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Analyzing socio-ecological interactions through qualitative modeling: Forest conservation and implications for sustainability in the peri-urban bogota (Colombia)

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ABSTRACT

Framing environmental issues in a sustainability context requires that we highlight the interdependencies between ecological, social and economic factors. Accordingly, the socio-ecological system (SES), which emphasizes the interplay between environmental and social dynamics, seems to be the appropriate framework for analysis. We applied this view to explore issues concerning the conservation of the remnant forests of the peri-urban area of Bogota (Colombia). Specifically, we characterized this territory as a SES through a parsimonious set of fundamental, across-domain variables. Using elicitation-based information we reconstructed interactions between these variables so that their interactive network could be visualized as alternative signed digraphs. We analyzed these models by Loop Analysis to show that exploiting the structure of the interactions may help disentangling causative mechanisms for the response of remnant forests and other components of this SES to natural events (loss of soil fertility), policies (subsidizing industrial production) and social events (internal migration, social activism) that we assumed as potential drivers of change.

Our results highlight that integrating ecological and social variables in a unique interactive network can reveal important causal linkages that make remnant forests unexpectedly vulnerable to certain drivers but also that unexpected beneficial effects may occur, clarifying why same drivers of change can be responsible for both deforestation and forest regrowth. Overall, the analysis reveals that trade-offs between desirable ecological and social outcomes are the rule and that potential win-win outcomes across the triple-bottom line of the sustainable development paradigm are difficult to achieve.

1. Introduction

Since the 1992 Rio de Janeiro summit on Environment and Development sustainability has become a uniting and purposeful focus for the twenty-first century. It recognizes that human society and nature are inevitably interdependent, with causal connections that cross the classical boundaries within which scientific and operational knowledge have been settled (Azapagic, 2003; Gallopin, 1994; Fiksel, 2006; Pappas, 2012; Binder et al., 2013). Accordingly, the socio-ecological system (SES) seems to be the appropriate framework for comprehensive sustainability assessments (Berkes and Folke, 1998; Ostrom, 2009; Levin et al., 2012; Berkes, 2017).

Interdependencies propagate policy effects, management actions and disturbances well beyond the targeted components. Anticipating the consequences may be important to design sustainable strategies, but this requires clarifying causal linkages. Socio-ecological interactions create multiple pathways through which impacts of the drivers of change can spread in the system. Pathway multiplicity creates an intricate scenario in which the chains of causally ordered events that produce the observed effects on system's components are not easy to reconstruct (Allen et al., 2011; Audouin et al., 2013; Vervoort et al., 2014).

We applied a qualitative modeling technique called Loop Analysis (Levins, 1975; Puccia and Levins, 1985) to the SES in which Neotropical, highly dynamic peri-urban forest ecosystem adjacent to Bogota, Colombia is embedded. We used Loop Analysis to disentangle the complexity associated with policy formulation as well as planning and

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management in this SES. Loop Analysis helps in this respect as it exploits the structure of the interactions to identify pathways responsible for the spreading of impacts and feedback that modulate their expression (Lambin and Meyfroid, 2010; Huber et al., 2013; Dawson et al., 2017; Bodini et al., 2018; Bodini and Clerici, 2016). This allowed reconstructing causal linkages and predicting expected impacts of drivers of change. Qualitative analysis seems appropriate here because quantitative predictions require that the magnitude of pathways that spread impacts is known. The lack of information concerning the form and intensity of most of the interactions precludes this possibility (i.e. the intensity at which agricultural activity modulates the rate of human migration is unknown). Thus, pathways could not be properly quantified, so that predicting quantitatively their effect would be impossible. We however overcame some of the problems of the pure qualitative approach by combining Loop Analysis with a numerical simulation technique which allowed us performing a semi-quantitative analysis (Martone et al., 2016; Bodini et al., 2018).

We focus on Colombia's capital Bogota since, similar to other urban areas in the Andes, it is surrounded by a large extent of peri-urban forests, and which are home to some of the highest levels of biodiversity and endemism in the world (biodiversity hot spots, Van der Hammen and Cleef, 1986; Grau and Aide, 2008; Moreno et al., 2017). Such ecosystems provide a large array of services to the growing Andean population (Baldi and Paruelo, 2008), but they have been strongly impacted by socio-political factors. Bogota and its surrounding suburban settlements, for example, have historically claimed agriculturally productive lands and large areas of natural forests and wetlands have been converted to productive areas (Baptista, 2008; Grau et al., 2008; da Gama Torres, 2011; Sanchez-Cuervo and Aide, 2013a). Protecting the remnant forests has become a pillar for the sustainable development of the area (Baptiste et al., 2017; Clerici et al., 2016).

Patterns of forest conversion and regrowth in the peri-urban Bogota and the Neotropics have been said to depend on the interplay of multiple socio-ecological factors, and reflect the complexity of the processes occurring in such a highly transformed and densely populated region, where the same factor can be a driver of both deforestation and recovery simultaneously (Bonilla-Moheno et al., 2012; Rubiano et al., 2017). Because of this complexity, however, cause and effect mechanisms responsible for these patterns are not fully understood. Further transformations are expected in this area because a future proliferation of economic and infrastructure development programs may follow the recent peace agreement between the Colombian government and the guerrilla group Fuerzas Armadas Revolucionarias de Colombia (FARC), has opened up.

Understanding patterns of deforestation and anticipating the effects of development programs on the forest ecosystem can be possible if interdependencies between the components of this SES are explored and clarified. The main objective of this paper is to show what useful insights Loop Analysis can provide to understand these interdependencies. To this end we identified a parsimonious set of social and ecological variables to characterize the peri-urban area of Bogota as a SES. Then we mapped out their interactions and reconstructed a series of plausible network models for this SES. Finally we applied Loop Analysis to these simplified representations to: i) show how causal chains can be reconstructed by exploiting the structure of the interactions and identify pathways through which impacts spread in the SES; ii) predict the response of remnant forests and other components of this SES to selected, across domain drivers of change and link the predicted impacts to their causal chains; iii) provide an explanation for the observed patterns of deforestation and forest regrowth; and iv) make an overall sustainability assessment by analyzing the effects of drivers of change on variables that can be used as proxies for indicators of environmental, economic and social conditions.

2. Materials and methods

2.1. Study area

The study area is located around the Colombian capital Bogotá, comprehending the vast *Sabana* high elevation plain and neighboring mountain slopes (Fig. 1). Andean forests are characterized by different structures varying from young even-aged shrub-like forests dominated by pioneer tree species to more mature stands with a diverse species composition (Chazdon, 2014; González et al., 2015). Andean forests have undergone substantial land cover change in the region due to a complex interplay between deforestation, land degradation, and local forest regrowth (Rubiano et al., 2017).

Most Andean forests in this region were strongly exploited in the past century for wood production and substituted by cropping activities and cattle grazing (Etter et al., 2008). Steep slopes favor forest persistence: more than 70% of the remnant forests are in fact located in areas with slopes over 25% (Mendoza and Etter, 2002). More accessible areas underwent transformation in which deforestation created patches of forests dispersed in a matrix of productive land (Etter and Villa, 2000). Size reduction in forest patches is also the result of residential expansion, road construction and industrial development that are connected to urban development (Fischer and Lindenmayer, 2007; Botero-Garcia, 2017). Land conversion to productive or residential lands is still underway; however, loss of soil fertility and social drivers, such as the Colombian armed conflict, have fueled land abandonment, which has favored forest recovery (Acosta-Restrepo, 2010; Andrade-Núñez and Aide, 2018). Shrubland, locally known as *rastrojo*, is an important component of the current landscape, and it may correspond to vegetation which is gradually recovering from past disturbances, or represents an arrested successional stage (Mesquita et al., 2001).

Andean forests have the potential for being important biodiversity reservoirs and providing crucial ecosystem services (Armenteras et al., 2007; Girardin et al., 2014) and their conservation has thus become matter of concern.

2.2. Loop analysis

Loop Analysis is a qualitative technique that uses signed digraphs to represent networks of interacting variables (Levins, 1975; Puccia and Levins, 1985). The signed digraph depicts interactions between variables by only two types of connections: arrows (→) for positive effects and circle-head links ($-o$) for negative effects. These links describe the effects of the variables on each other's rate of change. Loop Analysis predicts the direction of change in the level (e.g. biomass of a biological variable, amount of a given production, etc.) of system variables in response to parameter alteration targeted to one or more components (i.e. press perturbations; see Bender et al., 1984; Bodini, 2000). Examples of press perturbations are the increased mortality or fecundity of a given species, the increased rate of investment, or the political actions of social activists in the local communities.

When a press perturbation increases the rate of change of the target variable, this latter is said to undergo a positive input (Puccia and Levins, 1985). A negative input occurs when the press perturbation reduces the rate of change of the variable. Effects of an input may percolate to the other components that are connected to the target variable by the network. Their responses can be predicted using an algorithm whose main features are described in the Supporting Information, Appendix A. These predictions give only the direction of change for the level of the variables: increase (+), decrease (-), or no change (0). They are usually summarized in a Table of predictions that accompanies any model (examples of tables of predictions are presented in the Figs. 3, 4, and 5, below each graph).

In models with few variables and/or a limited number of connections, expected changes for the variables can be tracked through the graph anatomy (Bodini, 1998; 2000). When variables and connections

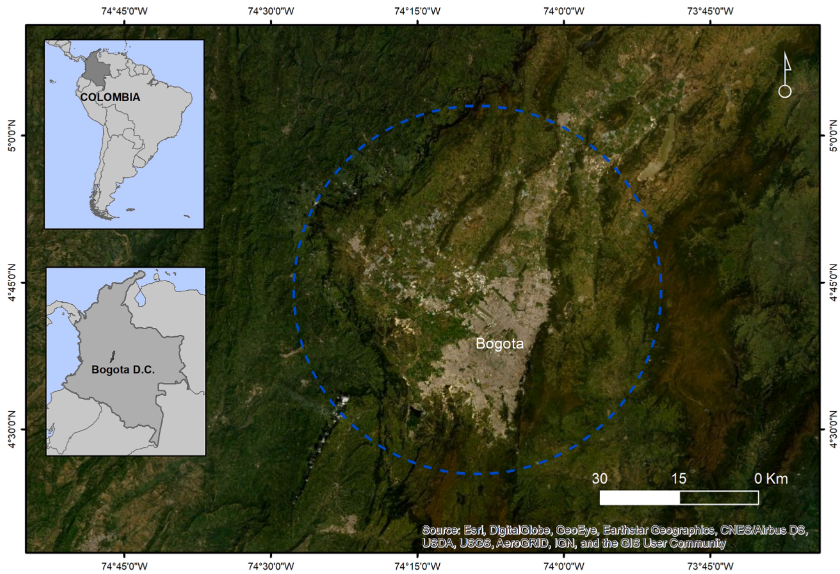


Fig. 1. Approximate study area (blue dotted line) that comprises urban and periurban Bogota, Colombia.

increase, multiple pathways of interactions emerge and the probability that pathways have opposite effects increases (i.e., some paths increase the variable, others reduce its level); consequently, predictions may remain ambiguous. To overcome this problem, we used a numerical simulation based on a routine that converts in a matrix implementation the algorithm of loop analysis. The routine assigns numerical values in the interval (0,1] to the coefficients of the community matrix (i.e., the coefficients of the links in the signed digraph) by randomly extracting them from a uniform distribution This procedure and the code for the R functions (R Core Team 2014) are described in detail in the Supporting Information, Appendix A-C.

2.3. Model development

Central to apply Loop Analysis is the possibility to diagram the structure of the interactions between the system's components. First, variables must be identified, and the way they affect each other's rate of change must be translated in graphical terms according to the Loop Analysis symbolic language. Making these interconnections explicit implies translating an idea about the world into a signed digraph model. Because the multiplicity of the variables and their interactions in a SES would make this task overwhelming, we simplified the analysis by focusing initially on a few key processes and a parsimonious set of variables and interactions, according to the work of Rubiano et al. (2017). Next, we extended the list of the variables to include some of the potential drivers of change associated with likely developmental scenarios or that are currently under consideration. Literature analysis guided this effort (Etter and Villa, 2000; Mendoza and Etter, 2002; Armenteras et al., 2007;Armenteras et al., 2011 Rubiano et al., 2017). We then evaluated these preliminary findings in a two-day expert elicitation workshop with 10 invited experts in the areas of socio-ecological systems, urban planning, landscape ecology, forestry, ecological modeling, and geospatial analysis.

This participatory approach helped defining the study area, the parsimonious set of variables to describe it as a SES, their interactions and some of the most relevant factors and processes that acted as drivers for the observed change and some that likely will affect this SES. This yielded an extended list of variables that were identified as being influential in the process of land cover change in the study area. The models that we present in this work emphasize on realism and generality (Puccia and Levins, 1985) and necessarily leave out details in favor of a more general representation, the characteristic approach that qualitative analysis privileges. Some of the approximations used in model representation will be elucidated while discussing the results.

3. Results and discussion

3.1. The study area core model: variables, interactions and graphs

According to the literature (Acosta-Restrepo 2010; Sanchez-Cuervo et al., 2012; Rubiano et al., 2017 and references there in) landscape transformations in the study area have been driven by the interplay of several processes: forest conversion, land reclamation for agricultural purposes, urban expansion, land abandonment, human migration, and forest recovery. A minimal set of variables that could grasp the dynamics of the above listed processes were identified. These core variables are described in Table 1. The extension of forested land (*FC*) is the proxy for the forest cover. Urbanization and agricultural development were identified as main factors of forested land consumption (Anselm et al., 2018): extension of the built-up environment (*BL*), and of land converted to agricultural production (*A*)are their proxy variables. Water quality and availability (*W*)was selected because remnant forests play a key role in the water cycle and in the provisioning of this resource for human consumption (Ellison et al., 2012Bonnesoeur et al., 2019). The number of migrants (*M*)considers a relevant social factor, migration, which has been responsible for land transformation of this SES (Etter et al., 2008). Extension of shrubland (*SL*)completes the list because shrubland is the intermediate step through which abandoned (agricultural) land becomes forested land.

Fig. 2 depicts the interactions between the core variables according

Table 1
Core variables used to describe the key processes responsible for the land cover change in the study area. Measurement units are made explicit to help understanding the meaning of the variables and not for quantitative purposes.

Variable	Key	Meaning of the variable and unit measurement
Built-up land	BL	Extension of the built-up environment (ha)
Forest Cover	FC	Land occupied by forests as sum of the patches that compose the remnant forests in the study area (ha)
Agriculture	A	Extension of the agriculture productive land (ha)
Water Resources	W	Water quality and availability for consumptive uses (qualitative scale)
Shrubland	SL	Extension of shrubland (ha)
Human migration	M	Amount of migrants from rural to urban areas (number of individuals)

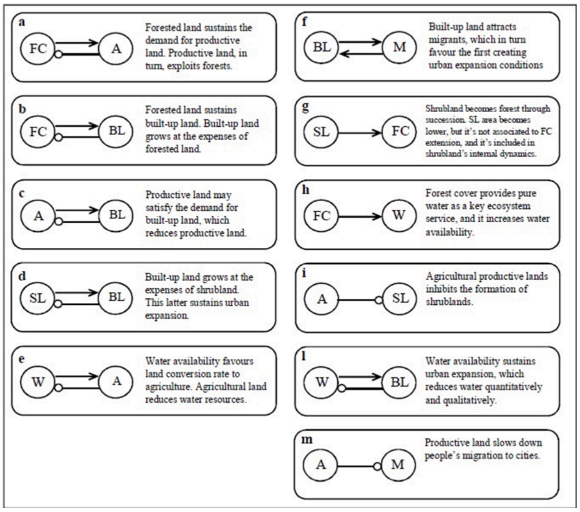


Fig. 2. List of the interactions between the variables of the core model for the study area. Descriptions regard how variables dynamically affect each other. These effects give rise to arrows and circle-head links according to Loop Analysis symbolic language.

to the Loop Analysis symbolic language and describes their dynamic effects. It must be pointed out that the relationships described in Fig. 2 in some cases can reproduce more general types of interaction, but others are specific for the system under investigation, such as, for example, interactions (h and m. In other contexts, or systems, in fact, forest may reduce water availability through evapotranspiration and people can be forced to migration due to mechanization and substitution of labor for economic capital. Considering the latter phenomenon, the specificity of the negative interaction between productive land and migration is due to the emphasis that in the workshop participants gave to the form of agricultural production that involve local communities and guarantee food security. The possibility to have access to land would prevent people to migrate toward urban areas.

We assembled variables and interactions to form the networks to be analyzed qualitatively. When knowledge about interactions is uncertain —because the reports in the literature disagree, information is unavailable, or experts suggest different mechanisms of interaction— then follow plausible alternatives. Here alternative graphs for the core model reflect different forms of land exploitation by the built-up environment. While there is no uncertainty about the urbanization of forested land, it is not certain whether the built-up environment grows also at the expenses of agricultural productive land and/or shrubland. Thus, we modeled four alternative configurations taking into account these possibilities. These alternative graphs are illustrated in Fig. 3.

In model 3a the built up land (*BL*) exploits only forested land (*FC*); in model 3b it grows at the expenses of forest cover and agricultural productive land (*A*); in model 3c exploitation is targeted to forest cover and shrubland (*SL*) and in model 3d the built-up land exploits forested land, shrubland and agricultural productive land. We assumed all the variables as self-regulated. This depends on several factors which we summarize here in: 1) mathematical convenience: negative self-loops tend to make the model qualitatively stable, a necessary condition for the moving equilibrium approach to be applied (Puccia and Levins, 1985); 2) realism: the graphs unavoidably simplify a complex reality in which several factors affect the dynamics of the system but do not enter in the model as explicit variables. To account for the connections with these external factors a self-damping on the model variables can be added (Levins, 1975; and Puccia and Levins, 1985 detail the logic and the mathematics of this process). Because such connection exists for all the variables in the model it follows that self-regulation can be extended to all of them. Thus, adding a self-damping term on all the variable can be realistic. One example of these external factors is soil fertility, which is also a prime cause of forest conversion to agricultural productive land, because deforestation for agricultural purposes is targeted preferentially to more fertile soils (Aide and Grau, 2004; Rubiano et al., 2017). As this conversion proceeds, more fertile areas become rarer in Bogota's Sabana high plain, and this may slow down the process of land acquisition for agricultural production.

Another crucial factor that controls deforestation is land morphology. Forest conversion to built-up land and agricultural productive land occurs mainly in areas of lower altitude and less steep slopes (Rubiano et al., 2017; Mendoza and Etter, 2002). As the conversion of forested area proceeds, less of the morphologically suitable land remains available for conversion. This may slow down forested land conversion to agricultural productive land and built-up land. This mechanism thus can be thought of as a regulative factor for built-up land and agricultural productive land dynamics. It is considered in the self-damping on *A*and *BL*.

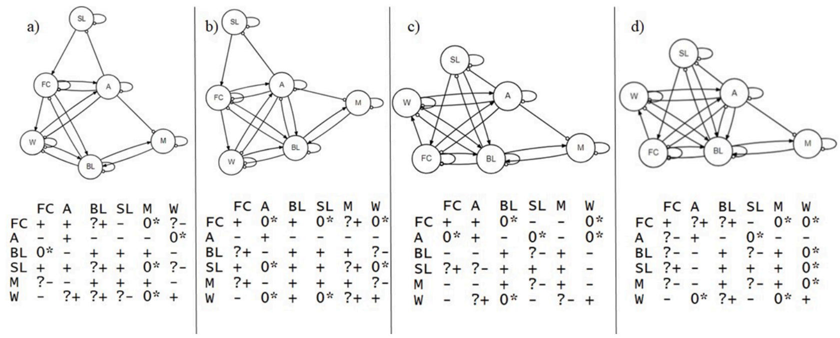
3.2. *Drivers of change: soil fertility loss and migration*

Factors considered to be drivers of land cover change were introduced in the models as press perturbations (input) on target variables. Forest regrowth has been taking over in the study area following land abandonment and the consequent migration toward urban areas (Aide and Grau, 2004). Soil fertility loss and /or agricultural intensification might have ignited this causal chain. Soil fertility has been indicated as favoring the rate of conversion of forested land into agricultural land (Aide and Grau, 2004; Rubiano et al., 2017; Moran et al., 2000). A reduced soil fertility thus acts as a negative press perturbation on A (agricultural productive land). For the sake of clarity in Fig. 4 we detail the predicted response of the system variables to this press perturbation using Model 3c as reference.

Rubiano et al. (2017) observed in the Sabana of Bogotá an increasing trend in woody cover with a characteristic pattern in which forest regrowth is accompanied by land abandonment, increased rural to urban migration, and the occurrence of secondary succession on abandoned land. A chain of causally ordered events was hypothesized to explain this pattern: the loss of soil fertility might have ignited land abandonment, thus fueling migration toward urban areas. Abandoned land may have undergone secondary succession that transformed fields no longer grazed or mowed in shrubland and then secondary forests. Similar dynamics have been documented in other areas of South America (Veldkamp et al., 1992Rudel et al., 2002; Aide et al., 2013).

This chain of events implies: i) land abandonment;; ii) increased number of migrants towards urban centers; iii) the augmentation of shrubland extension and forest cover and iv) a reduction in the agricultural productive land . The tables of prediction of Model 3a and 3b reveal that such concomitant variations are possible following a negative press perturbation on variable *A*(second row of the tables below the graphs, inverted signs): the number of migrant is predicted to augment ($M = \ +$), both shrubland ($SL = +$)and forest cover ($FC = +$)would increase and productive land is expected to decrease ($A = \ -$). As side effect, the built-up land is predicted to increase ($BL = +$), a plausible consequence of the augmented rural to urban migration.

Indeed, the Sabana of Bogotá has been experiencing soil degradation (Ministerio deAmbiente, 2003), its population has been constantly increasing (UniSabana, 2019), as well as the extension of built-up land at the cost of productive land (Martínez Herrera, 2015). Rodríguez et al., 2013Rodriguez et al. (2013) projected land cover change in the Colombian Andes according to three different scenarios that they simulated using spatio-temporal data on land use land cover change. The one which was constructed by assuming an extension of cropland predicted a reduction of the forest cover. In principle this scenario is simulated in our model assuming a positive input on A (extension of crop land). The models of Fig. 3 (the only exception is Model 3c) yielded a response of forest cover and agricultural land that coincides with the outcomes of Rodriguez et al. simulations: forest cover was predicted to



a)

	FC	A	BL	SL	M	W
FC	+	+	?+	-	0*	?-
A	-	+	-	-	-	0*
BL	0*	-	+	+	+	-
SL	+	+	?+	+	0*	?-
M	?-	-	+	+	+	-
W	-	?+	?+	?-	0*	+

b)

	FC	A	BL	SL	M	W
FC	+	0*	+	0*	?+	0*
A	-	+	-	-	-	-
BL	?+	-	+	+	+	?-
SL	+	0*	+	+	?+	0*
M	?+	-	+	+	+	?-
W	-	0*	+	0*	?+	+

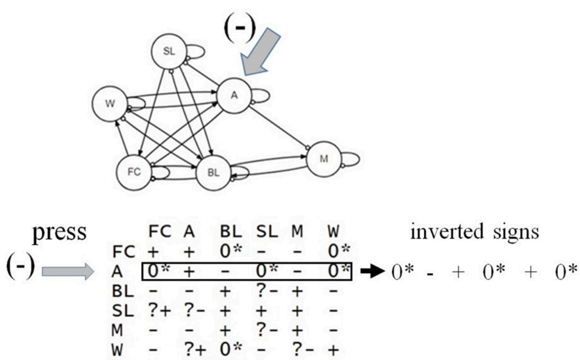
c)

	FC	A	BL	SL	M	W
FC	+	+	0*	-	-	0*
A	0*	+	-	0*	-	0*
BL	-	-	+	?-	+	-
SL	?+	?-	+	+	+	-
M	-	-	+	?-	+	-
W	-	?+	0*	-	?-	+

d)

	FC	A	BL	SL	M	W
FC	+	?+	?+	-	0*	0*
A	?-	+	-	0*	-	-
BL	?-	-	+	?-	+	0*
SL	?+	-	+	+	+	0*
M	?-	-	+	?-	+	0*
W	-	0*	?+	-	0*	+

Fig. 3. Alternative graphs for the core model and tables of predictions. All the variables are self-limited (see text for details). The table reads as follows: the variable at the beginning of each row indicates which component is subjected to input (positive); along the same row each column indicates the predicted response of the level of each variable in the system as increase (+), decrease (-) or no change (0). Predictions for negative inputs can be obtained by simply reversing the signs. The meaning of the question marks and the asterisks is explained in Appendix A.



	FC	A	BL	SL	M	W
FC	+	+	0*	-	-	0*
A	0*	+	-	0*	-	0*
BL	-	-	+	?-	+	-
SL	?+	?-	+	+	+	-
M	-	-	+	?-	+	-
W	-	?+	0*	-	?-	+

Fig. 4. Predictions concerning the effect of soil fertility loss as negative press perturbation on variable A in Model 3c. The gray arrow indicates which row of the table lists the response of the variables to this press perturbation. The signs along this row (highlighted in the box) must be inverted because the press perturbation diminishes the rate of change of variable A (negative input, see Methods and Appendix A).

diminish and agricultural land would increase.

The response of forest cover (*FC*)and shrubland (*SL*)to the negative input entering through A is different in the other models. Model 3c returns no expected change (0^*in the table of predictions) for both FC and SL. Model 3d predicts a tendency to increase for *FC*(?+) and no change for shrubland ($SL = 0^*$). The different articulation of the interactions in Models 3c and 3d in respect to Models 3a and 3b makes the number of pathways connecting *A*to *FC*and *SL*to increase (in Appendix B we single out the paths from *A to FC*to help understanding this point). Positive paths responsible for the negative effect,[1]increase in number, contrasting the (negative) paths that carry a positive effect. These positive paths counteract negative paths so that the positive predictions obtained in Models 3a and 3b become null predictions. This compensation depends on both the number of pathways and their magnitude; this latter is obtained multiplying the intensity of the links that make the path (see Appendix A).

Further insight can be obtained by focusing on the structure of the paths. For example, the negative input on *A*may yield a negative prediction for *FC*for particular combinations of link intensities.[2] Three of the paths that carry positive effect (and thus would decrease *FC* for a negative press on *A*) are formed by the links that account for the exploitation of shrubland by the built-up land ($SL\rightarrow BL; BL - o\ SL$, see Appendix B). If shrubland is intensively used to extend the built-up land the null prediction may turn into a negative expectation for *FC*.

In Model 3a and 3b, in which *BL*does not exploit shrubland, the loss of soil fertility (negative press on *A*) makes forest cover increasing with no uncertainty. If the built-up land expands on shrubland, (Model 3c and 3d) forest regrowth is less likely to occur because shrubland converted to urban area may not complete the succession to secondary forest. In this framework the conspicuous forest regrowth documented in the area near Bogota (Rubiano et al., 2017) can be due to a moderate or null conversion of shrubland to built-up land, a hypothesis that we present with circumspection and that should be corroborated by further data analysis and observations. According to these outcomes, Model 3a and Model 3b seem to better represent the observed dynamics (Rubiano et al., 2017).

In Colombia individuals internally displaced by conflicts produced strong migratory fluxes toward urban areas (Lozano-Garcia et al., 2010). Migration (*M*)has been selected as a core variable in the understanding that migratory flows have had a substantial impact on the territorial dynamics of the study area (Albuja and Ceballos, 2010). The incoming flow of individuals is described by assuming a constant positive parameter in the equation for the rate of change of *M*and this translates into a negative self-loop link on variable M in the graph (Puccia and Levins, 1985Puccia and Levins, 1985; and Bodini, 2000 explain why a positive constant flux in the dynamic equation for a variable becomes a negative self-loop on its node in the graph). The armed conflict augmented this migratory flow from outside the study area (Ibañez and Vélez, 2008) and a positive press perturbation can reasonably be assumed in the rate of change for M. In Fig. 3 predictions about this positive press are listed along the rows labelled *M*, the entry point of the perturbation. Forest cover shows a tendency to decrease across the models, except for Model 3b in which this component would be increasing ($FC = ?+$). A closer look to the pathways connecting the entry point of the perturbation (variable *M*) with the effect variables (*FC*)provides clues to understand model predictions (see Appendix B). In Model 3a three paths propagates to *FC*the effect of the migratory flow:

1) $M\rightarrow BL - oFC$; *sign* $(-)$;
2) $M\rightarrow BL - oW\rightarrow A - oFC$; *sign* $(+)$;
3) $M\rightarrow BL - oW\rightarrow A - oSL\rightarrow FC$; *sign* $(+)$.

Effects of the paths can be causally interpreted by combining the nature (sign) of each link forming the path with the predicted variations of the variables along the path. In path 1) migration flow increases the number of immigrants ($M = +$); this component exerts a positive effect on the rate of change of *BL*($M\rightarrow BL$), and this latter is predicted to increase ($BL = +$); *BL*increases at the expenses of the forested land ($BL - oFC$), which would be shrinking[3] ($FC = -$).

[1] It must be clarified here that, according to the loop formula (see Appendix A), because the sign of the path is multiplied by the sign of the press perturbation (negative variation in the rate of change of A, in this case), positive paths carry a negative effect, whereas negative paths produce positive effect.

[2] This possibility does not emerge from the numerical analysis because it mediates the outcomes of many simulation runs (see Appendix A), and particular cases are obscured for the procedure takes averages.

[3] This is not shown as a as a negative prediction on *FC*because the table of predictions shows the overall effect of the three paths.

On the contrary paths 2) and 3) have a positive effect on *FC*. In 2) the augmented built-up land increases water consumption rate ($BL - oW$), and water availability diminishes($W = -$). Water shortage diminish the positive effect that this resource has on the rate of change of A ($W \rightarrow A$) and this latter variable is expected to decrease ($A = -$). As a possible consequence it can be abandoned and natural succession would take over to shrubland which in fact is predicted to increase ($SL = +$). The lower level for *A*reduces its negative effect on forested land ($A - oFC$)with beneficial effect on this component. Path 3) includes also shrubland: the lessening predicted for *A*diminish its negative action on the rate of change of SL; so this latter would augment ($SL = +$) favoring forests ($SL \rightarrow FC$). The positive effects of paths 2) and 3) tend to mitigate the negative effect of the exploitation by the built-up land, which however remains preponderant. The two positive pathways in fact are longer than the negative path and the magnitude of their effect attenuates along the path. The overall effect can thus be a net loss of forested area.

Model 3b predicts a tendency to increase for $FC(?+)$following the positive press on *M*(increased migratory flow). In building this graph we hypothesized that the built-up environment *BL*would exploit also agricultural productive land (Corporación Cactus, 2014; El Nuevo Siglo 2020). Due to this connection the number of paths linking *M*to *FC*increases by two positive paths in respect to Model 3a: they are $M \rightarrow BL - oA - oFC$and $M \rightarrow BL - oW \rightarrow A - oFC$. Overall, there are 4 positive paths and one negative (see Appendix B) and the numerical analysis shows that the former prevail making the level of *FC*increase. In Models 3c and 3d the different ways through which built-up land exploits available land implies further paths but their overall effect remains negative and an increased migratory flow is predicted to negatively impact forest cover.

The causal interpretation of predictions based on the paths may help interpret the evidence that forest regrowth and deforestation, that are opposing forces, may act simultaneously (Rubiano et al., 2017), suggesting in what circumstances one may prevail over the other. So far two types of press perturbations have been considered: reduced soil fertility and increased immigration rate. In both cases we have shown that the existence of opposite paths may determine the occurrence of forest regrowth or deforestation. By scrolling down the first column of each table in Fig. 3 one can make an overall assessment about the possibilities that same press perturbations may induce regrowth and deforestation. The first column of each table in Fig. 3 shows expected changes in the level of forest cover for press perturbation entering through any of the system variables. Whenever a predictions is not certain (0^*, $?+$, $?-$)multiple paths with opposite effects exist that spread the impact of the press perturbation to *FC*: this creates the conditions for deforestation or forest regrowth to occur following the same cause (the press perturbation). The occurrence of either effects depends on the strength of the paths and thus on the magnitude of the interaction links. Model 3d shows the highest number of uncertain predictions (4 out of 6, for press perturbation on *A*, *BL*, *SL*, *M*). In the other three models uncertain predictions are 2 out of 6 for each graph (although not for the same input). The highest number of uncertain predictions in Model 3d depends on the complexity of its structure which accounts for the concomitant exploitation of forests, shrubland and agricultural productive land for urban expansion.

Also, with more interactions the number of paths connecting any two variables may increase and the probability that these paths have different effect (sign) increases as well. According to these results, it can be hypothesized that the increment of forested land in the study area (Rubiano et al., 2017), may not be as surprising as it may appear despite the many drivers that enhance deforestation. Through the analysis of the structure of the interactions that encompass a range of environmental and socioeconomic conditions, factors that contribute to gains and losses of forest area may become explicit. This suggests that also for other areas of Colombia where forest regrowth was documented (Sanchez-Cuervo et al., 2012; Sanchez-Cuervo and Aide, 2013b), elucidating the pathways that spread the effects of drivers might contribute to frame the observed changes in a causative perspective.

3.3. The study area extended model: variables, interactions and graph

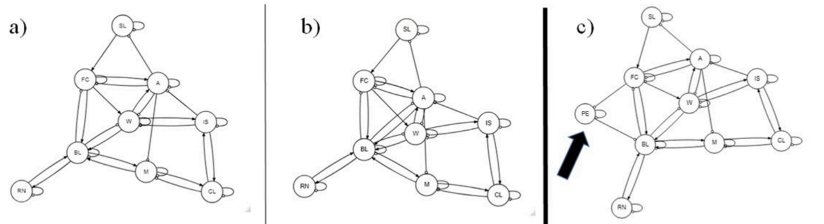
The extended models for the study area are summarized in Fig. 5. They have been conceived to capture some of the complex transformations that have happened in this SES in the last decades (Meza 2008; Armenteras et al., 2007; Acosta-Restrepo 2010 and references there in).

Some of the main drivers of transformation were introduced as additional variables in the core models to allow a glimpse at the dilemmas that characterize potential developmental trajectories and their implications for forest conservation and sustainability in the study area. A prominent feature of this territory is the development of industrial activities and services (Acosta-Restrepo 2010). They have been included as a unique variable called *IS* (industry and services). This component has been thought of as one that negatively affects the rate of change of variable $A(IS - oA)$ because medium industrial activity seeks for larger, less congested, less expensive locations to establish or resettle and it has progressively been leaving/avoiding the city, exploiting rural areas (Acosta-Restrepo 2010).

If industry and services create job opportunities and attract migrants to the urban and suburban areas, these opportunities are generally offered at low salary (Watkins 2001; Gillin 2014; Black 2015). Cheap labor may have become a diffuse condition, sustained by the consistent migration flows, and it has been included in the models as a new variable named *CL*. The models depict migration as if it favors the diffusion of cheap labor ($M \rightarrow CL$) which, however, may reduce the migratory flow ($CL - oM$) because cheap labor may be perceived negatively by people. Cheap labor is depicted as having a positive effect on industry and services ($CL \rightarrow IS$) which, in turn, favor the rate of diffusion of cheap labor ($IS \rightarrow CL$).

Road networks shape the dynamics of this SES and affect the disperse occupation of the rural territory. Overall, the transformation of rural areas into a developed urban continuum is sustained by a scattered and unplanned road expansion (Acosta-Restrepo 2010). To capture this uncoordinated development, road network (*RN*)is thought of as responding only to the built-up environment (BL) in a single connection with positive feedback: *RN*is enhancing the rate of expansion of the built up land ($RN \rightarrow BL$) and the built-up land returns a positive effect to $RN(BL \rightarrow RN)$ because urban expansion requires access facilities. The graphs of Fig. 5 (5a, 5b) were obtained by superimposing these new connections onto Models 3a and 3b. The counterparts for Models 3c and 3d did not add significant insights and are illustrated separately in the Supplemental Material (Appendix B, p.10–13).

Forest conservation carries a value *per se*, but in such a heavily modified environment, like our study area, it should be framed in an overall sustainability perspective in which environmental goals are combined with social and economic achievements. The models in Fig. 5 help making this comprehensive sustainability assessment. Some of their variables, in fact, can be easily and intuitively associated to the three dimensions of sustainability. Forest cover (*FC*) enhances the conservation of ecological functions and the associated ecosystem services so that preserving it contributes to the environmental dimension of sustainability. The same applies to water quality and availability (*W*) as it guarantees both human and wildlife survival as well as ecological functions. *IS* (Industry and Services) designate the level of economic prosperity and can be considered a pillar of the economic dimension of sustainability. Finally, the social dimension implies cohesion, level of welfare and other attributes that could not be considered in full by the models presented here. One variable that can be proxy for social conditions is *CL*(cheap labor). Diffusion of cheap labor, in fact, implies low salaries for the workers, with negative effect on family welfare (less access to services, education, health care, etc.). Such conditions may disrupt social cohesion. Thus the diffusion of cheap labor reduces the



a)

	FC	A	BL	SL	M	W	RN	IS	CL
FC	+	+	?+	-	0*	?-	?+	?-	0*
A	-	+	-	-	-	?+	-	?-	-
BL	?-	-	+	+	+	-	+	?-	?+
SL	+	+	?+	+	0*	?-	?+	?-	0*
M	?+	-	+	+	+	-	+	?+	+
W	0*	?-	+	?+	0*	?+	+	+	+
RN	?-	-	+	+	+	-	+	?-	?+
IS	+	-	0*	+	0*	?-	0*	+	+
CL	+	0*	?-	0*	-	0*	?-	+	+

b)

	FC	A	BL	SL	M	W	RN	IS	CL
FC	+	0*	+	0*	?+	?-	+	0*	?+
A	-	+	?-	-	0*	?-	?-	-	-
BL	?+	-	+	+	+	?-	+	?+	+
SL	+	0*	+	+	?+	?-	+	0*	?+
M	+	-	?+	+	+	?-	?+	+	+
W	0*	?-	?+	?+	0*	+	?+	+	+
RN	?+	-	+	+	+	?-	+	?+	+
IS	+	0*	?-	0*	-	?-	?-	+	?+
CL	?+	?+	-	?-	-	0*	-	?+	?+

c)

	FC	A	BL	SL	M	W	RN	IS	CL	PE
FC	?+	?+	+	?-	?+	-	+	?-	0*	?-
A	?-	+	-	-	-	?+	-	?-	-	?+
BL	-	-	+	+	+	-	+	?-	?+	+
SL	?+	?+	+	+	?+	-	+	?-	0*	?-
M	0*	-	+	+	+	-	+	?+	+	0*
W	0*	?-	?+	?+	0*	?+	?+	+	+	0*
RN	-	-	+	+	+	-	+	?-	?+	+
IS	+	-	?+	+	0*	-	?+	+	+	-
CL	+	0*	0*	0*	-	0*	0*	+	+	-
PE	+	+	-	-	-	+	-	?+	?-	+

Fig. 5. Extended models for the study area. Graphs a) and b) are the extended counterparts of Models 3a and 3b. Model 5c includes also variable *PE*(a black arrow points to it), which stands for "Protection Effort". It is imagined as the control action operated by a governmental agency with the goal of protecting the forests. *PE*actively responds to the reduction of forests$(FC - oPE)$and curbs built-up land expansion $(PE - oBL)$. The negative link from *FC*to it means that the lower the extension of forest the more intense the action of the agency is.

quality of living and, accordingly, it may be considered as a cost proxy for social sustainability. Considering that FC and W are benefit proxies (the higher their value the better it is) an ideal scenario is one in which policies or management actions create conditions for the latter to increase and for the cost indicator to diminish. On the other hand, increasing FC and W and reducing CL match with some of the sustainable goals that the UN defined to achieve a better and more sustainable future, such as goal 1 (no poverty), goal 6 (clean water and sanitation) and goal 15 (life on land) among others (Griggs et al., 2014).

Policies that increase the rate at which productive activities and services are created (e.g. subsidizing, incentives) introduce a positive press perturbation in the system through variable *IS*. Expectations are that production and services would increase $(IS = +)$, water quality and availability decrease $(W = ?-)$and a larger diffusion of underpaid work conditions is predicted $(CL = +$, and $?+$ for Model 5b). In this scenario, forested land is expected to increase $(FC = +)$. The analysis of the paths clarifies this result. In Model 5a as many as 11 paths connect *IS*to *FC*(see Appendix B), 6 of them are positive and 5 negative; the stronger, and shorter, are all positive:

$$(IS - oA - oFC); (IS - oA - oSL \rightarrow FC); (IS - oW \rightarrow A - oFC); (IS - oW \rightarrow BL - oFC).$$

In these paths the positive effect on *FC*depends on the interference that *IS*produce along the path with variables that consume forested land, mainly agricultural land and built-up land. In Model 5b the overall number of paths that connect these two components increase to 17, of which 9 are negative; still the shortest (and stronger) are positive, and the overall effect on forested land is positive.

The predicted increase of forest cover combined with the positive prediction on shrubland $(SL = +)$ indicates that Model 5a and 5b replicate the model that Rubiano et al. (2017)proposed to explain the pattern of land cover change they observed in this area and that was characterized by a substantial regrowth of secondary forests. They hypothesized that the development of productive activities and services could have made urban centers attractive to rural populations which moved to urban areas. Abandoned lands may have undergone succession passing through the state of shrubland to end in new secondary forests. This mechanism has been underlined by Calbi et al. (2020) and matches with one of the two deforestation models conceived by Rudel and Roper (1997), according to which the deforestation rate should be reduced as the economy develops, with beneficial effect on forest cover and their ecosystem services.

Nevertheless, the interpretation proposed by Rubiano et al. and the Rudel and Ruper's model imply a chain of events that includes land abandonment (nonfarm jobs that might attract people to cities) and consequent increased migration. In this study Model 5a predicts a null effect on the level of migration for a positive press on industry and services. This discrepancy depends on the hypotheses we made that i) cheap labor plays a crucial role in this SES and ii) it may prevent people to migrate. *IS*increases migration via the path $(IS - oA - oM)$ but inhibits it through the other path $(IS \rightarrow CL - oM)$. So the two paths tend to compensate each other and this yields the null prediction. However, if cheap labor would not be a sufficient reason to prevent people to abandon then the outcomes of Model 5a replicate in full the pattern of Rudel and Ruper's model. Overall, if the economy connected with industry and services is expected to prosper following the press perturbation on *IS*, it is not so for social welfare and ecosystem services (water quality and availability tend to decrease), although forest conservation seems to improve. Underpaid work is a threat for welfare. The unions and/or social activist act so as to curb the diffusion of this condition, for example by increasing self-consciousness of workers, soliciting the governmental levels to enforce legislative working frameworks, such as the "minimum employment rights", and increasing public opinion awareness (Watkins, 2001; Gillin, 2014; Black, 2015). This activity enters the system as a negative press perturbation on cheap labor *CL*. The models predicts that following this negative input (reverse the signs in the last row of the tables of predictions in Fig. 5) cheap labor would decrease$(CL = -)$, thus improving social sustainability; the level of industrial production and services would be lower $(IS = -)$and a reduction in the extension of forested land $(FC = -)$ would occur, with negative consequences for economic and environmental sustainability. Water quality and availability is predicted not to change, but, still, the multiplicity of paths that connect *CL* to *W*makes this prediction strongly dependent on paths strength.

If industrial production and service prosperity depended heavily on cheap labor for their prosperity, then it is straightforward that *IS*would decrease following a reduction in the rate of diffusion of cheap labor. This is a strong assumption of the models, but it also reflects a reality of the developing Colombia (Watkins, 2001; Gillin, 2014; Black, 2015).

An unexpected result is the predicted decrease of forest cover as due to initiatives against cheap labor. Browsing the paths that connect these two variables (see Appendix B) sheds light on this outcome. Out of 13 paths connecting *Cl*to *FC*as many as 8 are positive; the shortest, more intense paths, are in this group. Accordingly, positive paths prevail over negative ones and this prevalence is responsible for the negative effect to *FC*. As explained about the core models, positive paths reinforce the effect of the press perturbation: if this latter is negative (it reduces the rate of change of the affected variable, *Cl*in this case) the effect is negative. The causal chain at work here can be followed considering, as an example, the strongest path $CL - oM \rightarrow BL - oFC$ combined with the concomitant variation predicted for the variables that make the path. Because *CL*is expected to decrease $(CL = -)$its negative action on $M(CL - oM)$ diminishes, and this latter variable's rate of change would increase with a final beneficial effect on its level $(M = +)$. The number of migrants positively affects the rate of urban expansion $(M \rightarrow BL)$and the extension of the built-up land, shows a tendency to increase $(BL = ?+)$. Finally, because *BL*exploits forested land $(BL - oFC)$ this latter variable is predicted to decrease $(FC = -)$. This discussion holds also for Model 5b, with a slightly higher level of uncertainty (some predictions signal only tendencies to change as signs are accompanied by a question mark). These results highlight that efforts toward social sustainability might have adverse effect on environmental sustainability. To summarize, for press perturbations on *IS*and *CL*trade-offs between sustainability goals seem unavoidable, because the response of the variables that can be associated to environmental, social and economic sustainability is such that a win-win situation that involves their concomitant improvement never occurs.

The intensification of road construction is a positive press perturbation on *RN*and the expected consequences slightly differ between Models 5a and 5b. The former predicts a tendency reduction of the forested land $(FC = ?-)$, in agreement with Acosta-Restrepo's (2010) statements. Model 5b leads to opposite conclusions $(FC = ?+)$. This different behavior is clearly due to the exploitative dynamics of the built-up land which concentrates on forested land in Model 5a but it exploits also agricultural productive land in Model 5b. In particular, there are 9 paths connecting *RN*to *FC*in Model 5a, of which only three are negative, but they include the strongest paths. The negative paths remain the same in Model 5b but the number of positive paths increase and their overall effect prevails over that of the negative paths (paths are listed in Appendix B). The tendency to increase shown by *FC*in Model 5b is somehow counterintuitive and depends on the exploitation of agricultural land by the built-up environment. If *BL*grows more at the expenses of *A*than it consumes forested land, the outcome may be a positive effect on forests. Here quantitative statements about the link strength would be necessary for exact predictions .

The response of the other components to the positive press perturbation on road network coincide in the two graphs: cheap labor shows a tendency to increase $(CL = ?+ \text{ in } 5\text{a}, Cl = + \text{ in } 5\text{b})$, water resources deteriorate both quantitatively and quantitatively $(CL = - \text{ in } 5\text{a}, Cl = ?- \text{ in } 5\text{b})(W = -in5a, W = ?-in5b)$, industrial production and services are predicted to decrease in Model 5a but they would increase in Model 5b. An unbalanced road network which simply tracks the urban expansion, as it has been represented here, does not seem, at least according to our models' predictions, promoting environmental sustainability. This is in agreement with Acosta-Restrepo's (2010) and Botero-Garcia's (2017) statements that this form of infrastructure production, without integrating a rational, environmentally sound road network, has created a critical depletion of ecologically important corridors with negative effects on forests and has produced an overall degradation of the hydrological system. Road development has also revealed an explanatory variable in regression model aimed at explaining deforestation in this area (Rodríguez et al., 2013Rodriguez et al.,2013, although in other regions it is not so, Armenteras et al., 2013).

Protecting forests is a priority to preserve biodiversity and ecosystem services. Appropriate policies have been called for (Botero-Garcia, 2017) and conservation efforts for example could focus on areas with low levels of protection and high rates of land transformation (Romero-Ruiz et al., 2011; Sanchez-Cuervo et al., 2012) such as the study area. Remnant forests correspond to old-growth forests, harbor considerable levels of biodiversity, and could therefore be used as core areas to implement a protected areas network that can integrate the increasing areas of regrowth forests to shield against the high conversion risks. Implementing protection can be done through a regulatory agency empowered to slow down urban expansion rate by controlling the release of permits for new constructions. The action of such governmental agency is identified by variable *PE* (*PE* = Protection Effort) in Model 5c. Deforestation would activate the agency $(FC - oPE)$ which responds inhibiting urban expansion's rate $(PE - oBL)$. *PE*i s self-damped because it can act only within its local mandate for enforcement and is bounded by state laws, budget, personnel, bureaucratic lag-time, and is affected by lobbying pressure. Increasing the rate at which protection is made operational (positive press perturbation on *PE*) interestingly may have beneficial consequences on forested land $(FC = +)$, water quality and availability $(W = +)$, production and services $(IS = ?+)$, and social welfare $(CL = ?-)$. Thus, activating a mechanism of protection for forests seems to be, under the hypotheses of this model exercise, the sole action that can improve the overall sustainability and enhance ecosystem services.

Identifying the direct and indirect drivers of deforestation and understanding the complexity of their interlinkages are often difficult. Studies that investigated causes of land cover change in Colombia shared a common approach based on the analysis of land cover patterns from satellite images or aerial photographs combined with regression models that identified possible drivers of change among the explanatory variables that resulted significant (Rodríguez et al., 2012Rodriguez et al., 2012; Sanchez-Cuervo and Aide, 2013; Rubiano et al., 2017). These studies highlighted which variables could explain the observed patterns but did not inform about the mechanisms that produced such relationship. In this we see the potential for integration of the statistical approach with the modeling approach discussed here. For example qualitative models could be constructed using as variables the factors that resulted significant in explain the observed patters; at the same time qualitative models developed through expert elicitation with their predictions, can direct the selection of variables in the statistical analysis.

4. Conclusions

Contemporary environmental challenges call for research approaches in which the ecosystem is part of a larger unit of investigation that embeds socioeconomic dynamics. In this study we have framed the dynamics of Neotropical peri-urban forests in and around the Sabana de Bogota in the context of its SES. The results of this research confirm that integrating ecological and social variables in a unique interactive network can reveal unexpected causal linkages between across domain variables. Specifically, the models presented here bring to light mechanisms that may explain the observed patterns of deforestation and forest regrowth in the study area.

Any SESs is challenging to model because their vast array of interactions confounds cause and effects: that is why in the literature conceptual frameworks on the subject have flourished, whereas less methodological and practical applications have seen the light (Bodin and Tengö 2012). Using a parsimonious set of variables we reduced the complexity of the system to become tractable and by exploiting its network structure we simulated the response of the core variables to impacts of natural events (loss of soil fertility), policies (subsidizing industrial production) and social events (internal migration, social activism). Our conclusions suggest hypothesis that need to be corroborated by further analysis. The main hypotheses are that 1) remnant forests may be unexpectedly vulnerable to across domain drivers of change and also that unexpected beneficial effects may occur, suggesting possible mechanisms through which the same drivers can be responsible for both deforestation and forest regrowth; 2) trade-offs between desirable ecological and social outcomes are the rule and that potential win-win outcomes across the triple-bottom line of the sustainable development paradigm are difficult to achieve. The analysis of the causal paths may shed light on mechanisms responsible for overlapping and conflicts between desirable goals associated with nature conservation, urban expansion and social life. Qualitative modeling may also help prioritize competing demands for forest protection, ecosystem services, economic and social benefits.

That said, there are relevant variables that we did not include because their dynamics could not be clearly translated in the language of the loop models. One such variable is land value. Formal and informal land market, land price, are powerful drivers but depend on a multiplicity of factors (e.g. different income groups, economic activities, political pressures, lobbying) so that a clear pattern of interactions with the other variables was difficult to identify. Also, certain variables have been considered with a simplified dynamic. In forest cover, for example, patchiness was not taken into account despite its importance in forest dynamics. Simplification is both legitimate and necessary as long as we are cautious, are willing to change the original underlying assumptions as necessary and build new models, and carefully interpret the model's predictions.

In this work a rapid assessment of models predictions was conducted on the core models using evidences or hypotheses that emerged from the literature. Also extended models were developed to offer an example of the potential of the qualitative analysis applied to the study area's SES. For a practical impact of qualitative models, however, predictions must be tested against field data. To this end long term data set obtained under the effects of documented press perturbations are needed, but in the case of this SES historical records of data pertaining the variables of interests are either not existent or not organized in a meaningful data set useful to assessing qualitative predictions (Bodini et al., 2018). Only through a validation by field data appropriate models can be developed. Accordingly, this research has the merit to show the potential that loop analysis has in investigating complex SESs.

Loop analysis has the necessary adaptability and flexibility to be used in SESs. Making predictions in that context will become more difficult because of the uncertainty associated with new, unknown events, changing dynamics and lack of quantitative data. Loop analysis allows including and discarding variables easily and above all they permit working with variables and links that are not readily measurable, but their effects are crucial. Qualitative methods are also inexpensive. Therefore, the process of qualitative modeling can be public, reproducible, and intelligible in a way that a large simulation project cannot be. Other methods of qualitative analysis are employed to explore the complexity of socio-ecological systems. Causal Loop Diagrams (Sterman 2000) share a similar feedback approach to complex systems that loop analysis employs. However, although we recognize the validity and the aesthetics of the CLD, in our study, especially because it included a participatory approach, using loop analysis avoided misunderstandings about link definition (polarity in the language of CLD), confusion between rates and stocks in variable selection (in LA variables are only stocks or levels) and provided long term predictions a feature of LA in the framework of moving equilibrium. The conclusions derived from qualitative analysis do not allow for precise prediction or decisions about optimal courses of action, but they do permit us to decide the particular directions to push on a system in order to move it in a desired, e.g. sustainable, direction. Often this is all we need initially for shaping trajectories for a development that is socially inclusive, economically just and environmentally compatible. However sustainability is certainly dynamic: qualitative models outline that there may not be optimal solutions or final states, just trajectories.

Credit author statement

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Nicola Clerici: Reviewing and Editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.ecolmodel.2020.109344.

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