

Research

Resilience and tipping points in social-ecological systems of the southwestern Amazon: a participatory systems analysis

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ABSTRACT. Recent reports warn of the imminent surpassing of a tipping point that will transform the Amazon rainforest into a savannah. In the transboundary region shared by Bolivia, Brazil, and Peru (named the MAP region, an acronym for the states of Madre de Dios, Peru; Acre, Brazil; and Pando, Bolivia), this land-use conversion has been triggered by logging and farming, and recently intensified by the construction of a transcontinental highway. As economic incentives grow, so does social and environmental harm. We devised a participatory systems approach to evaluate and characterize the social-ecological system in a site in each of the three countries, and to identify the factors that may lead to the systems' loss of resilience and eventual trespassing of tipping points. Methodologically, the approach combines stakeholder analysis, network analysis, and systems analysis, and includes transboundary research and locals' participation as overarching premises adding plausibility and legitimacy to the findings. Results show that the three country-sites, despite their similarities, have evolved divergently into archetypal social-ecological systems, each confronting specific challenges, i.e., in Bolivia, dependence on the volatile commodity Brazil nut, and unstable politics, has weakened a previously stable and functional institutional landscape. In Brazil, the conversion of forests into pastures for cattle ranching remains the major peril, fueled by a steady market demand and, regardless of the party in power, insufficient restraining measures. In Peru, economic diversification has increased the system's resilience as a whole, however authorities struggle to exert control over the economic activities, some of which are illegal.

Key Words: *complexity; MAP region; tipping points; transboundary research*

INTRODUCTION

The Amazon rainforest covers 6 million km², mostly comprising evergreen rainforest, and is a global provider of ecosystem services, such as biodiversity conservation, climate regulation, biomass and water endowment (Nagy et al. 2016). It is also the home of 30 million people engaged in a multitude of livelihood activities, like forest-products extraction, extensive farming and livestock ranching, and in recent times, mining of non-renewable resources (Nepstad et al. 2008, Finer and Novoa 2015, Sonter et al. 2017).

Lately, the trade-offs between economic activities and ecosystem services provisions have reached a critical threshold, as the growth in scale and importance of certain activities threatens the stability and even existence of the overall ecosystem. Such developments have led scientists to believe that the whole region may undergo a systemic change; it is approaching a tipping point that will likely transform the humid rainforest into a savannah-like ecosystem (Lovejoy and Nobre 2018, Boulton et al. 2022). This will not only change the ecological makeup of the region but the many social-ecological systems that coexist in the region.

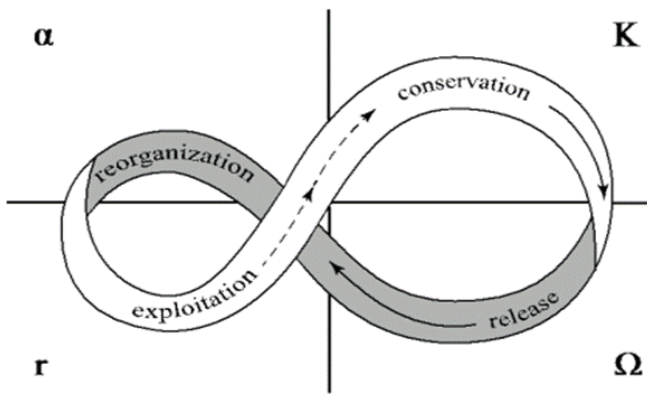
Decision makers in the region, such as the 2019–2022 Brazilian administration, have disregarded the scope and severity of the challenge, often acting in a unilateral and self-interested manner (de Area Leão Pereira et al. 2019, Trancoso 2021). Social-ecological systems are complex, their feedback loops intricate, and their behavior hard to foresee. It is therefore important that decision makers understand how such systems function so that they can take the necessary action to avoid instability and the reaching of tipping points that may endanger their overall performance.

The southwestern Amazon, although biophysically and ecologically more or less homogeneous, comprises countries with distinctive social, cultural, political, and economic characteristics, which determine very different social-ecological systems. This is evident in the case of the MAP region (acronym of the states of Madre de Dios, Peru; Acre, Brazil; and Pando, Bolivia; Callo-Concha et al. 2022). These three states are located at the fringes of their respective three countries and are historically marginalized within their respective nation-states. Still, their economic and socio-cultural inter-connectivity has been strengthened by the construction of a continental-scale highway in 2010, designed to integrate the region and boost its economy (Perz et al. 2010, Perz et al. 2013a, Reyes 2015). These conditions provide an ideal setting to study how environmental commonalities are differently addressed by contrasting governance models (Castanho et al. 2018).

The notions of resilience, complex systems and participation are key to this study. Resilience refers to the capacity of systems to adjust to disrupting events and/or creeping changes, by adjusting their behavior to recover or seek new steady conditions and functions (Holling 1973, Adger 2000, Holling 2003). Operationally, we adopted the adaptive cycle heuristic, that traces the course of a system's behavior during a disruption, by describing it in four successive archetypal phases: exploitation (growth), conservation (climax), release (collapse), and reorganization (re-start or transformation; Holling and Gunderson 2002). The tipping points, are defined as the momentum in the development of a system, that once surpassed would change it abruptly and possibly irreversibly (Lenton et al. 2008, Lenton 2013), momentum that should occur between the conservation and release phases of the adaptive cycle (Fig. 1).

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Fig. 1. The adaptive cycle (Holling and Gunderson 2002).



In situations where many components interact in ways that are difficult to predict, the complex systems approach facilitates the study of the underlying causes for the loss of resilience and occurrence of tipping points. A system is a collection of numerous components with numerous types of relationships, which altogether compose an organized and functional whole (Bertalanffy 1950). Complexity is a consequence of the system's large number of components and the intricate relationships among them, which makes it difficult to understand the details of its operation and functioning (Mitchell 2009).

The application of the complex systems approach has led to the acknowledgment of social-ecological systems as a unit of analysis, reaffirming the notion of interconnectedness between humans and their natural surroundings. This is evident in real-life situations, for instance, in the analysis of resilience or tipping points where the social circumstances are coupled with ecological hazards (Berkes and Folke 1998, Adger 2006, Ostrom 2009).

Finally, in research that deals with real-life situations, the participation of local actors is a precondition to accurately understand and characterize the system, and to promote the empowerment of the involved stakeholders to pursue and sustain a desired transformation (Walker et al. 2002, Stringer et al. 2006). The objective of this study is to use the outlined framework to characterize the social-ecological system of each of the three countries' areas within the MAP region, to disclose their commonalities and differences, and to identify critical components regarding their contribution to resilience and/or the reaching of tipping points.

STUDY AREA: THE MAP REGION AND THE COUNTRY-SITES

The MAP region comprises the Pando department in Bolivia, the Acre state in Brazil, and the Madre de Dios department in Peru, totaling 300,000 km² and accounting for more than one million inhabitants. The region is mostly covered by humid rainforest and is generously endowed with renewable and nonrenewable natural resources (Reyes 2015).

The history of the MAP region is defined by its relative isolation and its profiling as a natural resources provider. The well-known cases of rubber (*Castilla ulei* and *Hevea brasiliensis*), precious timbers, and Brazil nut (*Bertholletia excelsa*), illustrate well the

successive boom and bust cycles that continue to characterize the region (García 1982, Rumrill et al. 1986, Assies 2002, Killeen et al. 2008, van Lindert and Verkoren 2010, Callo-Concha et al. 2022).

Although the regional ecological conditions and historical antecedents are common in the MAP region, the establishment of the countries' borders in the early 20th century led to distinctive divergences in social, political, and economic developments that have greatly shaped the respective populations' current situations. The interconnections among the three countries persisted. Various efforts were made to encourage their further integration, which culminated in the construction in 2010 of the Interoceanic Highway. The stated aim of the highway, which cuts across the three countries connecting both oceans, is to boost the region's economy and promote its development. However it has also led to major social and environmental challenges (Perz et al. 2012, 2013a, 2013b; Fig. 2).

The intrinsic interconnectedness of the three country-sites compelled us to study them in parallel to assess the weight that the commonalities and divergences have on their functioning and more importantly, on their joint future and overall prosperity (Castanho et al. 2018). Such "transboundary research" is particularly appropriate in regions where public goods such as the rainforest and rivers are shared, and where an intensive exchange of legal and illegal goods occurs across borders with some interest groups benefiting and others losing out (Hataley and Leuprecht 2018).

In Pando (Bolivia), our study site extends along the eastern edge of the department. It includes communities outside and inside the Manuripi's Amazon National Wildlife Reserve, which is crossed longitudinally by a non-paved road, along which a string of communities has grown up (Fig. 2). The main economic activity in the region is Brazil nut collection, which composes more than half of the inhabitants' revenue. Key factors for this are the relatively good condition of the forests, the inhabitants' conservation awareness, and social and economic post-harvesting infrastructure (Marsik et al. 2011, Mathaess 2021). Other non-timber forest products (NTFP) like the palm fruits Açai (*Euterpe precatoria*, *Euterpe oleracea*) and Majo (*Oenocarpus bataua*) are increasingly exploited at a commercial scale (Arancibia 2021).

Fig. 2. The MAP region (acronym for Madre de Dios, Peru; Acre, Brazil; and Pando, Bolivia), indicating states, capital cities, protected areas, study sites, and the Interoceanic Highway and main roads.

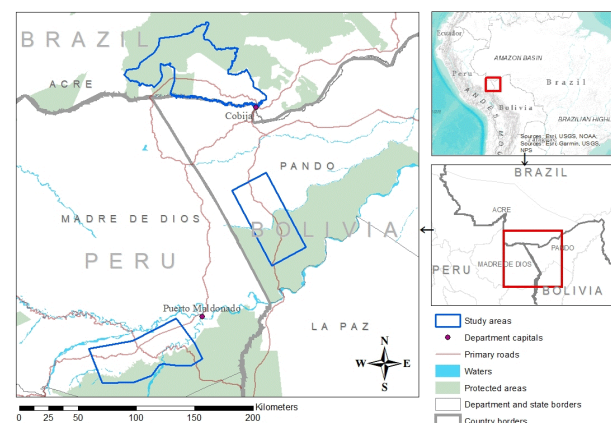


Table 1. Characteristics of the states hosting the research sites. Sources: IBGE 2021, IMF 2021, INEI 2021, City Population 2022, INE 2022.

Political demarcation in country	Estimated populat. 2021 (% of national)	Area in km ² (% of national)	GDP mill. US\$ (% of national)	Name of neighboring reserve (Area in ha)
Pando, Bolivia	154 000 (1.32)	63 827 (5.81)	373 (0.42)	Manuripi's Amazon National Wildlife Reserve (747,000)
Acre, Brazil	906 900 (0.43)	164 122 (1.93)	2 730 (0.2)	Chico Mendes Extractive Reserve (970,570)
Madre de Dios, Perú	173 800 (0.53)	85 183 (6.63)	4 017 (0.78)	Tambopata National Reserve (274,700)
Cumulative	1 234 700 (2.28)	313 132 (14.37)	7 120 (1.4)	(1,992,270)

In Acre (Brazil), our research site stretches parallel to the Interoceanic Highway and the southern flank, in and out the Chico Mendes Extractive Reserve (RESEX; Fig. 2). Here, deforestation to create large-scale cattle grazing land has become the dominant economic activity (Bastos Lima and Da Costa 2022). The creation of the Chico Mendes RESEX branded the site as an agro-extractive area, mainly of Brazil nut and rubber, and reignited age-old conflicts between ranchers and NTFP gatherers. The economic appeal of cattle grazing has attracted small owners too, despite the regulations that restrict it (ICMBio 2009, França Maia et al. 2016).

In Madre de Dios (Peru), our study area extends along the Interoceanic Highway in the proximity of the capital city, Puerto Maldonado. The site includes a range of land uses, including those outside the Tambopata National Reserve and the least disturbed areas inside it (Fig. 2). Besides traditional timber and NTFP extraction, farming, ecotourism, and especially mining have emerged as the most prominent economic activities, whose success have caused an economic boom and led to massive regional immigration (Álvarez et al. 2011, Doan 2013). Gold mining is notable because it has dynamized the regional economy, though its social and environmental side effects are worrying (Asner and Tupayachi 2016, Salo et al. 2016) (Table 1).

METHODOLOGY

This study applied mixed methods for data collection, analysis, and interpretation. First, in a preparatory phase, primary data, via field visits to the three research sites where interviews with rural householders and key stakeholders took place, and secondary data, through the review of grey and scientific literature, were compiled to gain a fundamental knowledge of the social-ecological system. In a second and third step, stakeholder and network analyses were applied respectively, aiming to identify key actors and select them for their subsequent participation in the system characterization. These steps intended to invert the conventional “top-down” analytical perspective to a “bottom-up” one that prioritizes the perspectives, interests, and objectives of local stakeholders. Finally, participatory systems analysis was implemented to identify together with stakeholders the system’s components, the interaction of components in the system, and the roles of components in the system overall functioning. Such an analytical framework (Fig. 3) was replicated in the three research sites to highlight the similarities and differences among them.

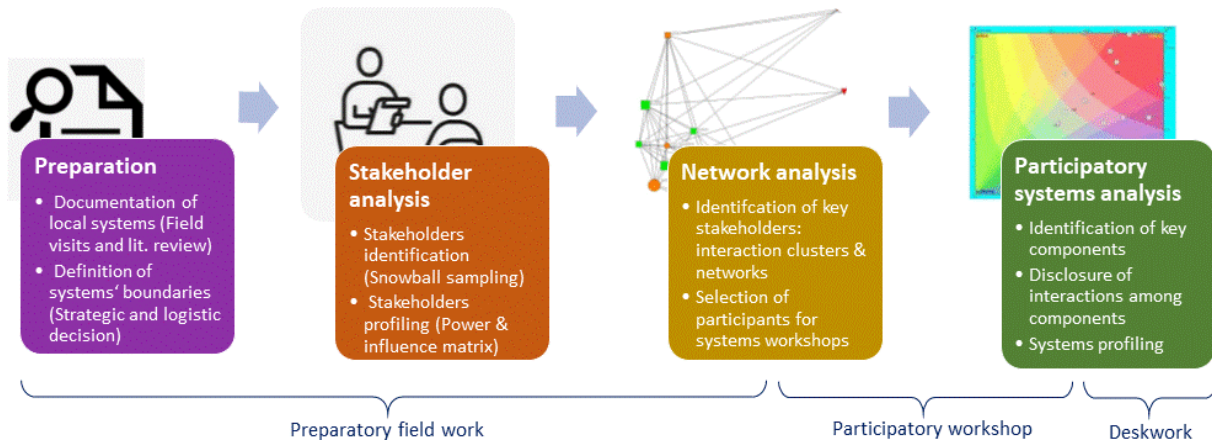
Stakeholder and network analysis

Through the stakeholder analysis, we aimed at the identification and profiling of actors representative of key areas of the system, whose distinctive characteristics and roles affect the system and are affected by it (Bryson 2004, Ackermann and Eden 2011). For that, a snowball sampling technique was applied to obtain a preliminary list of stakeholders in four categories: government, private sector, grassroots, and non-government organizations, which in practice included a wide array of actors interplaying in the system, such as, associations of farmers, indigenous groups, universities, research centers, NGOs, private companies, etc. With such diversity we aimed at equilibrating the interests and unavoidable biases that each stakeholder brings along. Once stakeholders were identified, a first screening was implemented, by placing them in a power vs. interest grid, to identify their relative influence on the country-site system (Appendix 1). Both activities were validated by local counterparts. Via network analysis we assessed the stakeholders’ behavior not as a function of their individual roles, but according to the relationships among them. Network analysis produces mathematical indices that measure the levels of the interconnection among components, and sociograms that summarize those indices graphically. The indices and sociograms enable the understanding of the degree of association among actors and the coordinated roles played by cohorts and the whole network (Freeman 2000, Prell 2011). Operationally, stakeholders were interviewed to gauge the frequency and categories of their interactions with one another. The results were analyzed using the software UCINET (Borgatti et al. 2002). Formally, the combination of stakeholder analysis with network analysis allowed us to shortlist the participants without the loss of representativeness, and practically, to invite them to the follow-up workshop on systems analysis, where intensive participation was needed to refine our hypotheses on the operation of each country-site system.

Participatory systems analysis

By applying a participatory systems analysis, we created a model for each of the three targeted country-site systems, which comprised the demarcation of the system boundaries, the identification of its main components, and the influence and degree of influence among them, which determines their functioning and identity. After outlining the overall social-ecological characteristics of the MAP region and each of the three country-site systems (Callo-Concha et al. 2022), and identifying the key stakeholders in each via stakeholder and network analyses, the stakeholders were invited to participate in a two-day systems

Fig. 3. Analytical framework.



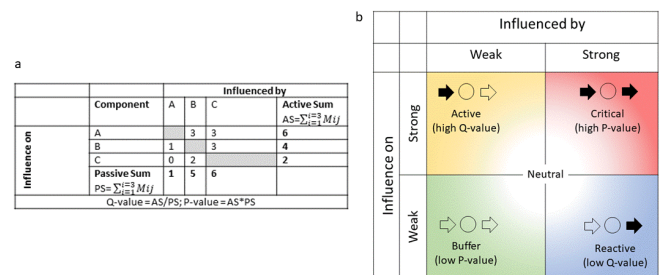
analysis workshop, one in each country, facilitated by an expert team. The workshops were public and participants acted on behalf of their specific institutions and stakeholder categories. Furthermore, they were informed that their inputs aimed at the construction of a country-site system model that would evolve into an academic outcome that would eventually be shared with them.

The Vester Sensitivity Model® (<https://www.frederic-vester.de/eng/sensitivity-model/>) was the tool chosen to operationalize the workshops for the following reasons: (i) it relies greatly on stakeholders to disclose a system's composition, structure, and function (Stringer et al. 2006); (ii) it is fuzzy logic-based, accepting ordinal as well as numerical input, which suits the diversity of available input in real-life, e.g. stakeholders' opinions (Zadeh 1975); (iii) as a modular software, it produces intermediate outcomes that allow recursive fine-tuning, and (iv) it generates subsystems that can be further analyzed to answer specific research questions.

In the demarcation of the three systems' boundaries, we combined the characteristics outlined for the three research sites with the given political borders and logistical accessibility (Fig. 2). For the identification of the systems' components, we mixed brain-writing and mind mapping techniques to elicit the most alluded components and to integrate the coinciding ones into a manageable number, up to 15.

Later, with the assistance of the Vester Sensitivity Model®, we (i) assessed the components' system-ness, by rating each one against predefined criteria that weigh features, and (ii) estimated the existence and degree of impacts of the components among themselves. For this we relied on the Influence matrix technique where participants rate the influence of a component on another (valuing it increasingly between 0 and 3; Appendix 2); these are then summed up to calculate the Q-value and P-value indices (Fig. 4a). These indices enable the categorization and ranking of the components according to their conditional probability of occurrence via their grouping into four functional types (comprising two pairs on a spectrum). Detailing each: critical (risk components, highly influenceable by other components and themselves highly influential toward others) to buffer (inert

Fig. 4. (a) Influence matrix mathematical rationale; (b) Schematic representation of the categories of influences and transitions across them (Cole 2006).



components, less influenceable, and less influential); and active (lever components, highly influential but less influenceable) to reactive (sensor components, less influential but highly influenceable). Components were then graphically placed in a four-quadrant scheme, which is read top-down and diagonally: from upper right to lower left (critical to buffer), and from upper left to lower right (active to reactive; Fig. 4b).

For instance, components related to markets and money tend to be influential and influenceable, hence have high P-values and are placed in the critical red quadrant. Contrarily, components like culture and traditions tend to be stabilizing, thus have low P-values and are located in the buffer green quadrant. The same logic applies to the Q-value and the active and reactive quadrants.

The interpretation is contextual: critical components signal change, instability, and urgency, whereas buffer components signal stability and firmness; also, active indicates the ability to induce, amend, and modify, whereas reactive indicates susceptibility to be induced, modified, or amended. Some components may fall between the quadrants and play dual roles, e.g. critical and active; or fall in the middle and be neutral. But, as a real-world model, the interpretation of components' behavior is circumstantial and made by contrasting their prescribed roles against their plausibility.

RESULTS

Stakeholders' networks

Concerning the stakeholders' roles, the power vs. interest grid shows that government institutions cover key aspects of the institutional functioning of each social-ecological system. Notable are the ones in charge of the neighboring natural reserves, i.e., Instituto Chico Mendes de Conservação da Biodiversidade (ICMBio) in Brazil, Reserva Nacional de Vida Silvestre Amazónica (RNVSA) Manuripi in Bolivia, and the Servicio Nacional de Areas Naturales Protegidas por el Estado (SERNANP) in Peru, as conservation appears to be a cornerstone and other economic activities relate directly or indirectly to it.

For the assessment of stakeholders' interconnectedness within each country-site, the case of Brazil is illustrative: centrality metrics like the degree (of centrality) represented the stakeholders' number of connections, e.g., ICMBio, Federal University of Acre (UFAC), and Ministry of the Environment (SEMA) are the most connected with 11.0; betweenness, showed by the number of shortest paths of other stakeholders to it (UFAC, the highest with 21.53), and eigenvector, the number of connections to the most connected stakeholders, e.g., SEMA 0.34, ICMBio 0.33 and WWF 0.32, respectively (Table 2).

The above described relationships were plotted in sociograms, visual representations of some of the identified relationships plus the features of the stakeholders (Fig. 5). These were used to select the key stakeholders to be invited for the subsequent systems analysis workshops (networks of the other two country-sites are found in Appendix 3).

Systems' components

Eight key stakeholders in Brazil, 10 in Bolivia, and 10 in Peru, participated in the social-ecological system analysis workshops, representing mostly government, NGOs, and grassroots organizations. The workshop participants determined each system's components, the interplay among them, and their overall character. About 15 components were identified per country-site. These were later bundled. Small conceptual differences were identified among them: six were common in all three sites, six repeated in two sites; and five were specific to Chico Mendes RESEX, Brazil, four to Manuripi, Bolivia, and six to Tambopata, Peru (Table 3).

The six identified common and transversal components relate to the MAP region's ecological make-up and its history: Extraction of NTFPs, Impacts and risks due to changes in climate, Extraction of timber, Lobbying of local organizations, Governance and laws in operation, and Market action and influence, all broadly recognized in the literature (Callo-Concha et al. 2022). The components common to only two countries tend to be the result of stakeholders' recent decisions: like Landscape/land-use planning and implementation, and the Ecosystem services provision program outlined by Law 1333 in Bolivia and Law 14.119 of the Brazilian government; Rural actors' agencies in Bolivia and Peru, initiated by their strong but scattered grassroots organizations; and the Expansion of road network, only in Brazil and Peru, because the Interoceanic Highway crosses those two and barely touches Bolivia (Fig. 1).

More insightful are the factors specific to each country, which highlight the defining themes they confront: Livestock rearing

expansion and Cross-border traffic in Chico Mendes RESEX, Brazil; issues associated with NTFPs (mostly related to Brazil nut) in Manuripi, Bolivia, like Storage and transport infrastructure and NTFP post-harvesting; and a palette of emerging natural resources-dependent economic activities in Tambopata, Peru, including Growth of productive activities (mostly farming), Growth of small mining, and Development of ecotourism.

Components' systemic role

Assisted by the Vester Sensitivity Model®, and using predefined categories, i.e., critical, active, buffer, and reactive, we grouped the components according to the roles they play in relation to the others (Fig. 4b).

In Chico Mendes RESEX, Brazil

The following critical components, highly determinant but also influenceable, were identified: Forest land-use conversion (component 1), Governance and laws in operation (11), Expansion of road network (8), Illegal extraction of timber (7), and Market action and influence (14). There was no buffering component. An active component, determining but hardly influenceable, was Influence of politicking and party bias (9). Reactive components, which were well-influenceable, were Extraction of NTFPs (5), Impacts and risks due to changes in climate (6), and Ecosystem services provision (13).

Several components played complementary and dual roles: Livestock rearing expansion (3) was critical/active; and Lobbying of local organizations (10) and Strengthening of origin branding (4) were critical/reactive. Cross-border traffic (15), Culture devaluation (12), and Landscape/land-use planning and implementation (2) were neutral (Fig. 6).

In Manuripi, Bolivia

The critical components were: Extraction of NTFPs (component 12), Rural actors' agencies (4), and Forest conservation/preservation (2); oppositely, the only buffer component was Influence of politicking and party bias (15). Active components were Lobbying of local organizations (3) and Landscape/land-use planning and implementation (1); while reactive components were Ecosystem services provision (13) and Storage and transport infrastructure (6).

Some components performed more than one function. Market action and influence (7) and Governance and laws in operation (8) were critical/active; while the following were critical/reactive: Sustainable management of natural resources (5), and Extraction of timber (14). Finally, Impacts and risks due to changes in climate (9), NTFPs post-harvesting (10), and Financial injection (11) were neutral (Fig. 7).

In Tambopata, Peru

The critical components were: Forest conservation/preservation (component 5), Rural actors' agencies (10), Growth of small mining (6), Growth of productive activities (3), Expansion of road network (2), Market action and influence (9), and Governance and laws in operation (1). There were neither buffering nor active components; and only one forthright reactive component: Extraction of timber (14). Neutral components were Increase of regional immigration (13) and Impacts and risks due to changes in climate (15).

Table 2. Key stakeholder centrality metrics in Chico Mendes Extractive Reserve, Brazil.

Stakeholder	Degree	n-Degree	Betweenness	Eigenvector
ICMBio (Chico Mendes Institute for Biodiversity Conservation)	11.00	0.79	5.20	0.33
Community X	8.00	0.57	1.07	0.26
Embrapa (Brazilian Corporation for Agricultural Research)	10.00	0.71	3.46	0.31
UFAC (Federal University of Acre)	11.00	0.79	21.53	0.31
IMAC (Acre Environmental Institute)	3.00	0.21	13.00	0.05
IMC (Institute for Climate Change and Regulation of Environmental Services of Acre)	6.00	0.43	0.13	0.21
Funtac (Acre State Technology Foundation)	9.00	0.64	3.19	0.29
AMOPREAB (Association of Residents and Producers of the Chico Mendes Extractive Reserve in the Assis Brasil municipality)	8.00	0.57	0.61	0.27
SEMA (Ministry of the Environment)	11.00	0.79	4.76	0.34
Índia Porã civil association	1.00	0.07	0.00	0.01
WWF (World Wild Fund for Nature)	10.00	0.71	2.02	0.32
Agrocortex timber extracting and processing company	5.00	0.36	4.17	0.15
Purus Payment for Ecosystem Services project	4.00	0.29	0.00	0.14
SOS Amazônia NGO for biodiversity conservation and awareness raising	10.00	0.71	3.39	0.31
Community Y	7.00	0.50	0.47	0.24

There were quite a few multifunctional components. The Increase of illegal activities (12) were critical/active; whereas Indigenous communities' existence and agency (11) were critical/reactive. Extraction of NTFPs (4) were neutral/reactive, and Development of ecotourism (7) and Lobbying of local organizations (8) were active/neutral (Fig. 8).

DISCUSSION

Chico Mendes RESEX, Brazil

First, our results show a disproportionate concentration of components in the critical zone, none in the buffering zone, a meager occupation of the active and reactive areas, and few in the neutral area. This suggests a social-ecological system with too many influential and hard-to-harness components, each of which can greatly alter the system, and an absence of components capable of equilibrating the system, a constellation prone to weaken its resilience. Still, few components are disproportionally influential (active), and many are reactive, and thus, subject to control.

Specifically, the model shows that cattle ranching (component 3, Fig. 6) and politicking (9) are the main drivers of the system, but operate in interaction with the expansion of roads (8) and deforestation (1), whose causation is well-documented (Arima et al. 2005, Walker et al. 2013). These components operate within the given political (11) and market (14) settings, which may be the greatest determining forces of the system. This constellation is validated by recent research and events: the expansion of ranching lands, market fluctuations, and political power struggles have all grown during the past decade, during which time governance has weakened (Perz et al. 2015, Mathaess 2021, Bastos Lima and Da Costa 2022).

The model also asserts that interventions that could have an impact include NTFP collection (5) and (payment for) the provision of ecosystem services (13), both of which are proven by research (Perz et al. 2013a); and addressing climate change side effects (6). Furthermore, local organizations' lobbies (10), once instrumental (França Maia et al. 2016), are now less influential. For example, the Chico Mendes RESEX, previously a hub for conservationist and extractivist movements, has lost its

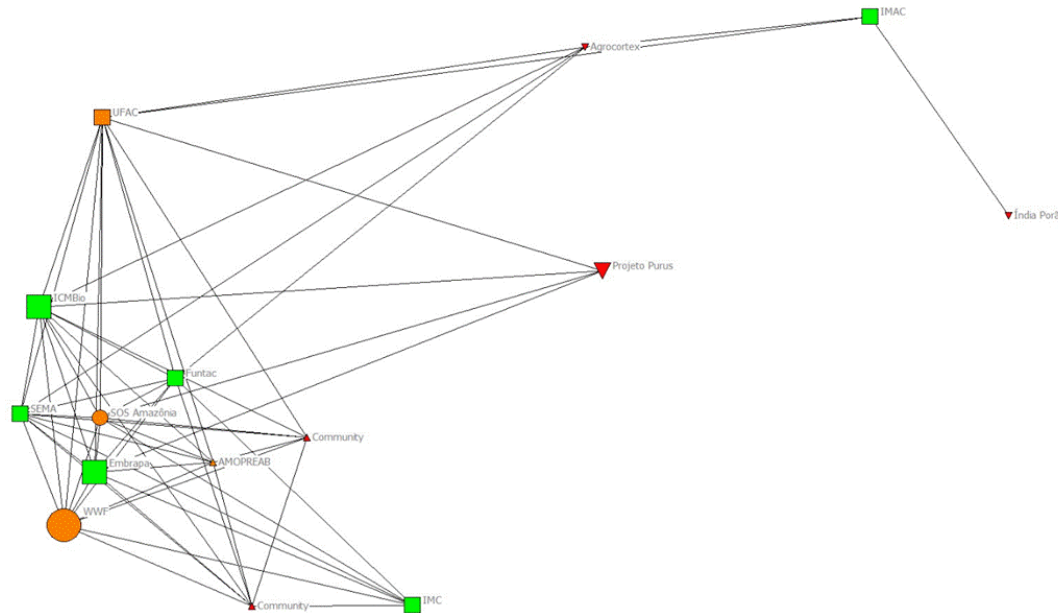
prominence. Finally, international traffic (15), landscape planning (2), and culture loss (3) are all components commonly alluded to, which may be important by themselves, but are now non-determinant of the system functioning (Froese et al. 2022, Perz et al. 2022).

Cattle ranching plays a determining role in the sustainability and resilience of Latin American social-ecological systems. When it is extensive, its economic importance attracts the involvement of government, private and academic institutions, although these focus mainly on the increase of productivity (Figuerola et al. 2022), neglecting the impacts of cattle ranching on the environment and climate, as well as the measures to address them (FAO 2023). On a smaller scale, ranching households face the usual difficulties of most farmers: limited financial means, lack of technological support, unfavorable trading conditions, and limited market access (Figuerola et al. 2022, 2025). So far, the profitability of ranching has driven its expansion and discouraged the search for alternatives, but livestock ranches' low diversification and vulnerability to global uncertainties, such as climate change and market fluctuations, require bottom-up awareness but also top-down actions, in which governance must play a key role (Figuerola et al. 2025).

Governance mediating ranching and conservation in the Amazon provide conclusive evidence: government policies, market interventions, and environmental institutions determine land uses, deforestation rates, and the final production/protection balance (Pacheco and Pocard-Chapuis 2012, Schielein and Börner 2018); and historical trends tend to favor livestock ranching (Moffette et al. 2021). However, there is also evidence that some measures can be effective in reconciling cattle ranching and conservation via more efficient land use and the involvement of other economic activities, but operating at territorial (small-scale) level (Painter et al. 2020, Chiaravalloti et al. 2025).

Politically, the gap between camps is not one of opposites. The clash of models, expressed in the popular depiction of Bolsonaro's exploitative and Lula's conservationist administrations is cartoonish: national and local governments held oscillating measures, and land-users themselves are both, conservationists and ranchers in turn (Hoelle 2014, Wallace et al. 2018). Not to

Fig. 5. Principal components sociogram of Chico Mendes Extractive Reserve, Brazil: (i) Type/shape: government (square), NGO (circle), private (triangle), and grassroots (inverted triangle); (ii) Role/color: decision making (green), leveraging (orange), and leadership (red); (iii) Scope of action/size (smaller to larger): local, regional, national, and international. See Table 2 for expansion of abbreviations.



mention the international community, which singles out large-scale environmental externalities as its main interest in the Amazon (Boulton et al. 2022, Albert et al. 2023, Lapola et al. 2023).

Our model summarizes this process well for the Chico Mendes RESEX. The expansion of cattle ranching at the expense of forests, supported by market forces and favorable policies and politicking, remain to be the challenges that are causing the loss of resilience and could lead to a tipping point, especially prominent is the Inter-oceanic Highway, whose opening accelerated the process. The prominence of cattle ranching has undermined other activities such as NTFP extraction and farming, and also invigorated the polarization between large-scale ranchers and small land-holders, conflicts that were upscaled to the political arena.

Manuripi, Bolivia

Our model shows that several components orbit around the critical zone, and only one lies in the buffer area. This implies that the social-ecological system is more prone to change and less resilient, however, those changes can diverge in quality. Furthermore, active and reactive components are fairly balanced, which offers some opportunities for the system's management.

Still, the system's specificities are elucidating. At its core are NTFPs extraction (component 12, Fig. 7), forest conservation (2) and rural actors' agency (4), confirming the importance of Brazil nut extraction (major NTFP). This is underpinned by various layers of organized stakeholders aiming at profit, but aware that their activities are contingent upon well-preserved forests (noticeably, the Manuripi Reserve is in much better condition than

Chico Mendes RESEX, where extractivism is also allowed). This constellation has been proven by previous research (Assies 2002, Mathäass et al. 2025).

Concurrently, the active components instrumental for NTFP extraction are: local organizations (3), governance (8), and markets (7). For the former two, the *Comité de gestión* (management committee, in Spanish), a coordination hub that intermediates between local organizations and government entities, has been central although recently it has resigned some of its authority because of national political struggles. Markets (7), mostly associated with Brazil nut's status as a commodity, are both a blessing and a curse because of the high volumes traded and international price volatility (TRIDGE 2020). A notable component is land-use planning (1; *Plan de Gestión Integral de Bosques y Tierra*, PGIBT, in Spanish), a regional initiative in charge of planning the land use at the household level and monitoring its implementation (ABT 2022). Infrastructure (6) and ecosystem services (13) were identified as influenceable components. Both are consequential to the prominence of Brazil nut extraction, and in the case of the former, infrastructure, its importance is validated by our own research (Mathäass et al. 2025).

NTFP post harvesting (10) and financial injection (11), interestingly, appear as neutral components. This is probably explained by the well-established roles played by the companies in charge of Brazil nut processing, and the monetary autonomy of gatherers in the absence of government presence or controls. Politicking (15), which has reshaped the institutional landscape more than once, is found to be a "stabilizer" component, e.g., key in the 2019–2021 political crisis and beyond (Velasco Guachalla et al. 2021).

Table 3. Systems' components by country-site.[†] RESEX = Extractive Reserve. NTFP = non-timber forest products.

Chico Mendes RESEX, Brazil	Manuripi-Bolivia	Tambopata-Peru
Exclusive to each site		
Forest land-use conversion	Sustainable management of natural resources	Growth of productive activities
Livestock rearing expansion	Storage and transport infrastructure	Growth of small mining
Strengthening of origin branding	NTFP post-harvesting	Development of ecotourism
Culture devaluation	Financial injection	Indigenous communities' existence and agency
Cross-border traffic		Increase of illegal activities
		Increase of regional immigration
In two sites (Chico Mendes Extractive Reserve, Brazil and Manuripi, Bolivia)		
Landscape/land-use planning and implementation		
Influence of politicking and party bias		
Ecosystem services provision		
In two sites (Manuripi, Bolivia and Tambopata, Peru)		
Forest conservation/preservation		
Rural actors' agencies		
In two sites (Chico Mendes Extractive Reserve, Brazil and Tambopata, Peru)		
Expansion of road network		
In all three sites		
Extraction of NTFPs		
Impacts and risks due to changes in climate		
Extraction of timber		
Lobbying of local organizations		
Governance and laws in operation		
Market action and influence		

[†] The definitions and detail of the components is provided in Appendix 4.

Much has been written about the roles and importance of Brazil nut at the regional level: as the only wild nut turned into a global commodity, its importance transcends local communities to become relevant for national economies. The relatively high income it generates discourages other more intrusive land uses and, consequently, favors the conservation of forests. Still Brazil nut adequate management is necessary to maintain the high production but also the healthy forest, and a condition for that is securing the rights on land (Duchelle 2007, Kainer et al. 2018).

The evaluation of Brazil nut extractivism under Ostrom's social-ecological system approach confirms these insights: the performance of the system lies in the interplay of four key parts, i.e., the resource (Brazil nut), the users (extractivist communities), the governance system (institutions), and the resource system (forests). Although it is acknowledged that trade, market, and institutional frameworks were established long ago and are largely effective, in correspondence with a commodity, extractivist communities remain the cornerstone of the system, as beneficiaries, but also as caretakers of the resource (Guariguata et al. 2017). All of this implies the understanding of the economic, environmental, and social interdependencies involved in Brazil nut extractivism (Rockwell et al. 2015, Thomas et al. 2017), which some consider to be already part of the identity and cultural makeup of local communities, such as those in the Manuripi reserve (Pellegrini 2023).

This consensus on considering Brazil nut extractivism as an example of harmonization between production and conservation, highlights the vulnerability of depending on a single resource, which is highly susceptible to market fluctuations and climate change blows. Against this, diversification, through the widening of the range of NTFPs, is emerging as a promising alternative (Arancibia Alfaro et al. 2024).

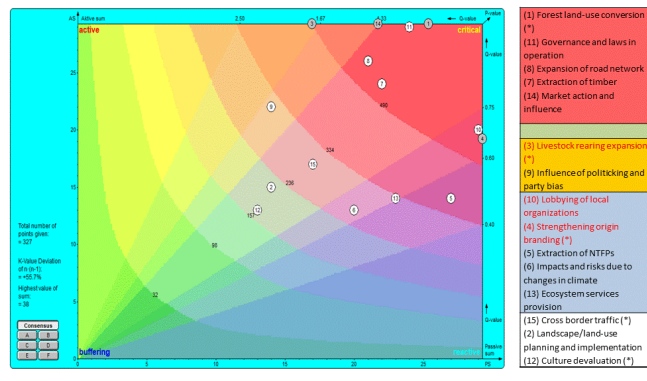
Our model, is consistent with this overview, as the Manuripi, Bolivia social-ecological system revolves overwhelmingly around the Brazil nut. The local economy, governance, social organization and even forest conservation, are intertwined and aligned to facilitate its extraction. This led to the system's dependence on Brazil nut, whose sporadic price fluctuations has hit local households hard. This makes it instrumental to Manuripi, Bolivia social-ecological system resilience, and if occurring, highly susceptible to a potential tipping point. Still, politicking remains locally relevant because it can alter the system's course too, as has recurrently happened in recent times.

Tambopata, Peru

As in the other two country-sites, our Tambopata, Peru model shows that more than half of the components are or tend to be critical, and there are no buffers (Fig. 8). This implies a social-ecological system endowed by various drivers, all strong enough to bring the others along, but lacking a counterbalancing force that stabilizes the system. Also, there is no frank active component, which limits its management, and still few influenceable components exist. In principle, this would insinuate a vulnerable system, but the situation is more complex.

Some of the critical components allude to diverging land-uses, such as forest conservation (5), agricultural production (3), and small-scale mining (6). Such diversification is well-documented: entrepreneurial activities such as fruit trees planting, agroforestry, livestock rearing, and pisciculture have boomed in recent times, so much so that they have displaced traditional projects like Brazil nut and timber extraction (Callo-Concha et al. 2022). Similarly, gold mining has skyrocketed, generating major economic gains, but also bringing serious environmental and social harm (Asner and Tupayachi 2016). These are contextualized by components like markets (9), governance (1), and road network expansion (2), whose determining roles are alike in all three country-sites.

Fig. 6. Components' systemic roles in Chico Mendes Extractive Reserve, Brazil: red: critical, green: buffering, yellow: active, blue: reactive, and white: neutral. Components with (*) are exclusive to the site. NTFP = non-timber forest products.



Ecotourism (7) and local lobbies (8) are rather neutral components, which may be inclined to play a kind of buffer role. Ecotourism is a growing sector, well-reputed by its environmental friendliness and profitability (Grzegorzak 2022), while local lobbies are key to circumvent Peru's convoluted politics.

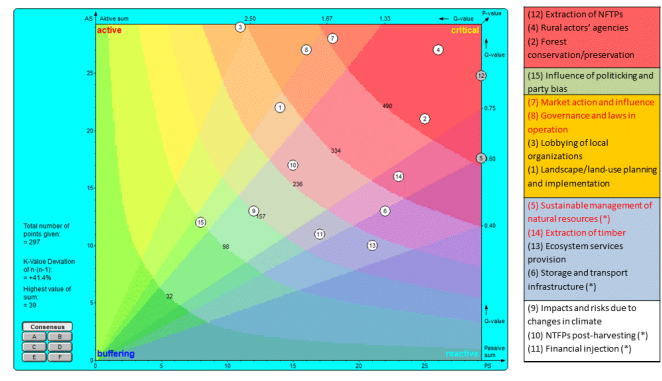
Illegal activities (12) are a critical but also active component, which implies their strong influence over the shaping of the system. Such activities grew in parallel to the region's economic growth, and are often associated with mining and migration, and criminality (Froese et al. 2022). Conversely, the influenceable components extraction of timber (14) and non-timber products (4) have lost prominence to, and now depend upon, farming and mining, as rural families tend to perform multiple economic activities (Thomas et al. 2017).

Last, regional immigration (13) is labeled as neutral, but is also critical and reactive, as it is quite prominent in the region. The department of Madre de Dios has the highest population growth in the country: 6% per annum (Jensen et al. 2018).

Mining has been fundamental to the economy of Madre de Dios' for decades. Mostly carried out on a small scale it is largely informal or illegal, and accused of ecological degradation through deforestation and mercury pollution, and responsible for increased social exploitation (Salo et al. 2016, Diringer et al. 2020), which has ultimately led to organized crime: extortion, trafficking of goods and persons, and contract killings, which is now discussed as a national security issue (Acuña et al. 2023).

The economy of Madre de Dios has historically been characterized by several boom and bust cycles, e.g., rubber, timber, Brazil nut, etc., which collapsed as the sustaining resource was depleted or lost economic viability; agriculture is expected to be the next (Lagneaux et al. 2024). In theory, agriculture could change the economic make-up of the region and, if successful, reduce dependence on mining. To some extent, this project has been taken up by entrepreneurs and the central government, through policies such as the Ley de Promoción Agraria 27360, that encouraged the production of crops for export. Thus, the sector's contribution to regional GDP has grown from 5.4% in 2007 to 12.2% in 2023 (Pastor and Vidal 2021, INEI 2023).

Fig. 7. Components' systemic roles in Manuripi, Bolivia: red: critical, green: buffering, yellow: active, blue: reactive, and white: neutral. Components with (*) are exclusive to the site. NTFP = non-timber forest products.

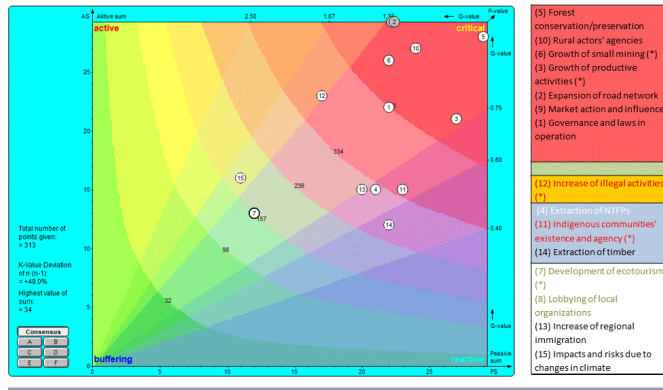


However, it should be noted that 80% of farms are family run, only 12% receive technical assistance, barely 6% have access to credit, and less than 1% of agricultural land is irrigated (Robiglio et al. 2015, MIDAGRI 2025), which translates into low yields and low competitiveness, when agriculture is not industrialized. Despite all this, the environmental impact of agriculture is already considerable. During the 15 years of construction of the Interoceanic Highway (1996 to 2011), croplands increased dramatically within 1 to 5 km on both sides of the highway (Chávez Michaelsen et al. 2013), and subsequent reports indicate that agriculture is the main cause of deforestation (72.9%) compared with mining, whose impacts are quite localized (Aguirre et al. 2021).

But regardless of the potential and sustainability of any economic activity, it is recognized that all of them are rooted in the economic liberalism predominant in Peru since the 2000s, which facilitated investment, trade, and fostered entrepreneurship. This ultimately produced wealth, but also underpinned the coercion of institutions and the weakening of the political order (Carrion 2019, Crabtree 2020). This weak governance and laissez-faire attitude manifests at both ends of the spectrum, for instance, in small-scale gold miners when they appeal to nationalism to justify their activities in opposition to large mining investors (Cortés-McPherson 2019), or by the rise of interest group representatives to the highest political levels, as in the case of the sole representative of Madre de Dios in the Peruvian parliament, who advocates for informal mining (Mathez-Stiefel et al. 2020, Valdivia 2024).

In a nutshell, our model reflects the situation and its risks: diverse activities have boomed and share preeminence: farming, mining, ecotourism, and a palette of forest products' extraction, which together increase the resilience of the system by mere diversification. Nevertheless, all of them rely on natural resources and their impacts on people and the environment vary greatly, as they are valued by their profitability and entrepreneurial drive rather than their sustainability. Overall, diversification has led to widespread economic growth, in spite or thanks to blurring of the fine line between legality and illegality, as reflected in institutions that bow to pressure groups.

Fig. 8. Components' systemic roles in Tambopata, Peru: red: critical, green: buffering, yellow: active, blue: reactive, and white: neutral. Components with (*) are exclusive to the site. Note: components 9 and 2 overlay partially and 7 and 8, fully. NTFP = non-timber forest products.



CONCLUSIONS

The objective of this study was to model the social-ecological systems of the three country-sites of the MAP region, and to identify the features that may lead to the systems' loss of resilience and eventual surpassing of tipping points. Our findings indicate that despite their ecological and historical commonalities, the three country-sites have evolved divergently and conform to three archetypical social-ecological systems each with recognizable compositions, structures, functions, and identities.

Despite their ostensible differences, there are commonalities among them: (i) The economies of the social-ecological systems in all three country-sites depend on natural resources for capital and wealth, i.e., timber and NTFPs extraction, ranching, mining, farming and tourism. However, the sustainability of their management differs, contingent to their profitability, environmental intrusiveness, and the balance between entrepreneurship and governance. (ii) The sites are operated by governance setups with three identifiable categories: formal government and non-government institutions, lobbies of local stakeholders, and other behind-the-scene influence networks, e.g., politicking, party politics favoritism, and corruption. Their interaction is dynamic and mutable, and at times volatile, as power and politics are intertwined. (iii) Each country-site, through its specific products, i.e., Brazil nut in Manuripi, Bolivia, meat in Chico Mendes RESEX, Brazil, and gold, farming goods, ecotourism, etc. in Tambopata-Peru, is strongly embedded in national and international markets, which largely define the type and degree of activities or interventions that affect the forests.

These models make visible the components and features of the three country-sites' systems that may lead to their loss of resilience, and eventual surpassing of tipping points. In Chico Mendes RESEX, Brazil, the riskiest factor is the conversion of forested lands into cattle ranches fueled by the high and steady value of meat as a commodity. The inability (intended or not) of institutions and the political classes to halt such land-use conversion makes it seem unstoppable. In Manuripi, Bolivia, the low diversity of economic activities and the overwhelming dependence on Brazil nut configure

its major vulnerability, because of the Brazil nut's international price volatility due to market- and climate-related variations. This, along with the country's political and power struggles, have weakened their so-far conducive institutional functioning. In Tambopata, Peru, economic diversification has increased the region's resilience, however the illegal and semi-illegal nature of some activities are in several ways dangerous. Relatedly, the lobbying behind such economic activities seeks and at times bends institutional and political action, which may open unpredictable weaknesses.

All three country-sites denote a strong tendency to instability, either by the dominance of a component and its side-effects, or by the struggle of several components that pull the social-ecological system in divergent directions. Given this constellation, obvious suggestions for action include encouraging economic diversification and strengthening the governance in all three cases. Regarding the former, only Tambopata, Peru appears to show a considerable development in the diversification of its economy, while efforts in Chico Mendes RESEX, Brazil and Manuripi, Bolivia remain timid and as yet insignificant. Concerning governance, the three countries have been (and still are) subject to successive political and institutional ups and downs: changes of course in conservation and production policies as in Chico Mendes RESEX, Brazil; rotation of authorities according to their political inclination in Manuripi, Bolivia; or the favoring of specific groups of interest in Tambopata, Peru.

Conventionally, addressing tipping points in social-ecological systems would require recognizing and featuring (potential) tipping points, accepting the inherent uncertainty surrounding them, and fostering resilience and adaptive capacity of the affected social-ecological systems, in addition to the eventual admission of the system's transformation (Halpern 2017, Olsson and Moore 2024). In the MAP region, in the southwestern Amazon, attempts to identify tipping points are ongoing. So far, these have consisted in recognizing the scales/subsystems in which they can occur, i.e., soil ecology, household livelihoods, institutions and governance, and regional climate; detecting a certain degree of causality between them; and scouting for intrinsic interconnectedness at all levels (Andrino et al. 2022, Froese et al. 2023). In this study, we have gone a step further by analyzing each country-site specifically. Our approach, based on local participation and systems analysis, has produced plausible models of each country-site system and indicated where the loss of resilience and overcoming of tipping points are likely to occur.

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Data Availability:

The data that support the findings of this study are available on request from the corresponding author, DCC.

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