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TOPICAL REVIEW

Taking stock of and advancing knowledge on interaction archetypes at the nexus between land, biodiversity, food and climate

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Abstract

Global challenges related to land, biodiversity, food and climate interact in diverse ways depending on local conditions and the broader context in which they are embedded. This diversity challenges learning and integrated decision-making to sustainably transform the nexus, that is to say the interactions between these land-based challenges. Providing aggregated insights, archetype analysis has revealed recurrent patterns within the multitude of interactions, i.e. interaction archetypes that are essential to enhance the understanding of nexus relations. This paper synthesises the state of knowledge on interaction or nexus archetypes related to land, biodiversity, food and climate based on a systematic literature review. It focusses on the coverage of thematic aspects, regional distribution, social dimensions and methodologies. The results show that consideration of comprehensive land–biodiversity–food–climate interactions is rare. Furthermore, there are pronounced regional knowledge gaps, social dimensions are inadequately captured, and methodological shortcomings are evident. To enhance the investigation of interaction archetypes, we have framed a future research agenda providing directions to fully capture interactions across space and time, better use the potential of scenario archetypes and up-scale transformative actions. These advances will constructively contribute insights that help to achieve the ambitious objective to sustainably transform the nexus between land, biodiversity, food and climate.

1. Introduction

The post-2020 sustainability framework urgently demands that the challenges of land degradation, biodiversity decline, food insecurity and climate change must be addressed (United Nations, 2014, European Commission 2020, 2021, UNCBD 2021). Clearly, it is impossible to solve these land-based challenges separately through siloed, sectoral management approaches. Instead, the scope of action needs to be radically extended to specifically focus on the nexus, i.e. interactions between all relevant thematic aspects (Biggs *et al* 2015, Lal 2016, O'Connor *et al* 2021). For example, enhancing biodiversity and associated ecosystem services, such as water purification, pollination and biological pest control, are fundamental for re-configuring agricultural systems so that production can be sustained while ensuring climate adaptation and mitigation (Chappell and Lavalle 2011, IPBES 2019). However, despite empirical evidence, integrated actions at large scale remain the exception and policies are misaligned (Schmidt-Traub *et al* 2019). Therefore, a central question is: what can we learn from specific local ways in which land use, biodiversity change, food production and climate dynamics co-evolve to overcome fragmentation and scale up integrative actions?

In response to this question, archetype analysis (Oberlack *et al* 2019, Sietz *et al* 2019) has revealed recurrent, i.e. archetypical patterns of factors and processes that repeatedly determine land-based interactions within the multitude of local conditions (Brzezina *et al* 2017, Hartel *et al* 2018, Dasgupta *et al* 2019, Bahri *et al*, 2020). We define interaction or nexus archetypes as recurrent patterns of co-evolving land, biodiversity, food and climate dynamics. Interaction archetypes provide insights into functionally similar interactions focusing on an intermediate level of abstraction (Oberlack *et al* 2019) in between the particularities of single cases and panacea perspectives (Schellnhuber *et al* 2002, Basurto and Ostrom 2009). Through cumulative learning, they can enhance understanding and inform action to sustainably transform, i.e. reconfigure land–biodiversity–food–climate nexus relations. Yet, archetype research has so far often focussed on particular phenomena separately (Eisenack *et al* 2021), thereby leaving valuable potential to realise the full benefits the approach offers for tailoring policies and actions to particular contexts untapped. Highlighting this potential, archetype analysis has been proposed to advance future research on biodiversity, ecosystem services and related feedbacks within land systems, particularly in the context of scenario development (IPBES 2016). Future studies seeking to realise the benefits of archetype analysis should pay in-depth attention to validating their findings, a currently under-utilised opportunity to demonstrate their credibility and hence usefulness for informing decision-making (Piemontese *et al* 2022). Clearly defined application requirements, including intended users, spatial scale and temporal aspects of application, are prerequisites for determining the degree to which archetypes suitably respond to knowledge needs and sustainability challenges.

Sustainably transforming land-based interactions requires a sound understanding of social-ecological system dynamics (Ostrom 2009, Mcginnis and Ostrom 2014, Díaz *et al* 2019). Social-ecological systems have been framed as complex adaptive systems highlighting that human land use is intrinsically tied to ecological dynamics (Allen and Garmestani 2015, Folke *et al* 2016). This reflects the close interdependence of all human and non-human beings and their environment that lies at the core of most Indigenous Peoples' notion of a good life (Acosta Espinosa 2011, Gregor Barié 2014). Hence, the capacity of all knowledge systems needs to be embraced to inform the transformation of complex adaptive systems. In complex systems, critical thresholds, cross-scale linkages and feedback loops imply nonlinear behaviour and associated patterns of system behaviour (Holling and Gunderson 2002, Scheffer and Carpenter 2003, Walker *et al* 2006, Sietz *et al* 2017a, Van Den Elsen *et al* 2020). Especially the social dimensions, including governance, human behaviour and human decision-making that shape complexity in land use (Ostrom 2009) deserve greater attention. Understanding their current influence and mechanisms is crucial for sustainability transformations. Lack of integration of complexity and the role of social dimensions in knowledge and action frameworks increases uncertainty in scenarios about future interaction trajectories (O'Connor *et al* 2021) undermining chances to reverse the persistent failure to achieve global sustainability goals (UN 2021).

This paper aims to take stock of and enhance knowledge about interaction archetypes to support learning and decision-making on the sustainable (re)configuration of land-based nexus relations. Based on a systematic literature review, we synthesise existing knowledge on interaction archetypes related to land, biodiversity, food and climate interlinkages in order to provide a state-of-the-art knowledge source. In particular, we capture the thematic aspects addressed, regional coverage, social dimensions and methodologies used to identify and apply interaction archetypes. Based on this synthesis, we frame an agenda for future research on interaction archetypes structured around three major frontiers. These frontiers provide directions to comprehensively investigate archetypical land–biodiversity–food–climate interactions, advance analysis of nexus scenario archetypes and support up-scaling and transfer of successful transformative action.

2. Methodology

As the basis for our synthesis, we conducted a systematic literature review (Petticrew and Roberts 2006, Booth *et al* 2012). We searched peer-reviewed studies listed in the Web of Science and Scopus databases (last access 1 April 2021) using the following combined terms applied to titles, abstracts and keywords: archetyp* AND ((land OR farm* OR agric*) AND (biodiv* OR 'ecosyst* service*' OR food OR climat*)). These searches yielded 280 unique references. We limited this set to only those studies that met the following inclusion criteria: focus on at least one type of interaction between land and biodiversity, food and climate, identification or application of archetypes and related interactions, sound methodological description, interdisciplinary approach and comprehensive interpretation of results. We excluded the subject areas of medicine, biotechnology, atmospheric science, sanitation and architecture as these subject areas are beyond our focus on land-based interactions. Since archetype analysis is an emerging field of scientific research (Oberlack *et al* 2019, Sietz *et al* 2019, Eisenack *et al* 2021), we focused our analysis on scientific literature. Using this selection procedure, we identified 50 thematic studies and two synthesis studies on archetype analysis. Although the selected thematic studies included research on syndromes, the predecessor of archetypes, capturing unsustainable patterns of human-nature interactions (Lüdeke *et al* 2004, Sietz *et al* 2006, Manuel-Navarrete *et al* 2007), we did not comprehensively cover syndrome studies. We were specifically interested in revealing the state of knowledge on archetype analysis as a rapidly advancing field of research capturing both sustainable and unsustainable patterns (Oberlack *et al* 2019) that supports decision-making on sustainability with evidence-based and contextualised generalisations.

We coded the 50 thematic studies according to the assessed types of interactions, their regional coverage, the main land systems addressed, social dimensions, archetype definitions, methods used to investigate archetypical interactions, data sources used, units of analysis and publication year. These categories emerged inductively during coding and subsequent analysis and provide important insights for advancing the knowledge on interaction archetypes. Investigating the type of interactions and regional coverage (section 3.1) yields insights into thematic and regional knowledge gaps. The social dimensions (section 3.2) critically shape current land use and provide insights into the potential for sustainability transformations. Archetype definitions (section 3.3) reveal variants and gaps in the conceptual foundations of archetype analysis. Investigating methods (section 3.4) provides insights into different methodologies yielding diverse types and qualities of insights. Lastly, we give a short overview of the temporal development of the research field (section 3.5). The two synthesis studies were dealt with separately providing the basis for evaluating archetype definitions and methodological portfolios. These studies were not a part of the quantitative synthesis. We drew lessons from a structured discussion of the synthesised findings to elaborate the future research agenda as a basis to enable better understanding and the sustainable management of land interactions with biodiversity, food and climate.

3. Results and discussion

3.1. Interaction types and their regional distribution

The synthesis of interaction types and regional coverage revealed insights into thematic and spatial knowledge and gaps in this knowledge. The reviewed studies primarily investigated archetypical interactions of land in combination with food (82%) and less so in combination with biodiversity (50%) and climate (48%; figure 1). These foci are a good reflection of the global debate on sustainable land and food systems (UN 2014, European Commission 2020, 2021, UNCBD 2021). Knowledge on archetypical interactions is offered for specific subregions defined by IPBES (2020). These subregions serve as a reference in our synthesis to directly feed insights into global assessments of the importance and trends of biodiversity and nature's contributions to people (e.g. Nexus Assessment and Transformative Change Assessment of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services IPBES). Some studies presented global insights either at least partly covering all IPBES (2020) subregions or providing a generic perspective with general applicability.

Few of the studies (20%) considered the full set of land–biodiversity–food–climate interactions (figure 1). These studies addressed agricultural land systems mainly in combination with various other land uses and sectors such as forestry, nature conservation, urban areas, tourism and energy (e.g. Jäger *et al* 2015, Dasgupta *et al* 2019, Harrison *et al* 2019). These interactions were mainly investigated in central and western Europe and in Asia, including multi-regional coverage.

Focussing on less comprehensive interrelations, 16% of the studies exclusively considered land–biodiversity–food interactions (figure 1), explored in agricultural land systems, often in conjunction with nature conservation, recreation and forestry (e.g. Levers *et al* 2018, Li *et al* 2018). These studies covered primarily Europe and the global scale. A comparable share of 18% of all studies assessed only land–food–climate interactions, again focussing on agriculture (e.g. Nyam *et al* 2020, Egerer *et al* 2021) sometimes in combination with food chains, forestry and land conversion (e.g. Weissteiner *et al* 2011, Vaclavik *et al* 2013, Loiseau *et al* 2020). These studies covered mostly Europe, Africa and Asia.

Alongside the earlier interactions, specific foci on biodiversity and climate interactions are increasingly receiving attention, in various combinations (18% of the studies; figure 1). Most of these studies were published between 2018–2021 (14% of the studies; see also section 3.5). They covered either only a few regions or the global scale. For example, archetypical land–biodiversity–climate interactions (6% of the studies) were examined only at global scale (figure 1, e.g. Haberman and Bennett 2019, Higuera *et al* 2019). In contrast, land–biodiversity interactions (8% of the studies) were investigated in western Africa, southeastern Asia and at global scale (e.g. Magliocca *et al* 2019, Valette *et al* 2020). Moreover, knowledge is available on land–climate interrelations (4% of the studies) in equal parts for western Africa, the Americas and northeastern Asia (Keys and Wang-Erlandsson 2018, Evers *et al* 2019).

The largest share of the studies (28%) exclusively assessed land–food archetypes disregarding other thematic aspects (figure 1), with insights mostly published since 2015 (22% of the studies; see also section 3.5). Insights into archetypical land–food interactions are available for all subregions but the Caribbean, addressing agriculture (e.g. Zare *et al* 2017) often in combination with water management and land acquisition (e.g. Gohari *et al* 2013, Oberlack *et al* 2016, Turner *et al* 2016).

In a regional perspective, most insights are available for central and western Europe, the global scale and western Africa (figure 2). A global scale extent enables regional comparisons encompassing diverse social-ecological contexts in which

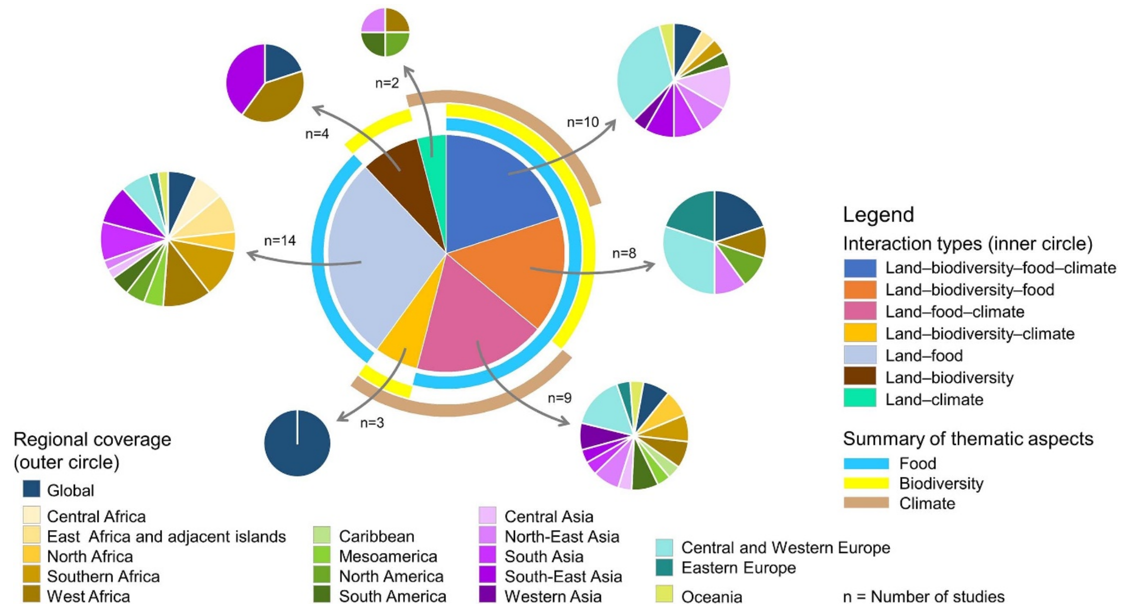

Figure 1. Interaction types analysed by the reviewed studies and their regional distribution according to IPBES subregions (IPBES 2020). (*Note:* Chart sizes in the outer circle reflect the respective number of studies.)

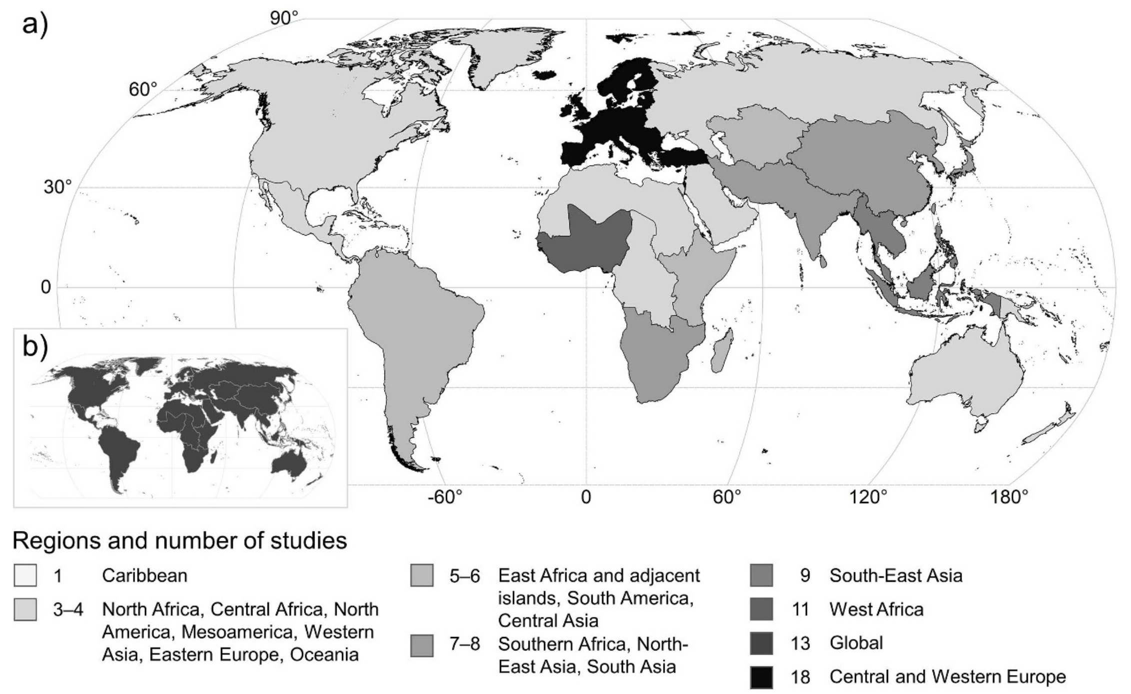

Figure 2. Regions covered by the reviewed studies: (a) by IPBES subregions (IPBES 2020) and (b) global scale (*Note:* The maps were produced based on IPBES 2020).

land–biodiversity–food–climate interactions evolve. However, it inevitably only captures regional specificities to some extent. This means that regional aspects of underlying processes, such as land use intensity, biodiversity management and food production, are only captured in a generalised way. In particular, spatially and temporally well-resolved quantitative data and qualitative information on underlying processes are often not available at global scale, thereby largely constraining efforts to gain a comprehensive understanding of archetypical interactions across the globe.

Beyond the insights derived at global scale, it is particularly disadvantageous that there is low coverage of specific regions such as central and eastern Africa, Mesoamerica, South America and southern Asia (e.g. Locatelli *et al* 2017, Vidal Merino *et al* 2019). These regions include areas that bear high

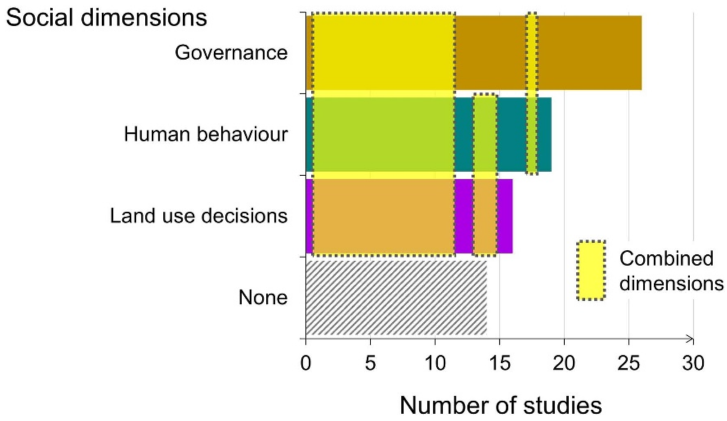

Figure 3. Social dimensions of interaction archetypes analysed in the reviewed studies.

risk of conflicts between biodiversity, food security and weather extremes. Risks arise particularly in those regions that include hotspots of biodiversity threats, food insecurity and future agricultural expansion (Delzeit *et al* 2017, Molotoks *et al* 2017). For example, the Peruvian Andes have not only been highlighted as a megadiverse biodiversity hotspot (Rodríguez and Young 2000) but also as an area with high risk of agricultural expansion due to large uncultivated areas suited for agriculture (Molotoks *et al* 2017). The Caribbean is least covered, revealing the most pronounced regional knowledge gaps. Questions remain, for example, about the social-ecological consequences of colonialism and their persistence until today, e.g. related to the depletion of native flora and fauna including wild food species caused by large-scale sugar cane plantations and the introduction of exotic taxa (Paravisini-Gebert 2016, Wallman 2018). These findings indicate the urgent requirement to advance our regional knowledge on nexus problems and potential solutions to address land degradation, biodiversity loss, food insecurity and aggravating impacts of climate change in synergistic ways.

3.2. Social dimensions of archetypical interlinkages

Insights into the social components (Ostrom 2009) of interaction archetypes help to recognise leverage points suited to trigger transformative change. Considering three social dimensions, firstly, we captured governance referring to organisations, institutions and processes that shape policies and policy-making. Secondly, we took into account the human behaviour related to the characteristics and decision-making logic of stakeholders who manage land and benefit from the products of natural resource use. Thirdly, we recorded land use decisions as the central connector between natural resources and stakeholders.

Overall, only about half of the reviewed studies ($n = 26$) investigated how governance shaped archetypical interactions (figure 3). In addition, human behaviour of stakeholders was an important topic of analysis in just 19 studies, while only 16 studies analysed land use decisions. Regarding combinations of social dimensions, merely 11 studies analysed all three social dimensions together (e.g. Banson *et al* 2016, Brzezina *et al* 2017, Almekinders *et al* 2019). Moreover, two studies (Levers *et al* 2018, Li *et al* 2018) focussed on human behaviour in combination with land use decisions, while one study (Oberlack *et al* 2016) investigated governance and human behaviour at the same time. In contrast, 14 studies did not investigate any of the social dimensions considered in our review.

The limited consideration of social dimensions, and above all combinations of these, greatly restricts our knowledge and capacity to (re)organise land use in a way that fosters synergies and minimises trade-offs between land, biodiversity, food and climate concerns. For example, this concerns the allocation of costs and benefits among stakeholders and also impedes balancing stakeholders' interests. This resembles the inadequate consideration of the ways in which governance affects other land-based interactions such as framed in the water-energy-food nexus (Urbinatti *et al* 2020). A better understanding of the ways in which governance, human behaviour and land use decisions typically co-evolve and influence land–biodiversity–food–climate interactions is clearly needed to develop response options that adequately address social-ecological dynamics. Consideration of sudden changes, feedbacks, historical trajectories and dynamics of the broader social context (Ostrom 2009, Cumming *et al* 2020) is important to effectively manage leverage points for transformative change.

3.3. Archetype definitions

Variants of and gaps in archetype definitions yield information on the conceptual foundations of the studies reviewed. Archetypes were defined from the perspectives of diverse meanings, features and reference literature. The meanings used to describe and

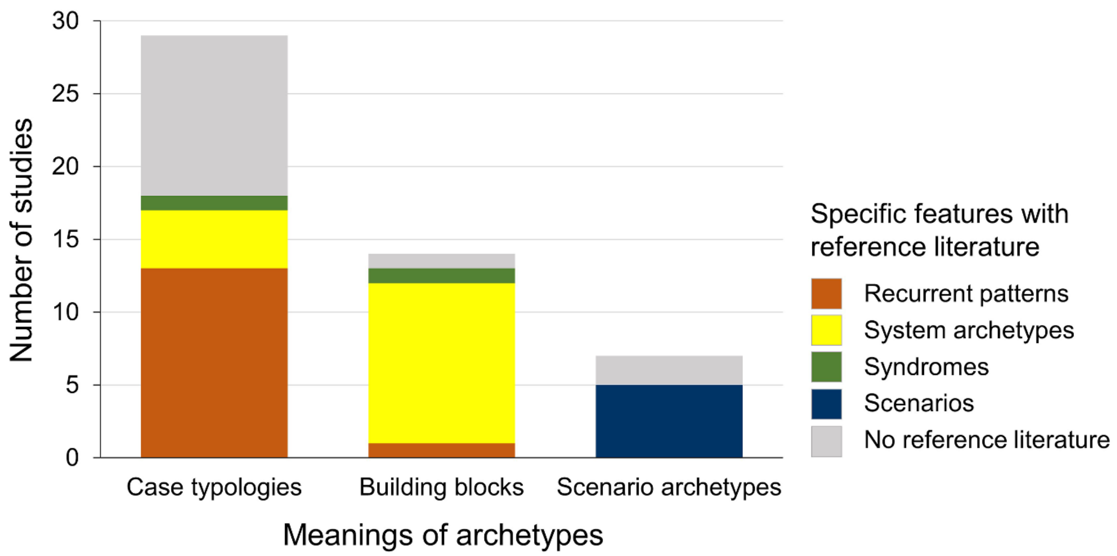

Figure 4. Meanings and specific features used by the reviewed studies to identify or apply interaction archetypes.

evaluate archetypes included case typologies, building blocks and scenario archetypes (Oberlack *et al* 2019). These were further differentiated according to specific features underlying the archetype analysis encompassing recurrent patterns, system archetypes, syndromes and scenarios.

In terms of specific meanings, the majority of studies (58%, figure 4) used a case typology approach capturing similarities across a set of cases. In contrast, around a quarter (28%) applied a building blocks approach in which individual cases can be characterised by one or a combination of several archetypes. Taking yet another perspective, a small proportion of studies (14%) investigated scenario archetypes depicting common features of possible future interaction trajectories.

Studies that used a case typology approach most frequently identified recurrent patterns (figure 4) in factors and processes that shape the interactions between land, biodiversity, food and climate (e.g. Adenle and Speranza 2021). Reference was mainly made to archetype definitions used in sustainability research (Oberlack *et al* 2019, Sietz *et al* 2019) and land system science (Vaclavik *et al* 2013). Some studies related to other schools of thought, e.g. regularities in economies (Sadoulet and Dejanvry 1992) and prototypes (Theodosiou *et al* 2012; based on Eugster and Leisch 2009).

In contrast, the majority of studies applying a building blocks approach used system archetypes as diagnostic tools to establish or synthesise insights into characteristic structures and dynamics of social-ecological systems (figure 4). These studies either diagnosed system dynamics or tested a hypothesised system change (e.g. Nyam *et al* 2020). Reference was specifically made to the field of system archetypes (e.g. Senge 2006) investigating typical causal interlinkages reappearing across many cases such as the 'limits to growth' system archetype (Gohari *et al* 2013). System archetypes offer particular potential for analysing interactions between land, biodiversity, food and climate due to their focus on reappearing systemic interlinkages.

Among the studies approaching archetypes as case typologies and building blocks, only two studies used syndromes, i.e. recurrent non-sustainable human-nature interactions, as specific features (figure 4). They described change processes as archetypical dynamic and co-evolutionary patterns of human–nature interactions (e.g. Weissteiner *et al* 2011), referring to Downing and Lüdeke (2002) and Müller *et al* (2014). These studies take integrative perspectives capturing complex sets of factors at multiple levels and in multiple sectors, aiming to overcome single-faceted sectoral approaches.

Most studies that investigated scenario archetypes expectedly referred to scenarios as specific features (figure 4). These referenced literature on 'scenario archetypes' or 'scenario families' (e.g. Pedde *et al* 2019) or the Global Environmental Outlook-4 (UNEP 2007, Dasgupta *et al* 2019). There is clearly potential to extend and deepen the use of scenario archetypes in the future as they hold great potential for visioning about desired future development (Kubiszewski *et al* 2016, Pereira *et al* 2018) and factors that foster or impede specific interaction pathways.

Overall, about one quarter of the reviewed studies (28%) neither provided an archetype definition nor reference literature. The proportion of studies without reference literature was found to be particularly high in those using a case typology approach (figure 4). This may impede the drawing

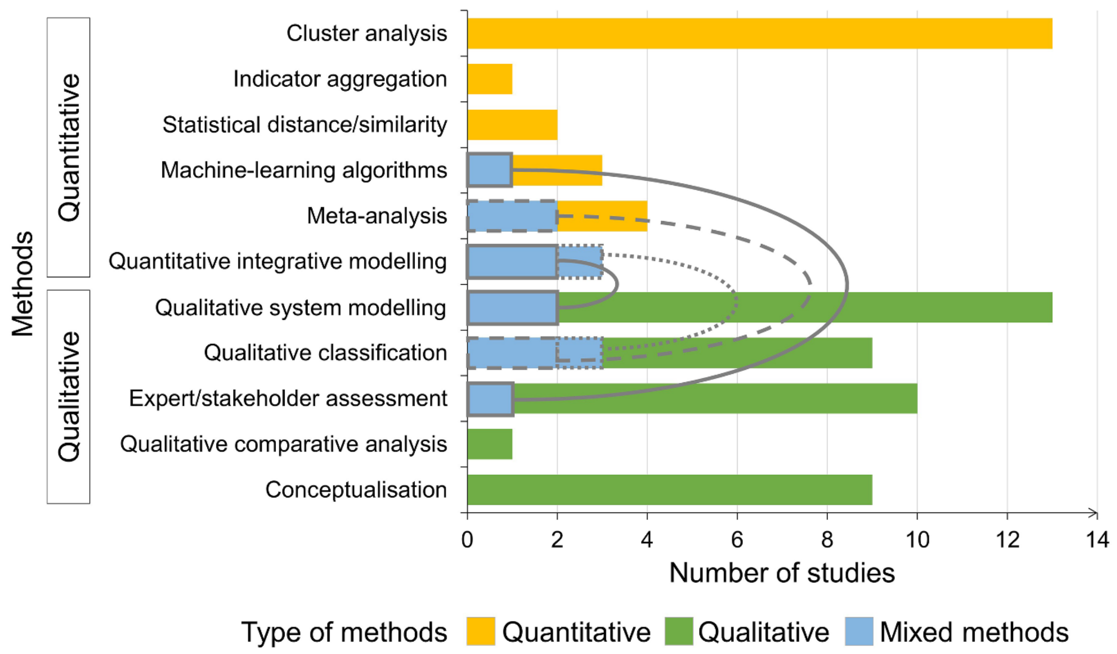

Figure 5. Methods used by the reviewed studies to identify and apply interaction archetypes, including multi-method approaches. Connected boxes represent combinations used in mixed method studies.

of comprehensive lessons aimed at informing transformative action, hence necessitating improvement in future research.

3.4. Methodologies

The reviewed studies employed methodologies resting on various methods, data sources and units of analysis. Influencing the type of insights gained from a study, these methodological aspects serve to reflect on epistemological and normative underpinnings, data requirements and implications in view of specific purposes and research questions (Sietz *et al* 2019). The methods used to identify and apply interaction archetypes stem from a broad methodological portfolio which has grown and diversified since the synthesis of the archetype methods applied in sustainability research (Sietz *et al* 2019). Overall, the reviewed studies used mainly qualitative methods (44%) and to a lesser extent quantitative (30%) and mixed methods, i.e. combining qualitative and quantitative approaches (26%). 36% of the studies used more than one method.

Among the purely qualitative studies (figure 5), the most frequently used method was qualitative system modelling (e.g. Turner *et al* 2016, Bahri 2020), often used to identify system archetypes (see section 3.3). Moreover, expert and stakeholder assessments, theoretical conceptualisations (e.g. Felgenhauer 2015, Hartel *et al* 2018) and qualitative classifications (e.g. Bay-Larsen *et al* 2018) also played a prominent role. Expert and stakeholder assessments were always used in combination with other methods, mainly with qualitative system modelling (e.g. Queenan *et al* 2020).

In the solely quantitative studies, cluster analysis was the most relevant method (e.g. Lim-Camacho *et al* 2017, Sietz *et al* 2017b, Tessier *et al* 2021). Less frequently used methods included meta-analysis (Gerst *et al* 2015, Lee and Lautenbach 2016), machine-learning algorithms (e.g. Adenle and Speranza 2021) and measures of statistical distance or similarity (e.g. Vaclavik *et al* 2016).

The mixed method studies most frequently combined qualitative system modelling with quantitative integrative modelling and meta-analysis with qualitative classification. Further studies combined machine-learning algorithms with an expert/stakeholder assessment and qualitative classification with quantitative integrative modelling. Spatial statistics and rule-based classifications used to identify social-ecological system archetypes (Sietz *et al* 2019) were not found in this review.

The reviewed studies used one or several types of data sources (figure 6). Firstly, existing data were used whereby available statistical, census and remote sensing data were drawn on. Secondly, literature information was extracted from scientific publications. Thirdly, participatory data collection took place. This involved processes in which stakeholders took part in the data collection. Fourthly, self-collected data were gathered through interviews and surveys of experts and stakeholders.

The most frequently used data source was scientific literature, followed by existing data, participatory data collection and self-collected data (figure 6). Most studies (64%) used only one data source. In contrast, 24% of the studies involved two sources, e.g. drawing on existing data in combination with

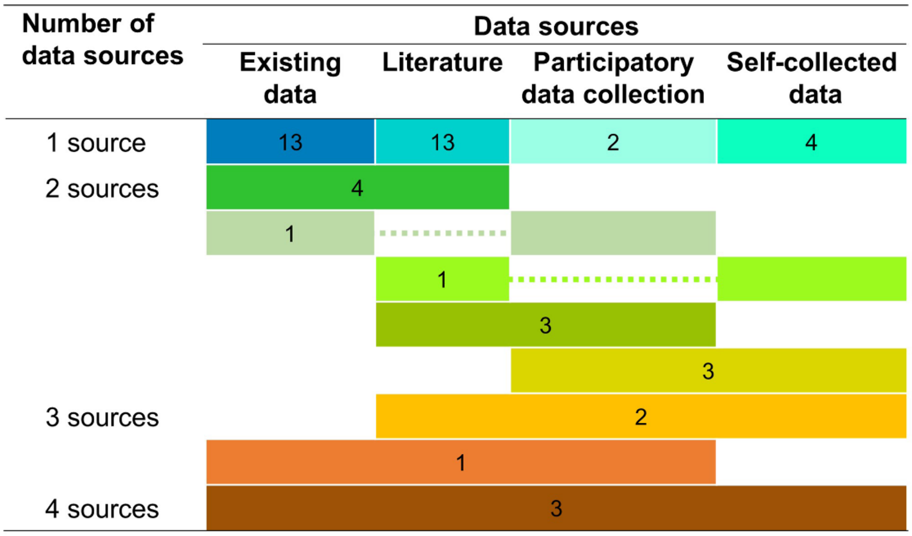

Figure 6. Data sources and combinations of these sources used in the reviewed studies. (n = number of studies; *Note:* Dotted lines indicate combinations of data sources in non-adjacent cells.)

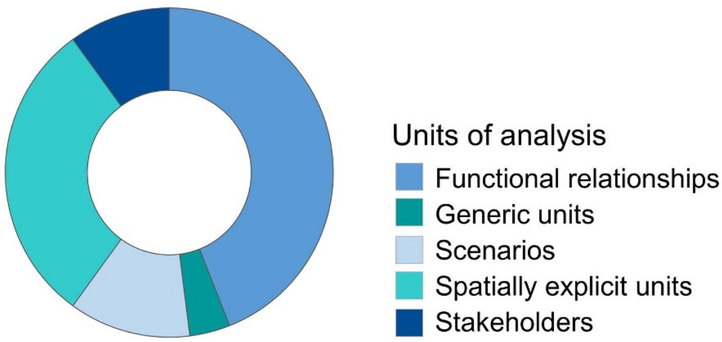

Figure 7. Units of analysis considered in the reviewed studies.

literature (e.g. Rocha *et al* 2020), combining literature and participatory data collection (e.g. Moraine *et al* 2017) or linking participatory and self-collected data (e.g. Karrasch *et al* 2019). Moreover, 6% of the studies used three data sources, including a combination of literature, participatory and self-collected data (e.g. Armatas *et al* 2018). Taking an even more comprehensive approach, 6% of the studies combined all four data sources (e.g. Bahri 2020).

Regarding units of analysis (figure 7), functional relationships most frequently underlay the archetype analyses (44%), often used to establish causal loop diagrams and investigate system archetypes (e.g. Banson *et al* 2016, Turner *et al* 2017, Bahri 2020). Since we reviewed studies of archetypical interactions, the units of analysis in nearly all studies had a functional dimension, but the studies focussing explicitly on functional relationships put this aspect in the foreground. Spatially explicit units were also prominently used (30%) such as grid cells and landscapes (e.g. Fischer *et al* 2017). Other units of analysis encompassed scenarios (12%; e.g. Thompson 2018, Leventon *et al* 2019), individual stakeholders (10%; e.g. Bay-Larsen *et al* 2018) and generic units such as conservation areas (4%, e.g. Whitelaw *et al* 2014).

Taken together, qualitative methods, functional relationships and information provided in scientific literature mostly informed the investigations on archetypical interactions, in various combinations. The knowledge derived provides valuable insights into principal relationships between factors and processes that recurrently shape the interactions. However, limited use of quantitative methods as well as participatory and self-collected data on stakeholders and scenarios leaves considerable unexplored potential to better understand the complexity determining the interactions and adaptive management options.

3.5. Publication year

The publication year provides information on the temporal development of research on archetypical interactions. The reviewed studies have been published since 1992, yet the majority (88%) have appeared since 2015 (figure 8). Until 2013, studies captured only archetypical land–food–climate

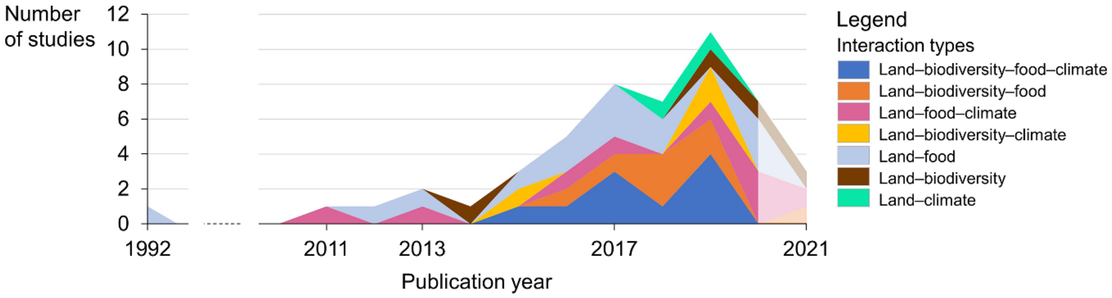

Figure 8. Publication year of reviewed studies according to interaction types. (*Note:* Publications are only covered until April 2021, indicated by lighter colours for the year 2021.)

and land–food interactions. Full sets of land–biodiversity–food–climate interactions were published between 2015–2019, mainly coinciding with less comprehensive land–biodiversity–food and land–food interactions. Specific foci on land–biodiversity interactions have been published since 2019 and land–climate interactions have regained attention since 2018.

4. Future research agenda

Our synthesis demonstrates that knowledge on archetypical interactions is limited in terms of interlinked thematic aspects, regional coverage, social dimensions and methodologies. The future agenda highlights research directions to capture archetypical interactions more comprehensively, close regional knowledge gaps, make better use of the potential of scenario archetypes and inform the up-scaling of actions.

4.1. Comprehensively capturing archetypical interactions across regions and scales

The next generation of interaction archetypes needs to pay attention to the full set of interactions between land, biodiversity, food and climate (see sections 3.1 and 3.2; figure 9(a)) to enable a solid understanding of the ways in which all involved thematic aspects typically co-evolve. Moving from fragmented perspectives to interaction archetypes helps to better understand recurrent challenges and opportunities (figure 9(a)). Investigation of system archetypes (see section 3.3) provides a particularly suitable way to synthesise feedback mechanisms and diagnose or test hypotheses about archetypical dynamics. However, greater efforts are needed to trace patterns over time. Particular consideration needs to be dedicated to integrated analytical approaches that capture complexity, i.e. interdependency and feedback mechanisms (Scheffer and Carpenter 2003, Suding 2011, Cumming *et al* 2020). Important characteristics to be addressed encompass non-linear dynamics including thresholds, resilience, time lags and reversibility (figure 9(b); Holling 1973, Walker and Meyers 2004, Walker *et al* 2006, Van Den Elsen *et al* 2020). Stability landscapes (figure 9(b)) are useful depictions for exploring non-linear interaction dynamics as a basis for analysing future scenario archetypes and adaptive management options. In the absence of alternative stable states, an existing, less sustainable stable state (see stability landscape I in figure 9(b)) requires adaptive management that substantially reconfigures the current social-ecological conditions so that another, more sustainable stable state emerges and a shift can occur. Yet, if another, more sustainable stable state exists, then there is potential for transformative change. In this case, interactions can be tipped out of the basin of attraction of their current state to shift to the alternative stable state (see stability landscape II in figure 9(b)). In contrast, more sustainable archetypical interactions require efforts to maintain or further improve their current state (see stability landscape III in figure 9(b)).

Systematic collection of time series data on interactions is key to be able to explore and effectively manage nexus relations. Participatory and self-collected data (see section 3.4) offer particular opportunities to capture relevant processes in necessary detail. Established long-term observation systems can provide important lessons for monitoring land–biodiversity–food–climate interactions. They highlight the importance of coordinated, comprehensive and sustained data collection to inform decision making and actions on interconnected challenges and opportunities (Bestelmeyer *et al* 2011, GEO 2015). Integration of diverse data sources, such as derived from remote sensing, *in-situ* experiments and citizen observatories, offers a powerful tool for filling functional and regional knowledge gaps (see sections 3.1 and 3.2). Predictable long-term funding is a prerequisite for ensuring that data collection, synthesis and monitoring can be continued at time scales that are sufficiently long.

In future research, attention needs to be paid to under-researched regions, above all the Caribbean, Mesoamerica, central Africa and Oceania (see section 3.1). This encompasses current hotspots of change at the interface between biodiversity

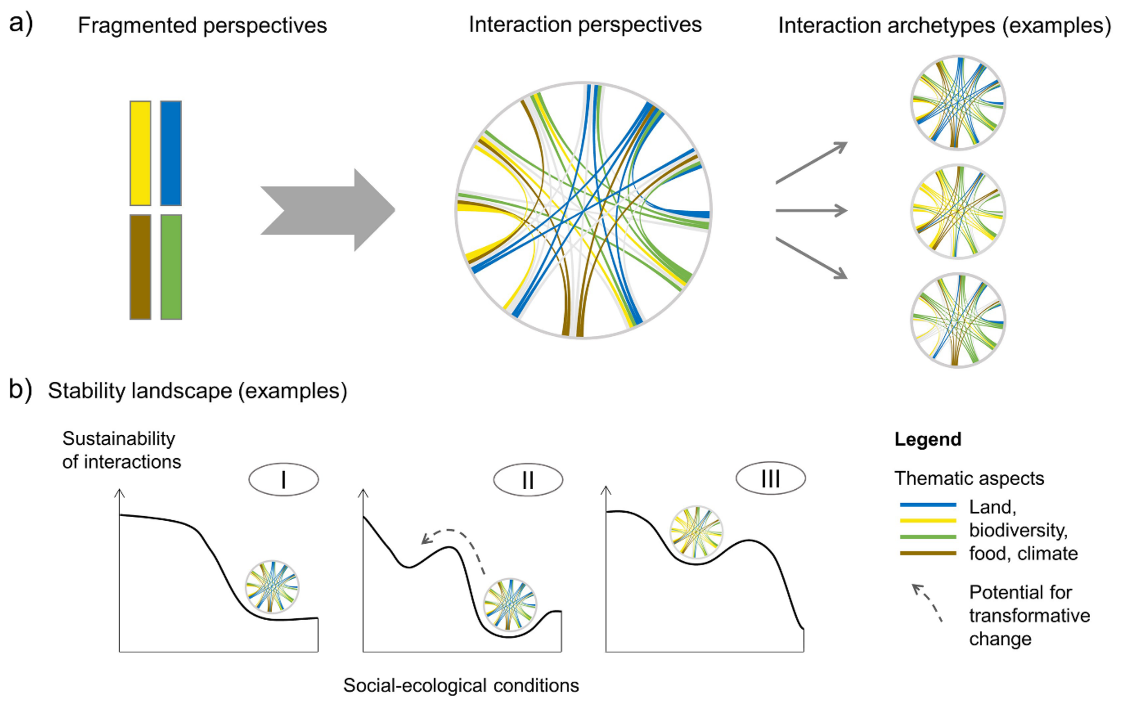

Figure 9. Advancing knowledge on interaction archetypes to support learning and adaptive management. (a) From fragmentation to interaction archetypes (*Note:* Interactions are defined as nexus relations between land, biodiversity, food and climate. In the chord diagrams, coloured connectors depict strong interactions, while grey connectors show weak interactions). (b) Stability landscapes illustrating multi-dimensional state spaces (Walker *et al* 2004) in which archetypical interactions unfold. (*Note:* The sustainability of interactions (see *y*-axis) captures values and normative assumptions that can differ among stakeholders. Valleys represent basins of attraction in which archetypical interactions are kept in equilibrium by internal feedback mechanisms).

conservation, agriculture and weather impacts (Molotoks *et al* 2017, Costello *et al* 2021). But in-depth research is also needed in regions with newly emerging risks and opportunities associated with future food system change and climate change (Sietz and Feola 2016, Leach *et al* 2020, O'Neill *et al* 2021). Interaction archetypes will ideally be investigated in spatially explicit ways. Spatial statistics (Kehoe *et al* 2015, Delzeit *et al* 2017), currently missing in the methodological portfolio (see section 3.4), provide suitable avenues to capture spatial interactions.

Trends observed at one spatial scale may evolve differently at higher or lower scales (Sietz 2014, Chase *et al* 2019). Hence, systematic understanding of the interlinking and nesting of feedbacks (Sietz *et al* 2017b) across spatial, temporal and decision-making scales (O'Connor *et al* 2021) is essential. Future research demands methodological innovation (e.g. spatially coordinated observations, multi-scale models considering pattern-process relationships; IPBES 2016) that support cross-scale synthesis. Varying the extent of the spatial scale and the resolution (Sietz 2014) are important considerations to explore non-linearity in the strength and direction of interactions. As demonstrated by ecological research, synergies and trade-offs may occur repeatedly at specific spatial or temporal scales, e.g. driven by recurrent weather extremes (Gonzalez *et al* 2020).

Advancing validation in future studies of interaction archetypes is important to strengthen the credibility of findings. Framed as a multi-dimensional procedure, validation should address conceptual validity (i.e. salience of research framing), construct validity (i.e. attribute selection) and application validity (i.e. usefulness of results for application by users), among other dimensions (Piemontese *et al* 2022). This requires the systematic planning of validation and the collection of validation data, alongside data on drivers of change, responses and action levers, as well as multi-stakeholder engagement.

4.2. Tapping the potential of scenario archetypes

Projecting possible future interaction pathways is key to identifying leverage points for adaptive management. Yet, the inherent complexity in interactions including uncertainty and surprise challenges stakeholders to make and adapt management decisions (Holling 1973, 1978). The basis of adaptive management, including governance and human behaviour (section 3.2), needs to be urgently addressed to provide insights into the conditions under which transformative change can most effectively be initiated or reinforced (Allen and Garmestani 2015). For example, analysis of scenario archetypes (see section 3.3) can help to explore the innovative potential of agroecological re-organisation of agriculture (Sietz *et al* 2022), a decoupling of resource use from habitat degradation and circular economic approaches. In particular, consideration of transformative future pathways tailored to the characteristics of agricultural land systems (Sietz *et al* 2022) can advance the analytical power of scenario archetype models. The baseline period needs to be carefully chosen (e.g. climate baseline, Liersch *et al* 2020) as a reference for analysing interaction scenarios. Analysis of archetypical system dynamics has substantial potential to inform scenario analysis and adaptive management, above all when advancing its use in quantitative approaches (see sections 3.3 and 3.4), as it focuses on non-linear behaviour of complex systems and systemic feedbacks (figure 9(b)). It supports adaptive management in its objective to use emerging windows of opportunities (Sietz *et al* 2017a), create synergies and balance trade-offs providing a vision and direction for action.

Future scenario research is urged to integrate indigenous and local knowledge and cultural practices that have been the basis for the implementation of adaptive governance and successful navigation of transformative change. Important questions relate to the role that unity between humans and nature (IPBES 2019) can play in sustainably governing social-ecological interactions. Moreover, what implications may the Rights of Nature as part of Sumak Kawsay (Buen Vivir, 'good living') codified in the Constitution of Ecuador (Acosta Espinosa 2011, Kauffman and Martin 2017) have? What insights does nature's entitlement with rights as a collective subject of interest as framed in the Bolivian Law of Mother Earth (Pachamama; Gregor Barié 2014) offer for adaptively governing interactions in the future? Addressing these questions is essential to (re)design inclusive socio-ecological policies.

4.3. Scaling up successful actions

Interaction archetypes support learning from the multitude of observations and can inform decision-makers on the up-scaling potential of the insights derived. Up-scaling refers to the expansion and transfer of successful actions (Linn 2012) as an integral part of systematically fostering desired trends and synergies while balancing trade-offs. Up-scaling involves testing, transferring and refining actions in regions with similar interactions based on the assumption that similar drivers and outcomes could be addressed by comparable actions (Sietz *et al* 2011). In particular, future research needs to expand the systematic investigation of potential transfer regions (Vaclavik *et al* 2016, Piemontese *et al* 2020) and discussion of transferability of successful actions (Sietz *et al* 2017b) using spatially explicit interaction archetypes in order to inform scaling considerations.

Different stakeholders' roles in scaling, e.g. their decision making and behaviour (see section 3.2) including expectations and evaluation of interactions and outcomes, need to be better understood to ensure successful expansion and refinement of actions. Scenario archetypes (see section 4.2) need to be appropriately inclusive to support stakeholders in exploring processes that may be triggered by up-scaling activities but cannot be fully anticipated.

Although strategies may diffuse spontaneously, systematic use of leverage points is needed to support the scaling of actions and sustain their success. This requires the identification of archetypical changes in highly influential social-ecological system properties. There are clear opportunities for investigating archetypical levers emerging at the interface between global sustainability goals. For example, climate adaptation priorities outlined in National Adaptation Plans established under the United Nations Framework Convention on Climate Change can support the achievement of Sustainable Development Goals. The future research agenda framed in this paper supports advanced analysis of archetypical leverage points as an indispensable means to design and implement the large scale action needed to transform the land–biodiversity–food–climate nexus.

Data availability statement

All data that support the findings of this study are included within the article.

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