Describing complex interactions of social-ecological systems for tipping point assessments: an analytical framework

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Humans play an interconnecting role in social-ecological systems (SES), they are
part of these systems and act as agents of their destruction and regulation. This
study aims to provide an analytical framework, which combines the concept of
SES with the concept of tipping dynamics. As a result, we propose an analytical
framework describing relevant dynamics and feedbacks within SES based on
two matrixes: the "tipping matrix" and the "cross-impact matrix." We take the
Southwestern Amazon as an example for tropical regions at large and apply the
proposed analytical framework to identify key underlying sub-systems within the
study region: the soil ecosystem, the household livelihood system, the regional
social system, and the regional climate system, which are interconnected through
a network of feedbacks. We consider these sub-systems as tipping elements
(TE), which when put under stress, can cross a tipping point (TP), resulting
in a qualitative and potentially irreversible change of the respective TE. By
systematically assessing linkages and feedbacks within and between TEs, our
proposed analytical framework can provide an entry point for empirically assessing
tipping point dynamics such as "tipping cascades," which means that the crossing
of a TP in one TE may force the tipping of another TE. *Policy implications:*
The proposed joint description of the structure and dynamics within and across

SES in respect to characteristics of tipping point dynamics promotes a better understanding of human-nature interactions and critical linkages within regional SES that may be used for effectively informing and directing empirical tipping point assessments, monitoring or intervention purposes. Thereby, the framework can inform policy-making for enhancing the resilience of regional SES.

1. Introduction

While the Earth System, as a major social-ecological system (SES), has sustained global human well-being throughout the Holocene, its sustaining functions are being put under stress by human activities and their consequences, such as climate change, land use, and land cover change (LUCC) and the loss of biodiversity and associated ecosystem services (IPCC, 2014; IPBES, 2019). These processes reduce "the safe and just operating space for humanity" (Rockström et al., 2009; Dearing et al., 2014) and have driven a transition into unstable environmental conditions in the Anthropocene (Steffen et al., 2018; IPCC, 2022). The scientific discourse about the "Anthropocene" asserts that investigation of the Earth System nowadays is only feasible considering human impacts (Donges et al., 2017). The integration of human interaction with the environment is conceptualized in the literature on SES, which exist at different scales and forms sub-systems of larger SES (Reyers et al., 2018). SES assume that environmental, economic, and social (including cultural and political) sub-systems are interconnected (Folke, 2006), e.g., a disturbance in a sub-system may affect others, via self-amplifying or stabilizing feedback loops that operate within or across sub-systems (Senge, 1991; Sterman, 2002; Hamilton et al., 2022). These dynamics may not be linear and lead to rapid, hardly predictable changes. One specific case of an extreme dynamic system behavior may occur after crossing a tipping point (TP), which drives a potentially irreversible system transformation from one state into another (Lenton, 2013). Approaching and eventually crossing a TP happens particularly when disturbances lead to internal self-amplifying feedback loops (Lenton et al., 2008). TPs and their impact on SES have been documented in recent studies (Lauerburg et al., 2020), but common definitions are lacking, e.g., regarding (i) the speed and pathway of a system shift and (ii) the potential (time) of system shift recovery (Milkoreit et al., 2018). Moreover, the empirical evidence for certain magnitudes of TPs is still limited (Hillebrand et al., 2020). However, whether there is a certain magnitude (threshold) or a range of magnitude (corridor) where dynamic system responses accelerate, a common understanding of the tipping behavior in SES is important for a more sustainable ecosystem-based management (Lauerburg et al., 2020).

In this regard, a joint analysis of the SES structure, dynamics, and interactions is useful and needed not only to better understand human-nature interactions and relationships but also to formulate policy recommendations at a regional scale where impacts become visible and actions are being implemented (Dearing et al., 2014).

In the present paper, we propose an analytical framework, which applies a global TP concept to a regional SES, and systematically assesses interactions and feedbacks within. The framework examines impacts across system elements that might turn out to expose the behavior of tipping dynamics.

We demonstrate the functioning of our analytical framework based on qualitative expert and literature-driven assumptions rather than novel empirical data. Our main contribution is the proposition of the framework. The illustrating examples are strongly dependent on the assumptions made but can be adapted to the situation of interest. Thus, the reader might disagree with some of the assumptions while retaining an appreciation for the value of the general framework.

The case study region is located at the tri-national border in the Southwestern Amazon, across the three states Madre de Dios (Peru), Acre (Brazil), and Pando (Bolivia), also known as the MAP region. The region comprises three different social and economic country situations but similar ecological conditions: the tropical humid rainforest, which is particularly important for the Earth System in terms of moist convection, biodiversity, and its function as a carbon sink and habitat to diverse social groups (Perz et al., 2013; Selaya et al., 2017; Callo-Concha et al., 2021).

To systematically describe the dynamics within the Southwestern Amazon, we apply and adjust the TP terminology proposed by Lenton et al. (2008) and decompose the SES into our framework of sub-systems and respective interconnected TEs: (1) the soil ecosystem, (2) the household livelihood system, (3) the regional social system, and (4) the regional climate system. We first characterize the key components and functioning of each TE before we identify linkages across them. Based on this description, we introduce the so-called tipping cascade (Lenton, 2020; Sharpe and Lenton, 2021), which describes the interdependencies between TEs, i.e., the crossing of the TP(s) of one TE may cause the tipping of another TE (and so forth). Finally, we demonstrate the cascading effect by describing one potential tipping pathway initialized by human disturbances originating from LUCC.

Our proposed analytical framework can be applied to any kind of regional SES, for systematically describing complex dynamic interconnections within and between individual TEs/sub-systems, independent whether a TP exists or not.

The paper is structured as follows: in section two, we provide an overview of our example, the Southwestern Amazon. In section three, we first describe the tipping point terminology for global Earth System analysis (3.1.1), apply this terminology to the regional SES and develop the "tipping matrix" (3.1.2). In a second step, we

focus on key linkages and the cascading effects among the TEs of the regional SES and develop the "cross-impact matrix" (3.2), which provides an entry point for assessing "tipping cascades." We summarize the section with some limitations and implications for future research (3.3) and summarize our findings in section four.

2. Example: the Southwestern Amazon

The MAP (Madre de Dios, Acre, Pando) region (Figure 1) is located in the Amazon Basin and is part of the Southwestern Amazon Moist Forests ecoregion (Olson et al., 2001) comprising an extension of about 31 million ha (Selaya et al., 2017). It is known for its vast areas of standing natural forests and its high biodiversity, its regulation function for regional and global climate processes (Arraut et al., 2012), and its substantial social diversity (Perz et al., 2013).

Since the 2000s, the MAP SES is undergoing rapid changes through heavy impacts of ongoing LUCC. The pavement of the Interoceanic Highway during the 2000s has triggered social, environmental, and economic processes with significant effects on increasing deforestation rates associated with road connectivity and migration (Southworth et al., 2011). Furthermore, gold mining has also significantly increased, posing major threats to biodiversity, landscape alterations, water quality, forest carbon stocks, and human health (Swenson et al., 2011; Asner and Tupayachi, 2016; Velásquez Zapata, 2020). Additionally, forest clearings through fires, agricultural activities, as well as regional climate change, such as droughts and floods, have further increased pressure on regional SES (Southworth et al., 2011; Perz et al., 2013; Da Silva et al., 2018; Schilling et al., 2021).

The climate of the Southwestern Amazon (about 10°S) features the typical characteristics of the moist tropics which are low thermal seasonality with an average annual temperature of 26–27°C and a mean annual precipitation of 1,500–3,500 mm, declining from west to east and with dryer conditions during austral winter (June–September) and more humid conditions during austral summer (November–February). However, distinct intrinsic natural, temporal variations, such as El-Niño-Southern-Oscillation (ENSO), reinforce seasonal patterns resulting in both frequent droughts and extreme precipitation events (Aragão et al., 2007; Marengo et al., 2011; Sulca et al., 2018; Souza et al., 2022).

The soils of the MAP region are derived from a wide variety of parent materials, landforms, geomorphic elements, and soil age (Quesada et al., 2011; Gómez et al., 2019). The three provinces within the MAP region share the presence of strongly weathered soils being poor in weatherable minerals and nutrients and rich in iron and aluminum oxyhydroxides, such as Acrisols, Ferralsols, and Lixisols (Wieder et al., 2014). In the region of Madre de Dios, additionally, soils of floodplains (Fluvisols) and less weathered Cambisols are present and characterized by higher nutrient availability (Batjes, 2016). According to Selaya et al. (2017), most of the region shows an elevation of 100–600 m above sea level and is considered submontane, while the predominant physiographic types are alluvial, i.e., ancient mostly not flooded or seasonally flooded floodplains (43% Madre de Dios, 6% Acre, and 19% Pando), and terra firme forests (48% Madre de Dios, 80% Acre, and 78% Pando). Furthermore, the same authors report the aboveground biomass stocks have been estimated to range between 100 and 300 Mg ha^{-1}, harboring great diversity of tree and palm species with high ecological importance. However, with future climate scenarios indicating more frequent and extensive droughts, an increase in the use of fire for new deforestation may lead to a potential increase in bamboo density and a decrease in species diversity (Da Silva et al., 2021).

The regional social system is characterized by a high social diversity comprising indigenous peoples and traditional forest extractivists as well as recent migrants including settlers, ranchers, and miners, along with a growing urban population (Perz et al., 2015). In addition, the region faces political and economic marginalization from the political centers of the three states due to their remote location and low political will, resulting in a lack of law enforcement and thriving organized crime (Froese et al., 2022a). At the same time, the transition between rural and urban involves complex mobility pathways and multi-sited households as well as diverse economic and social relations. For example, it is common for a family to live in the city while some members work in the city and others frequently travel to their agricultural plots where they produce crops and fruits for subsistence or to sell on the market. These result in much more permeable categories of the "urban" and "rural" compared to other regions in Latin America.

Consequently, the household livelihood systems of the MAP region comprise a complex combination of activities, with the most prominent being the harvest of Brazil nuts. Açaí is collected in Acre and Pando, while formerly important rubber tapping is close to extinction due to a loss of marketability of forest-collected latex. Hunting and collecting of non-timber forest products (NTFP) such as sap resins, oils, and palm fruits are practiced for subsistence (Da Lima et al., 2020). Furthermore, crop cultivation, cattle ranching, and mining are important income sources, with distinct differences between the three regions. While Acre has a longer tradition of large-scale cattle ranch farming, partly due to federal cattle subsidies up to the year 1991 (Valentim et al., 2002; Duchelle, 2009), Madre de Dios and Pando are largely characterized by small-scale farming practices (mainly cassava, rice, maize, and beans). Illegal gold mining and deforestation for coca plantations as well as poaching are increasing in the whole MAP region with the main emphasis in Madre de Dios, where also legal gold mining occurs on large scale (Salisbury and Fagan, 2013; Espin and Perz, 2021). This leads to negative impacts in environmental, economic, and social contexts (Vadjunec et al., 2009; Asner et al., 2013; Duchelle et al., 2014).

3. Analytical framework

The analytical framework indicates the complexity of the tropical systems, i.e., regarding (i) interactions and feedbacks and (ii) potential pathways that "disturbances" could trigger. Additionally, we design the analytical framework to reflect upon the different contexts and histories that the sub-systems are embedded in and that shape the current state and sensitivity to disturbances of each sub-system.

The analytical framework consists of two supplementing, structured approaches. First, the development of the **Tipping**

FIGURE 1
The MAP region in the Southwestern Amazon.
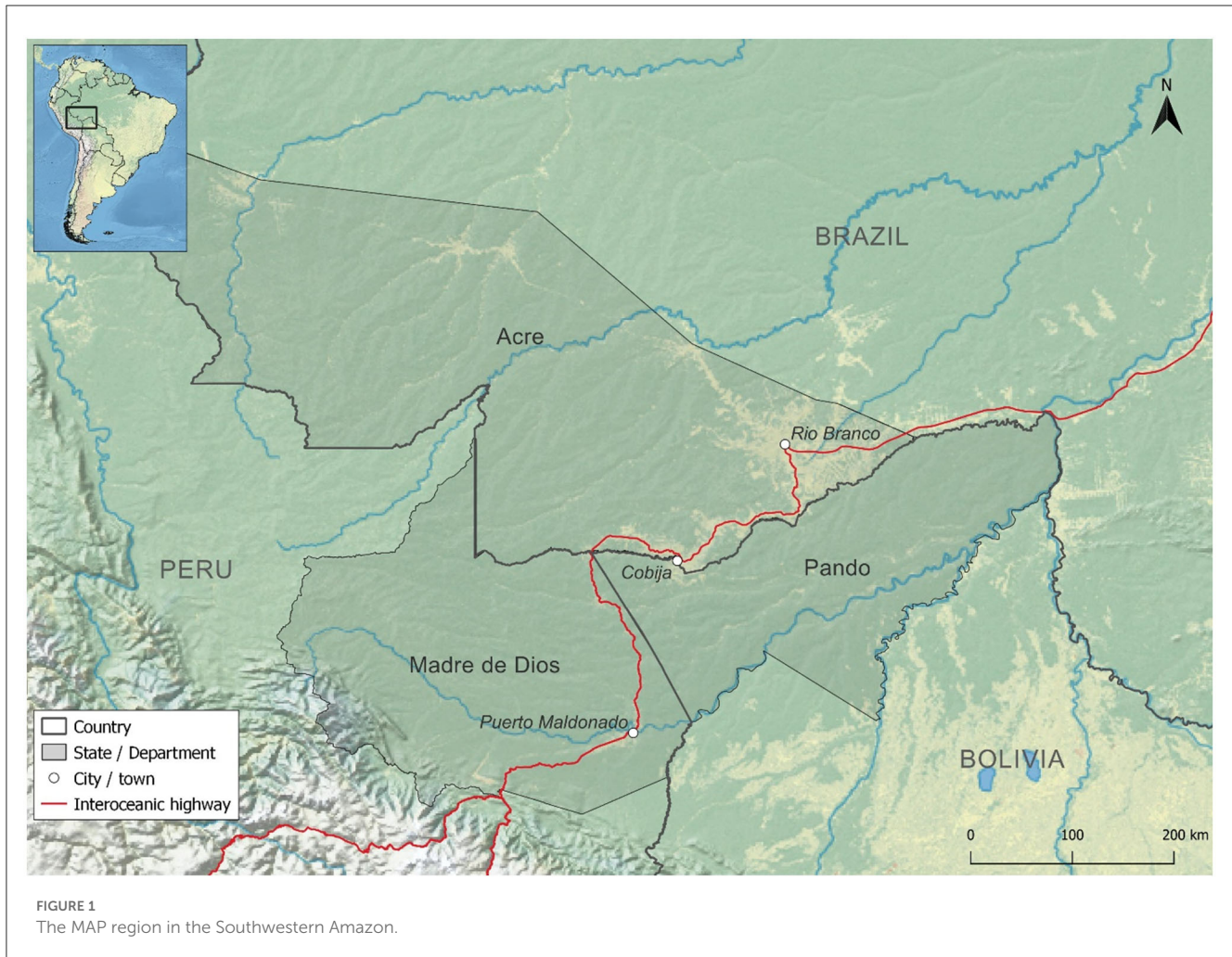
Matrix (see Table 1 and Section 3.1), which applies the global tipping point concept (Lenton et al., 2008) to the regional SES and its four identified sub-systems [referred to in the following as "tipping elements" (TE)]: (i) the soil ecosystem, (ii) the household livelihood system, (iii) the regional social system, and (iv) the regional climate system. The tipping matrix defines the core components and functioning of each TE (in isolation) and structures information, relevant for researching tipping dynamics. Second, the development of the **Cross-Impact Matrix** (Table 2), by highlighting critical linkages and feedbacks between the regions' TE. Critical linkages and feedbacks are considered to affect key processes and features of TE, initially identified in the tipping matrix (see Table 1 and the crucial system feature and control parameters—shown in bold letters in Table 2). In this regard, the analytical framework supports interdisciplinary, cross-scale research (of relevant processes within/between TE) on tipping dynamics in tropical SES. It provides an entry point for assessing potential cascading effects and dynamics in the Southwestern Amazon.

Within our analytical framework, we use the term "link" for any interaction between TE and the term "cascade," to refer to the dynamic of tipping that follows after an initial tipping point in one sub-system has been crossed. In the following, we introduce the tipping matrix and the cross-impact matrix that together form the analytical framework.

3.1. The tipping matrix

3.1.1. The tipping terminology

We base our tipping matrix framework on Lenton's (2011) approach to tipping dynamics which defines a TE as a large-scale sub-system of the Earth system or, simply put, a sub-system of the Earth system, in which a small perturbation can trigger a large response. The *crucial system feature* is the main property of the system, in other words, the core feature or combination of sub-features through which the complex system can be defined (Lenton, 2011). The parameters controlling the crucial system feature can be combined into a single *control parameter*, an independent variable. The control parameter includes a *critical control value*, defined as the value at which the control parameter reaches a point at which the crucial system feature experiences an abrupt/non-linear change after some observation time (Lenton et al., 2008). The critical control value remains difficult to predict and is currently a focus of research to identify early warning indicators to narrow down the interval in which a

TABLE 1 The tipping matrix for the four proposed TE in the Southwestern Amazon.

Major tipping element (a large-scale sub-system of the earth system)	Region's social-ecological system in the Southwestern Amazon			
Tipping element (a sub-system of the major tipping element)	Soil ecosystem	Household livelihood system	Regional social system	Regional climate system
Crucial system feature (principal properties of the system)	Soil functions (through plant water availability and nutrient provision)	Livelihood strategy (income and asset generating activities, legal vs. illegal, sustainable vs. unsustainable)	Social Cohesion (comprising shared identities, mutual trust, and perceived equalities)	Moist convection (land-climate interaction, i.e., land use and land cover affects evapotranspiration, cloud formation, and precipitation)
Single control parameter (combination of control parameters that control the crucial system feature)	Belowground/aboveground functional diversity and redundancy	Profitability of livelihood portfolio	Reflexive capabilities to govern change and transformation (Human Agency)	Land use and land cover pattern
Critical control value (value of the control parameter at which an abrupt change occurs)	Diversity/redundancy of plant and microbial functional traits	Benefit-cost ratio of livelihood portfolio	Critical reflexivity of formal and informal institutions	Ratio and shape of forest/non-forest cover
Driving forces (forces that impact the control parameter)	Droughts related to climate change; Land Use and Land Cover Change (LUCC)	Land use decisions, availability of ecosystem services (e.g., soil fertility), environmental variability, farm/forest output value, market prices, institutional constraints (e.g., land tenure security)	(Lack of) Commitment to general norms and values, income distribution, access to basic services and public policies, political efficacy, corruption, presence of powerful criminal cartels, institutional (social/political) learning and knowledge-holding capacity, land system reforms/planning, global governance mechanisms	Land use and land cover change (LUCC)
Internal stabilizing feedback mechanisms (negative feedbacks) (This occurs when the output of a TE (process or mechanism) is fed back in such a way that it tends to reduce fluctuations in the output, caused by changes in the input or by other disturbances)	The plant-soil feedback mechanism (PSFM) is enhanced if there is a greater diversity of plant functional traits and soil microbial functional genes, promoting soil buffering functions	Re-investments in current livelihood strategy. Households who could afford to reinvest part of their income in their current production activities could maintain such a livelihood strategy	Anti-corruption strategies and education enable civic participation. Stable income from cattle raising or monocultural crops confirms people's decision to lifestyle change	
Internal self-amplifying feedback mechanisms (positive feedbacks) (This occurs in a feedback loop that exacerbates the effects of a small disturbance. That is, the effects of a perturbation on a TE include an increase in the magnitude of the perturbation)	Reduced aboveground (e.g., plant functional traits) and belowground functional diversity and redundancy (e.g., microbial functional genes) result in a reduction of the soil buffering functions that support water and nutrient supply	Falling prices of agricultural products could lead to expanding agriculture at the expense of forests to maintain the same level of income. Similarly, falling prices of forest and environmental products could lead to over-harvesting and depletion of the natural resource base. The adopted changes in the livelihood strategy increase income which is then used to continue with the potentially unsustainable livelihood strategy. The depletion of the natural resource base could further strengthen the qualitative changes in the livelihood strategy	Interrupted institutional learning (social & political) may lead to non-adaptive management of changing environmental conditions, which may lead to path dependencies and lack of knowledge which may lead to further interruption of institutional learning	Reduced moist convection (i.e., reduced convective rain rates) increases the Bowen Ratio and again amplifies the reduction in moist convection. Reduced moist convection may (i) cause the transformation of the evergreen tropical rainforest into another (natural) vegetation type (LUCC) showing less diversity/structure causing a decrease in evapotranspiration and moist convection respectively
Indicators used to quantify qualitative change (Indicators that measure the change of the control parameter)	Greenhouse gas emissions; nutrient contents and stoichiometry; microbial functional diversity; plant functional traits	Reliance on sustainable vs. unsustainable income sources; household livelihood security	Law enforcement/implementation, degree of networked institutions, political interaction and participation, level of violence, illegal and informal activities, expansion of criminal networks, preferred lifestyle, life satisfaction/well-being, level of trust, level of perceived equality, etc.	Metric of forest cover and LUCC extend and patchiness

critical control value is anticipated (Dakos et al., 2015). Finally, *driving forces* are any natural or human-induced factor that causes a change in the controlling parameter and interacts across spatial, temporal, and organizational scales. Likewise any complex system, SES may respond to driving forces showing *internal and external feedbacks* with the surrounding environment, when the outputs of a (sub-)system are forwarded as inputs, as part of a chain of causation producing loops with *stabilizing* or *self-enhancing* effects on the (sub-)system response (Anderson, 1999; Lenton, 2013). While stabilizing feedback mechanisms buffer the response of the system to a driving force, self-enhancing feedback mechanisms act destabilizing, potentially causing the system to shift to a different state, thus facilitating the TEs to cross a TP. While we use the tipping terminology across human and natural systems, we acknowledge that these systems operate at very different scales and with different underlying mechanisms of feedback-driven non-linear abrupt changes, in particular concerning agency and networking behavior (see Steffen et al., 2018; Betsill et al., 2020; Winkelmann et al., 2022).

3.1.2. Application of the tipping terminology to the Southwestern Amazon

3.1.2.1. The regional soil ecosystem

Soils are a key component of the Critical Zone of the continental surface, which extends from the atmosphere to the bedrock, and ensures the functioning of the Earth's ecosystems and the continuation of life on Earth (Brantley et al., 2007). We assume that highly biodiverse and functional soils provide the underpinning of indispensable services that ensure the basis for sustainable economic livelihoods and societies. We choose the *soils* of the Southwestern Amazon region as a **tipping element** and the *soil buffering functions* (i.e., supply of water and nutrients to plants) as **crucial system feature** in the soil-plant-human continuum. Soil resilience to the regional **driving forces** is based on the interplay between belowground and aboveground *functional diversity* and *redundancies* of different structural biotic components (**control parameters**). Functional diversity involves three interrelated and distinct plant/microbial components: (1) variety, i.e., how many different components occur; (2) the balance of how many of each type of component there are; and (3) disparity, i.e., how different the components are from each other (Brinkman et al., 2010; Birgé et al., 2016; Barot et al., 2018). While redundancy involves the diversity of below and aboveground replication of certain functions in a system. In this regard, redundancy provides a safeguard to ensure soil's safe operation, by allowing plant/microbial components to compensate for the loss or failure of others (Yachi and Loreau, 1999; Fraccascia et al., 2018). Maintaining functional diversity and redundancy may allow soils to perform the same task in multiple ways and respond with different capabilities to various driving forces, thus enabling the persistence of its above/belowground elements and maintaining their stability under changing conditions (Wertz et al., 2006; Jurburg and Salles, 2015; Jia and Whalen, 2020).

Identifying and investigating the above and belowground feedback loops provides insights into the mechanisms by which the soil system regulates itself. While **internal stabilizing feedback loops** (negative feedback loops) are likely to lead to a stabilization of both above and belowground biotic communities, **internal self-amplifying feedback loops** (positive feedback loops) may accentuate slight inequalities that lead to the dominance or exclusion of various biotic communities, thus, partial impairment of the soil functions (Eisenhauer, 2012; Lou et al., 2014). This identification of relevant feedback mechanisms maintaining or destabilizing soil TE relies on scientific evidence accrued since the 1990s studying the plant-soil feedback mechanisms (PSFM) (Bennett and Klironomos, 2019). Studies of the interaction mechanisms between the physical, chemical, biogeochemical, and biological components of the soil system and the distinct plant communities have contributed to these findings (Ehrenfeld et al., 2005). The PSFMs have revealed their essential role in maintaining plant diversity, showing that primary production tends to increase in highly diverse plant communities and that the beneficial correlation between plant diversity-productivity seems to be reinforced over time (Thakur et al., 2021).

The soil physical factors that have the greatest influence on plant-soil interactions are water content, temperature, and particle structure resulting from the aggregation of mineral grains. These properties not only affect plant growth but are also conditioned by the nature of that plant growth (Ehrenfeld et al., 2005). While chemical and biogeochemical interactions between plants and soil are more complex to unravel and analyze when compared to the physical properties of soils. The reason is that plant-soil chemical and biogeochemical interactions often involve complex mechanistic pathways involving soil chemical components, soil moisture, temperature, and soil biota (Ehrenfeld et al., 2005; Mariotte et al., 2018; Wang et al., 2021). In this regard, van der Putten et al. (2016) identified the three major categories of soil biota shaping PSFMs: plant pathogens (microbial soil pathogens, herbivorous nematodes, insect larvae, and other invertebrates), symbionts (mycorrhizal fungi, non-mycorrhizal endophytic fungi, endophytic bacteria, nitrogen-fixing microbes, and plant growth promoting microorganisms), and decomposers (organisms involved in carbon and nutrient cycles that break down litter, root exudates, and soil organic matter). Each may have an impact on plant development both directly and indirectly, by influencing soil physicochemical qualities such as pH, organic matter content, water holding capacity, temperature, and soil structure. Furthermore, a better understanding of aboveground-belowground feedbacks and underlying mechanisms will assist in better predicting and mitigating the consequences of human-induced global changes, improve restoration and conservation efforts, and promote the sustainable provision of soil ecosystem services in a rapidly changing world (van der Putten et al., 2013).

We hypothesize that soils will show an enhanced resilience to regional **driving forces** when they hold a greater diversity and redundancy of functional traits provided by aboveground /belowground components. We expect enhanced PSFMs, such as plant-mediated nutrient cycling and plant–microbial interactions if there is a greater diversity and redundancy of plant and microbial functional traits. Reduced above and belowground functional diversity and redundancy will result in a reduction of the soil functions supporting water and nutrient supply to plants. We finalize the characterization of our **soil TE** by offering a suitable

set of **indicators used to quantify the qualitative change** in aboveground/belowground diversity and redundancy derived from the **critical control values** (Table 1).

3.1.2.2. The regional household livelihood system

The second TE in our tipping matrix is the *household livelihood system*. To define it we draw on the conceptual framework developed by Niehof and Price (2001). This system is composed of several subsystems, processes, activities, inputs, and outputs, and interacts with other systems such as ecological systems, markets, and sociocultural contexts. The system includes the family, farm, and household subsystems, and the process of "householding" or "household production," which entails the activities and inputs (resources and assets) used to satisfy the material needs of household members and generate the basis for meeting their immaterial needs. The system's throughput is determined by the processing, use, and management of these inputs. One of the main outputs of the system is livelihood security when the household can provide for its members' needs sustainably. Typically, there are numerous different activities targeted at securing and improving livelihood. A household that gathers Brazil nuts, for instance, might also grow corn for their consumption and to feed their chickens, as well as produce grains for the market (Duchelle et al., 2014). Such activities are planned and structured based on strategies, which together with the decision-making (e.g., land use decisions) and management of strategies' implementation are part of the system's throughput.

In our matrix, we consider this strategy, or more specifically, the livelihood strategy, as the **crucial system feature**. The **parameters controlling** the livelihood strategy comprise (1) livelihood assets (human capital, natural capital, financial capital, social capital, and physical capital), (2) structures and processes that affect livelihoods assets (e.g., market, policies, institutions, migration), and (3) livelihood outcomes themselves, that is, through a loop (e.g., more/less income, reduced/increased vulnerability, more/less sustainable use of land, improved/deteriorated income security) (DFID, 1999). In the tipping matrix, we focus on the *profitability of the portfolio of activities* as a key **control parameter** of the livelihood strategy.

In our matrix, the **critical control value** is the one at which a particular livelihood strategy will change qualitatively, say from a legal to an illegal activity-dominated strategy, or vice-versa. For example, a livelihood strategy that includes only legal activities will be maintained as long as this strategy is profitable. Once overall costs increase and outweigh the benefits, a household could switch its portfolio to include some illegal activities (Yonariza and Webb, 2007; Vasco et al., 2017; Chaves et al., 2021). It is important to note that the costs will also comprise the risk of being fined or prosecuted for having committed crimes. The risk will depend on the governance context (Börner et al., 2015a). In the same way, benefits do not only consider tangible but immaterial ones (Huynh et al., 2022). At the extreme, a household's livelihood strategy could completely switch to be based on illegal activities when these provide significantly larger profitability than that provided by the legal ones. In theory, the trend could be reversed, from illegal activities to legal ones, if profits associated with legal activities increase again. However, as in all complex systems, other

controlling parameters not exemplified here could come into play (e.g., cultural aspects, see for example Hoelle, 2021).

Several **driving forces** affect the profitability of livelihood strategies. Examples are agricultural technologies (Angelsen and Kaimowitz, 2001), levels of natural resource use (Coomes et al., 2004), historical conditions (Coomes et al., 2016), soil fertility (Heger et al., 2020) and the availability of other ecosystem services (Junqueira et al., 2016), environmental variability (Börner et al., 2015b; Ajefu et al., 2020; Alfani et al., 2021; Girard et al., 2021), farm/forest output level (i.e., productivity) (Klemick, 2011), market prices (e.g., the decline in Brazil nut retail prices) (Ubiali and Alexiades, 2022), and institutional constraints (e.g., land tenure insecurity, encroaching) (Tseng et al., 2021).

The livelihood strategy as the crucial system feature plays a key role in determining potential feedback mechanisms within the household livelihood system (Girard et al., 2021). Re-investments in the current livelihood strategy can be considered as an **internal stabilizing feedback mechanism** if households that could afford to reinvest part of their income in their current production activities could maintain their livelihood strategy (Su et al., 2019). On the other hand, **internal self-amplifying feedback mechanisms** could be indicated, when falling prices of agricultural products lead to expanding agriculture at the expense of forests to maintain the same level of income (Angelsen and Kaimowitz, 2001). Similarly, falling prices of forest and environmental products could lead to overharvesting and depletion of the natural resource base. The adopted changes in the livelihood strategy increase income which is then used to continue with the potentially unsustainable livelihood strategy. The depletion of the natural resource base can become an incentive for actors to rethink and change their livelihood strategy.

3.1.2.3. The regional social system

As a third **tipping element** in our tipping matrix, we consider the *regional social system*. We define the *regional social system* as corresponding to the boundaries of the social-ecological sub-system under consideration to embrace all dynamics relevant to LUCC within this SES. These boundaries do not necessarily correspond to political or administrative boundaries. However, the consideration of administrative boundaries in a second step adds more complexity to the system analysis by introducing sub-systems that may differ substantially in terms of institutions and applicable laws, resulting in land use patterns and vulnerabilities to external shocks, such as varying climatic conditions. At the same time, this differentiation facilitates the analysis of interactions between the different systems, through migration, flows of products, criminal networks, etc.

Land use change and related changes in soil functions and subsequent changes in livelihood strategies may impact the social fabric within the Southwestern Amazonian regional society—and vice-versa. Hence, we consider *social cohesion* as the **crucial system feature** (see also Uzzell et al., 2002; Fonseca et al., 2019). The actors/agents between which cohesion is analyzed can be social sub-groups, such as indigenous peoples (ethnic groups) and traditional populations (extractivists, quilombolas, ribeirinhos, etc.), farmers, miners, youth, and migrants, or political sub-systems such as resource governance or community leadership structures. To approach social cohesion, we orient our research along a definition by Chan et al. (2006) as "a state of affairs concerning

both the vertical and the horizontal interactions among members of society as characterized by a set of attitudes and norms that includes trust, a sense of belonging and the willingness to participate and help, as well as their behavioral manifestations." We advance this definition through its systematic threefold constitution into (1) shared identities, (2) mutual trust, and (3) perceived equalities—which have been widely discussed in the social cohesion literature (Bernard, 1999; Chan et al., 2006; Green et al., 2009; Dickes et al., 2014; Dragolov et al., 2016). These three constituents will be relevant when identifying the qualitative state and potential approach of a TP within the regional social system.

The parameters that control social cohesion are manifold and can be subdivided into parameters of different sub-systems: (1) beliefs, norms, interests, experiences (norms and value system; e.g., Mann, 1970; Holtug, 2017); (2) class, ethnicity, gender, age (social stratification system; e.g., Lockwood, 1999); (3) monetary income, subsistence activities (production system; e.g., Coburn, 2000); (4) pensions, education, insurance, housing, healthcare (social security system; e.g., Berger-Schmitt, 2002); (5) participation, political representation (political system; e.g., Aall and Crocker, 2019); (6) knowledge diffusion, cooperation (knowledge systems; e.g., Green et al., 2009; Radzvilavicius et al., 2021). In the tipping matrix, we combine these parameters into one key **control parameter**: the *reflexive capabilities of the social system to govern change and transformation* (Sen, 1985; Dryzek, 2016)—in other words, *human agency* (Betsill et al., 2020). The control parameter includes a **critical control value**, which we define as the *critical reflexivity of formal and informal institutions*, meaning the dynamic transformation of institutions to overcome path dependencies and to react to the ever-increasing dynamic and unstable conditions of the Anthropocene.

We will understand the tipping of the regional social system as ruptures in these functions of the social system. We hypothesize that the regional society is more resilient to **driving forces**, such as incoherent laws or lifestyle changes when social cohesion is generally high, i.e., more functions of the social system are fulfilled and the society holds capabilities to govern change, transformation (and even crisis). These capabilities control what we defined as determining a cohesive society: mutual trust, shared identities, and perceived equality. Human agency is crucial for designing the adaptive capacities of the social system and depends on the critical reflexivity of formal and informal institutions to govern change and transformation to ensure the maintenance or creation of functions of the social system. Formal and informal institutions and governance structures are how people and societies organize themselves and their interactions with nature at different scales. They are the underlying steering elements of change and influence all aspects of relationships between people and the environment. Their effect can be positive or negative, either in absolute terms or context-dependent. Thus, we conceptualize that a social TP is crossed after society experiences a qualitative change in the region's social fabric, e.g., through norms and value changes that reduce reflexivity and social learning within social groups or the crossing of critical reflexivity (meaning the escape of path dependencies) within formal and informal institutions. An additional layer of complexity is added through potentially catalytic drivers such as the social-economic effects of climate change and lately the COVID-19 pandemic (Froese et al., 2022b).

Within the regional social system, **stabilizing and self-amplifying feedbacks** are manifold and often strongly connected to the economic and environmental system. In addition, due to the volatile and highly context-specific nature of the regional social system, we include normative assumptions to determine a potentially stable state of the system and respective **stabilizing feedback mechanisms** that alter or stabilize this state of the social tipping element. For the creation of the human agency and the strengthening of reflexive capabilities, institutional learning (social and political) is crucial. Hence, the major **self-amplifying feedback mechanism** we consider in Table 1 is the interruption of institutional learning which may lead to non-adaptive management of changing environmental conditions which again implicates potential path dependencies and a lack of knowledge-holding capacities (Dryzek, 2016; Pickering, 2019). Other feedback loops, that contribute to the amplification of this major loop are manifold and only some examples can be mentioned here: (1) normalization of non-adherence and group pressure may lead to inactivity and fear (victim) or unavailability of an independent body to report crimes which again may lead to increasing impunity and less fear (perpetrator) of being reported which may again lead to increasing non-adherence (Schönenberg, 2002); (2) marginalization due to inaccessibility of public policies may lead to repeated intergenerational marginalization (spiral of poverty) (Bradshaw, 2007); (3) unemployment or reduction of income may lead to exploration of alternative income sources and shifts in lifestyles and related norms and values (Hoelle, 2017); (4) nepotism and the co-optation of power structures may lead to one-sided representation, or even state capture that may support further nepotism and increasing unequal access to resources (Damonte, 2016); (5) frustration with current public system may lead to poor voting participation and consequent poor representation of interests which may lead to further frustration; (6) shifting control over democratic spaces may affect the agency of community organizations and further shift the control over democratic spaces (Carretero, 2008).

3.1.2.4. The regional climate system

The fourth **tipping element**, that we consider in our tipping matrix, is the *regional climate system*. It is highly dynamic with strong self-amplifying feedback mechanisms (Staal et al., 2020). The climate is a principal driver of environmental processes affecting the soil ecosystem TE, the household livelihood TE, and the regional society TE. In turn, particularly the regional climate is a process response system affected by regional environmental and societal changes such as agricultural expansion and intensification or infrastructure development (settlements, roads), which drive deforestation and fragmentation of natural ecosystems (LUCC). Regional LUCC drives regional spatial variations in thermally driven turbulent mixing, deep convection, and related cloud and precipitation formation (Rieck et al., 2014). Detailed systematic analyses of the influence of surface features and processes on the local hydrological cycle still suffer from lacking observational data (Böhner et al., 2020). However, the tight coupling between surface heterogeneities (i.e., human-made surfaces), moist convection, and related atmospheric circulations is confirmed by simulations explicitly resolving local scale surface processes and moist convection (Rieck, 2015). In this regard, we argue that diverse (i.e.,

species and structure-rich) evergreen rainforest land cover types and their high primary production and evapotranspiration rates contribute greater to water recycling, i.e., cloud and precipitation formation than less diverse land cover types such as cropland, pasture or urban areas with their lower evapotranspiration rates.

In our matrix, we assume *moist convection* to be an integral **crucial system feature** of the regional climate system, not only controlled by the extent of forest cover but likewise by the pattern and size of the forest and non-forested patches (**control parameter**). In accordance with our tipping matrix, the *ratio and shape of forested and non-forested areas* is considered as **critical control value**. We identify LUCC as **driving force** that impact our control parameter. Given that LUCC and especially deforestation alter the surface energy and moisture fluxes this will have significant consequences for the diurnal circle of moist convection (D'Almeida et al., 2007). Ongoing LUCC and respective forest cover loss beyond the critical control value result in reduced moist convection (i.e., reduced convective rain rates), prolonged dry spells and increased droughts. It ultimately provokes **internal positive self-amplifying feedback mechanism** due to an increase in the Bowen Ratio (i.e., the ratio of sensible heat to latent heat transport from the ground to the atmosphere), further reducing moist convection. This feedback may cause a decline in primary production as well as a response e.g., in the composition, structure and diversity of forest systems, which again lead to less evapotranspiration, cloud and precipitation formation (Leite-Filho et al., 2021). The **indicator used to quantify qualitative change** is the quantity and patchiness of forest cover and LUCC activities.

3.2. Cross-impact matrix

To analytically describe the multiple interactions between our four TE, we use a systematic approach (Table 2) that illustrates cross-linkages. A depiction of the Table 2 is shown in Figure 2.

Table 2 can be read in two directions: (1) row-wise, where each row describes how changes in the TE (row) influence each key TE functioning (column), and (2) column-wise, where each column indicates how the functioning of the TE (column) is influenced by changes in each TE (row).

To illustrate the functioning within and across sub-systems, we select one (among many) potential tipping pathways in the Southwestern Amazon. In the following, we illustrate what a potential tipping cascade might look like. For simplicity we assume a two-phase like cascade dynamic emerging from linear unidirectional couplings of pairs of TE (i.e., from A to B, from B to C, and from C to D, see Figure 2). That is, only after one TE tips, will the second TE tip (Klose et al., 2021). However, other dynamics, such as the domino cascade and the joint cascade could occur (Klose et al., 2021). Moreover, we recognize that multiple tipping cascade dynamics could simultaneously emerge from linear and non-linear bidirectional coupling of pairs of the TE.

As depicted in Table 1, we consider land use and land cover change as the starting driving force affecting the soil ecosystem TE (A) and triggering the tipping cascade. In particular, we assume such change as an outcome of the livelihood strategies of local

households (e.g., forest conversion for agricultural expansion and increasing cattle herd size, logging, roads, and mining). Thus, such strategies lead to conversion of forests in order for the household to provide livelihood. Consequently, land use and land cover change may result in a reduction in functional diversity and redundancy above and belowground leading to PSFM destabilization and reduction in primary production. This can be aggravated when erosion comes into play, which may lead to the creation of bare soil elements in the landscape through certain land uses causing the TE soil to tip. A tipping soil system affects in turn the livelihood system (B) because the levels of production are constrained due to a lower primary productivity. Specifically, the reduced levels of production imply less income for the household, forcing it to adjust its livelihood strategy. Households can no longer reinvest in the same livelihood strategy and expand then their agricultural lands further in order to compensate for the reduced level of income in a feedback loop mechanism: less primary productivity leads to more forest clearing, which leads to less primary productivity and less income, which again leads to more forest clearing. At some point along this path, forest conversion will exceed the legal limits set by environmental laws. That is, households would have to make the decision to deforest more than allowed by the local laws and risk the chance of being caught and sanctioned. If the risk is taken, the livelihood strategy of the household changes to one that could no longer be considered legal and the household livelihood system (B) has also tipped. What follows is the alteration of norms, values, interests and traditions of the households and communities affected. The outcome could be seen as the stable income from cattle raising or monocultural crops confirming people's decision of lifestyle change. Also, such economic transformations lead to out- and in-migration, processes that further change the social system by changing lifestyle, culture and governance. In this sense the social system (C) has also tipped. At the aggregated level, that is, at the social TE, such changes impact household's land use decisions back, amplifying the pattern of land use change (e.g., deforestation). Total increases as well as the spatial configuration of forest cover loss affect vegetation characteristics, evapotranspiration and moist convection, causing the tipping of the regional climate system (D). Reduced moist convection transforms the evergreen tropical rainforest into another (natural) vegetation type showing less diversity and/or structure causing further reductions in evapotranspiration and moist convection respectively. It further reduces precipitation and primary production on agricultural land.

As such, Table 2 provides an entry point for analysis on cascading tipping processes in the region's SES. We apply the term tipping cascade (Klose et al., 2021) to describe the interdependencies between the TE, i.e., that the stable state in one TE favors stability in the other TE. In contrast, the tipping of one TE may destabilize the crucial system feature of another TE and trigger its tipping once a threshold of the respective critical control values has passed. We assume that the direction and linkages in the tipping cascade are neither static nor linear. Instead, the tipping cascade may follow different multidimensional pathways, depending on the history and initial state of the TEs and the source(s) and strength(s) of the initial disturbance [driving force(s)] that causes stress to the TEs. Following this argumentation, the tipping of one TE may finally lead to the tipping of the entire regional's SES.
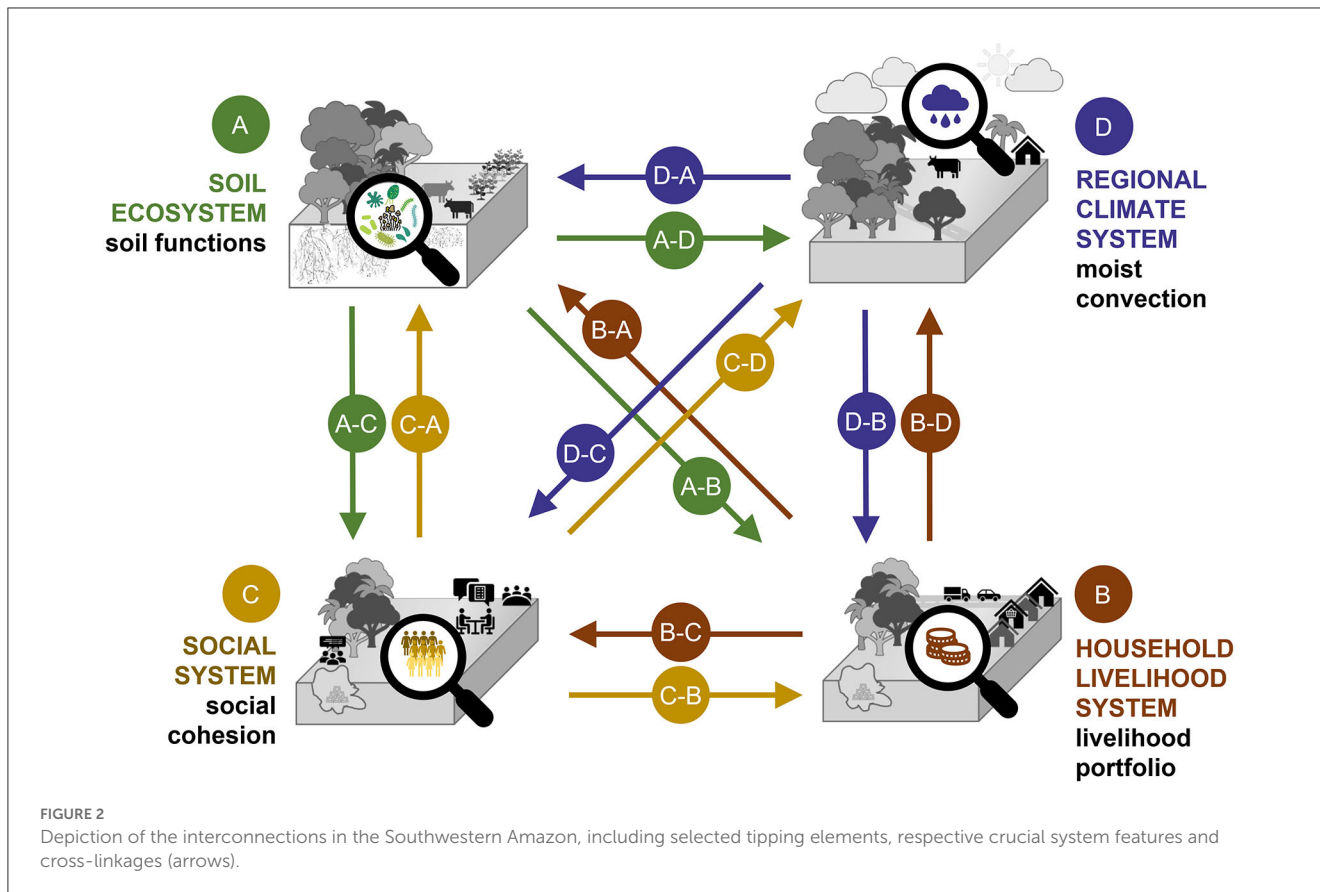
TABLE 2 Cross-impact matrix indicating the multiple interactions across tipping elements [bold: crucial system feature and control parameter (from Table 1), *italic*: linkages to other TEs].

		How TE (column) is affected			
		Soil Ecosystem (A)	Household Livelihood System (B)	Social System (C)	Regional Climate System (D)
The effect of TE (row)	Soil Ecosystem (A)		Changes in the quantity and quality of the *soil functions* lead to **changes in primary productivity in the agricultural and environmental sectors. The profitability of the current livelihood portfolio** is then affected, as shown by its benefit-cost ratio. Net benefits from the current livelihood strategy are reduced/increased and households might consider switching to new strategies. Context-specific alternative strategies could include less sustainable or illegal activities. (A-B)	Changes in *soil functions* may lead to decreasing/increasing buffering capacities for contaminants (e.g. mercury from artisanal gold mining) and consequently impact **people's health and well-being.** Changes in the access to specific places and their respective *materials of healthy soil* may lead to a loss of **knowledge, traditions,** and **identity.** These changes may impact household decisions regarding their *livelihood strategies* and traditional medicinal practices. Changes in *soil functions* and related productivity may lead to food insecurity and potential riots, if not buffered by the government. (A-C)	Change in *soil functions* affects primary production on agricultural and natural land with respective impacts on evapotranspiration rates and **moist convection** processes (without LUCC). However, strong changes in soil functioning may lead to **LUCC** and modified vegetation characteristics (e.g. diversity and structure of plant composition), which may strongly impact evapotranspiration and **moist convection.** (A-D)
	Household Livelihood System (B)	Changes in the *livelihood strategy* leading to LUCC drive change in *primary productivity.* LUCC associated with **reduced aboveground functional diversity and redundancy** will impact the **belowground diversity and redundancy,** thereby destabilizing the plant-soil feedback mechanism (PSFM). (B-A)		Changes in the *profitability of the current livelihood portfolio* may lead to the exploration of alternative income sources (e.g., cattle) and thus alter **norms, values, interests, and traditions** of the respective people/community. If a certain threshold in *profitability* is exceeded, people may migrate. (B-C)	Changes in the *livelihood strategy* can directly drive **LUCC,** i.e. when land-based ecosystem services become utilized (e.g. for improving the *benefit-cost ratio* of the *household livelihood portfolio*). Respective changes in primary production and vegetation characteristics (e.g., diversity, structure, and biomass), impact evapotranspiration rates and **moist convection** processes. (B-D)

(Continued)

TABLE 2 (Continued)

		How TE (column) is affected			
		Soil Ecosystem (A)	Household Livelihood System (B)	Social System (C)	Regional Climate System (D)
The effect of TE (row)	Social System (C)	Changes in *lifestyle and governance* may lead to an increase/decrease in land degradation through deforestation, agricultural practices, mining, etc. (economic activities) affecting **soil functions by reducing belowground/ aboveground functional diversity and redundancy**, thereby destabilizing the plant-soil feedback mechanism (PSFM). Protection through public policies (*establishment of protected areas*) would favor the conservation of **soil functions by maintaining belowground/ aboveground functional diversity and redundancy.** **C-A**	Changes in *land use policies and levels of corruption and crime (i.e. human agency)* may lead to **less/more agricultural, forestry, and environmental profitability**. The profitability of the current livelihood portfolio is then affected as the benefit-cost ratio shows. For example, stronger law enforcement against illegal deforestation in the form of applied fines, will reduce the production of agricultural crops and income. Net benefits from the current livelihood strategy are reduced and households might consider switching to less sustainable or illegal activities. Impacts on *people's health and well-being* may impact household decisions with regard to their livelihood strategies. **C-B**		Changes in *lifestyle* (e.g. perception of natural habitats) and *governance* (e.g. law enforcement for environmental protection) impact decisions on land use activities (non-economically driven, e.g. on the management of protected areas). They can drive **LUCC** in the total amount as well as in spatial patterns with respective impacts on vegetation characteristics, evapotranspiration, and **moist convection**. **C-D**
	Regional Climate System (D)	*LUCC* and *moist convection* affect **soil functions** by **reducing below/above-ground functional diversity and redundancy**, thereby destabilizing the plant-soil feedback mechanism (PSFM). **D-A**	Changes in regional climate patterns such as the duration of the dry season or precipitation levels (*moist convection*) through storms, heat damages or the shift in the production window**.** The profitability of the current livelihood portfolio is then affected by changes in its **benefit-cost ratio**. For example, by increases in fertilizers demand or new seeds resistant to drier conditions. If the new costs exceed the current benefits, households will need to adapt. **D-B**	Change in regional climate (e.g. *moist convection)* and *LUCC* may lead to a change in lifestyle and governance (stop deforestation/creation of new protected areas) *Potential for formation of new (informal) institutions* (e.g. youth groups, NGO coalitions). Changing climatic conditions, in particular extreme events, may lead to civil protests for more government support / more governmental climate action. **D-C**	

FIGURE 2
Depiction of the interconnections in the Southwestern Amazon, including selected tipping elements, respective crucial system features and cross-linkages (arrows).

3.3. Application, limitations, and outlook

Our analytical framework qualitatively describes relevant variables, features and interconnections within a regional SES in a common language applied across disciplinary boundaries. In this respect, it can guide monitoring programs or supplementing interdisciplinary empiric analysis on concrete causal-consequences and respective quantitative relationships. The framework itself does not provide empirical data and the potential tipping cascade is described as a hypothetical cascade. This means, that the interactions and pathways we describe are only some out of many more interconnections to be described. Hence, the framework can only inform decision-makers about the complexity of the system while specific policy recommendations cannot be derived from the analytical framework. However, a supplementing empirical analysis along the analytical framework would allow concrete decision making in the light of tipping cascades. Hence, the provided framework can provide further information to the indication of early warning indicators (Lenton, 2011). While the framework is limited in its complete depiction of reality, we believe that the simplification we take is necessary to cover the various different sub-systems in one framework. This means that we had to sacrifice detailed description of internal processes within each TE in order to focus on the interconnections between the TEs. Nevertheless, the analytical framework bears the potential to be adaptable and transferable to other regional tropical SES and is therefore particularly relevant for interdisciplinary research approaches.

4. Conclusion

This study provides an analytical framework to identify entry points to potential tipping cascades, via (1) the application of a global tipping points (TP) concept to a regional tropical SES (tipping matrix), and (2) the systematic assessment of interactions and feedbacks within it (cross-impact matrix). In this regard, the analytical framework supports interdisciplinary, cross scale research (of relevant processes within/between sub-systems) on tipping dynamics. Along the example of the Southwestern Amazon we have identified the key underlying sub-systems (TE) and their interlinkages: the soil ecosystem, the household livelihood system, the regional social system and the regional climate system. The example from the Southwestern Amazon shows the analytical potential of our proposed framework and advances the understanding of the regional SES by identifying core processes and functioning of each TE. The identified cross-linkages between the TEs are considered to be a first step to the identification of potential tipping cascades. For a tipping cascade to be prevalent, the crossing of a TP in one TE leads to critical changes in another TE. Such dynamics are increasingly covered by the literature, both in life-sustaining and detrimental directions (Lenton, 2020; Klose et al., 2021; Franzke et al., 2022). The joint analysis of interactions and potential cascading TPs as proposed through the analytical framework, promotes a better understanding of human-nature interactions and critical linkages that may serve to indicate early warning indicators for cascading

tipping dynamics. Additionally, the analytical framework can be applied for monitoring or intervention purposes or information for policy makers to better understand interconnections that are relevant to promote resilient SES.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Author contributions

RF, AA, RG, and BS contributed equally to the conceptualization, further elaboration of the initial idea of the manuscript and which was conceived by HJ, JBo, JBö, OF, GG, MH, RScha, JS, and RSchö. RF led the writing process and the organization and communication among all co-authors. AA, RG, BS, SK, JBö, DB, JBo, FB, DC-C, ED, DF, OF, GG, MH, SH, MJ, CJ, EL, KM, CP, RScha, SR, JS, FS, RSchö, GS, CV, VV, MV, and HJ contributed on the writing and editing and literature curation on every version of the manuscript. All authors contributed critically to the drafts and gave final approval for publication.

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Conflict of interest

GS was employed by EcosConsult.

The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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