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Agent-based models for integrated water resource management: quantifying land use changes by integrating economic and social incentives. Case study: Vista Hermosa (Meta)

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Abstract
Water management is essential in the face of growing global demand for domestic consumption, food production, and energy generation. This study applies the Integrated Water Resources Management (IWRM) approach to the Güéjar River basin in Colombia, a complex system with productive activities such as agriculture, livestock farming, and oil extraction. An agent-based model developed in NetLogo was used to analyze land use changes under a climate scenario characterized by reduced precipitation and increased temperature. The analysis integrated hydrological data from the GR2M model, a high-resolution land cover map, and a causal diagram representing decision-making processes related to water use and land occupation. The study area covered 2,372 km². Results show that shrublands and secondary forests are the most vulnerable, with losses of approximately 25% and 15%, respectively. In contrast, grazing areas increased by 35%, and small-scale producers declined by 40%, displaced by larger actors. These findings underscore escalating socio-environmental risks.

Keywords: Güejar River; land use changes; causal diagram; AGENT-based modeling.

Modelo basado en agentes para la gestión integral del recurso hídrico: cuantificación de los cambios en el uso del suelo mediante la integración de incentivos económicos y sociales. Estudio de caso: Vista Hermosa (Meta)

Resumen
La gestión del agua es fundamental ante la creciente demanda global para consumo, producción alimentaria y energética. Este estudio aplica el enfoque de Gestión Integral de Recursos Hídricos (GIRH) en la cuenca del río Güéjar (Colombia), un sistema complejo con actividades productivas como agricultura, ganadería y explotación petrolera. Se utilizó un modelo basado en agentes en NetLogo para analizar cambios en el uso del suelo frente a un escenario climático con menor precipitación y mayor temperatura. Se integraron datos hidrológicos del modelo GR2M, un mapa de coberturas de alta resolución y un diagrama causal sobre decisiones de uso del agua y del suelo. El análisis de 2.372 km² mostró que arbustos y bosques secundarios son los más vulnerables, con pérdidas del 25% y 15%, respectivamente. En contraste, las áreas ganaderas aumentan un 35%, y los pequeños productores disminuyen un 40%, desplazados por actores de mayor escala.

Palabras clave: Río Güejar; cambios uso del suelo; diagramas causales; modelación basada en agentes.

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1 Introduction

Water, an indispensable element for sustaining life and fostering human development, is confronted with substantial challenges in the contemporary context. These challenges are directly related to population growth, industrial expansion, and the intensification of agricultural activities. These factors have increased water demand to levels that exceed the natural renewal capacity of water systems in many regions [1]. Over the past two decades, water consumption has increased by 0.8% annually, a rate that has consistently exceeded the estimated population growth rate of 1% [2]. Furthermore, climate change is altering hydrological cycles, and land use transformations are degrading ecosystems essential for water regulation [3].

Despite its abundant water resources, including more than 2,132 major rivers, an average annual precipitation of 2,600 mm, and a total available annual water supply (TAWS) of 900,000 Mm^3, Colombia is confronted with challenges related to its water resources. The uneven distribution of rainfall throughout the year gives rise to agricultural, economic, and social dynamics that give rise to dissatisfaction with water access, affecting communities. In the Orinoquia region, the average annual precipitation is 2,740 mm/year, with a TAWS of 267.000 m^3, representing 32% of the country's water reserves [4]. Conversely, the region exhibits a 35% land transformation rate due to deforestation and the conversion of forests into monocrop such as rice and corn, which has reduced the soil's capacity to retain water. According to González (2022), over 30% of the forests in the Serrania de la Macarena (Meta) have been converted into agricultural areas, impacting both surface water availability and biodiversity, which sustains local communities. The repercussions of the armed conflict, which for years promoted the establishment of illicit crops and hindered the sustainable management of resources, continue to be a challenge. Subsequent to the ratification of peace accords in 2016, initiatives promoting the transition to legal crops such as cacao and coffee have been implemented with the objective of mitigating environmental degradation and providing economic alternatives to local communities. Nevertheless, these initiatives continue to confront obstacles, including constrained access to legitimate markets and enduring disputes concerning land utilization.

From an integrated perspective, contemporary water management must acknowledge that water constitutes not only a natural resource but also an economic and social asset with profound ramifications for public health, food security, and economic growth. In this context, Integrated Water Resources Management (IWRM) has emerged as a key strategy to address these issues. This approach aspires to achieve a balance between economic development, social welfare, and environmental protection. In Colombia, Law 896 of 2017 signifies a landmark in this endeavor, as it establishes regulations for the efficient use of water and promotes sustainable practices. However, the implementation of this legislation has been uneven, as over 60% of municipalities lack the institutional capacity to meet the established standards, creating a significant gap between policies and their application. Furthermore, the interaction between traditional water users, such as rural and indigenous communities, and new economic actors, such as large agricultural companies, has led to an escalation in social conflicts.

A notable challenge pertains to the limited integration of social and physical factors within water management models. Historically, hydrological models operated under the assumption that water demands remained constant, failing to account for the adaptive capacity of users. This methodological shortcoming has hindered a comprehensive understanding of water systems and the efficacy of public policies [5]. However, recent advancements have introduced innovative tools such as Agent-Based Modeling (ABM). This methodology facilitates the simulation of interactions between human decisions and environmental dynamics. For instance, in simulated scenarios, agents representing farmers, water users, and managers have been employed to identify more effective policies for the sustainable management of water resources. These tools have also facilitated the design of long-term strategies that integrate social and economic realities [6].

The present study aims to quantify changes in land use under different economic and social incentives, analyzing its potential as a tool for implementing IWRM at the regional and local levels. The integration of simulation models, such as Agent-Based Modeling (ABM), is a central tenet of this study. The objective is to identify more effective policies to promote water sustainability, balancing the needs of the agricultural, livestock, industrial, and domestic sectors. This approach will not only deepen the understanding of the interactions between human decisions and environmental dynamics but also contribute to the design of adaptive strategies that acknowledge the social, economic, and ecological realities of Colombian regions.

2 Methodology

2.1 Study area

The municipality of Vista Hermosa, located in the southern department of Meta, is a region of strategic importance both economically and ecologically (Fig. 1). It borders the departments of Caquetá and Guaviare, and its location in a transition zone between the Andes, Orinoquía, and Amazon regions endows it with exceptional biodiversity and a wide variety of ecosystems [7,19]. In terms of natural resources, the area is rich in mining, agriculture, forestal, and water, and its biodiversity includes a remarkable variety of flora and fauna as well as natural landscapes [7].

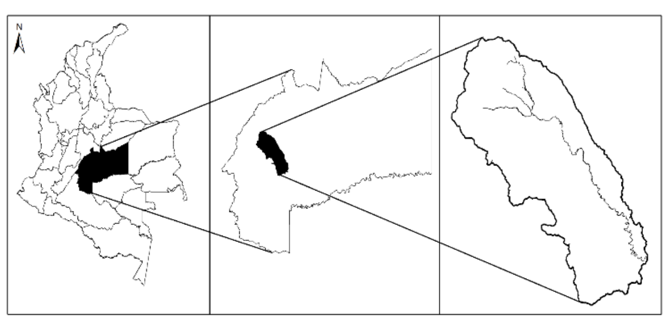

Figure 1. Study area map: the Güejar river basin, Meta, Colombia
Source: Authored

Vista Hermosa's water resources are primarily linked to the Güejar River basin, one of the country's most important river systems. The basin is crucial for the local ecosystem, feeding a system of wetlands and swamps in its alluvial zone, creating an ecologically valuable habitat. The region is also part of the Macarena Special Management Area (AMEM), a protected area due to its ecological importance, although it is undergoing rapid changes due to recent socioeconomic dynamics, such as the expansion of cattle ranching, affecting both governance and environmental conservation [7].

The tropical climate of the region is characterized by an annual rainfall of more than 2,000 mm, divided into two rainy seasons: the first from March to June and the second from October to December. The remaining months are dry, which affects the hydrological dynamics of the basin. The Güejar River has an average annual flow of 2,361 m^3/s, with marked seasonal variability, reaching maximum flows (Q_5) of 4,298 m^3/s and minimum flows (Q_{95}) of 1,578 m^3/s. The average annual temperature in Vista Hermosa remains above 24°C, and elevations range from 50 m to 3,700 meters above sea level, supporting diverse microclimates and ecosystems.

2.2 Materials and methods

2.2.1. Data sources

The digital elevation model (DEM) was derived from SRTM with a height correction of the HydroSHED system [8], with a 30 m resolution, covering the coordinates 3° 05' 13.6" N and 73° 49' 46.9" W. This DEM has an average vertical error of 6.2 m (at a 90% confidence level) and a geolocation error of 9 m for South America. Physical parameters, such as elevation and slopes, were extracted from this DEM. The closing point of the basin was located at the Piñalito station (cod 32077070), and the drainage networks provided by the Instituto Geográfico Agustín Codazzi (IGAC) were used to delineate and characterize the basin.

The study area was delineated using ArcGIS software version 10.0. With the basin delineated, land cover types were identified qualitatively using the Corine Land Cover methodology, which was obtained from the open IDEAM repository. The most recent map with information is from 2018, and comes with information on six different detail levels. For the case of the study area, the first three levels of detail were used, and the total number of land covers was estimated to be 20.

Meteorological and hydrological data in Colombia are freely accessible through the Institute of Hydrology, Meteorology, and Environmental Studies (IDEAM). For this study, daily rainfall data from stations covering the entire Güejar basin were used. A missing data analysis was conducted, ensuring that only stations with less than 10% missing data were included. Additionally, 39 variables, categorized as Ordinary Climate, Main Climate, Limnigraphic, Limnometric, and Pluviometric, were considered for the analysis based on the basin area. Precipitation within the basin was estimated using the Thiessen method [9,10], while Evapotranspiration (ETo) was calculated using the Hargreaves-Samani method [11,12].

The calibration period for the model was set between 1991 and 2010, while the validation data came from 2010 to 2020. Missing values for the calibration period were filled in using linear regression methods. With the calibrated data, it was possible to estimate the minimum and maximum flows for the basin over 5, 10, and 20-year periods, and to conduct a preliminary analysis of potential flood areas using the Rainfall-Runoff-Inundation (RRI) model.

2.2.2. Hydrological model GR2M

The GR2M model is a simple basin conceptual hydrologic model developed by CEMAGREF (Center for Agricultural Research and Environmental Engineering of France). It is one of the most widely used models in the world for estimating runoff in river basins, especially in situations where data availability is limited. This model is based on a reservoir approach, where multiple reservoirs simulate the hydrological processes occurring in a basin (Fig. 2). The GR model consists of four key components, or reservoirs, that simulate the transformation of precipitation into streamflow:

- Precipitation and Evapotranspiration: These are the main inputs, with precipitation determining water storage and evapotranspiration controlling water loss from the system.
- Production Reservoir: Simulates the conversion of precipitation into water available for runoff, releasing accumulated water to the stream.
- Interception Reservoir: This reservoir handles small variations in runoff from intense rainfall by storing water before it reaches the drainage system.
- Drainage reservoir: Manages excess water from precipitation and releases it into the main stream of the watershed.

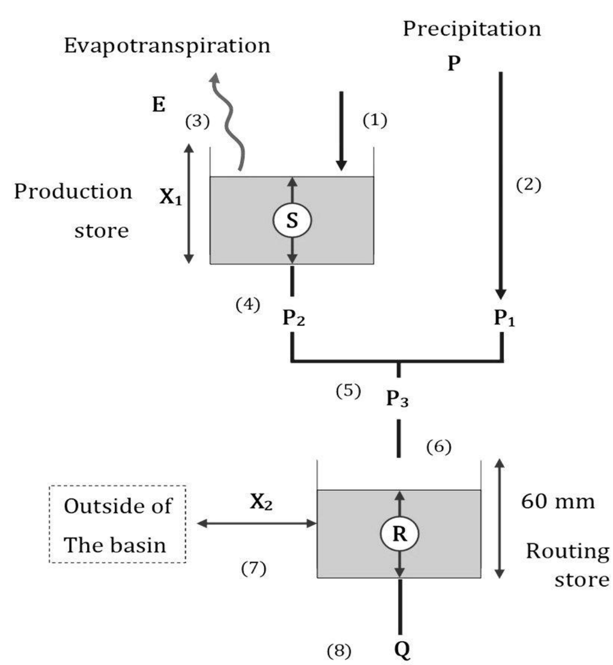

Figure 2. Structure GR2J Hydrological Model
Source: Ditthakit et al., 2021. [13]

The GR model assumes that the hydrologic behavior of a watershed can be represented by the response of the system to precipitation and evapotranspiration, considering that runoff depends on the storage capacity of the reservoirs. In simple terms, the model uses a reservoir approach with a limited number of parameters to describe the dynamics of the basin. One of the main advantages of this model is its simplicity and low data requirements, making it suitable for basins with limited data. However, the predictive ability of the model is directly influenced by the quality of the input data, such as the accuracy of precipitation and evapotranspiration. In addition, the GR2M model is monthly, i.e. it estimates outputs (flows) based on a monthly time frame, which simplifies the analysis of large amounts of data over the long term.

The GR2M model requires calibration of its parameters, which are typically adjusted using optimization techniques such as least squares or evolutionary algorithms to improve the match between observed and simulated flows. The main parameters that require calibration include: the storage capacity of reservoirs, coefficients for converting precipitation to runoff, and coefficients for the drainage and evapotranspiration processes. For the validation of the hydrological model, the Nash-Sutcliffe Efficiency (NSE) (Eq. 1) was used as a goodness-of-fit metric. The NSE assesses the predictive performance of hydrological models by comparing observed and simulated flows, serving as an objective function to evaluate the accuracy of model simulations [14,15]. Observed flow data from the study area were employed to validate the model by directly comparing them with the flows simulated during the analysis period.

$$NSE = 1 - \frac{\sum_{i=1}^{n}(O_i - S_i)^2}{\sum_{i=1}^{n}(O_i - \hat{o}_i)^2} \quad (1)$$

Where: NSE represents the efficiency in fractional terms, O_i represents the observations, S_i represents the simulation, and $\hat{o}_i$ represents the average of the observations.

2.2.3. Causal diagram

A causal diagram is a theoretical structure that illustrates the cause-and-effect relationships between variables [16]. It demonstrates how changes in one variable can directly influence others, visually highlighting the many factors that contribute to a particular observed outcome [17]. To enhance clarity and organization, the design of the diagram seeks to minimize overlapping arrows, ensuring a more precise representation of the drivers and dynamics behind land-use transformation.

The data processing for the designated study area was conducted using Vensim software, a program that facilitated the creation of a causal diagram that represents the causal relations in the region [17]. The development of the diagram was informed by three primary inputs: ecosystems, activities, and economic incentives. These elements were connected by arrows of varying thickness to indicate the strength of the relationship, color to denote the primary input, and direction to represent whether the relationship was positive or negative. A meticulous examination of the feedback loops within the diagram was undertaken to identify reinforcing and balancing interactions that affect the system.

2.2.3. Agent-Based Model

The Agent-Based Model (ABM) was developed in Netlogo Software [18]. This ABM has the previously described hydrological model and causal diagram as inputs, seeking to represent the decision-making of different actors within the basin, considering their main economic activity and available area [19].

At setup, we established the random seed at 10 (it could go from -9007199254740992 to 9007199254740992), to guarantee replicable randomness. Also, at setup, the user can select from three scenarios to see changes in the basins productive landscape: Reforestation, where there are active economic incentives to reforest the riparian forest; Protection, where the extirpation of small local farmers is lessened; Neutral, where there is no protection nor restoration.

When the user selects the scenario, a map of the catchment is drawn where each patch is assigned a land cover based on the Corine Land Cover Level 3 methodology with a pixel size of 30 meters. As the patches acquire their land cover, agents are also placed at random (based on the seed), are given a "scale" (small-scale family farmer or big expansionist producer), and acquire the corresponding productive activity (i.e. if they land on open grass, they have cattle as productive activity). With the positions set, the simulation begins according to the selected scenario, however, all scenarios run for 120 ticks which represent ten years (each tick being one month).

If the neutral scenario was selected, every big expansionist would search for the nearest non-occupied patch and transform it into its productive activity. If this agent finds a forest patch it will destroy it, changing its color and name. If, in its search for a patch, encounters a small-scale farmer, it can "eliminate" it and take the land. Both of these actions account for real processes that occur within the basin.

However, if the protection scenario was activated, an additional factor is added to the expansionists where they have to give the small-scale farmers a chance to stay. This action is called by randomness dictated by the same seed and by distance where closeness makes it more likely for small-scale farmers to disappear.

Likewise, if the restoration scenario is active, the riparian forest begins a healing process that is restrained by density factor, where each patch of riparian forest counts how many more of them are within a 2-patch radius, and if there are not enough ("enough" was subjectively stated as less than 35% and it can be changed within the code) then the closest grass patch has a chance of becoming a forest patch.

3 Results

3.1 Hydrological model GR2M

The calibration of the hydrological model yielded a Nash-Sutcliffe Efficiency (NSE) coefficient of 0.52, indicating a moderate correlation between the simulated and observed flows of the Guéjar River at the closure station. As shown in the figure, the model effectively captures the seasonal variability of the flow during the period analyzed, showing a general agreement between simulated and observed values. However, it struggles to accurately represent extreme events, particularly during peak flow conditions, where significant discrepancies are evident. This suggests that further parameter adjustments could improve the model's ability to reproduce extreme hydrological events, which is essential for flood risk management and water resource planning in the basin [19].

The application of this calibrated model provided the median flow rate of 137.30 m³/s, a critical result that not only serves as a baseline, but also allows the definition of a variability range (Fig. 3). This range of variability was then incorporated into the agent-based model to increase the robustness of the overall framework. By introducing this variability, the agent-based model can better simulate the dynamic interactions within the system, providing a more comprehensive understanding of the hydrological processes at play. In turn, this integration allows the analysis of both typical and extreme scenarios, providing valuable insights for more effective management of water resources and preparation for potential flood risks. Although the hydrological model has limitations in reproducing extreme events, its performance in capturing seasonal trends and its response to precipitation variability make it a suitable tool for this analysis, particularly in understanding average monthly patterns and assessing the impact of climate variability on the system.

Despite these limitations, the results can be considered satisfactory for the purposes of this study, which focuses on the analysis of average monthly patterns of climatic and hydrological variables. The response of the model to precipitation variability is physically consistent, indicating that its conceptual framework is appropriate for representing the hydrological behavior of the basin at a monthly scale. This reinforces its usefulness as a tool for assessing the impact of climate variability and supporting decision-making in water resource management in the region [19].

3.2 Causal diagram

The causal diagram of Vista Hermosa (Fig. 4), highlights the complex interplay between changes in land use, economic activities, and environmental degradation. Agricultural practices (Fig. 4.-3), including coffee, rice, corn, and

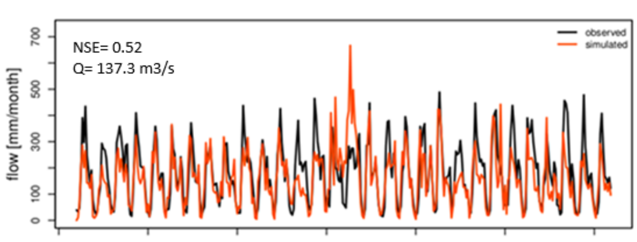

Figure 3. Hydrological model calibration
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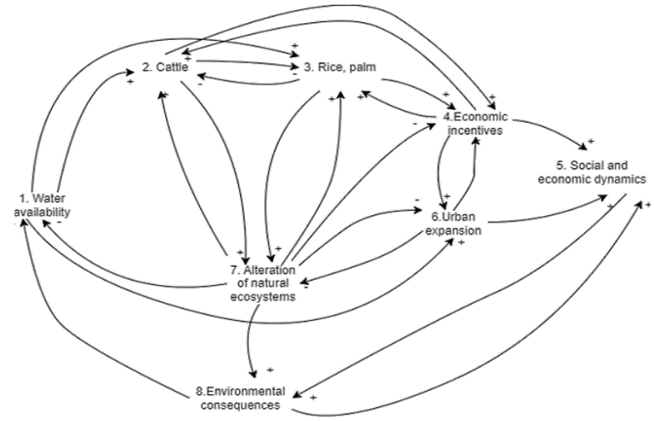

Figure 4. Causal Diagram of Vista Hermosa
Source: Authored

sugarcane farming, in conjunction with pasture grazing, have been identified as significant contributors to deforestation. These activities have been identified as key contributors to the transformation of dense forests into pastures and fragmented vegetation, resulting in a reduction of biodiversity and ecosystem alterations. Furthermore, the tourism, commercial and manufacturing sectors, in their indirect role, contribute to the exacerbation of these land-use changes by increasing demand for land and natural resources. While Tourism offers the potential for sustainable development, its benefits can be undermined in the absence of adequate regulations to prevent habitat destruction.

The environmental consequences (Fig. 4.-8) of these activities are profound, with deforestation resulting in the proliferation of secondary vegetation and fragmented forests that exhibit a diminished capacity to support biodiversity and regulate water cycles. Critical ecosystems, such as gallery forests, are particularly vulnerable to land conversion and urban expansion, which threatens their ecological functions and climate-regulating capacities. To elucidate these relationships, a causal diagram was constructed using the Vensim software [19]. This diagram represents the intricate interplay among ecosystems, activities, and economic incentives within the Vista Hermosa region. The direction of the arrows in the diagram is indicative of the strength, nature (positive or negative), and key drivers of these relationships. This analysis revealed feedback loops that highlight how human activities and natural processes reinforce one another, worsening environmental degradation if left unchecked.

Social and economic dynamics (Fig. 4.-5) play a pivotal role in the observed changes in land use in Vista Hermosa. Communities, particularly resettled families and small-scale farmers, frequently prioritize short-term economic survival due to constrained access to alternative livelihoods and deficient infrastructure. These conditions give rise to unsustainable practices, including deforestation and overgrazing, which in turn further degrade the integrity of the ecosystems. Socio-economic inequalities influence community participation in conservation initiatives, often marginalizing those who depend most on natural resources. The implementation of targeted programs, complemented by economic incentives that promote sustainable practices, is imperative for ensuring long-term environmental sustainability and enhancing community well-being.

Although stronger conservation laws provide an essential framework for sustainable land management, they alone are insufficient to address the complex and interconnected challenges of environmental degradation. While stricter penalties for illegal deforestation and well-enforced zoning policies to ecosystems, such as gallery forest, are crucial steps, they must be complemented by strategies that go beyond regulatory measures.

Economic incentives (Fig. 4.-4), such as subsidies for sustainable farming practices or financial rewards for ecosystem services, play a pivotal role in aligning individual and community actions with conservation goals. However, incentives alone may falter without effective organization and collaboration among users. Capacity-building programs that empower local communities with the knowledge and resources to implement sustainable practices are key. Additionally, promoting alternative livelihoods can reduce the reliance on environmentally damaging activities, creating a more resilient socio-economic foundation.

The synergy between legal frameworks, economic incentives, and grassroots organization is essential. By fostering networks of cooperation among users, enabling shared governance, and ensuring equitable distribution of benefits, communities in regions like Vista Hermosa can collectively work toward preserving natural ecosystems while achieving sustainable development. This multifaceted approach tackles both the underlying causes and the visible effects of environmental degradation, laying a solid foundation for sustainable long-term solutions.

3.3 Agent-based model

Social and economic incentives are clearly observed in a protection scenario where the local population has a higher prevalence compared to scenarios without incentives. This is illustrated in Fig. 5, which shows the evolution of the relative population in the community of Vista Hermosa, Meta, over time under different scenarios of social and economic incentives. The X-axis represents the simulation time steps (1 tick = 1 month), while the Y-axis shows the relative population of residents. Several series of data are compared: the population with no incentives, the population with standard protection, the population with an additional 20% increase in incentives, and the total impact of social and economic incentives on the community.

Fig. 5-A indicate that in the absence of incentives, the local population experiences a rapid decline over time (from 280 to 260 in 37.5 ticks), suggesting migration or displacement due to adverse socio-economic conditions. In contrast, the implementation of conservation strategies slows down the rate of population loss, suggesting improved community stability with support measures. In particular, a 20% increase in social incentives results in even greater demographic stability, mitigating the out-migration of local residents. These findings are particularly relevant in Vista Hermosa, a region with a history of armed conflict and an economy largely based on agriculture and livestock, where population retention is critical for sustainable development.

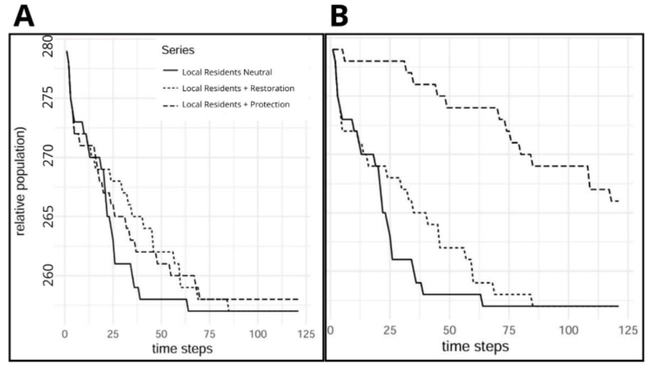

Figure 5. Comparison of the evolution of the relative population of local producers under different incentive scenarios. A- Social incentive scenario. B- Economic incentive scenario.
Source: Authored

In this context, the results of the model shown in Fig. 5-B reinforce these conclusions. The evolution of the relative population of local producers under different restoration conditions-no restoration, 5% restoration, and 9% restoration-shows how different strategies can affect population dynamics. The most favorable scenario appears to be the 9% restoration, where the population stabilizes around 253 individuals despite some decline. This scenario mirrors findings from the broader study, where social incentives and restoration efforts contribute to demographic stability and can help mitigate displacement, further supporting the idea that well-designed conservation and incentive strategies are critical to promoting socioeconomic stability, reducing vulnerability, and fostering resilient communities in regions like Vista Hermosa.

Fig. 6-A shows a direct relationship between the implementation of restoration strategies and the evolution of vegetation cover in Vista Hermosa, Meta. The observed trend shows a steady increase in grasslands in the absence of incentives, suggesting a continued expansion of the agricultural frontier, possibly at the expense of natural ecosystems. In contrast, the 5% and 9% restoration scenarios show a smaller reduction in natural forests and shrubs, demonstrating that economic incentives for conservation have a positive impact on the region's environmental resilience.

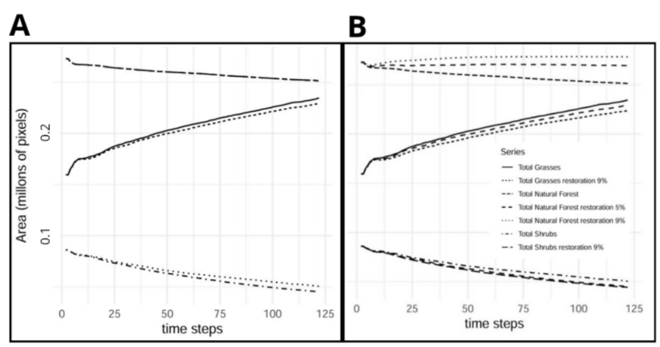

Figure 6. Analysis of the Coverage Areas by Time Steps. A- Social incentive scenario. B- Economic incentive scenario.
Source: Authored

Fig. 6-B shows that the 9% restoration scenario has a significant effect of economic incentives to mitigate the loss of natural habitat. These incentives, combined with restoration efforts, reduce the expansion of grasslands and help maintain a more balanced ecosystem. The expansion of grasslands without incentives highlights the pressure that agricultural activities place on the landscape, particularly in a region where livestock and agriculture have historically been dominant. This suggests that without intervention mechanisms, ecosystem degradation could continue, affecting biodiversity and essential ecosystem services such as water regulation and erosion control. Therefore, integrating economic incentives into restoration strategies not only promotes environmental sustainability, but also contributes to the long-term resilience of the region by ensuring a more sustainable coexistence between agriculture, livestock and natural ecosystems.

On the other hand, the changes in rice and oil palm area under three protection scenarios: no incentives, 5% protection and 20% protection (Fig. 7). For both crops, there is a significant reduction in area in the first 10 months. For rice, the no-incentive scenario shows the largest reduction, while the 5% protection scenario is the most advantageous in mitigating this loss. For oil palm, the most favorable scenario is the 20% protection scenario, which minimizes the reduction in area.

The geographic representation of changes in the study area (Vista Hermosa, Meta) under different protection scenarios (Fig. 8) allows the identification of specific areas where these changes are most pronounced.

In addition, Fig. 9 illustrates the geographic transformation of the region under 5% and 9% restoration scenarios, highlighting the positive impact of economic incentives and conservation policies in promoting restoration and sustainability. These maps provide a more detailed understanding of where the most significant changes are occurring, highlighting regions where forest protection and restoration efforts - supported by economic incentives - are leading to improved environmental outcomes. The geographical concentration of these changes highlights the targeted nature of the interventions and helps to identify areas that may require further attention to maximize the benefits of conservation strategies.

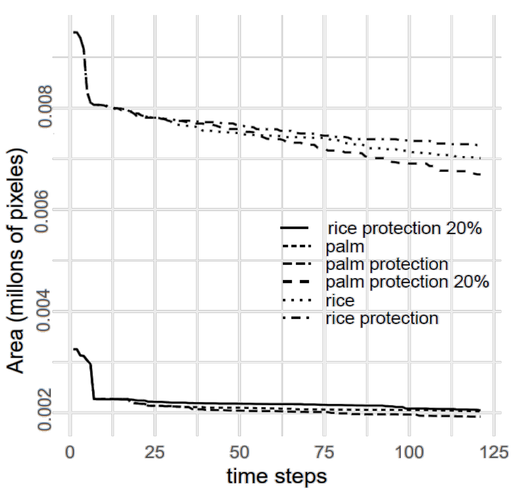

Figure 7. Changes in rice and oil palm area under three protection scenarios.
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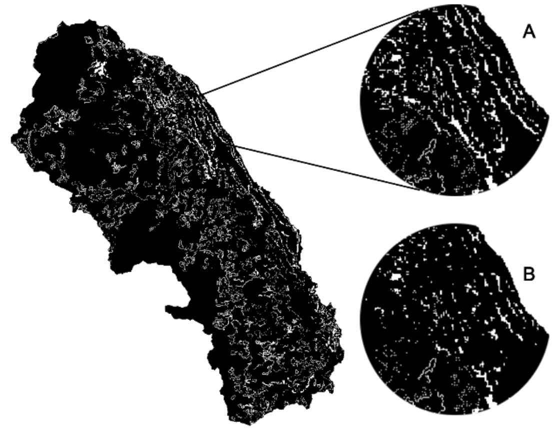

Figure 8. Geographic transformation of riparian forest where no incentives are active. A- initial moment of the model (tick 1), B- consolidated at the end of the simulation (120 ticks), if no modification (local protection or restoration) is activated. The white color represents the riparian forest in the neutral scenario.
Source: Authored

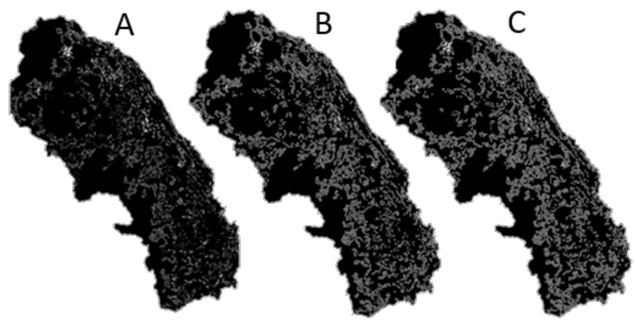

Figure 9. Geographic change under restoration scenarios. A. Scenario without incentives or restoration. B- Final scenario with 5% restoration, and C- Final scenario with 9% restoration
Source: Authored

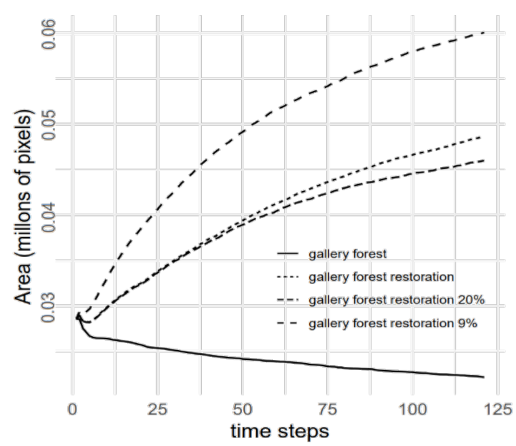

Figure 10. Gallery Forest restoration with economic incentives.
Source: Authored

In the restoration scenario, the primary goal is to restore the gallery forest, as it is located closest to the water source. Fig. 10 shows four (4) scenarios faced by this forest: (i) no restoration or economic incentive, (ii) 5% restoration, (iii) 9% restoration, and (iv) a restoration scenario where rice and oil palm crops are adapted to retain 20% more water. The results show a significant difference, highlighting that if no incentives or restoration efforts are applied, the gallery forest tends to disappear. In contrast, under scenarios with incentives and restoration efforts—regardless of the percentage applied—the forest area not only avoids disappearance but increases significantly. The most favorable outcome is observed under the 9% restoration scenario, where the forest area expands to 0.06 million pixels.

4 Discussion

Based on the results obtained, it is possible to identify significant patterns in the response of vegetation cover and the socio-economic dynamics of the region with respect to the integration of economic and social incentives. These findings highlight the interconnectedness of human and environmental systems and emphasize the importance of well-designed incentives in promoting sustainability.

Social incentives proved to be effective in mitigating local population decline, particularly in the conservation scenarios. As shown in Fig. 3, the relative population of locals in a neutral scenario declines rapidly, reaching critical levels in less than 40 months. However, conservation scenarios with a 5% increase in incentives significantly prolong the retention of the local population, underscoring the importance of social policies to support local producers. This not only ensures the permanence of local communities, but also creates conditions for improved natural resource management and stronger social ties, which are essential for long-term sustainability.

The analysis of vegetation cover further supports the effectiveness of these measures. Fig. 4 shows that protection scenarios have a positive impact on land use, with grassland areas increasing and natural forests and shrubs declining at a slower rate compared to scenarios without incentives. This shows that social incentives not only benefit communities, but also promote more sustainable land use practices that contribute to the conservation of biodiversity and the maintenance of ecological functions. However, the consistent increase in grassland area across all scenarios raises concerns about potential over-expansion, which could lead to soil degradation and biodiversity loss. This highlights the need for complementary strategies to regulate land use change and balance grassland expansion with forest and shrub conservation.

Economic incentives, especially in restoration scenarios, also have a significant positive impact on the conservation and restoration of critical ecosystems, such as gallery forests. These forests, which are essential for hydrological regulation and biodiversity, are at risk of disappearing in scenarios without incentives. As shown in Figs. 7 through 10, restoration scenarios-especially those with a 9% increase-achieve substantial recovery, with areas reaching up to 0.06 million pixels. This highlights the potential of targeted economic incentives to protect ecosystems critical to environmental health and water regulation. At the same time, restoration scenarios show that natural forest and shrub cover declines less drastically compared to neutral conditions, suggesting that economic incentives can influence local actors to adopt more sustainable practices. However, the expansion of grasslands in all scenarios highlights the importance of balancing incentives to avoid unintended consequences that could compromise ecosystem integrity.

The dynamics of rice and palm provide further insight into the effectiveness of these incentives. Both crops show an initial decline in area in the first 10 months under all scenarios. However, protection incentives, especially those that include a 5% increase and water use restrictions that require crops to use 20% more water, mitigate this trend. For rice, the 5% protection scenario proves to be the most favorable, demonstrating the need to tailor incentives to the specific dynamics of each crop to maximize effectiveness and minimize negative impacts on the local economy.

When considering the relative population of local producers, restoration scenarios with a 9% increase in incentives prove to be the most beneficial, maintaining the population at a relatively stable level of 253 individuals. This highlights the importance of combining social and economic incentives to ensure the sustainability of both human and environmental systems. Social incentives help stabilize local populations and reduce pressure on ecosystems, while economic incentives drive the restoration and conservation of critical areas such as gallery forests. Together, these measures create a positive feedback loop that promotes resilience and long-term sustainability.

The integration of well-designed social and economic incentives is proving essential to achieving sustainability in the region. Social incentives stabilize local populations, promote community resilience, and reduce pressure on ecosystems. At the same time, economic incentives promote the restoration and conservation of vital ecosystems. Their success depends on careful design and implementation to ensure that they meet the specific needs of the region while minimizing unintended consequences. Taken together, these approaches are a powerful tool for promoting sustainable development and preserving the delicate balance between human and environmental systems.

5 Conclusions

The integration of social and economic incentives in environmental management demonstrates significant potential to promote sustainability by addressing both human and ecological challenges. Social incentives, focused on protecting local communities, effectively mitigate the decline of local populations, as seen in protection scenarios where their permanence is extended. This not only supports the socio-economic fabric of the region but also contributes to more sustainable resource management by reducing pressure on ecosystems. Furthermore, economic incentives aimed at restoration, particularly those targeting critical ecosystems like gallery forests, show substantial benefits for biodiversity and hydrological regulation. Restoration scenarios, especially with higher levels of investment, lead to significant recovery of forested areas, highlighting the effectiveness of targeted interventions in preserving key ecological functions.

The findings also underscore the need for a balanced approach to incentive design, as unintended consequences, such as the overexpansion of grasslands, may arise. Tailoring economic measures to the specific needs of crops, such as rice and palm, and integrating restrictions on resource use, ensures greater effectiveness while mitigating adverse effects on the local economy. The combination of social and economic incentives proves crucial for achieving long-term sustainability, as these measures work synergistically to stabilize local populations, foster sustainable land-use practices, and conserve vital ecosystems. This study demonstrates that a strategic, context-sensitive application of incentives can serve as a powerful tool for addressing the complex interplay between human and environmental systems, paving the way for resilient and sustainable development.

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