→ F_t1 = Fallow_Year_1

☐ Fallow_Year_2(t) = Fallow_Year_2(t − dt) + (F_t1 − F_t2) * dt

INIT Fallow_Year_2 = 0
INFLOWS:
→ F_t1 = Fallow_Year_1
OUTFLOWS:
→ F_t2 = Fallow_Year_2

☐ Fallow_Year_3(t) = Fallow_Year_3(t − dt) + (F_t2 − F_t3) * dt

INIT Fallow_Year_3 = 0
INFLOWS:
→ F_t2 = Fallow_Year_2 OUTFLOWS:
→ F_t3 = Fallow_Year_3

☐ Fallow_Year_4(t) = Fallow_Year_4(t − dt) + (F_t3 − F_t4) * dt

INIT Fallow_Year_4 = 0
INFLOWS:
→ F_t3 = Fallow_Year_3 OUTFLOWS:
→ F_t4 = Fallow_Year_4

☐ Fallow_Year_5(t) = Fallow_Year_5(t − dt) + (F_t4 −deforestation_fallow) * dt

INIT Fallow_Year_5 = 0
INFLOWS:
→ F_t4 = Fallow_Year_4 OUTFLOWS:
→ deforestation_fallow = Fallow_Year_5*fallow_efficiency

☐ Farm_Land_Year_1(t) = Farm_Land_Year_1(t − dt) + (deforestation_fallow + deforestation_natural_forest_t1- t2) * dt

INIT Farm_Land_Year_1 = 0
INFLOWS:
→ deforestation_fallow = Fallow_Year_5*fallow_efficiency
→ deforestation natural_forest_t1 = (net_requirement*year*land_productivity_rate_in_time)-deforestation_fallow
OUTFLOWS:
→ t2 = Farm_Land_Year_1

☐ Farm_Land_Year_10(t) = Farm_Land_Year_10(t − dt) + (t10) * dt

INIT Farm_Land_Year_10 = 0
INFLOWS:
→ t10 = Farm_Land_Year_9*(1-F_y9)

☐ Farm_Land_Year_2(t) = Farm_Land_Year_2(t − dt) + (t2 − t3) * dt

INIT Farm_Land_Year_2= 0
INFLOWS:
→ t2 = Farm_Land_Year_1
OUTFLOWS:
→ t3 = Farm_Land_Year_2

☐ Farm_Land_Year_3(t) = Farm_Land_Year_3(t − dt) + (t3 − t4) * dt

INIT Farm_Land_Year_3 = 0
INFLOWS:

→ t3 = Farm_Land_Year_2
OUTFLOWS:
→ t4 = Farm_Land_Year_3

☐ Farm_Land_Year_4(t) = Farm_Land_Year_4(t − dt) + (t4 − t5) * dt
INIT Farm_Land_Year_4 = 0
INFLOWS:
→ t4 = Farm_Land_Year_3
OUTFLOWS:
→ t5 = Farm_Land_Year_4

☐ Farm_Land_Year_5(t) = Farm_Land_Year_5(t − dt) + (t5 − Fallow_1 − t6) * dt
INIT Farm_Land_Year_5 = 0
INFLOWS:
→ t5 = Farm_Land_Year_4
OUTFLOWS:
→ Fallow_1 = Farm_Land_Year_5*F_y5
→ t6 = Farm_Land_Year_5*(1-F_y5)

☐ Farm_Land_Year_6(t) = Farm_Land_Year_6(t − dt) + (t6 − Fallow_2 − t7) * dt
INIT Farm_Land_Year_6 = 0
INFLOWS:
→ t6 = Farm_Land_Year_5*(1-F_y5)
OUTFLOWS:
→ Fallow_2 = Farm_Land_Year_6*F_y6
→ t7 = Farm_Land_Year_6*(1-F_y6)

☐ Farm_Land_Year_7(t) = Farm_Land_Year_7(t − dt) + (t7 − Fallow_3 − t8) * dt
INIT Farm_Land_Year_7 = 0
INFLOWS:
→ t7 = Farm_Land_Year_6*(1-F_y6)
OUTFLOWS:
→ Fallow_3 = Farm_Land_Year_7*F_y7
→ t8 = Farm_Land_Year_7*(1-F_y7)

☐ Farm_Land_Year_8(t) = Farm_Land_Year_8(t − dt) + (t8 − Fallow_4 − t9) * dt
INIT Farm_Land_Year_8 = 0
INFLOWS:
→ t8 = Farm_Land_Year_7*(1-F_y7)
OUTFLOWS:
→ Fallow_4 = Farm_Land_Year_8*F_y8
→ t9 = Farm_Land_Year_8*(1-F_y8)

☐ Farm_Land_Year_9(t) = Farm_Land_Year_9(t − dt) + (t9 − Fallow_5 − t10) * dt
INIT Farm_Land_Year_9 = 0
INFLOWS:
→ t9 = Farm_Land_Year_8*(1-F_y8)
OUTFLOWS:
→ Fallow_5 = Farm_Land_Year_9*F_y9
→ t10 = Farm_Land_Year_9*(1-F_y9)

☐ Natural_Forests(t) = Natural_Forests(t − dt) +(deforestation_natural_forest_t1) * dt
INIT Natural_Forests = 50
OUTFLOWS:
→ deforestation_natural_forest_t1 = (net_requirement*year*
land_productivity_rate_in_time)-deforestation_fallow

○ average_price_@_cattle_U$ = 50 (30,40,50)
○ average__C_price = 0 (0,1.0,2.5,5.0)

- Avoided_deforestation = fallow_efficiency*total_area_fallow
- C_per_ha = 200
- ecological_footprint = 10
- fallow_efficiency = 1
- F_y5 = 0 (0,1)
- F_y6 = 0 (0,1)
- F_y7 = 0 (0,1)
- F_y8 = 0 (0,1)
- F_9y = 0 (0,1)
- land_rent_requirement = Population_Estimate*ecological_footprint
- net_requirement = DERIVN(land_rent_requirement,1)
- prod1 = 2
- prod2 = 1.25
- prod3 = 1
- prod4 = 1
- prod5 = 0.75
- prod6 = 0.5
- prod7 = 0.3
- prod8 = 0.2
- prod9 = 0.2
- prod10 = 0.2
- revenue_U$_ranching = total_cattle_production*weight_conversion_@*average_price_@_cattle_U$
- revenue_U$_REDD = C_per_ha*average_C_price*Avoided_deforestation
- total_area_fallow = Fallow_Year_1+Fallow_Year_2+ Fallow_Year_3+Fallow_Year_4+ Fallow_Year_5
- total_area_farming = Farm_Land_Year_1+Farm_Land_Year_2

  +Farm_Land_Year_3+Farm_Land_Year_ 4+Farm_Land_Year_5
  +Farm_Land_Year_6+Farm_Land_Year_7+Farm_Land_Year_8
  +Farm_Land_Year_9+Farm_Land_Year_10
- total_revenue = revenue_U$_ranching+revenue_U$_REDD
- total_cattle_production = (Farm_Land_Year_1*prod1)

  Farm_Land_Year_2*prod2)+(Farm_Land_Year_3*prod3*)
  +(Farm_Land_Year_4*prod4)+(Farm_Land_Year_5*prod5)
  +(Farm_Land_Year_6*prod6)+ (Farm_Land_Year_7*prod7)
  +(Farm_Land_Year_8*prod8)+(Farm_Land_Year_9*prod9)
  +(Farm_Land_Year_10*prod10)
- weight_conversion_@= (average_cattle_weight/2)/15
- year = counter(1,9)
- land_productivity_rate_in_time = GRAPH(year)
- (1.00, 2.00), (2.00, 1.25), (3.00, 1.00), (4.00, 1.00), (5.00, 0.75), (6.00, 0.5), (7.00, 0.3), (8.00, 0.2), (9.00,0.2), (10.0, 0.2), (11.0, 0.2)

Appendix B

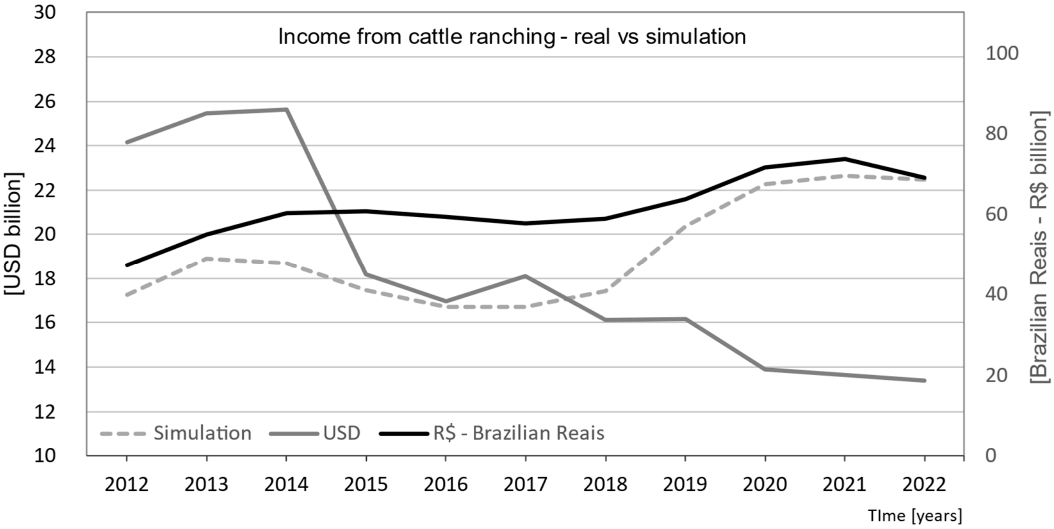

Figure A1. Annual income from cattle ranching (observed and modeled), 2012–2022. Note: Annual exchange rate—USD/BRL ('R$' in the figure.) [85].

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