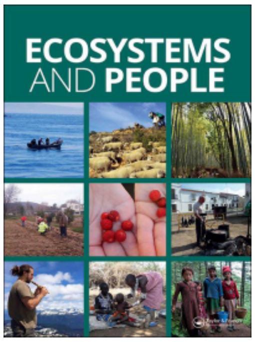

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RESEARCH: RELATIONAL TURN IN SUSTAINABILITY

Seed exchange networks: metrics for examining the resilience of social-ecological agricultural systems

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ABSTRACT

Agricultural systems are dynamic social-ecological systems which are rarely examined under relational approaches. The analysis of seed exchange networks represents a growing empirical pathway to relational thinking for examining the resilience of social-ecological agricultural systems and their dynamic cycles. We conducted a literature review to (i) explore the advances of seed exchange network research, and (ii) identify and synthesize the network metrics used for examining social-ecological structures linking human and other-than-human actors to understand the resilience of agricultural systems. Complementarily, we explored what a relational approach to seed exchange network analysis might entail. Our work shows a growing use of network analysis to explore coupled social-ecological relations in agricultural systems. However, in the past quarter century, most seed exchange case studies often omitted the inherent relational nature of network data and lacked recognition of the agency of other-than-human entities in seed exchange networks. We identified over 20 network metrics broadly used in network analysis, including structural and locational metrics such as 'density', 'modularity', and 'centrality'. These metrics have the potential to inform about the dynamics that may either enhance or constrain the resilience of agricultural systems. For example, 'density' and 'centrality' can reveal pathways of agrobiodiversity access and key actors, respectively. This information may enhance the efficiency of agrobiodiversity flows in agricultural systems. Finally, we discuss some practical implications of adopting a relational approach to seed exchange network analysis to better understand people-agrobiodiversity relations under local, regional, and global changes.

KEY POLICY HIGHLIGHTS

- We draw on seed exchange network analysis as an example of the growing body of empirical approaches to relational thinking aiming to understand the resilience of agricultural systems.
- We present the advances of seed exchange network research in the past quarter century and explore what a relational approach to seed exchange network analysis might entail.
- We present over 20 network metrics that help to understand the resilience of agricultural systems and might be translated into policy indicators to guide decision-making.
- We finally explore the practical implications that, in our experience, may arise when applying a relational approach to seed exchange network research.

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1. Introduction

Agricultural systems are prototypical social-ecological systems (SES) resulting from the inextricable relationship between people and nature across time and space (Pacheco de Castro Flores Ribeiro et al. 2021). Like other SES, they are embedded in complex interaction networks influenced by processes of social-ecological change (Tavella et al. 2022). Agricultural systems have heterogeneous configurations, from diversified small-scale homegardens to extensive monoculture areas, that represent a dominant land use in many landscapes of the world (Altieri et al. 1987; Altieri 2004; Pacheco de Castro Flores Ribeiro et al. 2021). Nevertheless, such heterogeneity may also imply an asymmetrical access to agricultural information and sources to cope with multifaceted challenges in adaptation to local, regional, and global changes (Whitfield et al. 2015).

Agricultural systems face escalating social demands in a broad call to increase their productivity while reducing the ecological impact of agricultural intensification (e. g. reduction of agricultural inputs

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and fossil energy dependence) (Darnhofer et al. 2016). In fact, intensive agricultural systems are considered the main responsible for current global crises, including biodiversity loss and climate change (Rockenbauch and Sakdapolrak 2017; Coomes et al. 2019). However, while academic and policy debates stress the consequences of agricultural intensification, little attention has been paid to understanding how these SES ride the waves of global change by learning and incorporating new information in response to broader social-ecological changes (i. e. the 'system's resilience') (Reyes-García et al. 2014; Darnhofer 2021). The ability of agricultural systems to cope with shocks and keep functioning in 'much the same way' is usually defined as resilience (Holling 1973; Carpenter et al. 2012; Meuwissen et al. 2019; Walker 2020). Although this is a popular conceptualization, it may lead to the most common misinterpretation of resilience as a static, fixed state, and not as a continuously unfolding property of SES (Darnhofer et al. 2016; Walker 2020). To avoid this misinterpretation, resilience has more recently been defined as the ability of SES to continually transform and adapt to social-ecological changes while learning from these processes (Folke et al. 2010; Ibarra et al. 2020; Darnhofer 2021).

The resilience of agricultural systems does not emerge in isolation; it is strongly linked to and dependent on several interconnected SES properties, including adaptability, heterogeneity, memory, redundancy, and transformability (Table 1, Appendix 1) (Folke 1998; Adger 2000; Olsson 2003; Folke et al. 2010; Aldrich 2012; Walker 2020; Kliem 2022). For example, organic farmers in France have highlighted the relevance of farm heterogeneity as a major property enhancing the resilience of their livestock farms. This heterogeneity has improved their agricultural systems' adaptive and transformative capacity by increasing farmers' resources and options to cope with unexpected changes (Perrin et al. 2020). Similar results were found in Chile, Mexico, and Guatemala where heterogeneous agricultural systems had a relatively higher resilience based on their ability to reduce their environmental impact while coping with processes of change (Calderón et al. 2018; Ibarra et al. 2019; Fenzi et al. 2022; Cortés et al. 2023). In Northern Uganda, Andersen et al. (2019) modeled epidemics in seed exchange networks. They reported that some actors exchanging potato varieties resembled each other in their functional roles, enhancing redundancy and, consequently, the system's resilience. Similarly, in Dutch arable areas, Slijper et al. (2022) found that heterogeneity and memory, two SES properties associated with learning processes, were influenced by farmers' social networks. Indeed, farmers commonly exchange experiences with peers through these channels. This way, these networks were found to be critical to increase the farmers' response options to deal with broader changes (Dardonville et al. 2020, 2022; Kharrazi et al. 2020; Walker 2020; Schreiber et al. 2023).

In current studies on the resilience of agricultural systems, we commonly find two approaches. The first focuses on biological entities, examining the components and structures that drive specific outcomes such as the robustness of the system (i. e. its capacity to withstand stresses and [un]anticipated change) (Cavechia et al. 2014; Darnhofer et al. 2016; Meuwissen et al. 2019; Slijper et al. 2022; van der Lee

Table 1. Properties of social-ecological systems related to the systems' resilience.

Property	Definition
Adaptability	Adaptability is defined as the system's capacity to adjust or change in response to broader social-ecological transformations. This property, embodied in the continuous acquisition of knowledge and its realization to cope with change, does not imply structural or systemic reconfigurations impacting the agricultural system's functions. In an agricultural system, such changes may include input substitution and adoption of new agricultural practices or management schemes, among other strategies (Bodin et al. 2006; Folke 2016; Barnes et al. 2017; Rockenbauch and Sakdapolrak 2017; Meuwissen et al. 2019; Bruce et al. 2021; Haider et al. 2021; Slijper et al. 2022).
Heterogeneity	Heterogeneity is expressed by the uneven nature of interacting actors and their behaviors, spatial location, structural organization, and history. In agricultural systems, interacting actors (e. g. plants, fungi, animals, people) are heterogeneously distributed at different scales, contributing to spatial heterogeneity in agricultural diversity (i. e. agrobiodiversity) supporting resilience through the diversity of plant genes, knowledge, experiences and skills that allow to respond in different ways to global change (Bodin et al. 2006; Cavechia et al. 2014; Quinlan et al. 2016; Caillon et al. 2017; Ticktin et al. 2018; Meuwissen et al. 2019; Wesselow and Mashele 2019; Ibarra et al. 2020; Walker 2020; Bruce et al. 2021; Sellberg et al. 2021; Fenzi et al. 2022).
Memory	Correspond to the record of historical events, collective experiences, memories, or shared knowledge that continues to influence the system's structural and functional states. Memory in agricultural systems is present at different scales from memory stored in physiological traits of agricultural species to the actors' collective memory, or experiences, to be used in times of change and uncertainty (Bodin et al. 2006; Pentland 2007; Beilin et al. 2013; Quinlan et al. 2016; Caillon et al. 2017; Wesselow and Mashele 2019; Ibarra et al. 2020; Song et al. 2020; Walker 2020).
Redundancy	Degree to which actors within a system resemble each other in their functional roles. In agricultural systems, redundancy entails the degree to which organisms, from microorganisms to social actors, act as buffers allowing to compensate in case of loss of another providing the same function. For example, in a resilient SES, if one or more social actors are weakened or lost, others can fill their position and continue to perform the function that lost actors used to provide (Bodin et al. 2006; Janssen et al. 2006; Biggs et al. 2012; Meuwissen et al. 2019; Wesselow and Mashele 2019; Song et al. 2020; Walker 2020; Bruce et al. 2021).
Transformability	Transformability is the capacity to change significantly in response to broader social-ecological changes and pressures. Resilience and transformation are not opposites, they can be complementary. Maintaining resilience at one scale can require transformational changes at other scales. Transformability entails radical changes in the system's structure or functions. In agricultural systems, transformation can occur after tipping points and collapse but may also result from a sequence of small and incremental changes leading to considerable redistributions of production factors (e. g. land, labor, capital) or yields (Darnhofer 2014; Termeer et al. 2017; Vermeulen et al. 2018; Meuwissen et al. 2019; Walker 2020; Slijper et al. 2022).

et al. 2022). This approach is generally built on a substantialist perspective which tries to bring order to experienced complexity by identifying the static foundational 'substances' or 'entities' (e. g. attributes or variables) driving change, instead of dynamic processes or unfolding relations. Thus, this first approach is based on variable-driven analyses, searching for cause-effect relationships in which ecological dynamics are conceived to be shaped by anthropogenic drivers of change (Emirbayer 1997; de Vos et al. 2019; West et al. 2020; Ibarra et al. 2022). In contrast, a second approach focuses on social actors putting human agency at the heart of the analysis along with the historical and contemporary drivers of change in agriculture (e. g. power relations and cultural norms) (Adger 2000; Darnhofer et al. 2016; Violon et al. 2016; Heikkurinen et al. 2019; Ibarra et al. 2022). Therefore, the practical application of resilience thinking seems to keep inadvertently reproducing the biological entity/human agency dichotomies that constitute a fundamental challenge to overcome in SES research (Darnhofer et al. 2016; West et al. 2020; Darnhofer 2021; Haider et al. 2021; Ibarra et al. 2022).

In reaction to such challenges, a third perspective, named the relational approach, has emerged to promote a different understanding of agricultural systems' resilience through a conceptualization of SES relations as foundational rather than entities or agents (Gonzalès and Parrott 2012; Darnhofer 2020, 2021; Ibarra et al. 2022). Here, the resilience of agricultural systems is conceived as a property that emerges from unfolding relations across scales rather than an outcome driven by substances (e. g. static 'entities or variables' acting independently) (Emirbayer 1997; Darnhofer et al. 2016; Oliveira et al. 2022). This approach highlights the unfolding social-ecological relations and worldviews shaping them, overcoming mainstream theoretical and practical limitations (Selg 2016; Cretney and Bond 2017; West et al. 2020; Gallegos-Riofrio et al. 2022; Ibarra et al. 2022). Although there are several approaches to examine crucial topics for sustainability science from a relational lens (see Latour 2007; Fuhse 2015; Cretney and Bond 2017; Heikkurinen et al. 2019; West et al. 2020, 2024; Raymond et al. 2021; and Gallegos-Riofrio et al. 2022), agricultural systems have sat times been studied using network analysis as an empirical method to examine diverse social-ecological processes focusing on the system's relational structures (Calvet-Mir and Salpeteur 2016; Rockenbauch and Sakdapolrak 2017; Bruce et al. 2021).

1.1. A relational approach for network analysis

Networks are sets of nodes representing actors interwoven through relationships, shared activities, or processes where information (i. e. nodal and relational attributes) is interdependent (Marin and Wellman 2014; Fuhse 2015; Borgatti et al. 2022). The environment where networks occur can be expressed as patterns or regularities in relations among interacting actors. In network theory, this environment is formally defined as the network structure, and the measures that allow to quantify such structure correspond to the structural and locational properties of networks, and the content of their relational ties (e. g. tie attributes) (Wasserman and Faust 1994). Respectively, those properties, also defined as network metrics, can be examined at three analytical levels named the micro, meso, and macro levels (Borgatti et al. 2022). However, there are still practical challenges to overcome, because a relational approach in network analysis should comprehend networks as part of complex systems shaped by dynamic and often unpredictable processes, not merely as structures connecting individuals acting independently, where other-than-human entities (e. g. agrobiodiversity) are also taking part of change, thus having agency (Darnhofer 2020). Therefore, a relational approach to network analysis might consider using mixed qualitative and quantitative analytical techniques, along with appropriate statistical methods, that recognize its interdependent nature (e. g. multiple quadratic assignment procedure regressions or exponential random graph models, among others) (Pautasso et al. 2013; Abizaid et al. 2018; Raymond et al. 2021; Rezvani 2022).

A relational approach in agricultural network analysis may significantly enhance our understanding of a wide range of fundamental relationships that nurture the resilience of agricultural systems, such as seed exchange (Abizaid et al. 2018; Wesselow and Mashele 2019). Our work draws on seed exchange networks (SEN) analysis – a type of social-ecological network that links actors through their agrobiodiversity exchanging practices – to exemplify the use of relational empirical methods in agricultural research. We conducted a literature review to (i) explore the progress of SEN research over the past quarter century, and (ii) identify and synthesize the network metrics used in SEN research to examine coupled social-ecological relations and understand the dynamic cycle of agricultural systems' resilience. Complementarily, we explore what a relational approach to SEN research might entail and discuss some practical implications that may arise when applying SEN analysis from a relational lens. Our work may help address some limitations in studying the resilience of agricultural systems and encourage new research using relational approaches.

2. Seed exchange networks and resilience: integrating social and ecological relations

Network analysis has been positioned as an integrative approach to study complex social-ecological relations

(Gonzalès and Parrott 2012; Pautasso et al. 2013). Rooted in a specific focus on relations and a conceptual apparatus grounded in assumptions from graph theory and statistics, network analysis has been applied in a wide range of sciences to study different phenomena under 'the mantra' that relations matter (Freeman 2004; Borgatti et al. 2009, 2022; Marin and Wellman 2014; Scott and Carrington 2014). Furthermore, it has a known potential for intermediating between micro and macro levels of analysis, from individuals and dyads (i. e. pairs of nodes) to structural configuration of SES (Emirbayer 1997; Wellman 1997; Rockenbauch and Sakdapolrak 2017). Thus, research under this approach is expected to provide answers to central challenges pertinent to sustainability science, such as promoting social learning, linking knowledge with action, and enhancing collaborative endeavor (Rockenbauch and Sakdapolrak 2017).

In the agricultural arena, network analysis has been increasingly applied to the study of diverse topics ranging from natural resource governance and agroecosystem management to agency and social innovation (Bodin and Crona 2009; Downey 2010; Pautasso et al. 2013; Haselmair et al. 2014; Calvet-Mir and Salpeteur 2016; Hauck et al. 2016; Balázs and Aistara 2018). Nevertheless, most network research to date has focused on separate social or ecological networks (Figure 1a,b) (Bodin and Tengö 2012; Sayles et al. 2019; Barnes et al. 2019). Consequently, the concept 'social-ecological networks' has emerged to embrace an integrated type of network that represents society, the environment, and their interdependencies giving room to innovative re-definitions on the inextricable interaction between people and nature in SES (Suweis et al. 2014; Bodin et al. 2016; Sayles et al. 2019). Therefore, we draw on SEN as an example of social-ecological networks that are shaped by the interactions between human and other-than-human actors through seed exchange practices (Galluzzi et al. 2010; Labeyrie et al. 2015; Calvet-Mir and Salpeteur 2016).

Like other networks involving human actors in agriculture, SEN are commonly defined as social networks (Calvet-Mir et al. 2012; Calvet-Mir and Salpeteur 2016). However, they are, in fact, social-ecological networks as they assemble human and other-than-human actors as nodes linked through seed exchange (Calvet-Mir et al. 2012; Calvet-Mir and Salpeteur 2016). SEN mobilize the multiple expressions of agrobiodiversity, which refers to the diversity present in agricultural systems from genes to crop varieties and species, through farming methods to landscape processes; besides SEN are also interwoven with knowledge and cultural meanings (Figure 1c) (Pautasso et al. 2013; Fuhse 2015). We argue that, from a relational approach aiming to emphasize the agentic capacities of other-than-human actors involved in farming processes (e. g. agrobiodiversity, assets, and worldviews), it is critical to acknowledge the multiplicity of interdependencies present in seed exchange. Then, our proposal is to recognize this complexity through a re-definition of SEN which recognizes the material and non-material expressions attached to a single term such as 'agrobiodiversity' or 'seeds'. This way, it may be possible not to limit the range of processes that could be mapped through the analysis of seed exchange networks while recognizing the role of other-than-human entities as actors also taking part of change, decisions and in the unfolding dynamics of SES resilience (Chambers and Brush 2010; Calvet-Mir et al. 2012; Tatlonghari et al. 2012; Balázs and Aistara 2018). For instance, a seed may have multiple material expressions, from a seed itself to tubers and cuttings (e. g. Díaz-Reviriego et al. 2016; Buddenhagen et al. 2017; Adam et al. 2018), or even from agricultural knowledge to social convictions (e. g. Calvet-Mir et al. 2012; Thomas and Caillon 2016; Violon et al. 2016; Mazé et al. 2021). From a single interaction, such as a seed exchange, we may observe several complex processes embedded in the agricultural context where these exchange practices occur (Figure 1) (Ellen and Komáromi 2013). These different ways of conceptualizing agrobiodiversity are crucial for recognizing the mosaic of perspectives in agricultural practices. This diversity may enable the representation of innovative narratives in policies that promote different ways of being (Novo et al. 2024).

Focusing on seed exchange as the unfolding of relational processes may allow new conceptual openings, particularly a re-focusing on the ever-present possibility of change. Moreover, considering the agency of other-than-human actors, highlights how the interaction with them affects human subjectivities and contributes to the unpredictable dynamics of change (Darnhofer 2020). In this way, a relational approach can help shorten the path to understanding the resilience of agricultural systems. Furthermore, since relational approaches are composed of multiple approaches creating spaces for intercultural dialogue, this shift in SEN research can help close the gap between social and ecological sciences by strengthening the collaboration between researchers, communities, and stakeholders (Ibarra et al. 2023; West et al. 2024). In addition to seed saving, SEN are still the main mechanism to obtain seeds in many parts of the world, mainly in rural remote locations (Altieri et al. 2012). Nevertheless, while their role in agrobiodiversity conservation has been broadly documented, research addressing the resilience of agricultural systems through these social-ecological networks is still limited (Table 2) (Chambers and Brush 2010; Delêtre et al. 2011; Calvet-Mir et al. 2012; Díaz-Reviriego et al. 2016; Porcuna-Ferrer et al. 2023). Hence, our work encourages SEN research under a relational

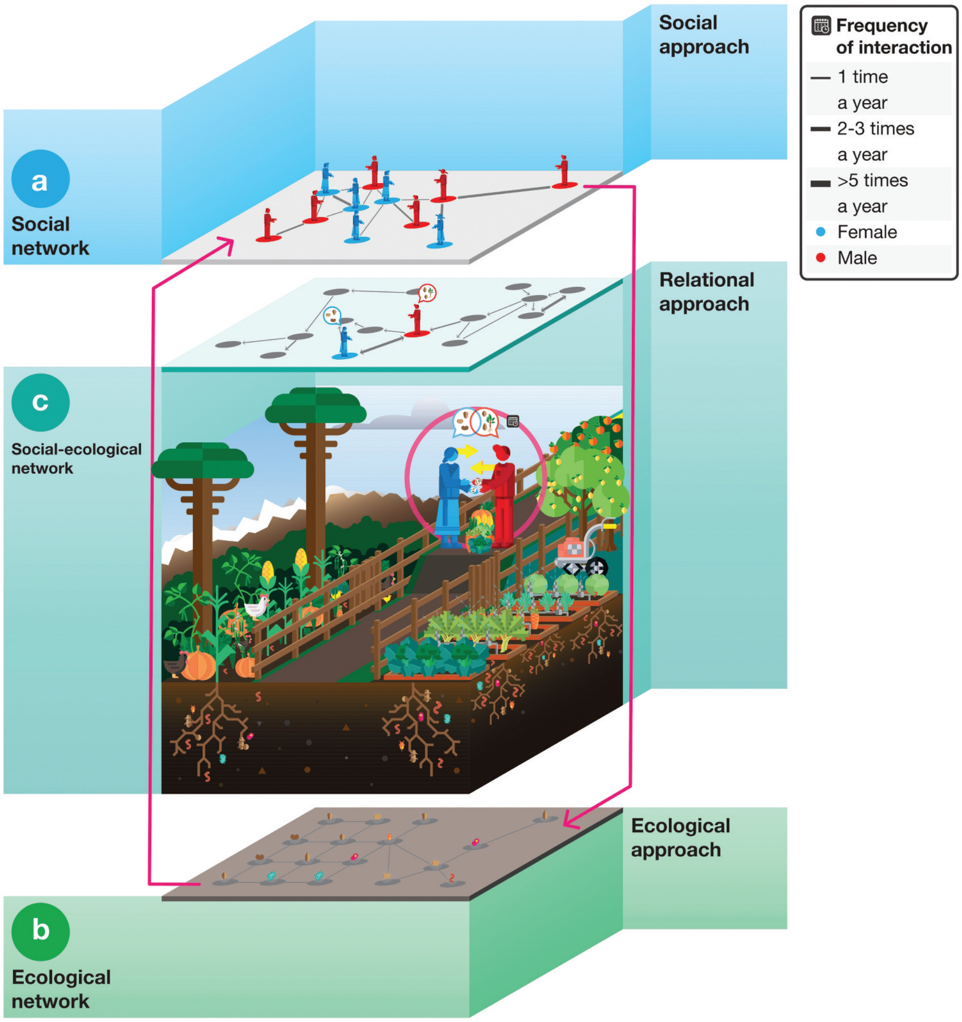

Figure 1. A relational approach for social-ecological network analysis in agricultural systems. Historically, there have been two main approaches for network analysis in agricultural systems' research: (a) the social approach focusing on human agency, and (b) the ecological approach examining biological entities. (c) We propose a third one, called the 'relational approach', based on seed exchange network analysis which considers nodal attributes and relational characteristics expressed as network ties; this approach supports the use of appropriate analytical methods for relational data. We use the frequency of exchange as a relational characteristic. As shown, seed exchange networks link social and ecological components of agricultural systems, recognizing the agency to those other-than-human actors present in such SES. These networks drive agrobiodiversity conservation and facilitate information flows increasing farmers' adaptive and transformative capacities. Moreover, the multiple connections they form also contribute to maintaining adequate levels of redundancy, nurturing the resilience of agricultural systems.

approach that supports the use of qualitative and quantitative techniques, network metrics, and appropriate statistical methods for relational data. Indeed, network metrics offer valuable insights that can be translated into policy indicators to guide decision-making and development agendas to nurture the resilience of agricultural systems.

3. Methods

We performed an Internet-based search for peer-reviewed journal articles examining agricultural systems through SEN analysis in the Academic Search Ultimate platform provided by EBSCOhost. Following the systematic literature reviewing stages proposed by Cardoso (2021), we combined English and Spanish terms that represent a variety of ways for describing our topic of interest, including '*seed exchange networks*' and one or more of the following keywords: *network analysis, resilience, seed sharing networks, plant exchange networks, redes de intercambio de semillas, seed networks, seed exchange, seed sharing, agrobiodiversity exchange, plant exchange, germplasm exchange, germplasm sharing, and seed diffusion* (Appendix 2). We reviewed research papers published over a period of 25 years from January 1997 to February 2022. Complementarily, we examined the publications returned in the search for relevant papers which were not identified by the searching platforms (Machi and McEvoy 2016); this literature was imported to Mendeley removing duplicates. This search returned 527 papers, of which 192 were screened using the abstract and main text if necessary.

Table 2. The role of seed exchange networks in resilience related processes of agricultural systems.

Resilience related process	Functions of social-ecological networks
Adaptability, heterogeneity, and transformability enhancement	Social-ecological networks such as seed exchange networks, facilitate the exchange of genetic material, and agricultural knowledge among farmers. This agrobiodiversity is vital for the resilience of agricultural systems because it provides a broader genetic base, making them less susceptible to biological hazards and changing environmental conditions. On the other hand, the diversity of knowledge and experiences within the network members opens opportunities to cope with unexpected change in innovative ways (Buchmann 2009; Calvet-Mir et al. 2012; Cassidy and Barnes 2012; Rockenbauch and Sakdapolrak 2017; Wesselow and Mashele 2019; Porcuna-Ferrer et al. 2020, 2023; Bruce et al. 2021; McDaniel et al. 2021).
Fostering crop improvement and innovation	Seed exchange networks connect actors from different backgrounds promoting the sharing of knowledge and expertise among farmers. Through these networks, farmers can learn from their peers innovative farming practices, seed-saving techniques, and traditional knowledge related to crop cultivation. This exchange of information fosters continuous improvement in agricultural practices and contributes to the development of innovative strategies to ride the waves of change (Janssen et al. 2006; Isaac et al. 2007, 2014; Calvet-Mir et al. 2012, Isaac, 2012; Labeyrie et al. 2015; Porcuna-Ferrer et al. 2023).
Food security promotion	These networks contribute to food security by ensuring that farmers have access to a wide range of seeds and even animal breeds, including traditional and locally adapted varieties. In times of food scarcity or crop failure, these genetic diversity can serve as a buffer, providing farmers with alternative options for maintaining food production (Coomes et al. 2015; Helicke 2015; van Niekerk and Wynberg 2017; Mbugua 2019; Schramski and Barbosa de Lima 2022).
Maintenance of cultural heritage	Many traditional seed varieties are deeply embedded in the cultural identity of communities and are often associated with specific rituals, stories, and culinary traditions. By exchanging agrobiodiversity through these networks, farmers help safeguard cultural diversity and maintain valuable agricultural heritage. Moreover, by facilitating information and knowledge flows, these networks simultaneously nurture memory in social-ecological systems (Reyes-García et al. 2014; Salpeteur et al. 2017; Gallois et al. 2018; Cámara-Leret et al. 2019).

Finally, 130 were retained as candidates for the review.

Papers were included in the final review if they met the following criteria: (1) They were empirical or substantive SEN studies based on primary field or desk research, case-study synthesis, or computational modeling. Review papers were included only for discussion purposes; (2) Papers needed to explicitly observe and analyze agrobiodiversity exchange relationships using network analysis as chief analytical method (Appendix 3); (3) Papers addressing or discussing agricultural systems' resilience were desirable, but this was not an excluding criterion. Publications were included and excluded according to the Preferred Reporting Items for Systematic Reviews (PRISMA) Statement (Page et al. 2021). Therefore, only 45 case studies examining SEN were considered in the final set (Appendix 4). The selected studies were reported in a literature matrix which contained information about the authors, year of publication, objectives, theoretical framing, network construction, addressed topics, and methods used (Calvet-Mir and Salpeteur 2016; Cardoso 2021). We also stratified the reviewed studies by geographic region based on the location where they were held according to the World Bank world region classification (World Bank 2018).

3.1. Coding and analysis

Based on the perspectives provided by Borgatti et al. (2022); Cretney and Bond (2017); Darnhofer (2020); Emirbayer (1997); Gallegos-Riofrio et al. (2022); Raymond et al. (2021); and West et al. (2020), we classified the methods used for network analysis in our sample as either partially relational or fully relational approaches. These categories were defined to determine whether the analytical methods used in SEN research align with the relational approach described above, and the methods supported by the aforementioned authors. We classified studies as 'relational' if they met the following criteria: (1) they used appropriate statistical models for network analysis, meaning models based on the inherently relational nature of network data; (2) they considered relational attributes, such as tie strength, to address their research objectives; and (3) they examined agrobiodiversity exchange from a broader relational perspective that incorporated both qualitative and quantitative data. Conversely, we classified studies as 'partially relational' if they: (1) used standard statistical models based on independence assumptions, such as linear regression, to analyze network data; (2) did not considered relational attributes in addressing their objectives; and (3) examined agrobiodiversity exchange solely through graphical or descriptive network analyses. To identify the network metrics used in SEN research for examining social-ecological relations to understand the resilience of agricultural systems, we constructed a matrix listing the metrics used in the reviewed case studies and recorded their description. The listed metrics were categorized according to the network analytical levels described by Borgatti et al. (2022) (i. e. the network—macro, subgroup—meso, and dyadic—micro, analytical levels). For each case, we also reported the multiplicity of metric names and recorded how those metrics inform about the resilience of agricultural systems through their relationship with the SES properties described in Table 1. In addition, we triangulated this information with complementary evidence reported in network analysis studies in other SES.

4. Results

We identified 45 case studies, spanning five continents, that used seed exchange network analysis to explore a wide range of processes related to the dynamic cycle of agricultural systems' resilience (e. g. social capital, resource flows, knowledge transfer, and risk response) (Figure 2a, Appendix 5). Our sample included publications from journals that range from social sciences (e. g. Current Anthropology), through agricultural (e. g. Phytopathology), to interdisciplinary studies (e. g. Sustainability) (Appendix 4). Although we found case studies worldwide, most were conducted in Sub-Saharan Africa (14), Latin America and Caribbean (11), and East Asia and Pacific (7); and published after 2010 (Figure 2b). There were several material expressions associated with the term 'seed' as part of the agrobiodiversity spectrum. They range from seeds to diverse expressions that also included agricultural products for human consumption (edibles) and agricultural knowledge (e. g. Calvet-Mir et al. 2012; Reyes-García et al. 2013; Gupta et al. 2020; Schramski and Barbosa de Lima 2022) (Appendix 3). In some cases, more than one agrobiodiversity material expression was observed on a single exchange network. The highest diversity of expressions for 'seeds' were found in Latin America and Caribbean, and East Asia and Pacific, regions represented by Global South countries (Figure 2c).

We found that most SEN research did not follow a relational approach, since most of the studies were conducted using standard statistical models (Figure 2a). Studies following a relational approach, based on their analytical methods, represented less than half of the total reviewed cases (Appendix 4). Three types of statistical inference models developed for network analysis were used in our sample, including the Dyadic multiple regression analysis (DRA), the Multiple Quadratic Assignment Procedure Regressions (MQAPs), and the Exponential Random Graph Models (ERGMs); the ERGMs were the most popular. While some of the reviewed studies had not limited their analyses to a single topic, these statistical methods were used to address topics that range from key actor identification to seed flow and crop varietal distribution.

4.1. Network metrics for examining coupled social-ecological relations in agricultural systems

We identified 24 network metrics used in SEN research to examine structural and locational properties of networks. Most studies focused on examining structural properties such as the network 'density' and 'modularity', and locational properties such as the 'actors' centrality'. Although our sample considered the mapping of agrobiodiversity exchange as an inclusion criterion, we found that it is common to observe several relationships on a single seed exchange network (Appendix 6). Following our categorization by network analytical level, we found that 17 out of 24 metrics were commonly used to examine networks at the macro level (Table 3). These structural metrics were a typical starting point in SEN analyses where the most popular structural metric in SEN research was 'density', a metric that refers to the proportion of ties that are present out of all possible ties in an observed network. While most structural metrics reported in Table 3 refer to structural metrics, more than half of the metrics were also used at the meso analytical level to inform subgroup compositional mechanisms (e. g. 'homophily'). We also found a few examples examining network topologies, or the way in which the nodes and ties are arranged within a network (e. g. 'cliques' and 'components') (Figure 3a,b). Studies following both analytical levels, macro and meso, also included averaged versions of 'centrality' metrics on their estimations, a set of locational metrics that inform about the actors' function in their network based on the number of exchange relationships they form (e. g. 'average degree centrality').

A small proportion of studies examined 'centralization', a metric that refers to the extent to which a network is dominated by one node, in this context, a single farmer influencing control over its peers. Over a third of the reviewed cases analyzed network topologies relevant to the study of exchange networks (e. g. 'dyad census', 'reciprocity', and 'transitivity'). Like other network topologies, these metrics were used to understand variations on 'reciprocity' and 'transitivity' in agrobiodiversity flows, mainly in directed networks. Finally, we found that it is uncommon to examine network metrics such as 'size' or the 'proportion of isolates' as part of the overall analyses. These metrics were typically explored for descriptive purposes in over a quarter of the reviewed studies.

At the micro analytical level, we identified seven locational metrics (henceforth referred to as nodal metrics), which are broadly used in SEN research to measure dyadic relationships (i. e. relations between pairs of nodes) (Table 4); all of them are extensions of 'centrality'. In our sample, 'degree centrality' and its extensions for directed networks (i. e. 'in-degree' and 'out-degree'), represent the most popular nodal metrics used in seed exchange studies. Following in popularity, almost half of SEN studies used 'betweenness' to identify if a node is important in connecting SEN structures (Labeyrie et al. 2021). Less than a fifth of the reviewed studies employed uncommon extensions of 'centrality' in their analyses (e. g. 'closeness', 'Eigenvector', and 'PageRank' centrality) (Figure 3). 'Closeness centrality' was the most popular

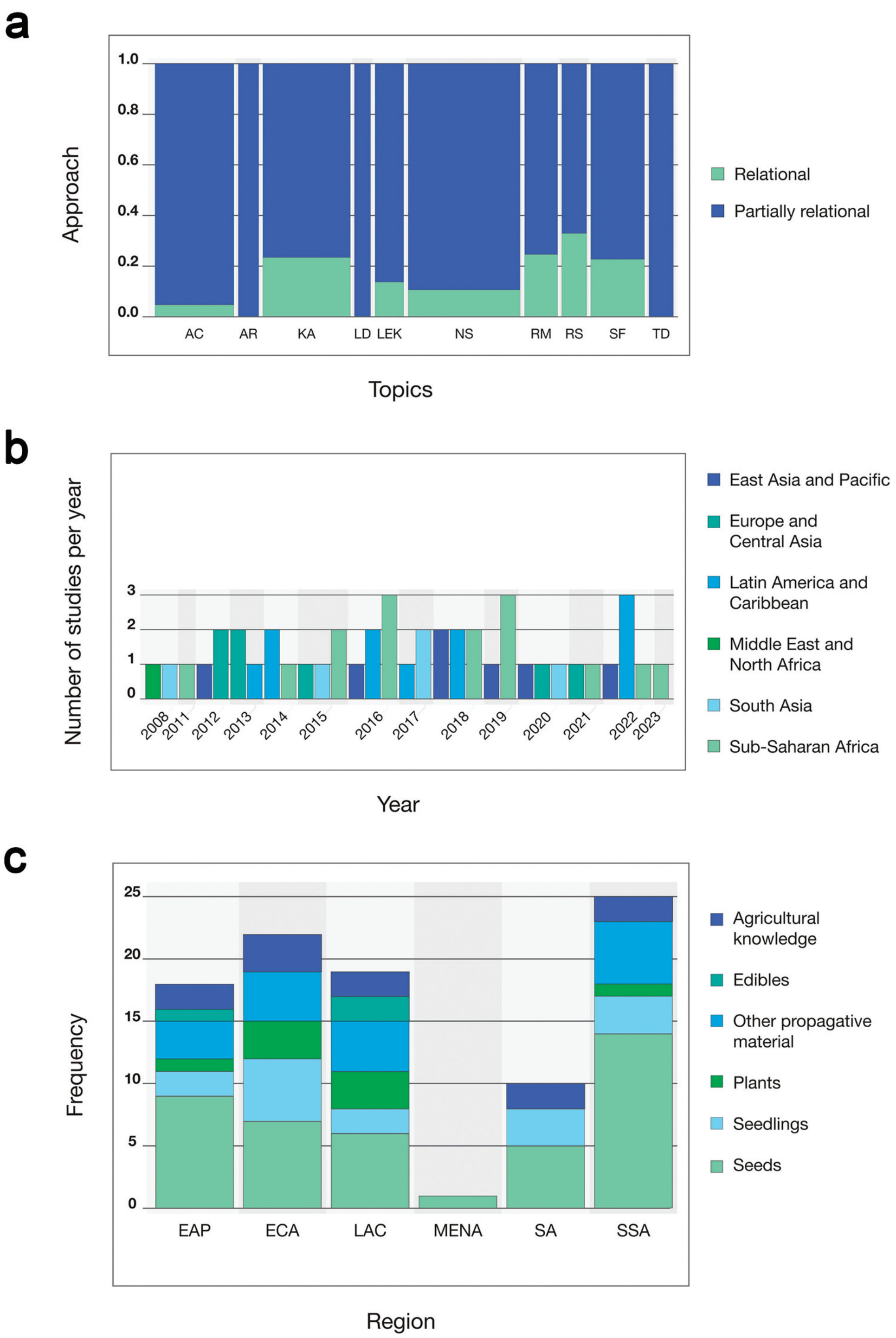

Figure 2. Publication patterns of the reviewed studies. (a) Seed exchange network studies by topic and methodological approach. Most of seed exchange network studies did not follow a relational approach based on the analytical methods used to conduct such research. We found that there is a popular interest on key actor identification and social structure exploration through SEN analysis. Topic acronyms: agricultural system's resilience (AR), agrobiodiversity conservation (AC), key actor identification (KA), livelihood diversity (LD), local ecological knowledge, knowledge transfer and/or information spread (LEK), network structure and/or social organization (NS), resource management and access (RM), risk spread (RS), seed flow and crop varietal distribution (SF), and technology diffusion/adoption (TD). (b) Seed exchange network studies conducted per region. Most seed exchange studies were conducted after 2010. (c) Agrobiodiversity expressions on the reviewed case studies, stratified by region. There are several agrobiodiversity expressions attached to the term 'seed', most diverse expressions were identified in global south countries. Region acronyms: East Asia and Pacific (EAP), Europe and Central Asia (ECA), Latin America and Caribbean (LAC), Middle East and North Africa (MENA), South Asia (SA), and Sub-Saharan Africa (SSA).

centrality extension used to examine agricultural systems' processes through SEN analysis. On the other hand, we found a limited proportion of case studies including relational attributes (i. e. 'tie attributes') in their analyses. Nevertheless, the most popular relational attributes included in SEN analyses were relationship categories (e. g. kinship and friendship) and quantities or frequency of exchange; expressed as the 'tie strength'

(Appendix 7). For all analytical levels, we found that there were several alternative names to describe a single metric (Tables 3 and 4).

4.2. Understanding the resilience of agricultural systems using network metrics

We did not find a single case explicitly examining agricultural systems' resilience through SEN analysis. However, we found that 6 out of the 45 reviewed studies discussed resilience in their analyses, pointing out that SEN analysis may provide new insights in the understanding of this dynamic property of SES (e. g. Cavechia et al. 2014; Violon et al. 2016; Ticktin et al. 2018; Wesselow and Mashele 2019; Song et al. 2020; Fenzi et al. 2022). Furthermore, the set of metrics we reported have been associated directly and/or indirectly with the systems' resilience through their relationship with interconnected SES properties, including adaptability, heterogeneity, memory, redundancy, and transformability (Figure 4a). We found that 'density', 'modularity', and 'centrality' were the structural metrics most discussed in SES' resilience literature. Apart from 'modularity' any metrics were particularly examined regarding this subject at the meso analytical level. On the other hand, at the micro level, 'degree' and 'betweenness centrality' were the most popular nodal metrics linked to the referred SES properties (Figure 4b). The main properties of SES linked to network metrics for examining social-ecological relations to understand the resilience of agricultural systems through network analysis were heterogeneity, adaptability, and redundancy. However, most studies recognized the relevance of analyzing the reported network metrics together rather than in isolation; only one study examined SEN using a single metric (i. e. Aw-Hassan et al. 2008).

5. Discussion

In this study, we draw on social-ecological network (SEN) analysis as an example of the growing body of empirical relational methods to address different sustainability-related issues, such as the resilience of agricultural systems. We position SEN as an example of networks that allow to examine the structural patterns of complex SES and may help avoiding the reproduction of the social/ecological dichotomies that represent a significant challenge to overcome in SES research (Cretney and Bond 2017; West et al. 2020; Ibarra et al. 2022). In this study, we have shown the network metrics used in SEN research to examine coupled social-ecological relations to better understand the resilience of agricultural systems. These metrics are relevant to encourage new SEN studies that can inform policy and decision making in agriculture from a relational approach. Some practical implications of a relational approach to SEN research are discussed below.

Although network analysis has been presented as a promising empirical method in relational thinking, we showed that SEN studies may be 'in tension' with a relational approach for SEN research as some substantialist assumptions still prevail in the reviewed studies. This means that those studies interpret actors as autonomous individuals having specific attributes

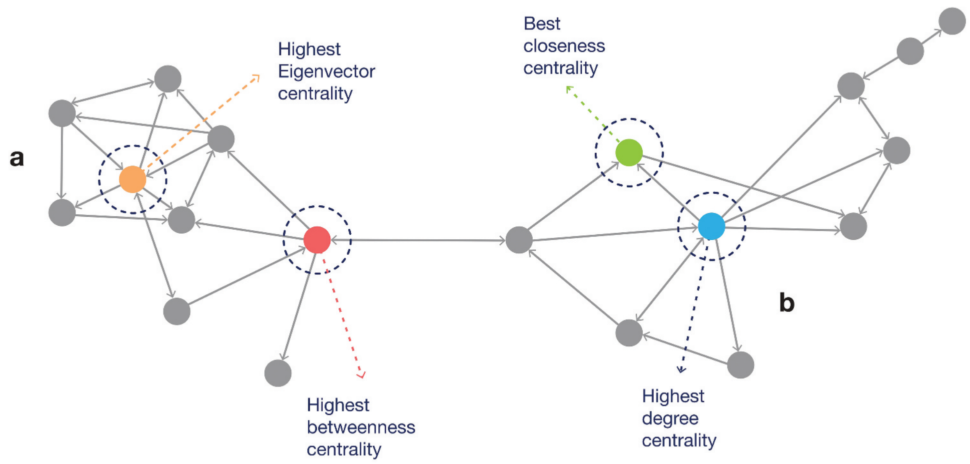

Figure 3. A graphical representation of a seed exchange network structure. It depicts a directed network composed of (b) three 'components' or connected subgroups wherein all nodes are connected directly or indirectly with at least one tie and (a) one 'clique', or dense subgroup where all nodes are adjacent to each other. In the figure, the node with the highest 'degree centrality' has seven ties with other actors in the network (blue node). The node with the best 'closeness centrality' is the one with the shortest path connecting it with others in the network (green node). The red node has the highest 'betweenness centrality', functioning as an intermediary connecting subgroups within the network. On the other hand, 'eigenvector centrality' gauges the influence of the orange node, deemed the most influential in the network based on the 'degree centrality' of its neighbors. This depiction underscores how each centrality notion provides distinct insights into an actor's influence within their network.

Table 3. Structural and subgroup metrics used in seed exchange networks research.

Metric	Description	Alternative names	Analytical level	Frequency
Average betweenness centrality	This metric measures the proportion of actors functioning as bridges connecting others in the network. It refers to the mean of centrality betweenness scores reported in a network.	Mean betweenness	N, S	1
Average degree centrality	This metric informs the mean degree centrality in a network. Although this metric can be estimated regardless direction of the network, it is also possible to estimate the average in/out-degree scores for directed networks.	Average degree, average in/out-degree; mean centrality; network centrality; network in/out-degree	N, S	7
Average path length	Refers to the mean of the shortest distance between each pair of actors in a network.	Mean closeness centrality; average geodesic distance; distance; diameter; mean of the shortest path	N, S	7
Centralization	Centralization is a metric that inform about the overall structure of networks. Expressed as a percentage, this measure refers to the extent to which a network is dominated by one actor. It shows the tendency for a few people to centralize the existing connections denoting the proportion of the structure that resembles a star-shaped structure (i. e. the representation of a centralized network).	Network centralization; network centralization index; degree of nestedness; nestedness	N, S	7
Cliques	This metric counts the number of cliques in a network. A clique in a network is a maximal complete subgroup of three or more actors. It consists of a subset of nodes, all adjacent to each other, where no other actors are also adjacent to all the clique's members.	n-cliques	N, S	3
Components	This measure refers to the number of components or connected sub-networks in which all actors are connected directly or indirectly with at least one tie. Unlike a clique, no restriction regarding the adjacency within all component members is stated. In other words, a component is a subgroup with low density.	Clusters; diversity; main components; number of components	N, S	7
Density	This metric, expressed as a percentage, corresponds to the proportion of existing connections in the network relative to the maximum possible number of connections.	Connectivity; cohesiveness	N, S	20
Dyad census	The dyad census provides a count of dyads, or paired relationships. This measure is useful to quantify mutual relations in a network, including such mutual but asymmetrical relations.	Dyads	N	1
Heterophily	Heterophily refers to the tendency to avoid forming ties with certain actors within a network based on their nodal attributes. This metric is built on the notion that social-ecological attributes may perform selectively in subgroup formation, acting as filters.	NF	N, S	3
Homophily	Analogous to heterophily, homophily is defined as the tendency of actors to form ties with those others who share similar attributes. This measure refers to the propensity of actors to have greater contact with individuals from similar attribute assemblies.	Assortativity; homophilous relationships	N, S	9
Isolates	This metric quantifies the number of excluded actors in a network (i. e. actors not forming ties). This measure can be expressed as a number or percentage.	Proportion of isolates	N	2
Modularity	Modularity refers to a structural metric that informs about subgroups built on denser ties between their members. Modularity expresses the proportion of subgroup formation in the observed network. It considers the number of cliques and components equally.	Clustering coefficient; modularization	N	4
Reciprocity	Derived from the dyad census, the reciprocity observed in a network correspond to the number of mutual ties (e. g. mutual nominations) among network actors. This measure refers to the proportion of reciprocal ties in the network when expressed as a percentage.	Arc reciprocity; dyad reciprocity	N	9
Size	The network size is a descriptive metric that refers to the number of actors in the network. Sometimes the number of ties in the network is also reported as part of the network size.	Network structure; network size	N	10
Transitivity	The transitivity of a network corresponds to the proportion of observed triads (i. e. three actor subgroup) concerning all possible triads.	Triadic transitivity	N	5
Triad census	Since the smallest group structure is the triad, the triad census corresponds to a count of the triads of a given network. The triadic terms are evaluated using pre-established criteria to classify all directed triads into one of 16 categories.	NF	N	1
Tie strength	This metric is the expression of the tie attributes. It may be displayed making the thickness of darkness of lines proportional to its strength for graphical analysis; or quantitatively evaluating attributes such as exchange frequency.	Tie attribute	N	3

Analytical levels: *N* = Structural metric; S = Subgroup metric; NF = Not found.

Table 4. Nodal metrics used in seed exchange networks research.

Metric	Description	Alternative names	Frequency
Betweenness centrality	Regardless direction on a network, betweenness centrality measures an actor's relationship with others in terms of the position it occupies to control flows in a network. It measures the number of times an actor lies on the shortest path between all other sets of actors.	Betweenness; egobetweenness; brokerage	22
Closeness centrality	Closeness centrality measures attempt to capture the notion that an actor is central if it is close to many other actors in a network. This metric measures the minimal distance from one actor to all other members in the network; a smaller number indicates it has more direct connections to others.	Closeness; harmonic closeness centrality; proximity; short path length; in/out closeness; geodistance	9
Degree centrality	Degree centrality represents an actor's level of direct connectedness with others in the network. This metric counts the number of ties an actor has with any given node in a network (both incoming and outgoing ties).	Centrality; degree; frequency of mention; node degree; node representativeness; node strength; total degree	33
Eigenvector centrality	Eigenvector centrality is defined as a weighted version of degree centrality based on the notion that the more central the neighbors of an actor's are, the more central that actor is. This metric measures the centrality of an actor as a proportion to the sum of centralities of the actors to which it is adjacent.	Weighted degree; normalized degree; standardized degree	4
In-degree	In directed networks, this metric counts the number of ties directed to an actor. Hence, in-degree refers to the number of nominations an actor received from others in the network.	Actor influence; ego size-in; incoming links; indegree; in-strength	21
Out-degree	Correspondingly, out-degree measures the number of ties that point out from a given node in directed networks. In the context of seed exchange, this metric is suitable for identifying prestigious seed givers.	Actor activity; ego size-out; out-strength; outdegree; outgoing links	16
PageRank centrality	A special case of eigenvector centrality suitable for directed networks. This centrality measure is a weighted sum reflecting both direct ties to an actor (degree) and the degree of its neighbors.	NF	1

Footnote: NF = Not found.

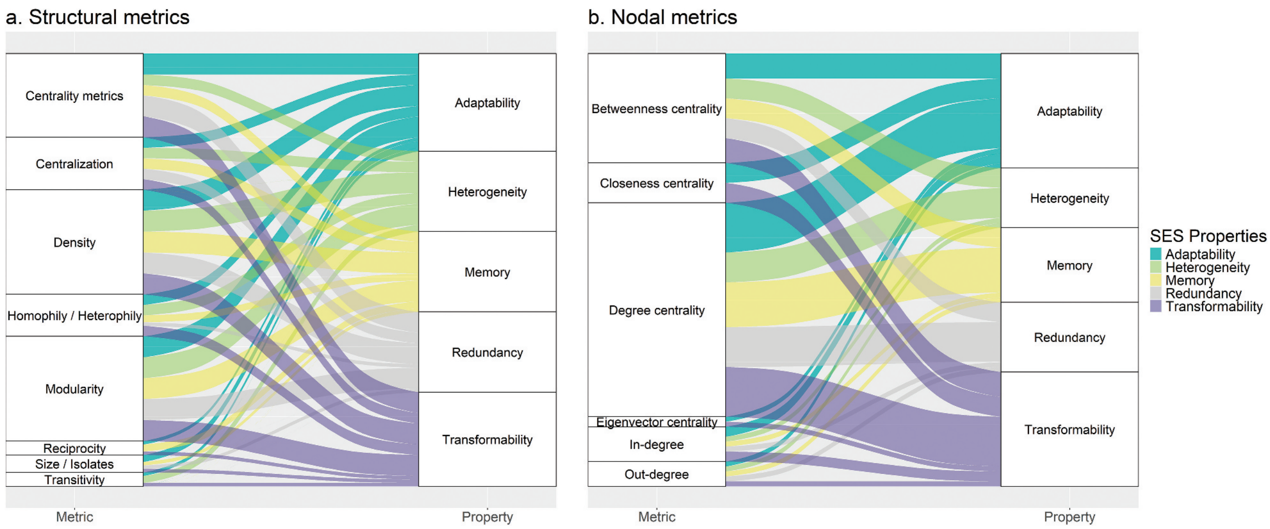

Figure 4. Trends in the association between network metrics and social-ecological system properties. The reported network metrics were related to five properties of social-ecological systems (SES) longstanding discussed in the resilience literature. (a) At the structural level, the trend in metric use was consistent with the popularity of the primary metrics used to describe networks (e. g. 'density', 'modularity', and averaged extensions of 'centrality'). (b) At the micro analytical level, 'degree' and 'betweenness centrality' were the most popular nodal metrics associated with the referred SES properties in seed exchange network studies. In both cases, the visual interconnectedness between network and SES properties highlights the relevance of examining the reported metrics together rather than in isolation.

(e. g. nodal metric values) that explain outcomes, for example, agrobiodiversity conservation (see Darnhofer 2020; Darnhofer et al. 2016; Emirbayer 1997; Latour 2007; Pan 2021; and West et al. 2020 to deepen on the ontological debate of the substantialist and relational approaches). This tension is evident in the treatment of relational data and networked actors as independent individuals (or variables) rather than dynamic interconnected actors capable of fostering change together. However, we acknowledge the limitations that come with our approximation to the relational approach. Since our analysis has substantially focused on the analytical methods used in SEN research, there is a risk of reducing the relational approach to a merely 'methodological turn' on SEN research. Nonetheless, it is crucial to recognize that adopting a relational approach in social-ecological research transcends the use of appropriate methods for analyzing relational data (Darnhofer 2020). Thus, we argue that a relational turn is also necessary in SEN research for re-imagining new possibilities for social-ecological research to build a new policy landscape that considers the complexity of SES through the agency of human and other-than-human actors. While our sample may be considered small, it is consistent with the ones used to conduct similar reviews on seed exchange and social-ecological networks (e. g. Pautasso et al. 2013; Labeyrie et al. 2015; Calvet-Mir and Salpeteur 2016; Sayles et al. 2019). Those similar SEN reviews also support our results regarding the multiple material expressions of 'seeds' mapped through SEN, in which Global South countries show the highest diversity for seed material expressions. Although we found that the Middle East and North Africa region present a single case tracing seeds on their literal material expression, this result should be taken with caution because there may be several agrobiodiversity material expressions in that region. However, the study by Aw-Hassan et al. (2008) represents the only example documented there.

Even when agricultural systems are examined through SEN, most of the analytical methods used in such studies make substantialist assumptions. For example, we found that the most frequent omission in the reviewed studies was the data treatment under analytical approaches built on independence assumptions. Most SEN studies followed a perspective focused on actors' individual characteristics rather than relational. This means that, in addition to such treatment, in most cases relational attributes were not considered either (i. e. the content of the relational ties). This result confirms the arguments provided by Emirbayer (1997); Gonzalès and Parrott (2012); Ibarra et al. (2022); and West et al. (2020) who found a similar trend in related research areas and discuss existing methods to analyze social-ecological complex systems. Despite this limitation, our work indicates a growing use of network analysis as a prominent empirical relational method to deal with coupled social-ecological relations, based on the increasing popularity of SEN research in the past quarter century.

SEN researchers have often reported the convenience of using a quantitative network analysis approach to study social-ecological relations. This finding is consistent with reviews that have highlighted network analysis as a promising empirical method for the study of complex social-ecological networks in agricultural contexts and other SES (Gonzalès and Parrott 2012; Pautasso et al. 2013; Bodin et al. 2016; Calvet-Mir and Salpeteur 2016; Sayles et al. 2019; Labeyrie et al. 2021). Nevertheless, it is critical to keep in mind that conducting network analysis does not necessarily mean following a relational approach just because it focuses on relations (Emirbayer 1997; Freeman 2004; Borgatti et al. 2009; Darnhofer et al. 2016; Darnhofer 2020, 2021). A relational approach in SEN research should reflect the inextricable interaction of human and other-than-human actors considering mixed data (i. e. qualitative and quantitative) to better interpret the information provided by the available network metrics (Caillon et al. 2017; West et al. 2020; Luxton and Sbicca 2021). Moreover, as stated by Emirbayer (1997) and Darnhofer (2020), a relational approach to SEN research should conceptualize seed exchange as a relational process shaped by human and other-than-human actors, thus inviting us to move from identifying separate entities or agents, towards thinking in terms of processes of interdependence, entanglement of ideas, and materialities. This way, seed exchange research to date differs with both a relational approach and the social-ecological network approach proposed by Barnes et al. (2019); Bodin et al. (2019); Bodin and Tengö (2012); and Sayles et al. (2019). A relational turn in SEN research may offer a deeper understanding of the resilience of agricultural systems (Luxton and Sbicca 2021).

Exchange networks represent transaction events between at least two individuals (Lomnitz 1977). By moving resources and providing support in times of uncertainty, exchange networks play a critical role in fulfilling livelihood challenges, especially in remote areas (Lomnitz 1977; Schweizer and White 1998; Delêtre et al. 2011). Thus, it is not a surprise that the most popular applications of SEN analysis were for identifying key territorial actors and examining social composition (i. e. network structure). Agrobiodiversity conservation, crop varietal distribution, technology adoption, and disease spreading risks were other popular processes addressed through SEN analysis in our sample, a result consistent with Calvet-Mir and Salpeteur (2016). As we showed, there are limited SEN studies discussing their role on the resilience of agricultural systems. Despite this result, we acknowledge that our review cut-off may have omitted the progress that has recently been made in SEN research (e. g. Porcuna-Ferrer et al. 2023). Anyhow, we found a wide range of SEN studies examining network metrics and linking their outcomes with diverse SES properties associated to the systems' resilience (Appendix 2).

The main properties of SES linked to network metrics for examining resilience through network analysis were heterogeneity, adaptability, and redundancy. For example, Abizaid et al. (2016, 2018) found that exchange networks of plant material in the Peruvian Amazon showed a positive association between homegarden agrobiodiversity and the frequency of exchanges per household (i. e. high 'degree centrality'). However, since the households with the highest diversity were constant in seed exchange activity, if an unexpected change affected their agricultural resources and there were no households fulfilling the same role in promoting agrobiodiversity within their seed exchange network (i. e. low redundancy), the systems' resilience may be undermined. This way, this finding provides evidence of the link between SEN nodal metrics such as 'degree centrality' and the systems' heterogeneity, and redundancy. Aguilar-Støen et al. (2009) and Coomes (2010) observed that the agrobiodiversity in Mexican and Amazonian homegardens, respectively, is strongly influenced by access and exchange of planting material (e. g. seeds and seedlings); this result suggests that exchanging networks are critical for increasing heterogeneity in agricultural systems as they facilitate agrobiodiversity flows that allow to respond in different ways to global change. Finally, in two cases in the Iberian Peninsula, the number of links that an individual had in the observed exchange network was positively related with their agricultural knowledge and on-farms' agrobiodiversity (Calvet-Mir et al. 2012; Reyes-García et al. 2013). This finding provides evidence of the role of such networks in adaptability and memory building, two SES properties embodied in the continuous acquisition of knowledge and its realization to cope with change (Folke et al. 2010, 2016; Armsworth et al. 2017). All these results are consistent with the arguments provided by Bodin et al. (2006); Bodin and Crona (2009); Calvet-Mir et al. (2016); Newman and Dale (2005); Janssen et al. (2006); Cassidy and Barnes (2012); Rockenbauch and Sakdapolrak (2017); and Wyss et al. (2015) who have provided evidence of the effect of the structural and locational properties of social-ecological networks as the patterns behind the resilience dynamics in SES.

Most of the reviewed studies have examined structural metrics such as the network 'density', 'modularity', and 'centralization' to describe the context where seed exchange thrives. We found that 'density' was the most popular descriptive measure and often the first metric observed while conducting SEN analysis. These structural metrics may provide opportunities and constraints for the resilience of agricultural systems as they may act selectively depending on the processes examined through network analysis (Wasserman and Faust 1994; Bodin et al. 2006; Janssen et al. 2006; Bodin and Crona 2009). For example, a network 'density' higher than 30% in social-ecological systems is considered a good indicator of network cohesion and positive to facilitating information flows (Borgatti et al. 2009; Albizua et al. 2020; Labeyrie et al. 2021). However, a very high 'density' can also constrain resilience by generating homogenization of information and knowledge, which results in less heterogeneity and/or reduced capacities to adapt or transform under changing conditions (Bodin and Crona 2009).

As suggested by Mazé et al. (2021), examining 'modularity' in seed exchange networks is complementary to network 'density' evaluations. 'Modularity' provides information relevant to take advantage of the geographical proximity to facilitating decision making, reducing transaction costs, and enhancing innovation processes (Moslonka-Lefebvre et al. 2009; Thomas et al. 2011; Pautasso and Jeger 2014; Coomes et al. 2015; Talukdar and Choudhury 2017; Schramski and Barbosa de Lima 2022). As observed in some SES, a modular structure with a certain degree of subgroups may enhance the maintenance of heterogeneity in agricultural systems since the combination of subgroup experiences might confer diversified information to ride the waves of change and uncertainty (Reyes-García et al. 2010; Kawa et al. 2013). However, if the subgroups in the network lack interaction, the structure could be fragmented into separated parts (Newman 2006). Thus, it has been suggested that to nurture resilience, different subgroups should interact, and seed exchange networks need to have actors connecting subgroups acting as bridging ties and facilitating agrobiodiversity and information flows. As reported by Isaac et al. (2014); Janssen et al. (2006); and Newman and Dale (2005), the actors with higher 'betweenness centrality' connecting subgroups can increase the module's adaptive and transformative capacities. Simultaneously, they can enhance the system's heterogeneity by increasing knowledge diversity and resource access within their groups.

None of the referred structural metrics inform independent properties in networks and SES. Indeed, they inform about relational processes that posit specific structural outcomes which may then be evaluated against observed network data (Wasserman and Faust 1994; Prell et al. 2009). Thus, at the structural level, 'centralization' represents another complementary metric to examine the social-ecological processes involved in the resilience dynamic cycle, such as influence and power relations (Abizaid et al. 2016; McGuire and Sperling 2016; Albizua et al. 2020; Labeyrie et al. 2021). A highly centralized seed exchange structure might constrain the resilience of agricultural systems because of the control that a single actor can posit over their neighbors, influencing their decisions or limiting their resource access (Bodin et al. 2006; Scott and Carrington 2014; Guerrero et al. 2020).

The reviewed studies confirmed that nodal metrics examining actors' roles in seed exchange relational structures are the most popular in SEN research because they provide individual values compatible with observational statistical methods such as multiple regression analysis. A large proportion of the studies examining SEN have exclusively focused their analyses at the micro analytical level, emphasizing actor characteristics and dyadic relations. This result is consistent with the topics identified as popular in SEN research, since nodal metrics are used to assess the territorial influence of actors in their social-ecological network (Bodin et al. 2006; Janssen et al. 2006; Bodin and Crona 2009; Cassidy and Barnes 2012). Nevertheless, despite this methodological challenge, 'centrality' metrics remain useful for examining social-ecological relations to understand the resilience of agricultural systems as they provide relevant information about the farmer's access to collective agricultural resources such as the heterogeneous expressions of agrobiodiversity (e. g. seeds, knowledge, agricultural information, among others) (Bodin et al. 2006; Janssen et al. 2006; Calvet-Mir et al. 2012; Labeyrie et al. 2021).

'Betweenness' and 'degree centrality'–including its extensions for directed networks– (i. e. 'in-degree' and 'out-degree') are widely used in SEN research to inform redundancy in exchange networks based on the notion that an actor's influence is given by their intermediating function on their network or the number of direct relations they possess, respectively (Freeman 1977; Ellen and Komáromi 2013; Lope-Alzina 2014; Barbillon et al. 2015; Borgatti et al. 2022; Llamas-Guzmán et al. 2022). Recently, Chen et al. (2019) and Tudisco et al. (2017) have argued that uncommon 'centrality' extensions such as 'closeness' and 'Eigenvector centrality' may provide new insights into the study of social-ecological networks because the information they provide is based on the notion that any individual characteristic is also influenced by the set of attributes of their related neighbors. Thus, recognizing the relational nature of network actors' interconnectedness using these metrics may broaden relational approaches to SEN (Estrada and Bodin 2008; Huang et al. 2014; Nita et al. 2016).

Seed exchange networks fulfill an important role in maintaining agrobiodiversity and social cohesion, enhancing the systems' resilience (Helicke 2015; Darnhofer et al. 2016). They remind us that SES do not consist of static components, but unpredictable unfolding relations acting together as a whole (Ibarra et al. 2022). Our review underscores the importance of integrating both qualitative and quantitative analytical methods to gain insights into the study of the resilience of agricultural systems using network analysis. As mentioned earlier, a relational approach to SEN research may enable new possibilities for enhancing sustainable agricultural transformations (Darnhofer et al. 2016; Darnhofer 2020). A relational approach to SEN may help identifying key actors and mapping information flows that are critical for leading effective collective action in response to global changes (Bodin et al. 2006; Isaac et al. 2007; Bodin and Crona 2009; Isaac and Dawoe 2011; Thomas et al. 2011; Guerrero et al. 2020; Reyers et al. 2022). Indeed, network analysis has been used to understand agrobiodiversity and information access among farmers in East Africa (Otieno et al. 2018, 2021). In both cases, the results revealed key actors and pathways of resource access, leading policymakers to develop targeted extension services to make information and agrobiodiversity flows more efficient. Other resilience-related issues that might be addressed using SEN analysis include assessing policy effects, territorial agglomerations or isolation of agricultural systems, cohesion and fragmentation, market failures (e. g. information asymmetry), and power relations (FAO 2018).

As West et al. (2024) noted, there are multiple relational approaches, making the integration of a relational approach to SEN analysis a dynamic process, as these approaches are constantly evolving. However, we acknowledge that adopting a relational approach in network analysis may arise multiple challenges and tensions. Thus, it is urgent to improve SEN research not only by refining the methodological portfolio, but also by expanding existing concepts from a relational perspective (Heikkurinen et al. 2019; Rezvani 2022). A key feature of network theory and relational approaches is that they require concepts, definitions, and methods in which social and ecological actors are linked to one another by one or various relations recognizing their coupled nature (Wasserman and Faust 1994; Wellman 1997; Borgatti et al. 2009). This conceptual plurality might give room for alternative narratives to be reflected in policies, leading to the promotion of different behaviors and ways of being. This way, it may be possible to expand the potential of network analysis for examining resilience in agricultural systems from a relational perspective (West et al. 2020; Raymond et al. 2021).

6. Conclusion

Although there are different approaches in the study of the resilience of agricultural systems, they often separate the social and the ecological dimensions of coupled social-ecological systems. Network analysis is at the heart of the relational turn in agricultural systems research (Pautasso et al. 2013; Labeyrie et al. 2021). The study of agricultural systems' resilience is relevant not only to understand how farmers are responding to change, but also creating and shaping it. Seed exchange networks connect farmers from diverse backgrounds and differentiated access to agricultural resources. Thus, we support the notion that by moving agrobiodiversity on its multiple material expressions, from genes to agricultural knowledge, seed exchange networks are relevant to nurturing the social-ecological systems' properties related to the systems' resilience, including adaptability, heterogeneity, memory, redundancy, and transformability. Our work showed the progress of seed exchange network (SEN) research synthesizing the metrics used in this study, and further discussed their analytical methods as a contribution to the relational turn in agricultural research. We also explored what a relational approach to SEN research might entail, describing some practical implications that in our experience had arisen in applying such approach. We highlighted the relevance of using a combination of qualitative and quantitative techniques to gain complementary insights into the study of the resilience of agricultural systems. This way, under a relational approach, seed exchange network analysis may help both bringing the gap between the natural and the social sciences and integrating agendas between researchers, policymakers, and stakeholders (Gonzalès and Parrott 2012; Reyers et al. 2022).

There are still many challenges to overcome and questions to answer. For example, are necessarily the central actors on seed exchange networks those with higher levels of resilience in agricultural systems? Such challenges and unsolved questions constitute possibilities for future inter- and transdisciplinary studies to enhance our understanding of the dynamism of agricultural systems. Finally, we encourage researchers to continue to explore seed exchange network analysis to increase the empirical evidence on the understanding of the dynamic cycle of the resilience of social-ecological systems under relational approaches.

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