Interactive visual syntheses for social-ecological systems understanding

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Abstract

Many social-ecological systems are in an unsustainable state. Bringing together disjunct published findings on complex interactions in social-ecological systems may enable the identification of leverage points for transformations towards sustainability. However, such interdisciplinary synthesis studies on specific regional social-ecological systems remain rare. Here, we pair a review of systematically identified studies with a cross-impact analysis to create an interactive visual social-ecological systems synthesis on conflicts and synergies between land use, biodiversity conservation, and human wellbeing in north-eastern Madagascar. The interactive visual synthesis (https://visualsynthesis.wyssacademy.org) depicts an archetypical regional landscape with 22 factors comprising physical landscape elements, ecosystem services, wellbeing, human activities, and telecouplings. To understand the connections between these factors, we assess directional causal links based on literature sources. The visual synthesis shows that research has so far focused on links between land use and biodiversity while links to human wellbeing were studied more seldomly. We then identify chains and cycles that emerge from the links between factors and rate them based on their plausibility and relevance. All eight top-rated chains and cycles relate to subsistence and commercial agriculture, revealing promising leverage points at which interventions could improve outcomes for biodiversity and wellbeing. In sum, we show how interactive visual syntheses can be a useful way to make disjunct published findings on regional social-ecological systems more accessible, to find research gaps, and to identify leverage points for sustainability transformations.

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Research synthesis, land use, biodiversity conservation, human wellbeing, Madagascar

Code & Data availability
All coded links are available as Table S1, all studies supporting links are listed in Table S2, and all identified for all chains and cycles are presented in Table S3 in the Supplementary Material. The interactive visual synthesis is available at www.visualsynthesis.wyssacademy.org. The code of the visual synthesis is available at https://github.com/davidpham87/visual-synthesis.

1. Introduction

In the face of interlinked social, ecological, and climate crises (IPBES & IPCC, 2021), improving the accessibility of policy-relevant findings in land system science becomes ever more important. Because of the steady increase in published research combined with access barriers (Rafidimanantsoa et al., 2018; Schutter & Hicks, 2020), synthesis of research findings is crucial to advance science and policy. However, much synthesis research is rather disciplinary. For example, meta-analyses tend to focus on biodiversity and biogeochemical cycles across a multitude of studies from various places, while reviews on socioeconomic drivers and consequences are rare (van Vliet et al., 2016) and usually not focused on specific social-ecological systems (Figure 1).

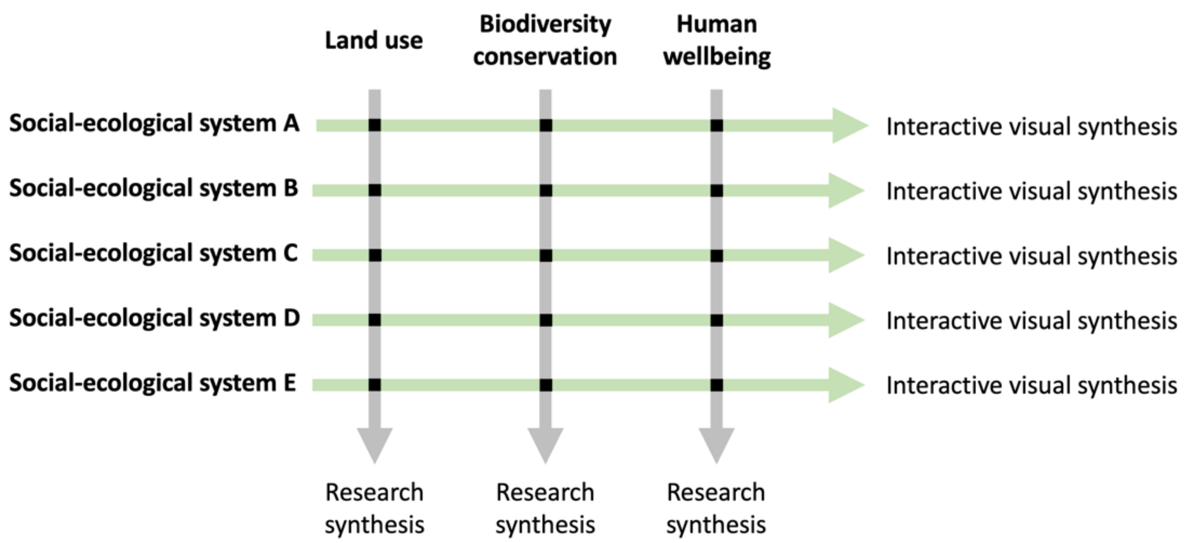


Figure 1: Overview of various forms of research synthesis. Research syntheses on one topic across social-ecological systems (vertical) are common, whereas syntheses that cut across topics within social-ecological systems (horizontal) are rare.

We argue that synthesis research would be strengthened through an extension to specific social-ecological systems, following recent calls (Balvanera et al., 2017; Ladouceur et al., 2022; Magliocca et al., 2018). However, one reason for the paucity of interdisciplinary social-ecological systems syntheses may be methodological challenges that arise when bringing together disciplinary knowledge on multiple aspects of social-ecological systems. Meta-analyses require a focus on few comparable variables, reviews covering multiple systems may miss regionally important factors, and suggested synthesis approaches may be limited to few aspects of social-ecological systems (van Vliet et al., 2016). Therefore, innovative synthesis approaches that account for the cross-scale complexity of social-ecological systems are needed (Balvanera et al., 2017). Examples for such approaches are archetype analyses (Oberlack et al., 2019), that distil patterns from complex heterogeneous cases (Martin et al., 2023), social-ecological systems modelling of anticipated causal relationships between different system components (Schlüter et al., 2012), and further systems mapping approaches that combine qualitative and quantitative data with insights from participatory processes (Barbrook-Johnson & Penn, 2022).

Here, we develop an innovative approach that tries to overcome some of these challenges. Our cross-impact analysis approach (Gordon & Hayward, 1968; Jodlbauer et al., 2022) builds on the identification of factors within the social-ecological system of interest, that are then crossed in a matrix to identify links between them. While such approaches typically rely on expert judgment (Messerli, 2000; Weitz et al., 2018), we use published studies identified through a systematic review to identify the factors and their links. This allows us to identify previously published relevant factors in the complex social-ecological system and to account for cross-scale effects (i.e., telecoupling). However, the approach creates challenges in terms of inclusion criteria (Barbrook-Johnson & Penn, 2022) and risks replicating biases present in the literature (more on this in the discussion). From the cross-impact analysis, we then build an interactive visual social-ecological systems synthesis where factors and links can be explored interactively in an online interface to enhance the accessibility of knowledge. Additionally, we analyse the matrix data to generate insights on research gaps and social-ecological systems dynamics to ultimately identify leverage points for sustainability transformations.

Our approach thus allows for an integrative analysis of a social-ecological system, providing literature-based insights into challenging trade-offs and promising synergies that are often impossible to capture in other types of research syntheses focused on a single topic across multiple social-ecological systems (Figure 1). It also differs from other approaches in synthesizing heterogeneous, often qualitative, information from published literature that can typically not be integrated in more quantitative models.

We apply this approach to the nexus between land use, biodiversity conservation, and human wellbeing, which we argue represents an inherent and fundamental trade-off underlying many social-ecological systems (DeFries et al., 2004; Fanning & O'Neill, 2019; Kellner, 2023; O'Neill et al., 2018). In this context, we define human wellbeing as the combination of material wellbeing, quality of life, and relational wellbeing (Hicks et al., 2016). In this way, multiple aspects of human wellbeing are directly related to biodiversity and the functioning of ecosystems (Haines-Young & Potschin, 2010; Isbell et al., 2017), as well as to land use (Foley, 2005). This is especially the case in rural areas of the Global South where people are more directly dependent on nature for their livelihoods (Fedele et al., 2021).

Geographically, we focus on the regional social-ecological land system of north-eastern Madagascar, a biodiversity hotspot, where extremely high levels of endemism meet with severe threats to the forest hosting this biological wealth (Myers et al., 2000). We restrict the research to the tropical humid southern part of the SAVA region (Area: 25'518 km^2; population: 1'123'013; population density: 44/km^2) as well as the Analanjirofo region (Area: 21'930 km^2; population: 1'152'345; population density: 53/km^2), since these areas have comparable climate regimes and land systems (Antonelli et al., 2022). The area is home to people with strong dependencies on nature (Fedele et al., 2021; Llopis et al., 2020; Zaehringer et al., 2017). Here, ongoing forest conversion to agriculture (Llopis et al., 2019; Zaehringer et al., 2016) threatens endemic biodiversity and important regulating ecosystem services (Llopis et al., 2021; Martin et al., 2022). However, shifting and paddy rice production are key to fulfil subsistence needs (Andriamparany et al., 2021), while expanding vanilla and clove agroforests are important for commercial agriculture (Andriatsitohaina et al., 2020; Martin et al., 2022).

Over the last eight years, two large international transdisciplinary research projects (*Managing Telecoupled Landscapes* and *Diversity Turn in Land Use Science*) have strongly advanced our knowledge on this land system, representing an opportunity for social-ecological systems synthesis research. We believe that this study will be useful for scientists and scientifically trained conservation and development professionals who want to develop an understanding of the social-ecological system in north-eastern Madagascar, to identify research and evidence gaps, and to inspire the co-design of interventions at identified leverage points which may improve outcomes for people and nature.

2. Methods

To synthesize place-based research on conflicts and synergies between land use, biodiversity conservation, and human wellbeing in north-eastern Madagascar, we chose a cross-impact analysis approach (Jodlbauer et al., 2022). This allowed us to synthesize published research as causal directional links between key factors in this social-ecological system. We operationalised this through six steps (Figure 2): 1) systematic study identification; 2) choice, definition, and artistic representation of factors; 3) establishment of links between factors based on literature review; 4) implementation of the interactive visual social-ecological system synthesis; 5) calculation of interconnectedness scores and activity ratios; and 6) analysis and rating of chains and cycles. The remainder of this methods section is organized according to these steps.

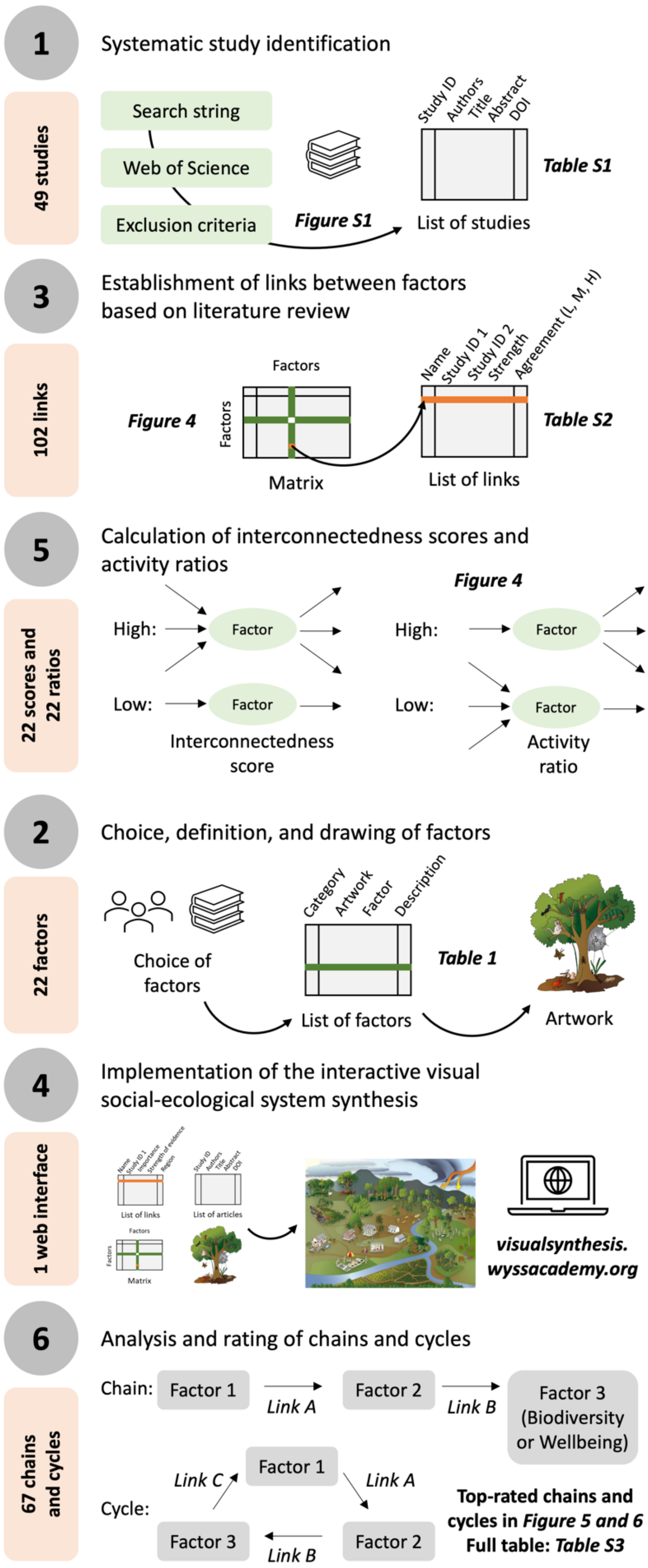


Figure 2: Six-step workflow applied for the interactive visual synthesis.

2.1 Systematic study identification

We searched the databases covered by Web of Science (Core collection, subscription of the University of Bern) on 22.11.2021 without restricting the type of research item. Our search string filtered out studies focussing on the provinces (Toamasina and Antsiranana), regions (SAVA and Analanjirofo), and geographic area (north-eastern Madagascar) of interest, as well as the synthesis research topic:

> *(ALL=(sava OR analanjirofo OR north-eastern madagascar OR northeastern madagascar OR toamasina province OR antsiranana province) AND ALL=(land use OR conservation OR ecology OR land system OR deforestation OR agroforest* OR protected area* OR national park OR ecosystem services OR human wellbeing OR sustainable development).*

Since we were interested in synthesizing the current state of the social-ecological system, we limited the search to research published in the last ten years (21.11.2011 – 22.11.2021). This resulted in 481 studies. Co-author LG then screened all 481 items at the abstract level. This led to the exclusion of 436 studies for various reasons, most commonly because the study did not focus on north-eastern Madagascar (see Figure S1 for an overview of the reasons for exclusion). LG and DAM then conducted a full-text screening of the remaining 45 studies. This led to the exclusion of another four studies that were irrelevant for conflicts and synergies between land-use, biodiversity conservation, and human wellbeing: one did not focus on the region, one exclusively focused on health, one purely focused on ecology, and one focused on a single species (Figure S1). To the remaining 41 studies, we then added eight that were not captured by the literature search, seven of which originated from the *Diversity Turn in Land Use Science* and *Managing Telecoupled Landscapes* projects. Overall, this led to a list of 49 studies (Table S1).

2.2 Choice, definition, and drawing of factors

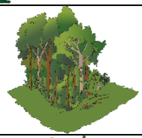
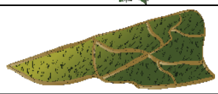
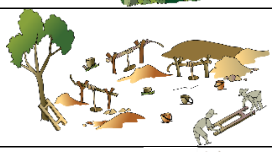
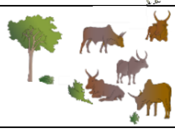
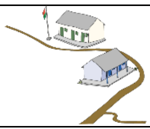
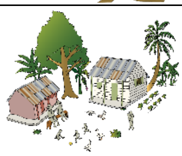
We chose factors in a two-tier process using the in-depth context knowledge of co-authors (RNA, AH, DAM, AANAR, MPT, and JGZ) that originated from many months spent in the study area. The process had the goal to adequately cover the topics of our research topic (conflicts and synergies between land use, biodiversity conservation, and human wellbeing) adapted to the regional context in the social-ecological land system of north-eastern Madagascar. Through a discussion among co-authors, we settled on an initial list of 21 factors. We chose the number of factors as a compromise between system representation and feasibility (more on this trade-off in the discussion). We then used this list to identify links (see 2.3 below). In that process, we realised that one factor did not match well with the systematically identified literature and renamed it (Off-land income → Non-agricultural income). Additionally, we found that one factor (Infrastructure) was missing. This process led to a final list of 22 factors (Table 1) that we classified into five categories: physical landscape elements, wellbeing, ecosystem services, activities, and telecoupled drivers. We then collaborated with a team of artists who depicted each factor graphically (Table 1).

2.3 Establishment of links between factors based on literature review

Our goal was to establish well-supported links between 22 factors based on the 49 systematically identified studies (Figure 2).

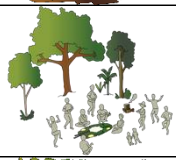
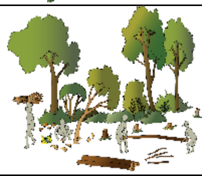
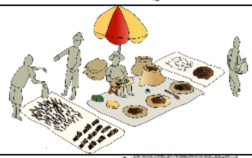
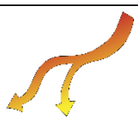
First, DAM went one-by-one through all 484 possible causal directional link combinations that exist between factors in a cross-impact matrix in which each factor is represented both in a row and a column and looked for causal directional links between each factor-pair, always starting from the factor in the row and noted the underlying source(s) for each link (i.e., Study ID; Table S2). Each link needed to be supported by at least one of the 49 articles. If more than one study supported a link, we noted multiple sources and adapted the link summary in a way that reflected findings from both sources (e.g., if the first source referred to firewood and the second one to charcoal, we replaced firewood with wood fuel, resulting in a broader link covering both terms). We also allowed two factors to be connected by more than one link in the same or opposite direction if an adaptation of the link summary was not possible due to inherent contradictions or complementary topics across multiple sources.

Table 1: Description of 22 identified factors across five categories covering conflicts and synergies between land use, biodiversity conservation, and human wellbeing in the social-ecological land system of north-eastern Madagascar.

Category	Artwork	Factor	Description
Physical landscape elements		Unprotected old-growth forest	Primary forest with no or only limited use by people (such as selective logging or hunting) without formal area-based protection.
		Protected old-growth forest	Primary forest with no or only limited use by people (such as selective logging or hunting) with formal protection status as protected area or national park.
		Forest fragment	Fragmented primary forest intensively used by people (such as logging, charcoal, hunting) without formal protection.
		Forest-derived vanilla agroforest	Agroforest focused on vanilla production, established directly inside forest (fragments); native shade trees remain. Extensive system with no fertilizer or pesticide use.
		Shifting cultivation	Land system regionally called *tavy* consisting of repeated slashing and burning of vegetation, ensued by crop cultivation (predominantly rice), and a fallow period.
		Fallow-derived vanilla agroforest	Agroforest focused on vanilla production, established on historically forested but open fallow land. Extensive system with no fertilizer or pesticide use.
		Irrigated rice paddy	Rice paddy field with irrigation.
		Clove-based agroforest	Agroforest focused on clove production, usually established on historically forested but open fallow land.
		Artisanal mines	Small-scale artisanal mining operations for sand, quartz, gold, or gemstones.
		Pasture	Pasture predominantly used to graze cattle (Zebu); sometimes interspersed with clove trees.
		Waterbodies	Rivers, lakes, and wetlands.
		Infrastructure	Health, education, and transport infrastructure.
Wellbeing		Wellbeing	Composite term encompassing mental, physical, emotional, and economic wellbeing.

(*Table continued on next page*)

Table 1 (*continued*)

Category	Artwork	Factor	Description
Ecosystem services		Biodiversity	Diversity of plant and animal species.
		Cultural ecosystem services	Ecosystem services contributing to cultural practices and wellbeing.
		Regulating ecosystem services	Ecosystem services that regulate processes essential to human wellbeing.
		Use of provisioning ecosystem services	Use of provisioning ecosystem services except agricultural yields.
Activities		Commercial agriculture	Agriculture practiced to sell crop produce; predominantly vanilla, clove, and rice.
		Non-agricultural income	Income generated from activities other than agriculture, for example a small shop or transport services.
		Subsistence agriculture	Agriculture practiced to satisfy subsistence needs; predominantly rice.
Telecoupling		Out-of-landscape influences	Telecoupled effects resulting from drivers outside the focal landscape.
		Climate change	Effects from events resulting from or made more frequent by climate change.

Second, we assessed the direction and strength of each causal link, i.e., whether and to what extent the link improved or worsened the state of the factor it was directed to, using a scale from strongly negative (-2) to strongly positive (+2), including negative (-1), no change (0) and positive (+1). After assessing all possible 484 pairs, DAM read all 49 studies again in full to identify overlooked links and to add further empirical evidence from the studies whenever an article substantiated a link but was not yet listed as a supporting source. In total, we described 102 links. For those, we assessed agreements between studies (low, medium, high) in supporting the link and counted the number of studies that supported each link. Additionally, we formulated 23 hypotheses of potential additional causal links not investigated in the literature (Table S2).

Third, we conducted an internal review and validation of the links with co-authors. For this, three co-authors who did not participate in the link identification (AANAR, MPT, & RNA) read through all links and their sources to vote blindly (i.e., without seeing the assessment from the other two) whether they found a link to be logical and well supported or not. Those 13 links that at least one co-author flagged as irrelevant, illogical, or not well supported, were then discussed in an online meeting leading to two new links, the relegation to hypothesis for two links, and the refinement of nine links. In total, this left us with 25 hypotheses and 102 supported links between 22 factors (Table S2).

Fourth, we created a full matrix with all factors to compactly visualise links (Figure 4). This allowed us, from the left to the top, to enter the direction of the links (i.e., positive or negative with the following colour gradient: green for strongly positive; light green for positive; grey for neutral; light violet for negative; and violet for strongly negative), the number of studies supporting them, and the agreement between those studies (low - L, medium - M, high - H). We also added the identified hypotheses including their hypothesised direction.

2.4 Implementation of the interactive visual social-ecological system synthesis

To implement the interactive visual social-ecological system synthesis we paired the artwork for each factor, including a background landscape drawing, with the data on links between factors, and the data on sources supporting each link (Figure 2). For this, we collaborated with an external programmer who built the webapp in Clojure. The webapp is based on a similar online repository (Pham-Truffert et al., 2019) and is open source (see Code & Data availability statement).

2.5 Calculation of interconnectedness scores and activity ratios

The full matrix (Figure 4) then allowed us to calculate an interconnectedness score and an activity ratio (Messerli, 2000). The interconnectedness score referred to the sum of incoming and outgoing links for each factor (see Pham-Truffert et al., 2020). In network analysis terms, this sum (of in-degree and out-degree) represents the *degree centrality* measure and is an intuitive way to assess how central a *node* (factor) is within the network (social-ecological system), i.e., how many *edges* (links) it has with other nodes (Freeman, 2002; Golbeck, 2013). The activity ratio, on the other hand, referred to the ratio between outgoing and incoming links. If above one, a factor is predominantly influencing other factors, i.e., is active (blue in Figure 4); if below one, a factor is predominantly influenced by other factors, i.e., is passive (red in Figure 4).

2.6 Analysis and rating of chains and cycles

To further analyse and visualise the data, we identified chains and cycles. In this context, a chain consisted of at least three factors that were linked to each other through at least two links. A cycle consisted of at least two factors that were linked to each other through at least two links, with the important distinction that all factors linked together in a cycle. Importantly, we only considered chains and cycles that consisted entirely of positive or entirely of negative links. To limit the number of chains that would result, we further only considered chains that consisted entirely of strong causal links (strongly negative or strongly positive) and that ended either with the factor biodiversity or with the factor wellbeing. We chose biodiversity and wellbeing because, first, these were factors that decision makers may want to optimise and, second, these were factors with an activity ratio below one, meaning they were more influenced by other factors than influencing other factors themselves (Figure 4). Put differently, this means they were outcomes rather than leverage points for policy interventions (Messerli, 2000).

To identify complete chains and reinforcing cycles that may represent promising leverage points (Abson et al., 2017; Meadows, 1999), we then rated all chains and cycles according to their plausibility and relevance. For plausibility, 10 co-authors with strong contextual knowledge on the social-ecological land system in north-eastern Madagascar looked at each chain/cycle and assessed the complete chain/cycle according to the following question: “How plausible is it that the complete chain/reinforcing cycle takes place in the landscape?” For relevance, the questions were: “How relevant is this chain to foster or hinder biodiversity or wellbeing in the landscape?” and “How relevant is this reinforcing cycle to foster or hinder biodiversity and wellbeing in the landscape?”, respectively. For both plausibility and relevance, assessors then rated blindly, i.e., without knowing the rating of others, each chain/cycle with -2 (highly implausible/highly irrelevant), -1 (implausible/irrelevant), 0 (neither plausible nor implausible), 1 (plausible/relevant), or 2 (highly plausible/highly relevant). Additionally, assessors had the option to tick “I don’t know” for cases where their knowledge about the social-ecological system did not allow them to decide. Subsequently, we calculated average plausibility and relevance scores for all chains and cycles (Table S3) and visualised the top-rated chains and cycles (top four relevance and plausible, i.e., rated ≥ 1; Figure 5 & 6).

3. Results

We synthesised findings from 49 studies situated in a social-ecological land system in north-eastern Madagascar using an interactive visual synthesis approach. Within the archetypical rural landscape, we identified 22 key factors that illustrate landscape elements, wellbeing, ecosystem services, activities, and telecouplings (Table 1), as well as a total of 102 causal links connecting them – each supported by one or multiple literature sources (Table S2). This approach makes it possible to 1) provide an accessible interactive overview of the complex social-ecological land system; 2) find research gaps, i.e., factor pairs, where no or few literature-supported links exist, despite an actual link; 3) identify plausible and relevant chains and cycles of factors that may represent leverage points for social-ecological systems transformations.

3.1 Interactive visual synthesis

The interactive visual social-ecological systems synthesis for north-eastern Madagascar is accessible at https://visualsynthesis.wyssacademy.org. The visual synthesis is optimised for use on a computer or tablet while smartphone users will encounter limited performance on small screens.

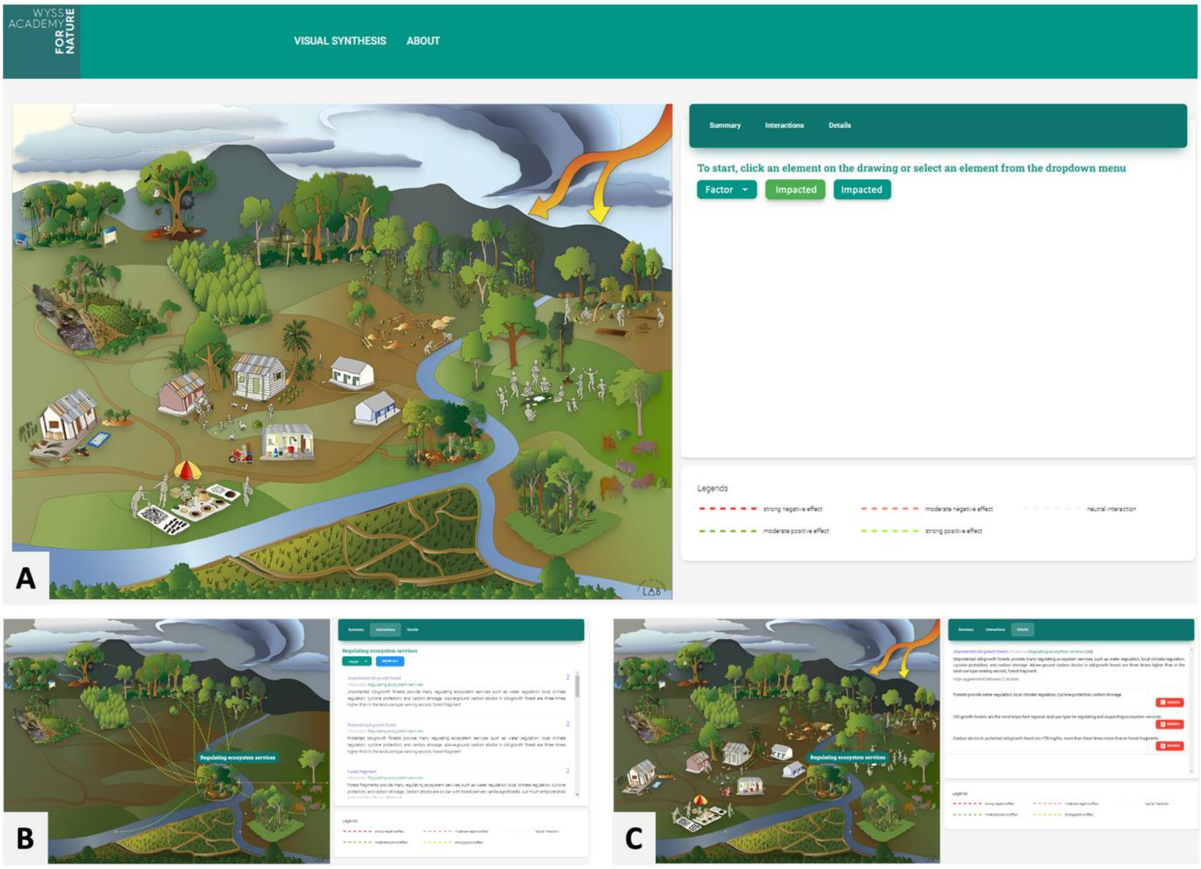


Figure 3: Screenshots of the online interactive visual social-ecological systems synthesis (https://visualsynthesis.wyssacademy.org) on conflicts and synergies between land use, biodiversity, and wellbeing in north-eastern Madagascar. **A**: Upon opening the page, users see the depiction of the archetypical landscape including 22 clickable factors on the left. On the right-hand side, the drop-down menu offers an alternative way of choosing a factor. At the top, users can access an 'About' section that describes the purpose of the visual synthesis in brief and that links to this paper. **B**: By clicking on factors – either in the landscape depiction or in the drop-down menu – users can then access information about the factors as well as about which researched links exist between the focal factor and other factors. **C**: Links can then be clicked on to reveal the full link description and the reviewed studies empirically supporting the link. Each study can be clicked on (red 'Source' icon) to show the studies' title, authors, abstract, and linked DOI.

3.2 Analysis on research gaps and open research questions

The visualization of links across the matrix (Figure 4) shows that factors of the categories 'physical landscape elements' and 'telecouplings' have more outgoing links than incoming links, meaning they are influencing other factors more than they are being influenced by others (Figure 4; highlighted in blue in column 'Ratio outgoing / incoming links'). On the other hand, 'wellbeing', 'ecosystem services', and 'activities' have more incoming links than outgoing links, meaning they are largely influenced by other factors (Figure 4; highlighted in red in column 'Ratio outgoing / incoming links'). Additionally, it becomes clear that links between physical landscape elements and ecosystem services have been studied most completely, both in terms of coverage (number of links) as well as in the number of studies supporting each link. We also find two cases where (hypothesised) links are within the same factor, for example, interactions among components of biodiversity. Hypotheses are most common concerning the outgoing links from artisanal mines, pastures, and waterbodies to other factors and the incoming links from other factors to waterbodies, biodiversity, and non-agricultural income (three or more hypothesised links each).

	Category	Physical landscape elements												WB	Ecosystem services				Activities			Tele-coup-ling		Summary			
Category	Factor	Unprotected old-growth forest	Protected old-growth forest	Forest fragment	Forest-derived vanilla agroforest	Shifting cultivation	Fallow-derived vanilla agroforest	Irrigated rice paddy	Clove-based agroforest	Artisanal mines	Pasture	Waterbodies	Infrastructure	Wellbeing	Biodiversity	Cultural ecosystem services	Regulating ecosystem services	Use of provisioning ES	Commercial agriculture	Non-agricultural income	Subsistence agriculture	Out-of-land influences	Climate change	# of outgoing links	# of hypothesized outgoing links	Sum outgoing + incoming links	Ratio incoming / outgoing links
Physical landscape elements	Unprotected old-growth forest														8H	2H	3H	5M						4	0	8	1.0
	Protected old-growth forest	2H						1H							8H	2M	3H	8H						6	0	10	1.5
	Forest fragment	2H	2H												10H	2H	4H	4H						6	0	9	2.0
	Forest-derived vanilla agroforest	3M	2M	3H											8H	1H	3M	3M	3H		3H			9	0	13	2.3
	Shifting cultivation	5H	6H	5H											7H	3M	1H	2H			3H			8	0	15	1.1
	Fallow-derived vanilla agroforest					3H									8H	1H	2H	2H	2H		3H			7	0	11	1.8
	Irrigated rice paddy					1H						HY			6H	2H	1H	2H	2H		3H			7	1	10	2.3
	Clove-based agroforest					2H									HY	1H	2L	2H	4H		2H			6	1	8	3.0
	Artisanal mines			1H								HY			HY		HY		HY	1H	HY			2	5	3	2.0
	Pasture					1H		HY				HY			HY		1H		2H		1H			4	3	4	NA
	Waterbodies							HY						HY				HY						0	3	0	NA
	Infrastructure													1H				HY	3H	HY	1H			3	2	4	3.0
Wellbeing	Wellbeing																							0	0	7	0.0
Ecosystem services	Biodiversity					1H									2H	HY	1H	2H						4	1	13	0.4
	Cultural ecosystem services																			HY				0	1	8	0.0
	Regulating ecosystem services				**2H**	1H	**2H**	3H	HY			HY		HY									1H	7	3	17	0.7
	Use of provisioning ES													4M	1H	HY		2H		2H				4	1	15	0.4
Activities	Commercial agriculture													**4H**						HY	**2H**	1H		5	1	14	0.6
	Non-agricultural income													1H										1	0	4	0.3
	Subsistence agriculture													4H					**2H**					3	0	13	0.3
Telecoupling	Out-of-landscape influences		5H		3H		3H		4H	1H			1H	1H				2H	1H	1H	1H		HY	11	1	12	11
	Climate change				2H	3L	2H	1H	2H		HY				HY									5	2	6	5.0
Summary	# of incoming links	4	4	3	4	7	4	3	2	1	0	0	1	7	9	8	10	11	9	3	10	1	1	**102**	**25**	**204**	**1.9**
	# of hypothesized incoming links	0	0	0	0	0	0	2	1	0	1	4	0	2	4	2	1	2	1	3	1	0	1	**SUM**			**Ø**

Legend

Dark green	Strong positive link from left to top	L	Low agreement between studies	HY	Hypothesis
Light green	Moderate positive link from left to top	M	Medium agreement between studies	B	Two independent links
Grey	Neutral link or multiple negative and positive links	H	High agreement between studies		
Light purple	Moderate negative link from left to top			Blue gradient	High to low value
Dark purple	Strong negative link from left to top	#	Number of studies	Red gradient	Low to high value ratio below 1

Figure 4: Matrix visualization of all 102 links between 22 factors in the social-ecological land system of north-eastern Madagascar. The visualization includes the direction (colour), strength (colour), number of supporting studies (numbers), and agreement between studies (Low - L, Medium - M, High - H) for each link, as well as 25 hypotheses. On the right, a summary shows the sums of (hypothesised) incoming and outgoing links (interconnectedness score) and the ratio between the two (activity ratio). Note that multiple links exist between the same two factors in five cases (bold). All links are documented and referenced in Table S2.

3.3 Chains and cycles

We found 34 chains of three to four factors that will ultimately impact biodiversity or livelihoods. The chains are restricted in that factors had to be connected through positive links. Additionally, they had to end with one of the two previously chosen outcome factors, biodiversity or wellbeing. However, only one chain ended with biodiversity while 33 ended with wellbeing. The rating reveals an average plausibility of 1.2 (SD 0.5; range -0.2 to 2) and an average relevance of 1.2 (SD 0.5; range 0.4 to 2). See Table S3 for a full list of the 34 identified chains as well as their plausibility and relevance scores.

The top four chains (highest relevance and plausible (≥ 1)) are visualised in Figure 5. Three of the four chains involve the effects of two kinds of vanilla agroforestry and infrastructure on commercial agriculture, which itself is positively linked to wellbeing. The fourth chain goes from waterbodies via irrigated rice paddy to subsistence agriculture, which itself is linked to wellbeing.

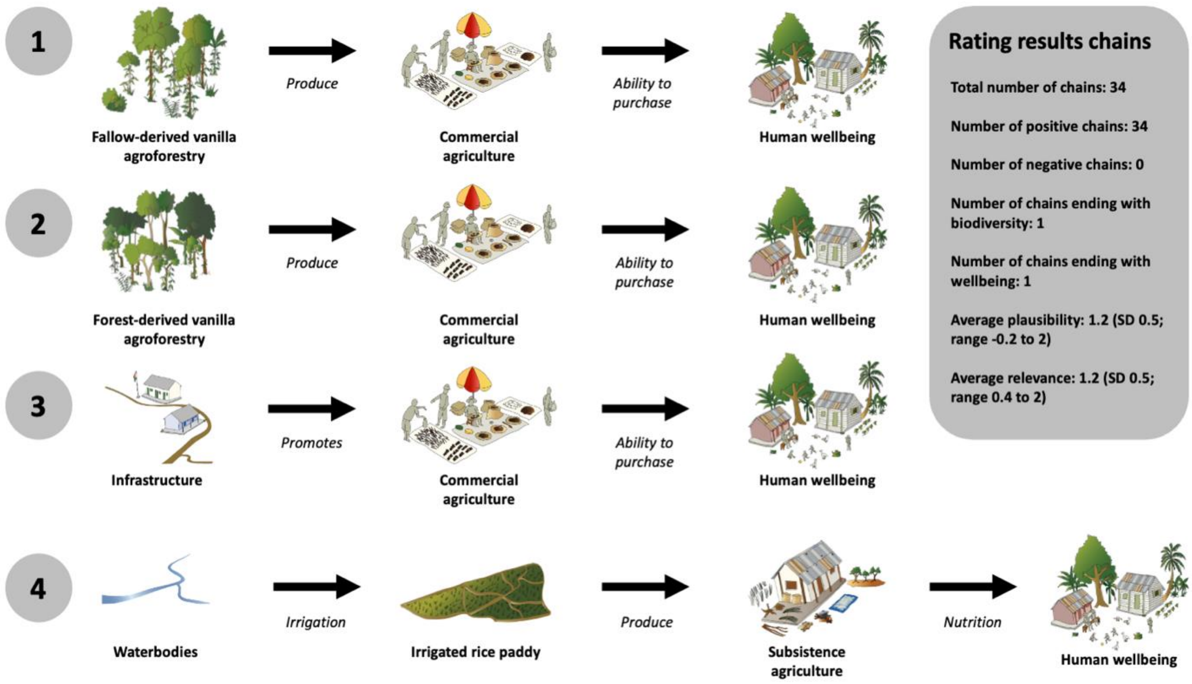


Figure 5: Visualisation of the four top-rated chains identified through cross-impact analysis and summary of chain rating results (grey box).

We found 33 cycles of three to six reinforcing factors. Eleven cycles contain the factor biodiversity, while none contained the factor wellbeing. For 30 cycles, factors are linked through positive links, while three cycles are linked through negative links. The rating reveals an average plausibility of 0.1 (SD 0.6; range -0.7 to 1) and an average relevance of 0.4 (SD 0.4; range -0.2 to 1.2). See Table S3 for a full list of identified cycles, their plausibility, and their relevance.

The top four cycles (highest relevance and plausible (≥ 1)) are visualised in Figure 6. One two-factor cycle relates to time constraints between subsistence and commercial agriculture, where farmers must make choices about where to invest time. Two two-factor cycles describe regulating ecosystem services in two types of vanilla agroforestry. A fourth cycle describes how forest-derived vanilla agroforests support biodiversity, which increases regulating ecosystem services that themselves provide pest control services to vanilla agroforests.

Longer chains and bigger cycles are more likely to be implausible (1.4 average plausibility for 3-factor chains, 1.1 average plausibility for 4-factor chains; 0.6 average plausibility for 2-factor cycle vs. -0.2 average plausibility for 6-factor cycles) and chains are generally much more plausible than cycles (1.2 average plausibility chains vs. 0.1 average plausibility for cycles).

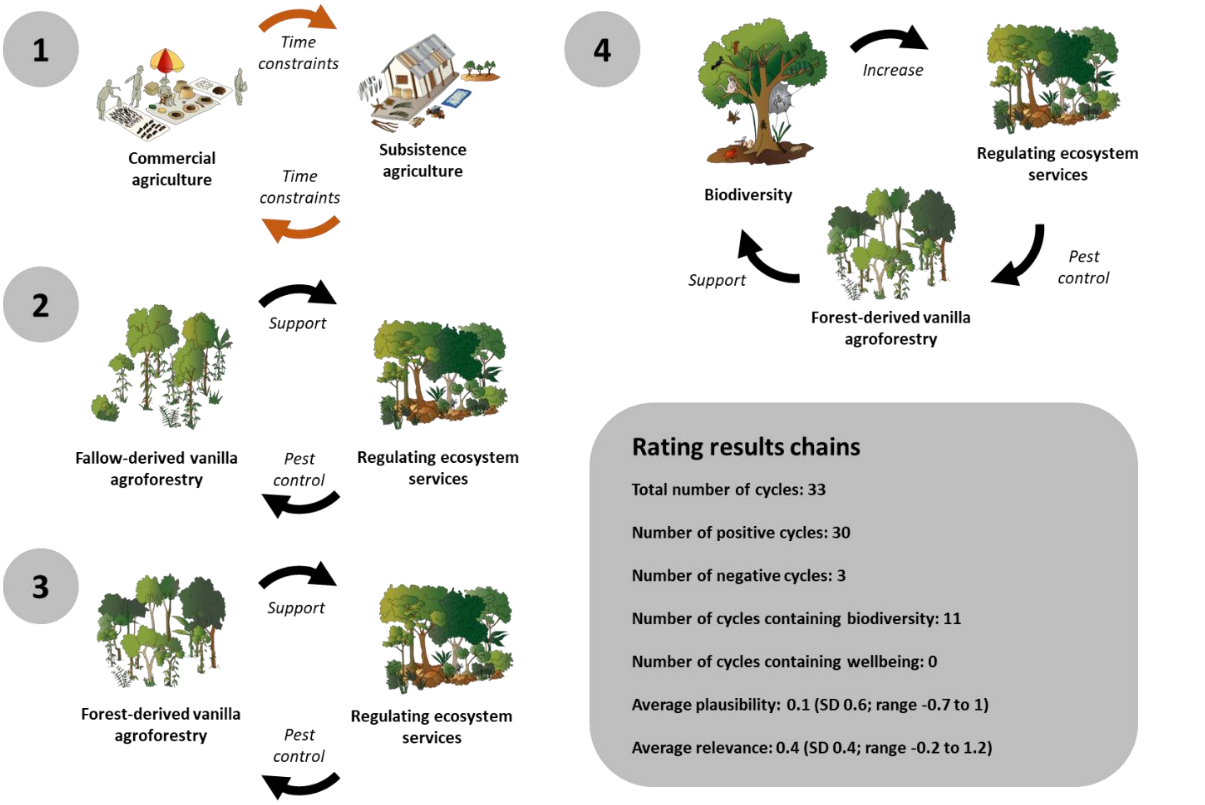


Figure 6: Visualisation of the four top-rated cycles identified through cross-impact analysis and summary of cycle rating results (grey box). Black arrows represent positive links while orange arrows represent negative links.

4. Discussion

We synthesised research on conflicts and synergies between land use, biodiversity conservation, and human wellbeing in north-eastern Madagascar, creating an interactive visual social-ecological systems synthesis. This synthesis has three main contributions: firstly, we provide a way to access research on a specific social-ecological system. Secondly, we link existing research and identify key research gaps in this landscape. Thirdly, we use the synthesis to identify chains and cycles of reinforcing links as leverage points for action aiming at improving outcomes for people and nature.

4.1 Research gaps and open research question on the social-ecological system in north-eastern Madagascar

Our synthesis shows that links between physical landscape elements and ecosystem services have been studied most completely (Figure 4). This is expected, given the focus of a large recent research project on these topics (synthesized in Martin et al., 2022 and Wurz et al., 2022). Links between ecosystem services and wellbeing, on the other hand, have been studied seldomly. This is especially the case for links between cultural ecosystem services and wellbeing. We most commonly highlight hypotheses concerning artisanal mines, pastures, waterbodies, biodiversity, and non-agricultural income (Figure 4) since little research has focused on these factors. Further research gaps exist in those cases where agreement between multiple studies supporting a link is low, for example concerning the link between climate change and shifting cultivation, or where links are only supported by a single study (Figure 4). This illustrates how the social-ecological systems synthesis also represents a chance to identify knowledge gaps and opportunities for future research.

However, this way of identifying research gaps also has its caveats. Foremost it is influenced by the choice of factors – for example, if we would not have chosen artisanal mines as a factor, we would not have identified the lack of research on them as a gap. Similarly, there may be important factors that were absent from the screened literature or that were present but did not make it into the factor list, for example, due to biases in knowledge and interests of the author team. This omission of factors and hence links between them and other factors would also result in a failure to identify research gaps.

4.2 The social-ecological system of north-eastern Madagascar – insights from the visual synthesis

Identifying causal chains within social-ecological systems may advance our understanding of driving forces by connecting proximate and underlying causes of change (Bürgi et al., 2022). It may additionally offer the opportunity to find leverage points where targeted interventions could stir positive change (Abson et al., 2017; Meadows, 1999).

To this end, we have analysed the literature-based links between factors and identified four chains between multiple factors that are plausible and rated as particularly relevant (Figure 5). Three out of the four most relevant chains contain the factor commercial agriculture (Figure 5, chains 1-3). This highlights the central role of agriculture in the focal social-ecological system. It shows how regionally farmed cash crops, mainly vanilla and clove, have contributed to people's income and well-being, particularly during recent high price phases (Llopis et al., 2022). Leverage points aiming at increasing wellbeing through this chain may act on increasing the inclusion of marginalized groups in the vanilla value chain (Blum, 2021) or could act on stabilizing cash crop prices at a fair level (Hänke & Fairtrade International, 2019). However, we identified a second link between commercial agriculture and wellbeing: High cash crop prices are documented to lead to an increase in the costs of living (Zhu & Klein, 2022) and to negative impacts on security (Neimark et al., 2019), showcasing important trade-offs. Thinking more broadly, this chain may also suggest the potential of additional cash crops and associated value chains for diversified income generation (Beillouin et al., 2019).

The fourth identified chain underlines the important role of irrigated rice paddy (Figure 5, chain 4). Irrigation provided by waterbodies enables subsistence rice production which is key for wellbeing (Andriamparany et al., 2021). Leverage points in this chain could aim at supporting efforts to increase the area under irrigation or the reliability of existing irrigation infrastructure in a system of rice intensification (Stoop et al., 2002); an action that is already undertaken regionally (Brimont et al., 2015) and that may increase in importance under climate change. While not explicitly part of this chain, forests may play an important role for river discharge regulation (Llopis et al., 2021), adding forest conservation as an additional leverage point for ensuring the functioning of this relevant chain in the future.

Turning to the four plausible and top-rated cycles between factors (Figure 6, cycle 1), we, first, find a cycle with negative links between subsistence and commercial agriculture. Fluctuating cash crop prices (Llopis et al., 2019), crop theft (Neimark et al., 2019), and regional traditions (Laney & Turner, 2015) create the need and desire for reaching full staple crop (rice) subsistence, despite higher labour productivity in vanilla cash cropping (Martin et al., 2022). Thus, many households must allocate labour resources to both pillars of family livelihoods, creating a direct temporal trade-off between commercial and subsistence agriculture (Messerli, 2004). The cycle shows again the important role of agriculture in the focal land system but does not present obvious leverage points.

Second, we find two two-factor cycles between forest- and fallow-derived vanilla agroforestry and regulating ecosystem services (Figure 6, cycles 2 & 3). Here, vanilla agroforests, where the vanilla crop is growing under the canopy of native or planted shade trees, provide a suite of provisioning ecosystem services, including pest control (Schwab et al., 2021). Leverage points in these cycles could be the establishment or maintenance of diverse vanilla agroforests, which can create win-win situations for biodiversity and yields (Wurz et al., 2022).

Third, we highly rated a three-factor cycle including biodiversity, regulating ecosystem services, and forest-derived vanilla agroforestry (Figure 6, cycle 4). Here, biodiversity increases the regulating ecosystem service pest control, which is at play in forest-derived vanilla agroforestry. Since vanilla agroforestry is a land system with high value for biodiversity (Martin et al., 2022), the cycle closes back to biodiversity. Again, a leverage point in this cycle could be the maintenance of biodiverse forest-derived vanilla agroforests (Wurz et al., 2022).

Overall, we find tight connections between land use, biodiversity conservation, and human wellbeing in north-eastern Madagascar, underlining the interconnected nature of this complex social-ecological system. Many of these broader connections involve ecosystem services that directly benefit people or that support agricultural activities, while links to relational aspects of human wellbeing have rarely been studied or did not result in chains or cycles. This is further illustrated by that all eight top-rated chains and cycles are directly related to agriculture. This is perhaps unsurprising, given that more than 80% of people in rural areas of the region are active in this sector (Hänke et al., 2018).

While the identified chains and cycles may represent the current social-ecological system, the prevalence of agriculture also illustrates a limitation of our approach. Basing the research on available literature, combined with the choice to focus on the current state of the social-ecological system and on factors that are predominantly landscape elements, limited the range of potential leverage points that could be identified. For example, changes in governance are widely recognized as important levers (Messerli et al., 2019), but did not show up in our analysis. Following literature on leverage points and systems transformation (Abson et al., 2017; Kellner, 2023; Meadows, 1999; Morrison et al., 2022), it is precisely such deep leverage points, related to the social structures and institutions that govern a system, and the underlying goals, world views and values of actors, that are the most effective.

Our analysis furthermore does not indicate how interventions that target identified leverage points could be designed and implemented. Potential approaches may focus on actors of change who have particular agency to stir change within the system (Andriamihaja et al., 2021), or on creating so-called "living labs" for co-creating and experimenting with systemic interventions (Enfors-Kautsky et al., 2021; Pathways Network, 2018). In general, it must be clear that the here-applied approach can never provide a full picture of the dynamics of the system and thus can only provide a starting ground for discussing governance changes. Ultimately, these are essential given that the expansion of agriculture threatens highly endemic biodiversity (Martin et al., 2022; Ralimanana et al., 2022) while many farming families struggle to satisfy basic needs off the land they have access to (Andriamparany et al., 2021; Llopis et al., 2022).

4.3 Visual syntheses as a way to advance social-ecological systems research

We see three main contributions of our approach. First, by identifying and synthesizing interdisciplinary studies from one social-ecological land system in a visual and interactive way, we create an accessible open access entry-point for researchers, NGOs, and policy makers to the available scientific literature (https://visualsynthesis.wyssacademy.org). Second, by identifying research gaps we hope to inspire future research (Figure 4). Third, we generate additional insights into the system by distilling out plausible and relevant multi-factor chains and cycles (Figure 5 & 6) on which one can identify leverage points for systems transformation to address social, ecological, and climate crises (see above).

However, we encountered multiple challenges when implementing the study. Some of them could have been avoided in hindsight while others are inherent to the approach. Most prominently, there is a trade-off concerning the number of factors. Indeed, having more factors may increase the precision with which the links can be formulated and may enable covering more system complexity. However, covering many factors poses problems concerning the visualization (crowded interface), the number of possible links to consider (exponentially increasing number of factor pairs), and the overall complexity when conducting the analysis. Here, we suggest limiting future analyses more strictly to a maximum of 20 factors; a goal we exceeded with 22 factors. This represents a classic example of common trade-offs modelling social-ecological complexity (Balvanera et al., 2017; Barbrook-Johnson & Penn, 2022; Schlüter et al., 2012). On top, factors are influenced by the focus of the analysis, here explicitly put on the nexus between land use, biodiversity conservation and human wellbeing, which could be changed to one that incorporates more socio-cultural or governance topics (Messerli, 2000).

Judgement was also necessary when establishing the links between factors. At first, we tried to start from the study side, i.e., reading a paper and then filling links between the 22 factors. However, we realised that links can be easily missed even when reading the paper carefully, so we changed the approach and systematically cycled through all factor pairs, allowing us to check each study for evidence on that link. This may have introduced biases in that studies that were better known to (or even (co-)authored by) the assessor (DAM) may have been overrepresented as evidence supporting links. Furthermore, the process entailed decisions on which studies provide 'enough' evidence for either a moderate or strong link. For example, some studies showed strong support for a link based on statistical data analyses while others only touched on a possible link in the discussion. In the latter cases, drawing the line on 'what counts' as support for a link was not always easy.

We also struggled with the identification of plausible and relevant chains and cycles. First, we took multiple *a-priori* decisions that influenced the chains and cycles we identified. We decided that chains would have to end with wellbeing or biodiversity – a justified yet criticisable choice. We then limited the analysis exclusively to strongly positive or negative links between factors (all strong positive or all strong negative). These choices combined restricted the number of chains and cycles to rate for plausibility and relevance to 67, which still represented a manageable number. Yet one could argue that this approach was too restrictive since chains with a mix of positive and negative links or weaker links could also be plausible and relevant and could contain important leverage points. An example for this may be old-growth forest conservation through protected areas. Here, research (Golden et al., 2016; Llopis et al., 2021) has demonstrated indirect negative links between protected area establishment and wellbeing, predominantly via a loss of provisioning ecosystem services. This was not captured in our analysis, since protected old-growth forests still show a weak positive link to provisioning ecosystem services, but this is a negative change compared to unprotected old-growth forest. Second, assessing chains and cycles was not trivial, even with deep social-ecological systems knowledge. Assessors faced the issue that their assessment of complete chains and cycles was strongly influenced by their knowledge on single links, making it difficult to consider complete chains and cycles. Third, even for those chains and cycles that we rated as plausible, the causality that they assume may be weakly supported by the literature, could be context-dependent, or might result from correlations with other factors that were missed in the underlying literature or in the validation. It may thus make sense to research those assumed causalities in top-rated chains and cycles in more detail through targeted modelling approaches (Bürgi et al., 2022), transdisciplinary field research (Schneider et al., 2019), or randomized control trials (Pynegar et al., 2020).

We further find that longer chains and larger cycles were more likely to be implausible since uncertainties scale with model complexity (Brugnach et al., 2008). More generally, cycles were less plausible than chains – which can in part be explained by their longer average length under our more restrictive criteria when selecting chains. However, there is a further phenomenon: since all factors were linked to other factors through incoming and outgoing links, we have multiple cases where incoming and outgoing links were on very different topics, making cycles implausible. For example, high vanilla prices, an out-of-landscape influence, affect vanilla agroforest expansion in a telecoupled way while remittances from money earned from cash crop sales linked commercial agriculture back to the factor out-of-landscape influences, since the money 'left' the focal landscape. However, such remittances do not affect global vanilla prices, rendering the cycle implausible.

It is also important to highlight the resources invested, which may hinder the feasibility of the approach for others. Indeed, this project took a significant amount of research time, complementary expertise, as well as financial resources for artwork and technical implementation. Applying the approach elsewhere would thus be facilitated by an interactive open-source platform which would guide users through the process and automatically create the here-presented visualizations – as pioneered by others for dynamic meta-analyses (Shackelford et al., 2021). Costs could be further reduced by generating the artwork through software applying artificial intelligence; however, it may be difficult to reach the level of detail and context-specificity that the artists achieved.

Furthermore, we see multiple ways of extending the approach. For example, conducting a validation workshop with diverse stakeholders in the focal region would have been an alternative way of validating and rating links, chains, and cycles. This could have also popularized the visual synthesis regionally and increased its use among stakeholders. It would additionally be possible to continuously update the visual synthesis element with future research, at least online. Thereby, the work would always incorporate the newest findings, a concept coined 'living systematic review' in other areas of meta science (Elliott et al., 2014; Nakagawa et al., 2019). Lastly, we believe that instead of using published scientific knowledge, the factors themselves as well as the links between factors could also be identified using local, Indigenous (Aminpour et al., 2020), or expert knowledge (Messerli, 2000; Pham-Truffert et al., 2020; Weitz et al., 2018). This would make it a form of participatory modelling (Andriatsitohaina et al., 2020; Hedelin et al., 2017) that can be as insightful as scientific knowledge synthesis (Aminpour et al., 2020).

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Authors' contributions

DAM devised the initial concept with EK, AH, PM, and JGZ. LG and DAM conducted the literature screening. RNNA, AH, DAM, AANAR, MPT, and JGZ defined the factors. DAM identified links. RNNA, AANAR, MPT validated links. MPT and DAM coordinated the technical implementation. MPT and DAM analysed the data to identify chains and cycles. ORA, RNNA, CLD, TRF, JCL, DAM, AANAR, ER, AW, and JGZ rated chains and cycles. DAM created the figures and wrote the first draft of the manuscript. All authors participated in discussions, revised the writing, and approved the final version.

Supplementary Material

The Supplementary Material for this article can be found online at:
https://sesmo.org/article/view/18637/18165 (Figure S1), https://sesmo.org/article/view/18637/18162 (Table S1), https://sesmo.org/article/view/18637/18163 (Table S2), and https://sesmo.org/article/view/18637/18164 (Table S3).

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