Rubem P. Mondaini *Editor*

Trends in Biomathematics: Stability and Oscillations in Environmental, Social, and Biological Models

Selected Works from the BIOMAT Consortium Lectures, Rio de Janeiro, Brazil, 2021

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Socio-Ecological Dynamics Generated by Hydrocarbon Exploration

J. M. Redondo, J. S. Garcia, and J. A. Amador

1 Introduction

Hydrocarbons meet the basic needs of today's societies such, as access to energy, heating, cooling, transportation, and production of inputs, as well as being important for promoting the industry and boosting economic growth. However, exploration and extraction activities have implications for the entire socio-ecological system, including environmental impacts, social problems, and governance asymmetries that lead to questioning the benefits of the use of hydrocarbons [1–3].

One of the environmental problems that hydrocarbon exploration brings with it is related to noise. Sound is an environmental feature used by some taxa for food, reproduction, navigation, and avoiding predators. Consequently, soundscape alterations have the potential to alter the behavior, physiology, and fitness of individuals [4]. In hydrocarbon exploration, noise pollution is caused by seismic exploration studies in which oil and gas reserves are identified, while during hydrocarbon exploitation, in addition to noise, the surface vegetation cover is removed for the construction of roads, camps, or platforms, and the increase in human activity that generates disturbance of wildlife and the migration of species necessary for the preservation of the ecosystem [4–6].

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It is highlighted that the implications of exploration and exploitation are different in intensity, duration, and frequency, being more impressive the exploitation activities, but opening the exploration door could open the exploitation door with it, so there is always the potential risk of losing the landscape ecological structure.

In the exploration of hydrocarbons, problems related to the impacts on biodiversity that can lead to the decrease of fauna in the exploration sites are recognized [7–9]. It is also known that hydrocarbon exploration is directly related to socioeconomic impacts that could determine the landscape dynamics. Some of the related positive impacts include business opportunities and local job creation [5, 10, 11], while negative impacts include price inflation, the generation of development expectations that may not come true, economic inequality, and the population transgression [1, 10].

This chapter focuses on the effects of hydrocarbon exploration in three different types of landscapes in the Amazon region: pristine landscapes, agricultural landscapes, and landscapes with licit and illicit crops. In this way, the coverage of the different land uses, biodiversity, soil productivity, the hiring of personnel for the economic activities of the landscape, and situations such as land retention and social coercion are articulated, with the absence or presence of hydrocarbon exploration.

For the analysis, a systemic approach based on the system dynamics[12, 13] methodology has been used, which allows obtaining a system of differential equations with which the simulation of the scenarios representing the three types of landscapes mentioned has been carried out. The simulation data are theoretical data that allow a phenomenon explanation, rather than a diagnosis or forecast in a specific situation. In this way, were obtained valuable arguments for decision-making via experimentation in controlled simulation environments.

In Sect. 2 the modeling process based on system dynamics is presented to obtain the mathematical model from which the simulations of the scenarios were carried out. In Sect. 3 the scenarios for the three proposed landscapes are evaluated, comparing the results of the presence and absence of hydrocarbon exploration on the variables of interest. Finally, in Sect. 4 the conclusions of this chapter are presented.

2 System Modeling

The modeling process involves the creation of a causal diagram and the discussion of its feedback structures (Sect. 2.1), the construction of the Forrester diagram, definition of the system equations, and the dimensional consistency validation (Sect. 2.2).

2.1 Causal Diagram

The proposed model is based on the causal diagram presented in Fig. 1, which is explained in the following lines. The causal diagram is explained firstly from

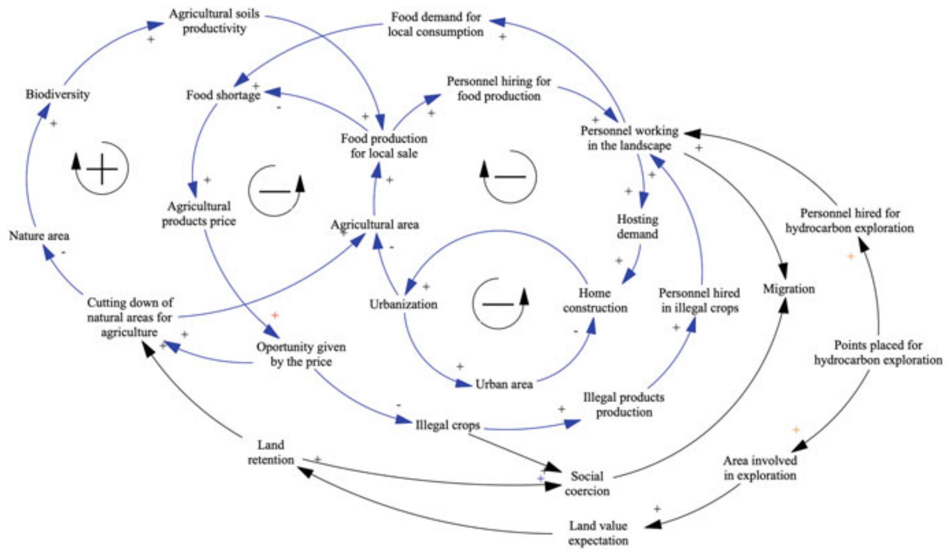

Fig. 1 Causal diagram

the landscape relationships without oil activities, while, towards the end, the hydrocarbon exploration activities are articulated.

The proposed model is based on the causal diagram presented in Fig. 1, which is explained in the following lines. The causal diagram is explained firstly from the landscape relationships without oil activities, while, towards the end, the hydrocarbon exploration activities are articulated.

Four types of general coverage were considered: natural, agricultural, illicit crops, and urban. It is assumed that the natural areas do not have the opportunity to increase in area, but they are diminished by agricultural activities and illicit crops, exclusively.

The agricultural crops vary due to the acquisition of natural areas, the adaptation of illicit crops to agricultural land, the adaptation of agricultural to illicit crops, and urbanization.

The illicit crops vary due to the transformation of natural areas, the adaptation of illicit crops to agriculture, and the adaptation of agriculture to illicit crops. Their urbanization is not considered because it is assumed that these crops are not usually very close to urban coverage.

Urban coverage, for its part, will always increase in area, although they do so very slowly.

The transformation drivers considered are the land retention due to the purchase speculation of the hydrocarbon industry and the price in the market of the agricultural products obtained, in comparison with the prices, generally very stable, of the products obtained in illicit crops (coca leaf, coca paste, and cocaine base).

Thus, the price of agricultural products increases the opportunity for profit in agricultural production, which leads to an increase in forest clearance for agricultural activities and a decrease in coverage of illicit crops. But forest clearing

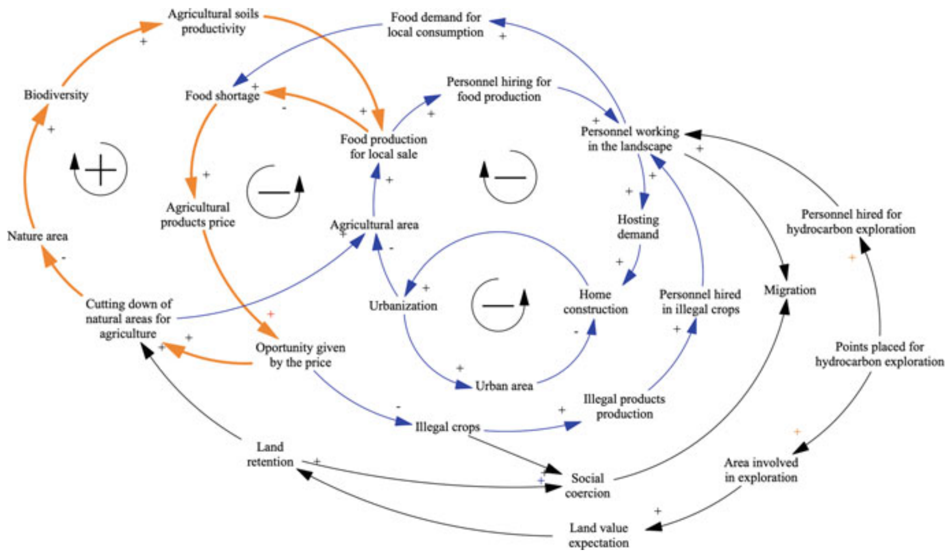

Fig. 2 First loop analyzed in the causal diagram

reduces the coverage of natural areas, which in turn decreases biodiversity, affecting the productivity of agriculture, thus reducing the food production for local sale. This decrease in production generates a food shortage for local consumption, making it scarce and, therefore, increasing the price of agricultural products. In this way, a positive feedback loop is formed (Fig. 2), which forms the vicious circle in which natural covers and biodiversity tend to disappear, thus affecting the productivity of landscapes to produce and supply food to the landscape population.

The price of agricultural products determines the opportunity for illicit crops, increasing the production of illegal products. This increase demands the hiring of people who will add within the total set of personnel working in the landscape, who demand food. If this demand for food is very high, either due to the number of people or the per capita amount of consumption, food will tend to become scarce, affecting the price of agricultural products for local consumption. In this way, a negative feedback loop is formed (Fig. 3) that limits the expansion of the coverage of illicit crops due to the need to supply food to the landscape population.

The total number of people who work in the landscape, which includes the personnel who work in agricultural crops, in illicit activities, and in goods and services, will demand a space to live, which will induce the construction of houses and, therefore, the increase in urbanization that will reduce agricultural coverage, affecting food production and, in turn, the person hired for agricultural activities, conditioning the total number of people who work in the landscape. The negative loop that emerges, (Fig. 4) explains that to maintain self-sufficiency, urbanization will have a limit on agricultural coverage or will have to import its supply.

In Fig. 5, is showed that the construction of houses for the accommodation of people who work in the landscape, including their families, leads to urbanization and

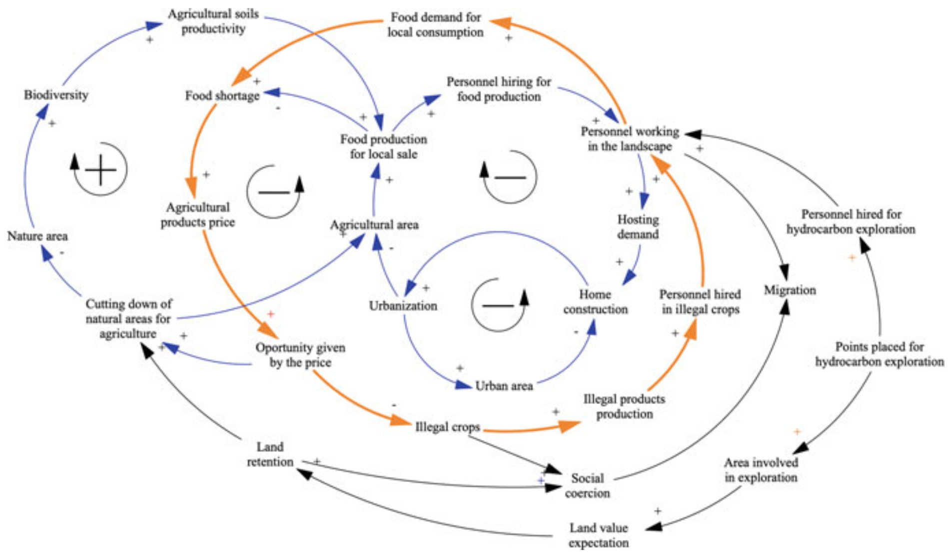

Fig. 3 Second loop analyzed in the causal diagram

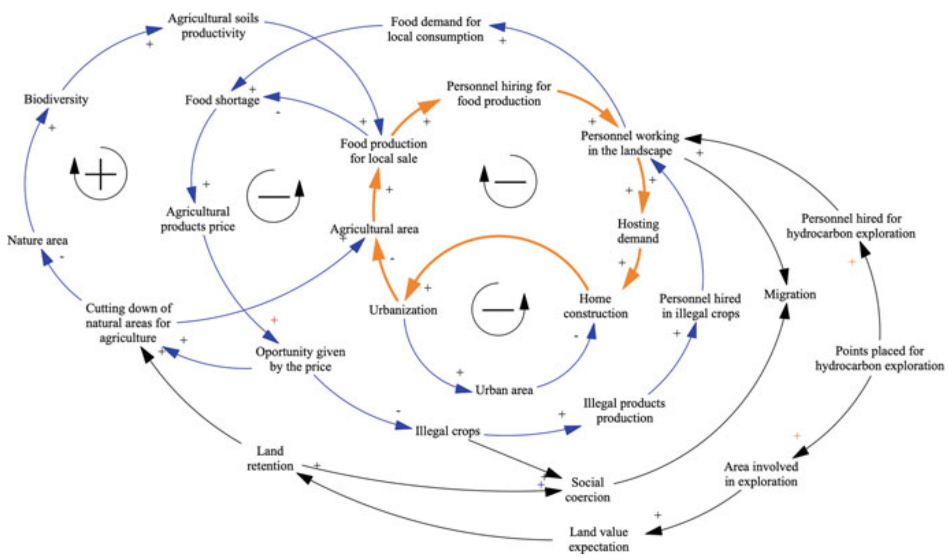

Fig. 4 Third loop analyzed in the causal diagram

an increase in urban coverage, and that enough urbanization reduces construction of housing. This negative loop shows that construction is limited by the need to urbanize, that is, the limit is given by the socioeconomic opportunity that the population finds in the landscape.

When the hydrocarbon exploration activity is carried out, the landscape is affected in two ways: by the hiring of personnel and by the area that is involved in the exploration.

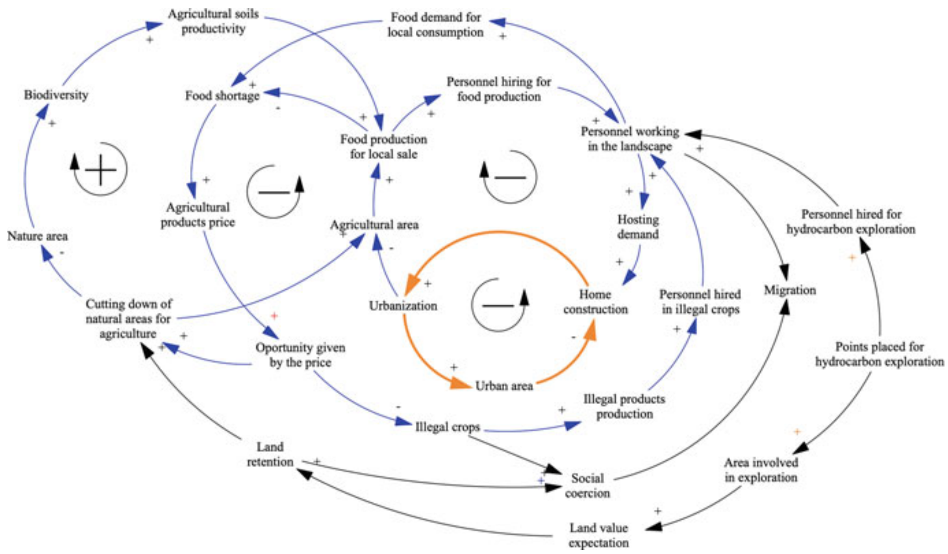

Fig. 5 Last loop analyzed in the causal diagram

In the first case and, according to the type of exploration carried out, the significant number of points used in the hydrocarbons exploration is considered, which increases the number of people working in this activity and the number of people who work in the landscape. This condition becomes changes in the local food supply and its prices, driving the urbanization in the landscape.

In the second case, the area involved in the hydrocarbon exploration, increases the expectation for the value of the land, increasing the land retention, which in turn leads to the forest clearing for agricultural activities.

This retention and the illegal activities lead to increased complaints of social coercion, which triggers the displacement or emigration of people from the region. In this way, while job opportunities in the landscape attract population to the landscape, social coercion forces them to seek opportunities in other places, from which it is concluded that exploration activity can weigh social coercion in those regions where the formality of land tenure and the presence of the state are scarce.

2.2 Forrester Diagram

From the causal diagram, were constructed the level and flow diagram presented in Fig. 6. The state variables were the four interested areas (natural areas, agricultural coverage, illegal crop coverage, and urban coverage), the four personnel hired to work in the landscape (for food production, goods and services, illicit crops, and exploration of hydrocarbons) and the local population, giving rise to the following differential system:

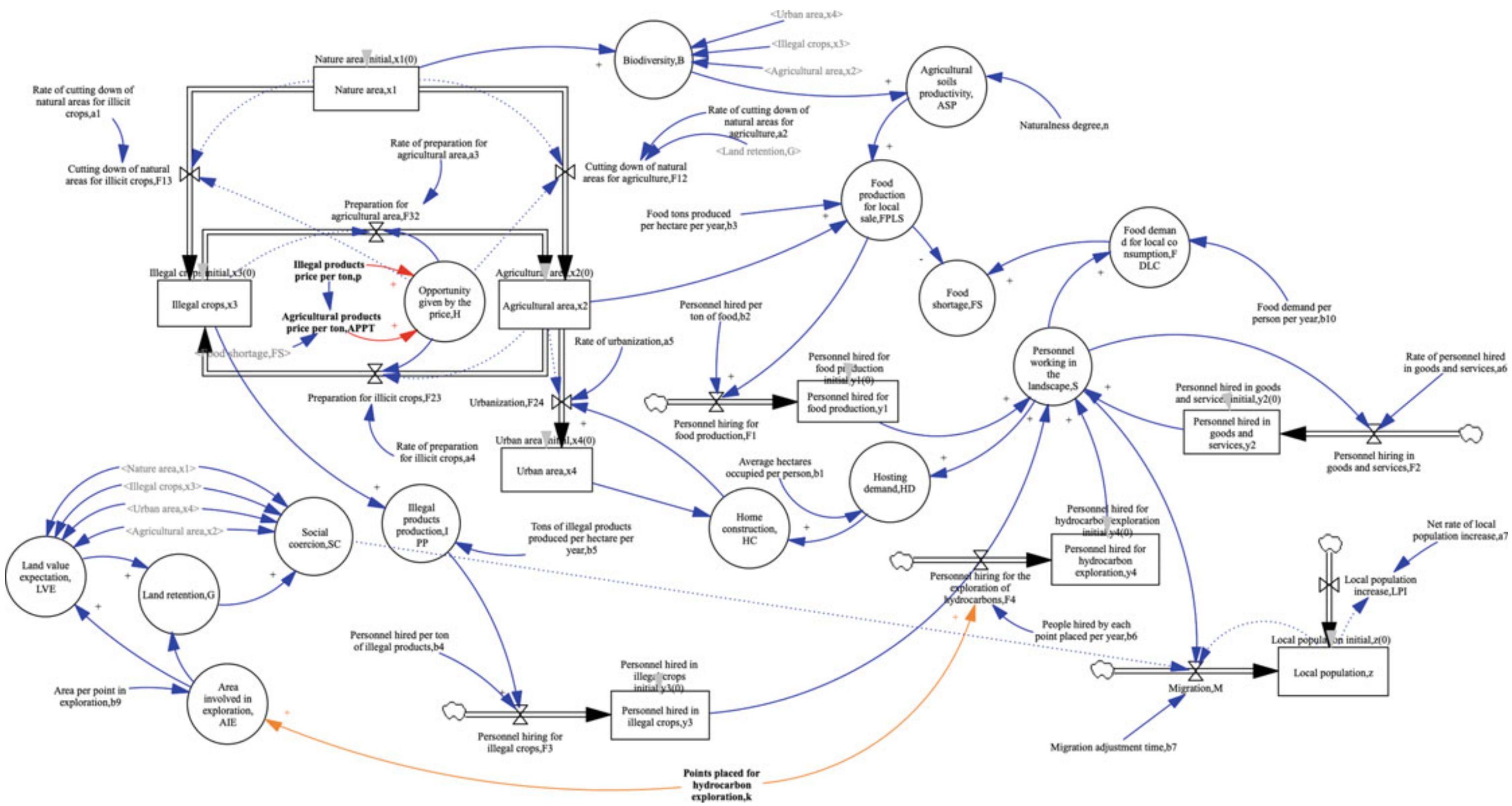

Fig. 6 Forrester diagram

$$\frac{dx_1}{dt} = \begin{cases} -a_1x_1 & H < 0, G \leq 0 \\ -a_1x_1 - a_2x_1 & H < 0, G > 0 \\ -a_2x_1 & H \geq 0 \end{cases} \tag{1}$$

$$\frac{dx_2}{dt} = \begin{cases} -a_4x_2 - a_5x_2\frac{b_1(y_1+y_2+y_3+y_4)-x_4}{b_1(y_1+y_2+y_3+y_4)} & H < 0, G \leq 0 \\ a_2x_1 - a_4x_2 - a_5x_2\frac{b_1(y_1+y_2+y_3+y_4)-x_4}{b_1(y_1+y_2+y_3+y_4)} & H < 0, G > 0 \\ a_2x_1 + a_3x_3 - a_5x_2\frac{b_1(y_1+y_2+y_3+y_4)-x_4}{b_1(y_1+y_2+y_3+y_4)} & H \geq 0 \end{cases} \tag{2}$$

$$\frac{dx_3}{dt} = \begin{cases} a_1x_1 + a_4x_2 & H < 0 \\ a_3x_3 & H \geq 0 \end{cases} \tag{3}$$

$$\frac{dx_4}{dt} = a_5x_2\frac{b_1(y_1+y_2+y_3+y_4)-x_4}{b_1(y_1+y_2+y_3+y_4)} \tag{4}$$

$$\frac{dy_1}{dt} = \frac{b_2b_3(1+n)x_1x_2}{x_1+x_2+x_3+x_4} \tag{5}$$

$$\frac{dy_2}{dt} = a_6(y_1+y_2+y_3+y_4) \tag{6}$$

$$\frac{dy_3}{dt} = b_4b_5x_3 \tag{7}$$

$$\frac{dy_4}{dt} = b_6k \tag{8}$$

$$\frac{dz}{dt} = a_7z + \frac{y_1+y_2+y_3+y_4-z}{b_7}\left(1 - \frac{b_8b_9k+x_3}{x_1+x_2+x_3+x_4}\right) \tag{9}$$

Where d/dt denotes the change in time, taking the year as the unit of time and the restrictions H and G are defined as follows:

$$H = \frac{-b_3p(1+n)x_1x_2}{b_{10}(y_1+y_2+y_3+y_4)(x_1+x_2+x_3+x_4)} \tag{10}$$

$$G = \frac{b_8b_9k}{x_1+x_2+x_3+x_4} \tag{11}$$

All the variable and parameter abbreviations used in the model, and their measure units, are found in Table 1.

Table 1 Abbreviations and measure units used in the model

Name	Abbreviation	Unit	Type
Nature area	x1	Ha	State variable
Agricultural area	x2	Ha	State variable
Illegal crops	x3	Ha	State variable
Urban area	x4	Ha	State variable
Personnel hired for food production	y1	Person	State variable
Personnel hired in goods and services	y2	Person	State variable
Personnel hired in illegal crops	y3	Person	State variable
Personnel hired for hydrocarbon exploration	y4	Person	State variable
Local population	z	Person	State variable
Rate of cutting down of natural areas for illicit crops	a1	Percentage/year	Constant
Rate of cutting down of natural areas for agriculture	a2	Percentage/year	Constant
Rate of preparation for agricultural area	a3	Percentage/year	Constant
Rate of preparation for illicit crops	a4	Percentage/year	Constant
Rate of urbanization	a5	Percentage/year	Constant
Rate of personnel hired in goods and services	a6	Percentage/year	Constant
Net rate of local population increase	a7	Percentage/year	Constant
Average hectares occupied per person	b1	Ha/Person	Constant
Personnel hired per ton of food	b2	Person/Ton	Constant
Food tons produced per hectare per year	b3	Ton/(Ha*Year)	Constant
Personnel hired per ton of illegal products	b4	Person/Ton	Constant
Tons of illegal products produced per hectare per year	b5	Ton/(Ha*Year)	Constant
People hired by each point placed per year	b6	Person/(Point*Year)	Constant
Migration adjustment time	b7	Year	Constant
Area per point in exploration	b9	Ha/Point	Constant
Food demand per person per year	b10	Ton/(Person*Year)	Constant
Points placed for hydrocarbon exploration	k	Point	Constant
Naturalness degree	n	Dimensionless	Constant
Illegal products price per ton	p	US$/Ton	Constant
Land retention	G	Ha	Restriction
Opportunity given by the price	H	Dimensionless	Restriction

The mathematical model constructed makes the restriction H strictly negative, unless the willingness to pay for the products obtained in illicit crops disappears, in which case it will be null, while the restriction G is strictly positive, provided that there are hydrocarbons exploration or an effective presence of the state in the exercise of formalizing land tenure.

3 Scenarios Assessment

From the mathematical model obtained, a simulation set of different scenarios was carried out, to review the prospective performance of the model and give some conclusions. The scenarios considered were: pristine landscape, agricultural landscape, and landscape of licit and illicit crops. Each scenario is evaluated with the presence and absence of hydrocarbon exploration, which is represented by placing exploration points on the landscape.

3.1 Scenario 1: Pristine Landscape

In this ideal scenario, the complete absence of socioeconomic dynamics is represented. This scenario was simulated considering that the initial coverage values are zero, except for the coverage of natural areas. The logging rates of natural areas have also been taken as zero and the local population is zero.

The simulations show a constant amount of natural areas, even with hydrocarbon exploration, see Fig. 7. Biodiversity simulates a value of 100 % and soil productivity of 125 %, while the production of licit and illicit crops appears at zero, see Fig. 7.

3.2 Scenario 2: Agricultural Landscape

In this scenario, a landscape with natural areas and socioeconomic dynamics revolving around agricultural production is represented. There is no presence of illicit crops. This scenario was simulated considering null the values of coverage of illicit crops, the clearing of natural areas for illicit crops, and the agricultural soils adaptation for illicit crops.

In the case in which there is no hydrocarbon exploration, there is less growth in urban areas from agricultural soils, while the coverage of natural areas remains intact (Fig. 8). The effect on biodiversity and soil productivity in this scenario leads to lower but constant values than those presented in the pristine scenario (Fig. 8).

On the other hand, with the hydrocarbons exploration in the landscape, the loss of natural areas and their conversion to agricultural and urban coverage is notorious, which in turn decreases both biodiversity and soil productivity (Fig. 9). Note also that the food production for local sale decreases drastically over time, thus showing a landscape that is highly dynamic due to its socioeconomic situation (Fig. 9).

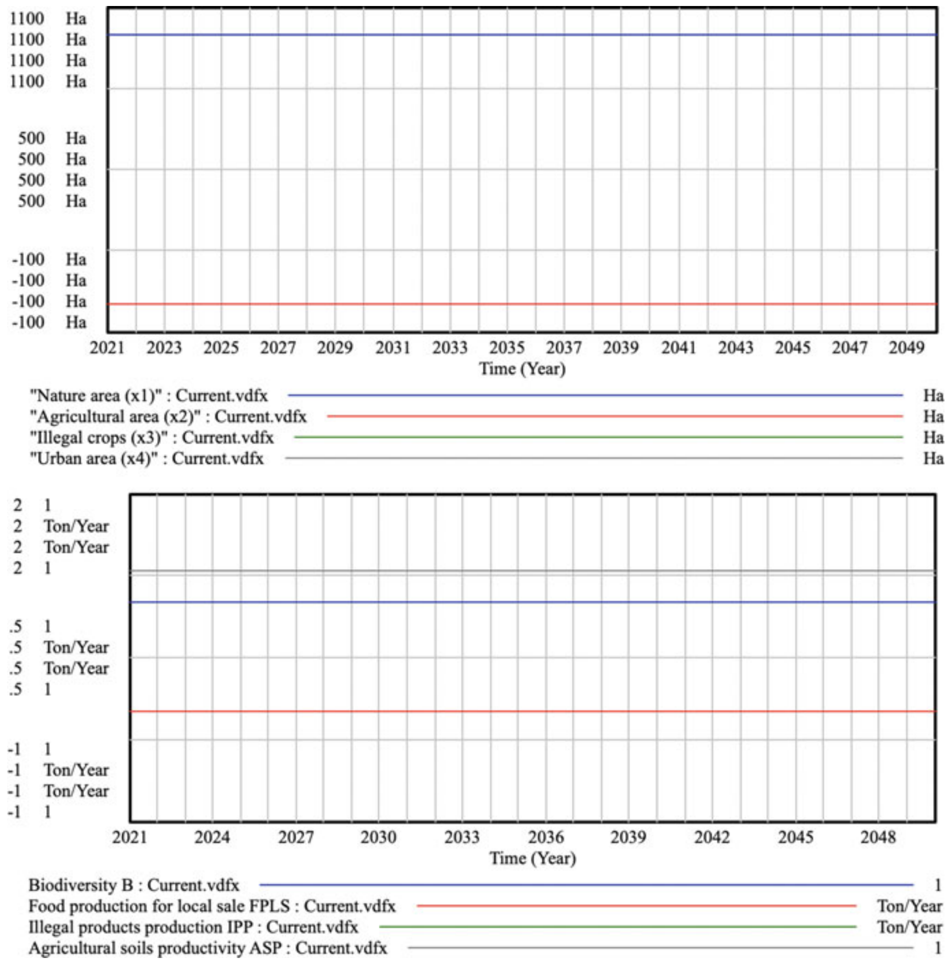

Fig. 7 Behavior of the covers, biodiversity, food production, production of illegal products and soil productivity in the pristine scenario

The social situation in this scenario shows that economic activity causes immigration to the landscape in conditions where coercion is non-existent (Fig. 8). However, with hydrocarbon exploration, there is a situation of constant coercion in the landscape becoming emigration.

3.3 Scenario 3: Landscape of Licit and Illicit Crops

In this scenario, a landscape with natural areas is represented, in which the socio-economic dynamics depend on agricultural production and illicit crops.

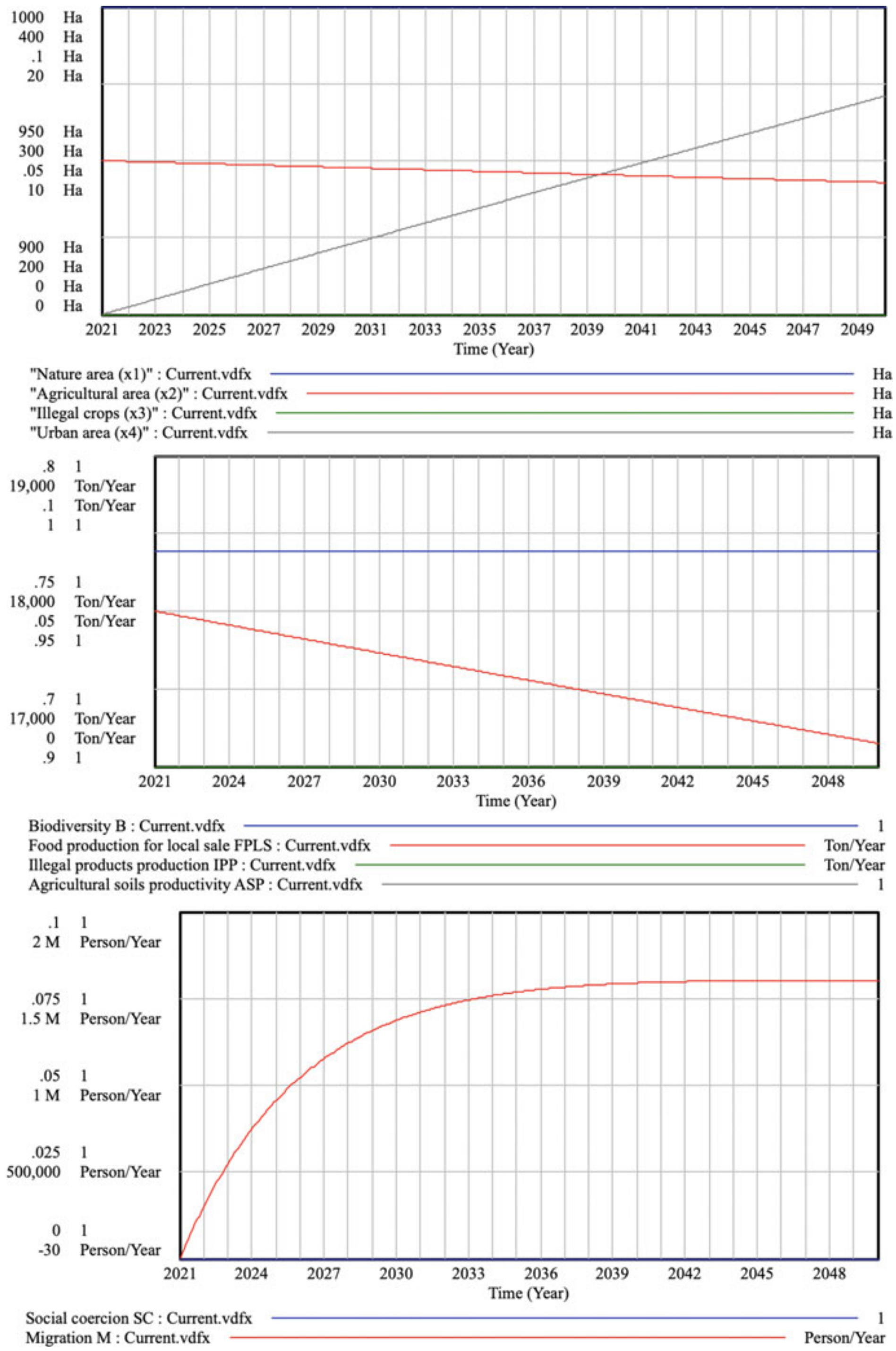

Fig. 8 Behavior of coverage, biodiversity, food production, production of illegal products and soil productivity in the agricultural landscape scenario

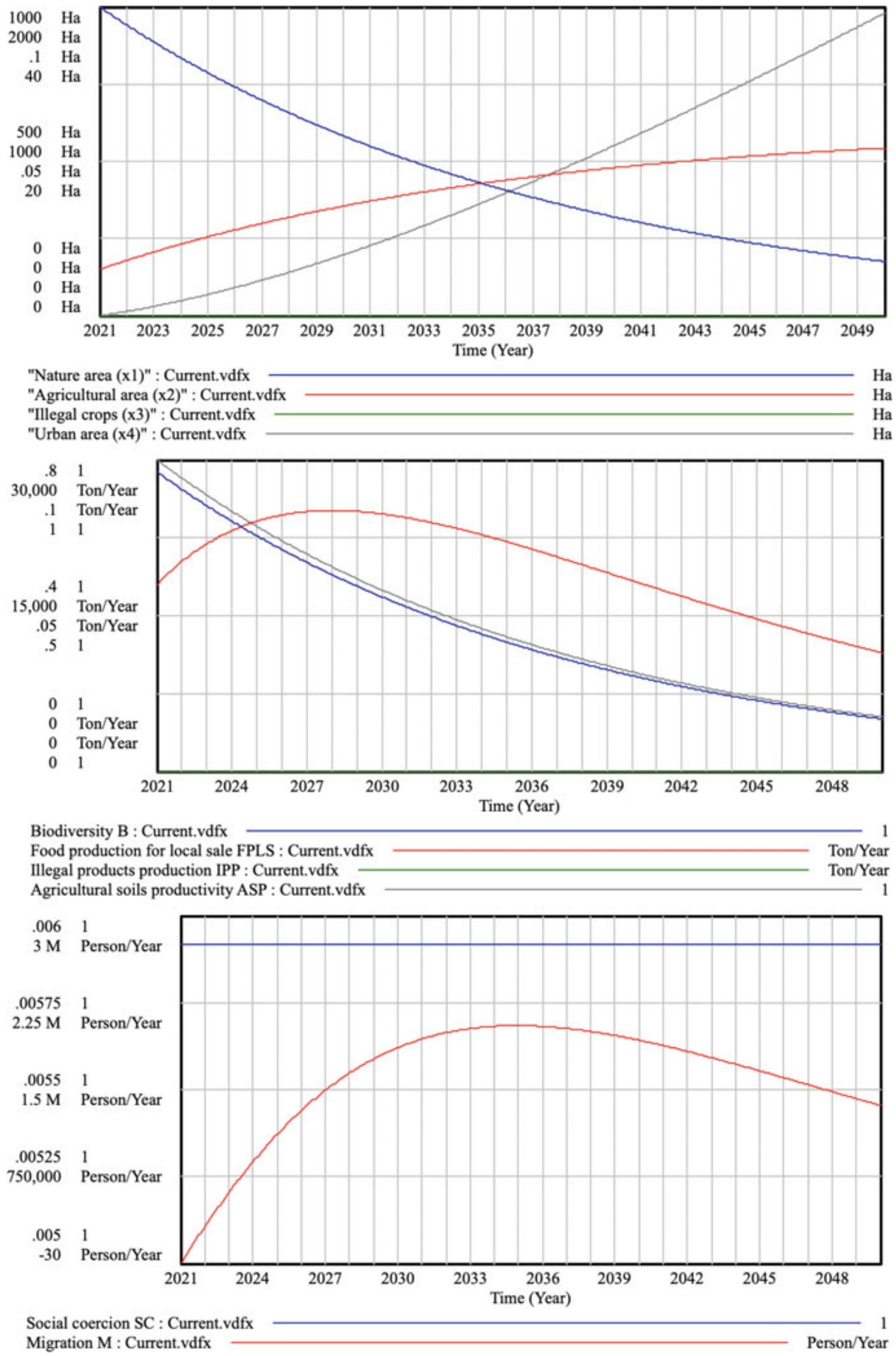

Fig. 9 Behavior of coverage, biodiversity, food production, production of illegal products and soil productivity in the agricultural landscape scenario with hydrocarbons exploration

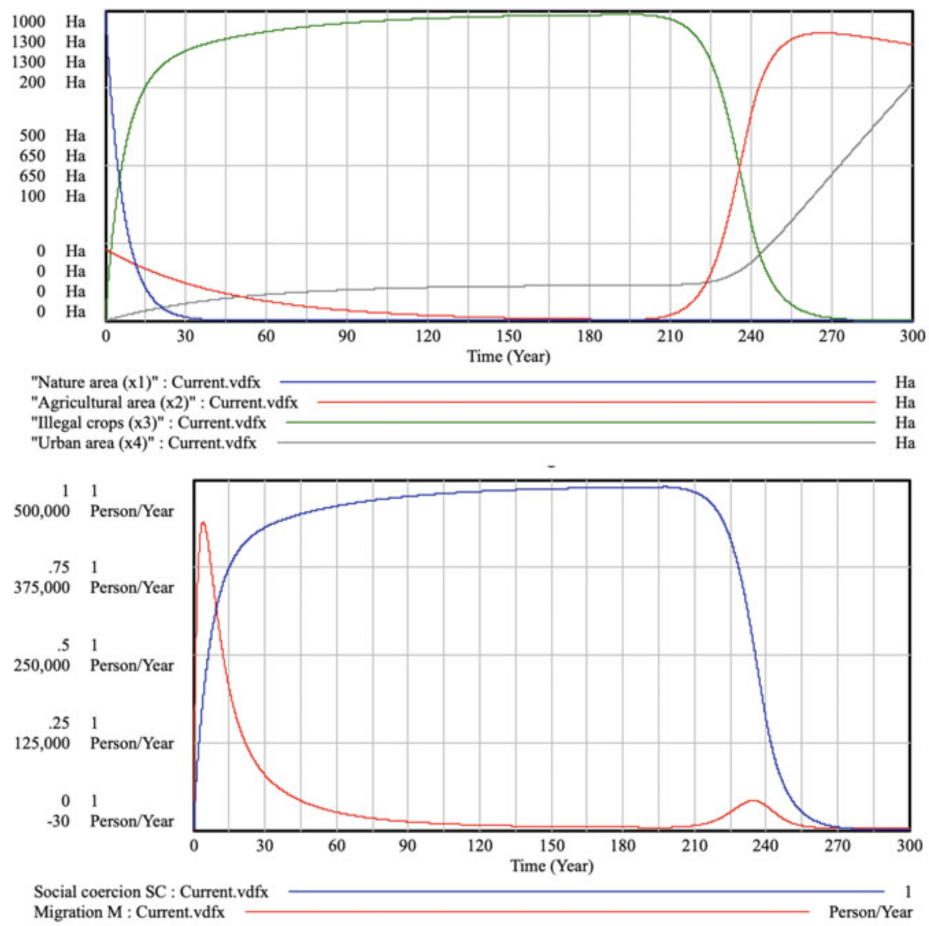

Fig. 10 Coverage and social behavior with licit and illicit crops

Without hydrocarbons exploration, illicit crops can grow above agricultural activity for a certain period (Fig. 10). However, with the increase in urban dynamics, the agricultural activity becomes dominant and the coverage of illicit crops tends to disappear. Natural areas are converted into lawful and illicit crop covers, which are also giving way to urban covers. In this way, a completely transformed landscape towards the urban-agricultural is obtained.

On the other hand, with hydrocarbons exploration, it is notable that the dynamics of behavior occur earlier in time, limiting the intensity and duration of illicit crops in the landscape, but accelerating its transformation towards urban agriculture (Fig. 11).

Regarding the social situation, it is notable that the presence of illicit crops in the landscape drastically increases coercion, which in turn increases the emigration of the landscape population. Once again, the hydrocarbon exploration activity acts as a social catalyst that does not prevent the existence of socioeconomic behavior but

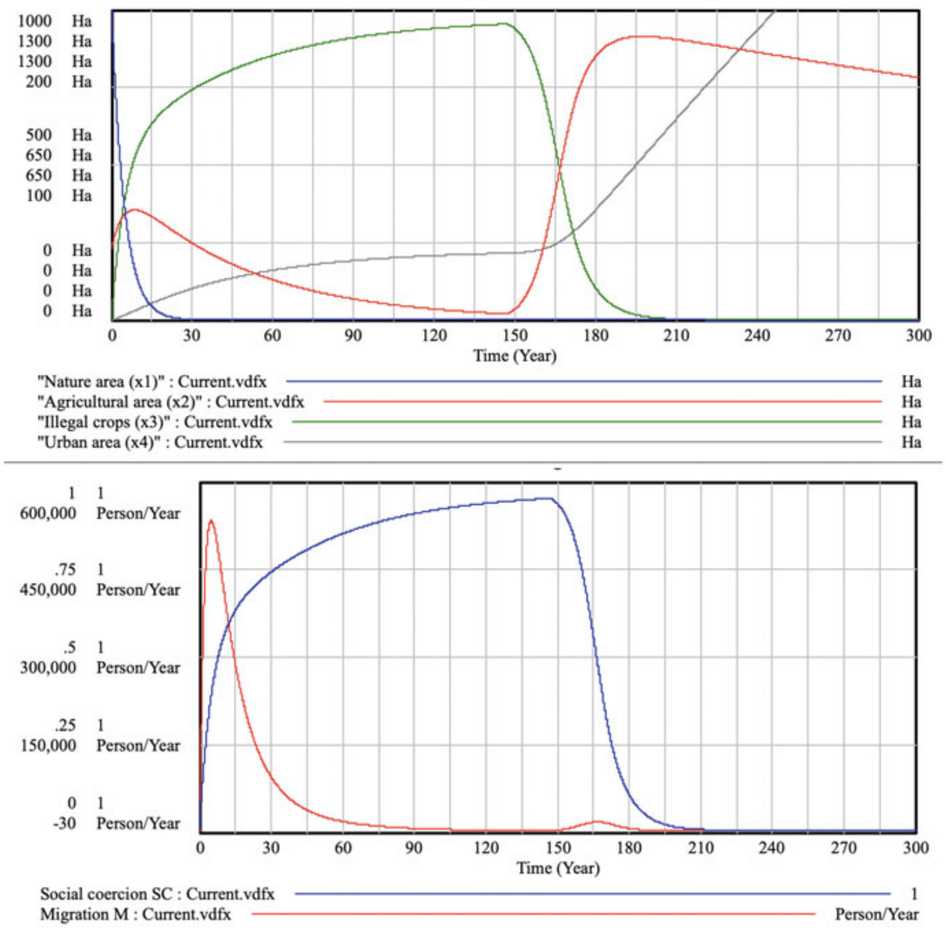

Fig. 11 Coverage and social behavior with licit and illicit crops, and hydrocarbons exploration

rather accelerates it. Check Fig. 10 for the absence of hydrocarbon exploration and Fig. 11 for its presence.

4 Conclusions

From the causal diagram, it is concluded that:

- There is a vicious circle in which natural covers and biodiversity tend to disappear, while the productivity of landscapes to produce and supply food to the landscape population is affected.
- There is a limit to the expansion of the coverage of illicit crops, given by the need to supply food to the population of the landscape.

- To maintain self-sufficiency, the urbanization of the landscape will have to impose a growth limit on agricultural coverage or it will have to import its supply.
- The landscape transformation is determined by the socioeconomic opportunity that the population finds in the landscape.

From the simulations carried out, it is concluded that:

- Exploration activity can intensify social coercion in the landscape, which will be weighted by informality in land tenure and the absence of state control.
- The cases in which the oil activity could bring undesirable consequences are the cases when the socio-economic dynamization is greater than the landscape is capable of assimilating.

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