



Understanding causal linkages in the post-conflict Colombia socio-ecological system

Antonio Bodini¹ · Jenny Vivian²

Received: 4 February 2026 / Accepted: 23 May 2026
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Abstract

Colombia's long-lasting internal conflict has profoundly shaped the country's socio-ecological system, imposing relational patterns that persist beyond the 2016 peace agreement. Whether post-conflict policies can effectively achieve socially and environmentally desirable outcomes, or whether conflict-related constraints may instead generate unintended consequences, remains an open question. This study conceptualizes the Colombian socio-ecological system as a parsimonious set of key social and ecological variables embedded within a conflict-related framework. Interactions among these variables as reconstructed using elicitation-based information and literature, are represented using a signed digraph. Loop analysis combined with numerical simulations is applied to assess system responses to policy interventions, including subsidized credit for capital-intensive activities and measures aimed at enhancing smallholder competitiveness and market access. Results show that persistent conflict-related mechanisms generate counterintuitive interactions between social and ecological components, with unexpected interdependencies between licit and illicit activities that undermine policy effectiveness. Synergies among desirable objectives emerge only under limited conditions.

Keywords Causal linkages · Colombia · Complexity · Conflict · Loop analysis · Socio-ecological systems

Introduction

The end of Colombia's long-lasting civil war, formalized through the 2016 peace agreement between the central government and the Revolutionary Armed Forces of Colombia (FARC), has been widely interpreted as marking the beginning of a transition toward sustainable development in Colombia (Ioris and Ioris 2018). However, conflict-related dynamics have persisted due to the presence of still-active armed factions and criminal groups linked to drug trafficking (Romero and Melissa 2023). These actors continue to exert a profound influence on social organization, exacerbating impoverishment of rural populations, forced displacement, land grabbing, social inequality, deforestation,

and widespread environmental degradation (Murad and Pearse 2018; Landholm et al. 2019; Corrales et al. 2019; Palma 2025).

Within this framework, designing sustainable policies becomes particularly challenging, as their enforcement may generate unexpected and undesirable consequences (Llanes 2022). This is because conflict-related processes and the components of the socio-ecological system generate complex dynamics that are difficult to disentangle, making it challenging to identify causal linkages (Cantillo and Garza 2022; Vanegas-Cubillos et al. 2022). To address this issue we focus here on the network of interactions shaped by conflict-related factors to uncover how it generates complex dynamics. Our analysis explores how the network's structure determines the response of the system to drivers of change, such as policies or interventions implemented to achieve specific management goals.

The specific objectives of this investigation include: (i) constructing a plausible web of socio-ecological interactions that incorporates conflict-related factors; (ii) analysing this web to predict how variables respond to external drivers, such as policies or interventions; (iii) reconstructing, on the basis of variables' responses to these drivers, plausible

✉ Antonio Bodini
antonio.bodini@unipr.it

¹ Department of Chemistry, Life Sciences and Environmental Sustainability, University of Parma, 43124 Parma, Italy

² Forest Research Institute, University of the Sunshine Coast, Sippy Downs, Queensland, 4556, Australia

causal linkages between conflict-related factors and socio-ecological dynamics.

To achieve these objectives, we selected a parsimonious set of variables from among the social and environmental components identified in the literature as crucial to conflict dynamics. We then mapped their interactions and derived a network, which we analysed using loop analysis (Puccia and Levins 1985), a qualitative technique particularly well suited to data-poor contexts (Martone et al. 2017; Scotti et al. 2020).

Methods

Loop analysis

Loop analysis is a qualitative modelling technique that uses signed, directed graphs (digraphs) to represent networks of interacting variables (Levins 1975; Puccia and Levins 1985). In a signed digraph, interactions among variables are depicted using two types of links: arrows ($\rightarrow$), which indicate positive effects, and circle-headed links ($\rightarrow\circ$), for negative effects on each other's rates of change. Loop analysis enables predicting the direction of change in the level (e.g. biomass, number of individuals, or spatial extent) of system variables in response to parameter variations targeting one or more components (press perturbations; Bender et al. 1984; Montoya et al. 2009).

When a press perturbation increases the rate of change of a target variable, the variable is said to receive a positive input (Puccia and Levins 1985). Conversely, a negative input occurs when a press perturbation reduces the rate of change of a variable. The input may propagate to other components connected to the target variable through the network. The resulting responses are summarized in a table of predictions that accompanies each model (Supplementary Material, henceforth SM, Appendix C). These predictions indicate only the direction of change in variable levels: increase (+), decrease (−), or no change (0). For simplicity, the table of predictions reports variations in response to positive parameter inputs (i.e. perturbations that increase the rate of change of target variables). Predictions for negative inputs can be obtained by reversing the signs in the table.

In models with few components and/or a limited number of connections, expected changes in variable levels can be inferred directly from the structure of the graph (Bodini 1998, 2000). As the number of variables and connections increases, multiple interaction pathways emerge, often exerting opposing effects, which may result in ambiguous predictions (Puccia and Levins 1985). The software *LevinsAnalysis* (Scotti et al. 2020; Pereira et al. 2023), performs numerical simulations by assigning random values

to the coefficients of the community matrix, the numerical counterpart of the signed digraph, where arrows and circle-headed links are replaced by +1 and −1 coefficients, respectively, and 0 denotes the absence of interaction. Coefficient values are drawn from a uniform distribution over the interval (0, 1], allowing the calculation of path strengths and the resolution of ambiguities arising from multiple pathways. The algorithm returns the direction of change in the level of each variable as the percentage of simulations predicting an increase (+), decrease (−), or no change (0). In addition, a stability analysis is performed across all simulated matrices, and prediction tables are constructed using the subset of stable matrices (Bodini et al. 2024). On this subset of stable matrices, the software program builds the tables of predictions¹. A detailed description of the methodology is in the SM (Appendix C).

Correlations from predictions

The prediction table summarizes the expected responses of each variable to press perturbations affecting any component of the system and serves as a diagnostic tool for model evaluation. When the target of a perturbation is known—for example, in controlled experiments or policy interventions focused on specific components—the model renders the expected response of all the variables to that input. Such expectations can be then compared with observed variations to assess model consistency and reliability. When the location and direction of inputs are unknown, the prediction table helps identifying the point of entry of the input through the analysis of covariation patterns among variables (Bodini 2000): an example is provided in the SM (Appendix E).

Unless the system is under control, over a sufficiently long-time interval (or spatial scale; Puccia and Levins 1985), multiple unknown inputs—not necessarily acting simultaneously—may affect the components. These inputs refer to multiple sources of stress, diverse and uncoordinated interventions or policies, or simply the effects of environmental variability. In these cases, variations observed in the level of the variables reflect the combined effects of such multiple inputs (Puccia and Levins 1985).

Under these conditions, Puccia and Levins (1985) suggest comparing empirical correlations between the variables with expected pairwise correlations that can be obtained from the table of predictions. Such a comparison is possible only when well-defined pairwise covariation patterns emerge from the table. This occurs if all inputs produce coherent responses in any pair of variables, causing them

¹ The scripts that compose the software tool for the simulations are stored in: Pereira et al. 2023. *Levins Analysis* R package (version 0.2) [Computer software]. URL: <https://github.com/DPardejo/LevinsAnalysis-v0.2>.

either to change in opposite directions (negative covariation) or in the same direction (positive covariation). Conversely, if at least one input generates a different response pattern between the two variables—such that they covary positively under all but one input, which instead induces opposite changes—their covariation remains undetermined (Puccia and Levins 1985).

To overcome this limitation, we simulated multiple inputs acting on all model variables by randomly varying combinations of positive and negative inputs across 1,000 simulation runs. This procedure yielded an overall expected direction of change for each variable, which we then used to identify pairwise expected covariations. Finally, we compared the predicted covariations with the observed correlations obtained using the available proxies for six of the nine variables included in the graphs. Details of this procedure are provided in the SM (Appendix E).

Model construction

Applying loop analysis requires explicitly representing the structure of interactions among system components. Relevant variables must first be identified and their mutual effects translated into a signed digraph following the loop analysis symbolic language (see “Loop analysis”). Because the complexity of socio-ecological systems cannot be fully captured by any model, simplification is necessary to highlight essential dynamics (Levins 1966). Using elicitation-based information from a workshop organized on the side-lines of the conference “Sustainability, conservation and resilience: strategies for the Colombian post-conflict”, held on March 2018 at the Universidad del Rosario² (Clerici et al. 2020; Rodriguez et al. 2021), complemented by an extensive literature review, a parsimonious set of variables has been identified and their interactions reconstructed. Appendix A of the

SM provides a detailed description of the variables and their proxies; in what follows a concise summary is provided. Forests (F) is a key variable due to the role of forests in livelihoods, ecosystem services, and illegal activities (Leiteritz et al. 2009; Prem et al. 2020; Vallejo-Zamudio 2023). Ecosystem function (EF) captures ecological processes sustaining forests and biodiversity (Brockhoff et al. 2017). Given the central role of land distribution in the conflict (Thomson 2011; Albertus and Kaplan 2012), we included small property (SP) and large property (LP), both dependent on available land (AL), an ancillary variable mediating land competition. The former refers to the small plots farmed for food security and small business by rural people. The latter indicates vast concentrations of land in the hands of few owners. Capital business (CB) represents capital-intensive agricultural activities. Conflict-related variables include violence (V), displaced people (DP), and illicit business (IB), reflecting the intertwined dynamics of conflict, displacement, and illegal economies (Armstead 1992; Carrillo 2009; Negret et al. 2019). Variables and the data set for their proxies are described in the SM (Appendix A, Table 1A).

When knowledge of interactions was uncertain or conflicting, alternative plausible interaction structures were developed based on stakeholder input and the literature. These interactions were combined into alternative models, which are not reported here but can be found in Bodini et al. (2024). Model selection was based on the models’ ability to reproduce observed correlation patterns derived from the proxy indicators, as well as on their stability. Stability was assessed during simulations by evaluating eigenvalues of the community matrix against the Lyapunov condition (SM, Appendix C), while coherence with observed correlations was evaluated as described above under the heading “Correlations and predictions” and detailed in the SM (Appendix D). Models thus span gradients of stability and empirical

Table 1 Pairwise correlations between the proxies for the model variables listed along the columns

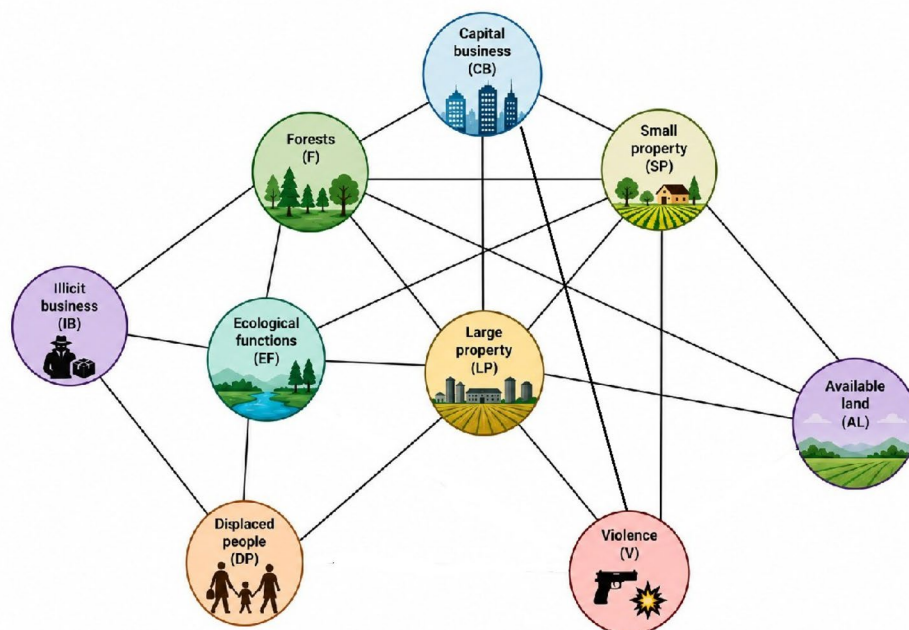
	Forest	Ecosystem	Rural Pop.	Agriculture	Oil Palm	Illicit crop
Forest	1	(+)**	(+)**	(-)**	(-)**	(-)*, ns
Ecosystem		1	(+)**	(-)**	(-)**	(-), ns
Rural Pop.			1	(-)**	(-)**	(-)*, ns
Agriculture				1	(+)**	(+)***, ns
Oil Palm					1	(+)***, <0.1
Illicit crop						1

Asterisks identify the level of statistical significance as follows: <0.001 “***”; 0.001 “**”; 0.01 “*”; 0.05 “.”; 0.1 “.”. When two symbols/values for the level of significance appear (e.g. (-)*, ns), they refer to the outcome of the Pearson’s test and the Spearman’s test, respectively. Appendix B in the Supplementary material details the values of the coefficients of correlation for both the tests we executed

² The participatory workshop that was organized following that event and entitled “Future scenarios: tools to create a better future” saw the participation of experts, mostly from the academic world, in the fields of socio-ecological systems, urbanization, land-use change, and deforestation. Through an open discussion, the workshop addressed the issues related to the post-conflict, socio-ecological dynamics, deforestation, and land use in the peri-urban environment.

support, and selection was based on both criteria. Figure 1b shows the structure of the interactions that give rise to the networks whose outcomes are discussed in this paper.

Fig. 1 Schematic representation of the components and their relationships in the parsimonious representation of the Colombia socio-ecological system



Data and statistical analyses

Time series for proxies associated with some of the variables included in the models are reported in the SM (Appendix A, Table 1A). The time series span over the period 2002–2020. Data are yearly values of the quantities considered. For example, the data set of forest cover reports yearly values of the extension of the Colombian forests in hectares. Appendix A indicates the official websites from which data were extracted. These time series underwent pairwise correlation analysis using Pearson's and Spearman's tests. Data normality was assessed through the Shapiro-Wilk test.

Results

A representation of the system is illustrated by the scheme in Fig. 1 in which components are characterized in pictorial term and connections between them are highlighted.

A total of 36 alternative graphs were analysed (the full suite of models is described in Bodini et al. 2024 and reported here in the SM, Appendix B, Table B2). Figure 2 provides the list of variables, the keys used to represent them in the graphs, and the scheme selected on the base of correlation and stability analysis.

Outcomes of the correlation analysis are summarized in Table 1 and reported in full in the SM (Appendix C, Table 2C).

Normality test and the analysis of the residuals showed that only in some cases the time series were normally distributed, so we performed two correlation tests. All the

correlations resulted significant applying the Pearson's tests and only four, all involving data about illicit crop extension (the proxy for illicit business, IB), resulted non-significant in the Spearman's test. In a precautionary approach, we based our analysis on the outcomes of the non-parametric test (Spearman). In the cases of non-significant correlations, it is however interesting that their sign coincides with those predicted by the models (Table 1).

The outcomes of the simulations that allowed to compare predicted with observed correlations are included in the SM (Appendix E, Table 1E). The graph that appears in Fig. 2 exhibited the highest matching performance. In 580 out of 1,000 simulation runs it successfully reproduced the observed correlations, so it was used to make predictions about the effects of developmental policies.

While enriching the dataset would further strengthen the robustness of the matching, the availability of time series for six out of nine variables imposes substantial constraints—namely, the simultaneous matching of 15 correlations—thereby providing a sufficiently reliable basis for model selection. Although the stability of the graph shown in Fig. 2 (20%) is lower than that of several alternative graphs (see SM, Appendix E, Table 2E), its overall performance identifies it as the most accurate representation of the system. Table 2a reports the predictions obtained for the graph shown in Fig. 1. Table 2b compares the observed correlations (signs in parentheses) with the fraction of inputs yielding the expected covariations between pairs of model variables, consistent with the observed correlations. Expected correlations were obtained from the prediction table by examining the columns corresponding to the pairs

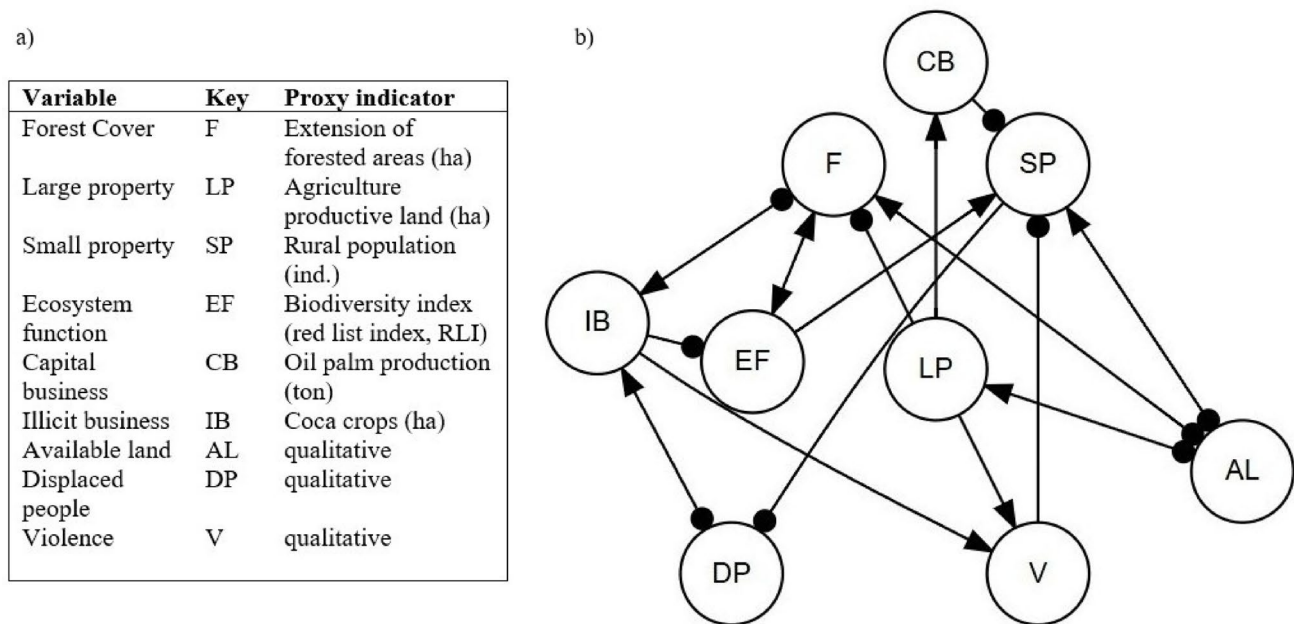


Fig. 2 a) List of the variables, their keys and their proxy indicators; and b) the graph of the main interactions (Model C7, SM, Appendix C)

Table 2 In the table of predictions (a) any row lists the response of each and all the column variables of the model when the row variable is affected by (positive) input, Pairwise correlations (b) between any two variables are obtained looking down their corresponding columns in the table of predictions and comparing for any row (input entering the model) the direction of change predicted for the two variables.

a) Table of predictions

	F	EF	AL	SP	LP	V	DP	IB	CB
F	?+	?-	?+	-	?+	+	?-	+	?+
EF	+	+	-	?+	-	0*	-	?+	-
AL	?+	?+	+	?+	+	?+	?-	0*	+
SP	+	+	-	+	-	-	-	?-	-
LP	-	?-	?+	-	+	?+	+	?-	+
V	-	-	+	-	+	+	+	?+	+
DP	-	-	+	-	+	+	+	?+	+
IB	-	-	+	-	+	+	0*	?+	+
CB	-	-	+	-	+	+	+	?+	+

b) Table of correlations

	FC	EF	SP	LP	CB	IB
FC	1	(+) 8/9	(+) 8/9	(-) 7/9	(-) 7/9	(-) 6/8
EF		1	(+) 9/9	(-) 9/9	(-) 8/9	(-) 6/9
SP			1	(-) 8/9	(-) 8/9	(-) 6/9
LP				1	(+) 9/9	(+) 6/9
CB					1	(+) 6/9
IB						1

Numbers quantify the fraction of inputs that yield, any given pair of variables, covariations that match with the observed correlations, the signs of which are in parenthesis

of variables for which proxies allowed computing correlations (Table 2, and SM, Appendix B).

For each pair of variables (columns in the prediction table), the expected variations in response to all inputs were compared to reconstruct the pattern of covariation for that pair. The minimum number of inputs for which two variables show the same pattern of covariation and in agreement with the observed correlations is six out of nine, and it is the case of the pairs involving IC (Table 2a, column IC). In two cases (pairs $F - LP$ and $F - CB$), seven out of nine inputs yielded same covariation and in agreement with the observed correlations. For all the other pairs ($F - EF$, $F - SP$, $EF - SP$, $EF - LP$, $EF - CB$, $SP - LP$, $SP - CB$, and $LP - CB$) eight and nine inputs out of nine rendered the same type of covariation. Interestingly, the weaker patterns (i.e., correlations involving IC) correspond to the cases in which the non-parametric correlation test was not significant (Table 2, Appendix B).

Discussion

Effects of policies: enhancing agroforestry or promoting large-scale capital-intensive agriculture?

Several authors highlighted the tendency of shaping agricultural development according to benefit large-scale, capital-intensive agriculture, such as palm oil production and soy cultivation. This could be pursued through subsidised credit, and tax exemptions (Castiblanco et al. 2013, 2015; Boron et al. 2016). On the other hand, the peace agreement contained auspices to enforce policies favouring agroforestry (Lopez-Barrera et al. 2022; Morales-Muñoz 2021).

Any measure or policy that enhances capital-intensive activity is understood as increasing its rate of change, that is, the speed at which such businesses grow. This translates in the language of loop analysis as a positive input on CB. Expectations (last row of the table of predictions, Table 2a) are for a reduced extension of forested land and associated ecological functions, as well as a contraction of the small farming (column F, effect (-); column EF, effect (-); column SP, effect (-). The negative prediction on F is coherent with observed effects of oil palm development (Butler and Laurance 2009, Garcia-Ulloa et al. 2012; Boron et al. 2016; Botero-Garcia 2017; but see Sullivan et al. 2020).

Another negative impact of these policies is the increased people displacement, coupled with the loss of traditional farming practices (Table 2a row CB, column DP, effect (+); column SP, effect (-)). The anatomy of the paths that connect CB to DP and to SP (see Appendix F) helps identify causal

linkages for this effect. Two paths make DP increasing³: $CB \rightarrow SP \rightarrow DP$ and $CB \rightarrow SP \rightarrow AL \rightarrow LP \rightarrow F \rightarrow IB \rightarrow DP$, whereas $CB \rightarrow SP \rightarrow AL \rightarrow F \rightarrow IB \rightarrow DP$ would make DP decreasing. This prediction agrees with the observation that oil palm development, increased internal displacement (Ocampo-Valencia 2009; Salamanca et al. 2009; Castiblanco et al. 2015).

There is only one path responsible for the negative effect on SP and it is the direct link $CB \rightarrow SP$ (SM, Appendix F). This link expresses the influence of capital business on small farming because of its powerful lobbying and financial capacity that make it easily expropriate land because of its competitive advantage over property rights (Salamanca et al. 2009; Grajales 2020). This prediction indicates that national policy agendas and trade agreements oriented to benefit strongly profitable land uses, rather than favouring labour intensive practices (small farming) would decrease small farming with social and environmental consequences (Martinez 2023). This trend runs counter to the objectives set out in the peace agreement and contradicts the commitments of the governments that followed it, which established that development policies should strengthen small-scale farming, social cohesion, and environmental protection (Lopez-Barrera et al. 2022; Morales-Muñoz 2021, 2023).

Policies aimed at enhancing business capital are expected to increase not only business capital itself but also the level of violence (V), while benefiting large property holders (LP). Although the establishment of palm oil plantations has not always involved violence or forced displacement, several authors have documented links between oil palm expansion, armed groups, and violence (Goebertus 2008; Ocampo-Valencia 2009; Castiblanco et al. 2015). Consistently, the model predicts higher levels of violence (V) and land tenure concentration (LP) in areas where oil palm production develops (Castiblanco et al. 2015). These three variables are systematically positively correlated, as shown by the predicted values reported in Table 2a b. The model also predicts a significant positive association between capital business (CB) and land concentration (LP), although the lack of data prevents assessing the joint relationship between CB, LP, and violence (V).

Policies in favour of small property would at the same time compensate for the loss of land that rural communities suffered during the conflict and respond to the need of a structural agrarian reform, that was among the main causes of the civil conflict (Pokorny et al. 2013; Tscharrntke et al. 2012; Boron et al. 2016; Quiroga et al. 2024). Such policies imply a positive effect on SP (small property). (Table 2a, row SP). An increase in the level of forest cover and the improvement of its associated ecological functions

³ The effect that a pathway carries is simply the sign of the product of the links that make the path.

would be expected (column F, effect (+); and column EF, effect (+)). Small farming itself would also increase (+ in the level of SP), bringing about food security and social cohesion, as people displacement (DP) would be reduced (– in the level of DP). Explaining why improvements in small-scale farming may benefit forest cover requires an understanding of the links between these two variables, as detailed in the SM (Appendix F, paths from SP to F). The causal effects of these paths can be disentangled by examining the predicted changes in each variable along the path, together with the effects transmitted through the links that constitute it. As many as four paths connects the two variables. Of particular interest (Appendix F) are the paths $SP(+) \rightarrow DP(-) \rightarrow IB(-) \rightarrow F(+)$ and $SP(+) \rightarrow DP(-) \rightarrow IB(-) \rightarrow EF(+) \rightarrow F(+)$. The signs in parentheses denote the expected direction of change of each variable, as reported in the SP row of the prediction table. Along the first causal pathway, SP exerts a negative effect on DP: by facilitating settlement stability and social cohesion, small property reduces displacement. This reduction, in turn, contracts the labour supply available to illicit business (IB), leading to a decline in its activity and, consequently, to a lower pressure on forest cover (F). The second pathway operates through EF (ecological functions), whereby decreases in IB are associated with lower levels of pollution and environmental degradation, that the environmentally unregulated nature of illicit production processes brings about. Taken together, these pathways suggest that policies enhancing small-scale farming may contribute positively to forests by attenuating displacement-driven illicit activity and its adverse effects on ecological functions.

This intervention is also expected to be effective in curbing illicit economic activity and violence: both IB (Table 2a row SP, column IB; effect (-) and V (row SP, column V; effect (-) are predicted to decline. The shortest causal pathway linking SP to IB is $SP(+) \rightarrow DP(-) \rightarrow IB(-)$, carrying an overall negative effect: a positive input to SP increases its level (Fig. 1b, row SP, column SP; positive effect); given the negative effect of SP on DP, displacement is consequently reduced (Table 2a row SP, column DP; negative effect); and, since DP positively affects IB by expanding the available labour supply, a decline in displacement leads to a contraction of illicit business activity. Violence (V) is linked to SP through five distinct pathways, four of which contribute to the predicted reduction in violence following a positive input to SP (SM, Appendix F). In the pathway $SP(+) \rightarrow DP(-) \rightarrow IB(-) \rightarrow V(-)$, the terminal link captures the violence-enhancing effect of illicit business. As IB is predicted to decline, its positive contribution to violence is correspondingly attenuated, resulting in a decrease in V.

Examples of social co-benefit are framed in the environmental peacebuilding (Castro-Nunez 2018; Morales-Muñoz

et al. 2021, 2023) which refers to the ways that different land management strategies, such cocoa agroforestry systems, contribute to conflict prevention, mitigation, resolution, and recovery (Ide et al. 2021). The model presented here highlights a potential synergy between the objectives of forest conservation and the promotion of small-scale farming, as reflected in the positive correlations among EF, F, and SP. Policies aimed at strengthening small farming practices (i.e., a positive input to SP), however, may not favour capital business—a conclusion that should be interpreted with caution. Trade-offs emerge when desirable objectives cannot be simultaneously achieved: in particular, the model suggests that combining increased profitability and income with reduced deforestation is unlikely under capital-intensive development pathways. By contrast, the model points to a complementary relationship between forest conservation, enhanced social cohesion, and reductions in violence and illicit economic activity.

Effects of policies: illicit business

Illicit crops (IB, illicit business) play a central role in Colombia's conflict-related socio-ecological system. Major environmental impacts—including water and soil contamination resulting from the intensive use of agrochemicals, as well as deforestation—have been documented alongside heightened levels of violence and forced displacement (Bernal et al. 2021). Assuming an increase in coca demand driven by illegal markets (a positive exogenous perturbation to IB), the model predicts a reduction in forest cover and a suppression of ecological functions, while both violence and illicit business activity intensify (Table 2a, row IB, columns F: (-); EF: (-); V: (+); IB: (+).

Capital business (CB) is also predicted to expand in response to an increase in illicit business (row IB, column CB; positive effect). Path analysis accounts for this outcome: five distinct causal pathways connect IB to CB, all of which carry a positive sign (see Appendix F). In one pathway, the effect of IB on CB is mediated by violence, as illustrated by the sequence $IB(+) \rightarrow V(+) \rightarrow oSP(-) \rightarrow oAL(+) \rightarrow LP(+) \rightarrow CB(+)$. An increase in coca production demand intensifies illicit business activity, which in turn exacerbates violence, negatively affecting small property. As land becomes more available for large property, capital business is correspondingly favoured. In the remaining four pathways (Appendix F), illicit business promotes capital business indirectly through deforestation and the inhibition of associated ecological functions, thereby reinforcing the overall positive effect of IB on CB.

One illustrative pathway is $IB(+) \rightarrow oF(-) \rightarrow oAL(+) \rightarrow LP(+) \rightarrow CB(+)$, whereby increases in coca production occur at the expense of forested areas, thereby expanding

land availability for large-scale property and ultimately fostering capital business. Although expanded land availability could, in principle, exert a positive effect on small property, the aggregate effect of illicit business on SP is negative. As documented in Appendix F, nine causal pathways link IB to SP, only two of which transmit positive effects through land expansion. The remaining seven pathways contribute to a contraction of SP and include the most influential mechanisms, notably $IB(+) - oEF(-) \rightarrow SP(+)$ and $IB(+) \rightarrow V(+) - oSP(-)$. In the former pathway, illicit business undermines small property by degrading ecological functions and eroding the productive foundations of small-scale agriculture; in the latter, violence generated by illicit activities directly suppresses small property.

Novelty and limitations of the study

System-thinking approaches to the study of Colombia's socio-ecological dynamics are well established (Diaz 2008). For instance, Arias-Gaviria et al. (2021) apply a whole-system perspective using causal loop diagrams to examine the feedback mechanisms underlying deforestation, mapping the interconnections among key drivers and variables. Once this mapping is achieved, understanding how feedback mechanisms shape system dynamics—and how state variables respond to changing conditions such as management interventions, policy shifts, or external perturbations—remains a significant challenge. This paper addresses this gap by proposing a method to disentangle chains of causally ordered events through the systematic analysis of interaction pathways, thereby unveiling the underlying causal linkages. By enabling a clearer attribution of system responses, the proposed approach facilitates the explanation of unexpected outcomes whose origins are often obscured by the complexity of interacting pathways.

Within the Socio-Ecological Systems Framework (SESF; Ostrom 2009), system complexity often remains partially concealed by statistical analyses, which identify patterns of association but provide limited insight into the mechanisms through which such patterns are generated. As a result, statistical regularities tend to reveal correlations rather than causal linkages. By contrast, examining the network of interactions and explicitly mapping causal pathways allows chains of causally ordered events to be reconstructed, thereby unveiling interdependencies among variables that extend beyond mere association.

The model presented here does not capture all the mechanisms operating within the Colombian socio-ecological system. Like any socio-ecological system, it is inherently difficult to model due to the multitude of interacting processes that blur causal relationships. By relying on a parsimonious set of variables, system complexity can be reduced

to a level that allows general mechanisms to be identified. Such simplification is both legitimate and necessary, if assumptions are critically examined, revised when needed, and complemented by new models, and that the resulting predictions are interpreted with appropriate caution.

Making predictions in socio-ecological analysis is difficult because of the uncertainty associated with new, unknown events, changing dynamics and lack of quantitative data. Loop analysis helps overcoming these difficulties as it allows including and discarding variables easily; it permits working with variables and links that are not known and neither readily measurable, although their effects are crucial. Because information for model construction was collected during a workshop in which stakeholders offered information only in terms of positive or negative effects between the variables, loop analysis seemed the most appropriate tool.

Conclusions

Representing the post-conflict Colombian socio-ecological system as a network of interacting components provides a useful framework for addressing its complex dynamics. The network structure was derived through an elicitation-based approach involving relevant stakeholders. In line with the first objective of this study, the plausibility of the resulting network was subsequently assessed by comparing model-predicted correlations—obtained from signed digraph prediction tables combined with simulations of multiple sources of variability—with observed correlations derived from time series of proxy variables available for six of the nine modelled components. This validation approach, which has not been applied previously, enables the identification of interaction structures that are consistent with both elicited knowledge and empirical system behavior.

Loop analysis offers a means to predict the effects of external drivers on network components. In this study, policies were simulated as changes in the rates of change of the variables, allowing their potential system-wide effects to be assessed, in accordance with the second objective of the research. Furthermore, by analyzing the anatomy of the graph through path analysis, loop analysis made it possible to decompose the expected variation in variable levels into the contributions of individual pathways, thereby identifying causal linkages, thus fulfilling the third objective of this work.

The analysis reveals the potential for unintended consequences. When strategies aimed at promoting sustainable development rely on policies that favor capital-intensive activities, economic growth risks becoming tightly coupled with violence, displacement, and deforestation, within

a context in which licit and illicit economic activities are deeply intertwined. Policies intended to effectively address rural poverty must therefore contend with the persistence of conflict-related factors that shape a system in which legal and illegal activities mutually reinforce one another.

Supplementary Information The online version contains supplementary material available at <https://doi.org/10.1007/s42974-026-00318-0>.

Acknowledgements This contribution represents a shortened and partially revised version of the study by Bodini et al. (2024); this version was prepared specifically for presentation at the 5th International Conference on Community Ecology, held in Budapest, Hungary, on 3–5 September 2025. The author thanks the experts that contributed to this work by taking part in a workshop during the event “Sustainability, conservation and resilience: strategies for the Colombian post-conflict,” held on March 14–16, 2018, and organized by the Faculty of Natural Sciences, Universidad del Rosario, Bogotá, Colombia. I also thanks are due to dr. Francisco J. Escobedo (Pacific Southwest Research Station, U.S. Department of Agriculture) for constructive comments and suggestions and for coordinating the workshop. This research has not received any specific grant from funding agencies in the public, commercial, or not-for-profit sectors and it was developed in the framework of the COMP-HUB Initiative, within the ‘Departments of Excellence’ program of the Italian Ministry for Education, University and Research (MIUR, 2018–2022 and MUR, 2023–2027).

Author contributions A.B. conceptualization and writing J.V. Data curation, modelling, editing.

Funding Open access funding provided by Università degli Studi di Parma within the CRUI-CARE Agreement.

Data availability No datasets were generated or analysed during the current study.

Declarations

Conflict of interest The authors declare no competing interests.

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