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Autonomous Innovations in Rural Communities of Developing Countries II—Causal Network and Leverage Point Analyses of Transformations

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Abstract: Solving complex system challenges such as natural resource management in social-ecological systems (SESs) is fraught with great uncertainty. To cope with these challenges, socially vulnerable people in developing countries have created various autonomous innovations. This study focuses on the concept of leverage point (LP) to understand the emergence of innovations and the transformation mechanism of SESs. An LP is a part of a complex system where a small change can cause transformations in the entire system and can be identified from causal networks in an SES. This study analyzed the emergence processes of autonomous innovations as causal networks through transdisciplinary collaboration with innovators in communities and succeeded in visualizing the initial conditions, outcomes, and challenges. We constructed a new definition of LPs based on graph theory and classified LPs into three types based on their characteristics. The network analysis of the causal networks of two innovations in developing countries revealed that the three types of LPs functioned synthetically in complex systems to promote transformation. Based on these results, we propose the potential ways of interventions for the transformation of complex system networks including plural LPs and discuss their effectiveness as boundary objects in transdisciplinary processes collaborating with diverse stakeholders. Further research is expected to accumulate knowledge for solving the various challenges faced by SESs.

Keywords: system thinking; social-ecological system (SES); transdisciplinarity; graph theory; betweenness centrality; leverage centrality; intervention; boundary object

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1. Introduction

Complex challenges such as natural resource management in social-ecological systems (SESs) are associated with great uncertainty [1–3]. In complex SESs, research approaches linearly progressing toward a specific goal or vision of the future cannot cope with uncertainty. We need to be flexible and adaptive to cope with dynamic changes in society and ecosystems [4]. Therefore, it is important to have a process in which stakeholders from diverse perspectives consider multiple options and adaptively improve practices through collaboration, trial and error, and mutual learning among the parties [5,6].

Diverse local stakeholders around the world develop practices aimed at solving various complex and difficult challenges with uncertainties, such as natural resource management, in local SESs, and a vast amount of knowledge on these practices has been accumulated [6–9]. Natural resource management practices are embedded in complex

SESs, and it is very difficult to understand and analyze the impact of each practice on the social-ecological system because of its complexities. Although sustainability science researchers have devised many analytical frameworks for SESs, the definition of SESs is ambiguous [10], and attempts of comparative case studies are limited [11,12]. Therefore, a new research approach is needed to compare and analyze the impact of practices in communities around the world aimed at solving complex and difficult challenges in SESs from a comprehensive perspective.

For example, previous studies attempted to identify, from a comprehensive perspective, the factors that contributed the most to achieving sustainable fisheries [11], marine ecosystem conservation [13,14], and co-management in small-scale fisheries [12]. The factors identified in these studies were major breakthroughs in sustainability science, as they provided local stakeholders with the direction for realistic remedial measures. However, Charles [15] found that multi-layered approaches are more robust to uncertainty than a single measure, especially in natural resource management facing uncertain and difficult challenges. Charles suggested the importance of accessing the performance of collective actions and taking measures matching the realities of the community, rather than using a single and directional approach. Recently, Eggert et al. [16] developed the Fisheries Performance Index (FPI) [17] to measure the performance of fishery management efforts based on a unified SES analytical framework to make comparisons among 149 case studies. The Japan Fisheries Research and Education Agency (FRA) developed the "Fisheries Management Toolbox (Hama no Dougubako)," a tool for stakeholders to self-evaluate their own efforts in resource management compared with other successful cases for improving their own actions [18–20]. The European Commission and the European Environment Agency (EEA) developed Climate-ADAPT, a platform with a database of knowledge obtained from advanced initiatives, where stakeholders can follow the Climate-ADAPT guidelines to explore the knowledge of advanced practices, learn ideas and approaches, and implement their own initiatives [21]. These tools are very useful in applying them to complex challenges through the improvement of collective actions in the real world. However, these studies have yet to analyze the mechanisms of transformation of SESs as a whole through the impacts of innovative collective actions delivered by stakeholders to manage their resources.

To tackle complex and difficult challenges such as the sustainable management of resources in SESs, we need research approaches to identify challenges via comprehensive thinking and to consider and implement coping strategies through the integration of different types of knowledge through transdisciplinary collaborations with diverse actors [6,22]. Such an approach, called "system thinking," has been applied in research on coping strategies for the complex challenges in areas such as climate-change adaptation [23]. For example, a study conducted in the Murray–Darling watershed in Australia identified institutional complexity as a factor that reduces the effectiveness of management organizations by analyzing the structure of water resource management systems based on stakeholder relationships [24]. A study conducted in the Cat Ba Biosphere Reserve, Vietnam, drew and qualitatively analyzed the key powers and dynamics affecting the Biosphere Reserve as a causal network and found that pollution, freshwater scarcity, and the degradation of the quality of ecosystem services were core challenges that impeded sustainable, long-term tourism development [25]. Thus, analyzing SESs using the system thinking approach provides useful insights for the stakeholders in various local communities to work together to identify the sustainability challenges they face, consider measures to address them, and adaptively implement their collective actions.

To address the complex and difficult challenges faced by SESs, this study focuses on the concept of leverage points (LPs) in system thinking. An LP is defined as "the part of a complex system where a small change can lead to an essential transformation of the entire system" [26]. LPs can be qualitatively identified from the causal networks of various components in complex SESs [25]. LPs have also been classified into two categories: LPs that are easy to intervene upon but have limited potential to bring about transformation (shallow) and LPs that are difficult to intervene upon but have great potential to bring about transformation (deep) [27]. The various characteristics of LPs can thus be categorized into multiple types, and they hold promise as a methodology for building boundary objects that offers realistic options for collaboration when stakeholders from different backgrounds address complex and difficult challenges, such as natural resource management [28].

Star and Griesemer [29] described a boundary object as hybrid and portable and as a representation of the reality of the interactions of science and policy from an integrated perspective. Examples of boundary objects include model-based decision-making systems, scenarios, and maps. The success of boundary objects depends on credibility, salience, and legitimacy in the eyes of various stakeholders [30]. For example, the City of Phoenix, Arizona, USA, developed WaterSIM, a simulation model for the sustainable management of water resources, and initially, diverse decision-makers (policy makers, data analysts, and consultants) were skeptical about its credibility, salience, and legitimacy [31]. Therefore, scientists introduced an approach to redesign and refine WaterSIM in collaboration with stakeholders in the water management community. This approach has been successful in enhancing the credibility of the model through stakeholders' feedback, improving salience for decision making, and increasing the legitimacy of the model for multiple stakeholder groups [32]. Therefore, we co-created narratives via the transdisciplinary collaboration with innovators in communities regarding the emergence of autonomous innovations to solve complex and difficult challenges, such as natural resource management, and graphically represented these narratives as causal network diagrams from a system thinking perspective. This could lead to the construction of boundary objects with credibility, salience, and legitimacy to share the path and intervention points for the transformation of complex social-ecological systems.

Previously, we collected "autonomous innovations" that actors in local communities produced to solve challenges related to the sustainable management of natural resources and the improvement of human well-being in complex SESs and described the emergence processes of innovations as narratives [33,34]. From the perspective of system thinking, the emergence processes of autonomous innovations can be viewed as a causal chain. Autonomous innovations form a feedback loop in causal chains to solve the challenges, promote adaptive collective actions, and dynamically transform SESs [33]. Therefore, the emergence process of autonomous innovations that lead to the transformation of SESs can be described as a causal network. By conducting a network analysis of the causal network based on graph theory, it should be possible to define LPs in a new theoretical way. Using this definition to analyze the causal network of the emergence processes of innovations in real society could also lead to comparative research on the characteristics and functions of LPs. Detailed analyses of the emergence processes of autonomous innovations and their outcomes through the lens of LPs would be an important step in the development of a new theoretical definition of LPs, which could be applied to various SESs and should lead to a better understanding of the mechanisms of transformation.

Against the above background, this study contributes to the understanding of the mechanisms of the transformations of social-ecological systems through LPs by answering the following three research questions:

1. Can the emergence processes of autonomous innovations be represented as a network to clearly show the initial conditions, outcomes, and challenges?
2. How can LPs be classified by defining them theoretically based on graph theory?
3. Can a causal relationship network of emergence processes of autonomous innovations in the real world be analyzed based on the new definition to reveal the characteristics of LPs that lead to the transformations of social-ecological systems?

2. Materials and Methods

2.1. Causal Networks of Emergence Processes of Autonomous Innovations in the Real World

Tajima et al. [33] defined autonomous innovation as "collective actions emerging from local practitioners with the potential to transform social-ecological systems (SESs), and mechanisms that support them." We conducted research to identify the emergence processes of autonomous innovations and their mechanisms in 20 cases in 6 developing countries [33]. We developed a TD research methodology called Dialogic Deliberation in Living Sphere (DIDLIS) to explore autonomous innovations [34]. This method is designed to co-create narratives about the emergence processes of autonomous innovations through dialogue and deliberation with diverse people classified as the socially vulnerable and scientists on an equal partnership from a perspective very close to the lives of people. We also developed an autonomous innovation toolbox for the cross-sectoral comparative analysis of the narratives collected in this way [33,34]. The developed toolbox accumulated narratives about the initial conditions, outcomes, and challenges of autonomous innovations.

We positioned the emergence processes of narratives accumulated in the autonomous innovation toolbox as a complex network of causal relationships and clarified the initial conditions, outcomes, and challenges of autonomous innovations through analyses of the network structures. Following Alexandridis et al. [35], we tried to identify various components of knowledge (knowledge, the background or context of knowledge, and the practices and outcomes that emerge based on knowledge) in the process of innovation emergence as nodes in a causal network. Links between nodes indicate that one node is the cause/condition for the emergence of the next node. Thus, the network created in this way is a directed graph. For each autonomous innovation, we constructed a causal relationship list (an edge list of the network) consisting of nodes and links and used this list to draw the network. Using this method, we could visualize feedback loops from the narratives of autonomous innovations, which represented outcomes created by the innovations that led to the transformation of the SES. We also visualized the initial conditions of the innovation and the remaining challenges as a network structure. Note that the causal network depicted in this way is a snapshot of the time when the autonomous innovation was collected. The structure of this network and the nodes and links that make up the network continue to transform dynamically over time.

To eliminate arbitrariness as much as possible and to construct an evidence-based causal network, we adopted the methodology by Williams et al. [36] and extracted the nodes and links of the causal network from the narratives accumulated in the autonomous innovation toolbox using the following procedure to create a causal relationship list:

1. We extracted various components of knowledge involved in the emergence of autonomous innovations as nodes from the sentences listed in each item in the toolbox. We based the coding of a single component from a single sentence in the toolbox. If the sentence was separated by punctuation marks, it was assumed that the sentence could be split into multiple components according to its meaning;
2. We organized the causal chains of these nodes into causal relationship lists. The causal relations were based on the principle of the order in which the sentences appeared. However, there were cases in which the causal relationships between sentences described in different items of the toolbox were unclear, or causal relationships were convoluted. In such cases, we extracted the part of the sentence described in the other item that contained the content that complemented the causal relationship and added it to the causal relationship list, thereby logically resolving the causal relationship inconsistency;
3. In some cases, the causal relationships that made up the feedback loop could not be read directly from the toolbox text. In such cases, we connected nodes related to outcomes from the "Innovation contents" or " Outcomes, impacts and challenges of the innovation " sections of the toolbox with initial nodes related to the triggers and motivations of the innovation to complete a feedback loop, only if it was logically clear that the outcome of innovation (a feedback loop thus emerged) clearly contributed to sustainable resource management and improved human well-being.

This study sought to increase the objectivity of the data by having two independent teams: one was in charge of constructing the causal relationship list; the other, in charge of reconfirming the causal relationship list, consisted of the person who was not involved in the construction of the list. If any discrepancies were found via reconfirmation, the two teams discussed to resolve them. See Supplementally Materials for the causal relationship list and the data on which it is based.

2.2. Definition and Classification of Leverage Points Involved in the Transformation of Social-Ecological Systems

This study attempted to theoretically define the leverage points (LPs) involved in transformations of social-ecological systems (SESs) based on the causal network of the emergence processes of autonomous innovations [33]. In a complex network composed of various components of knowledge, the nodes represent the components of knowledge involved in the emergence of autonomous innovations, and the links represent the relationships where one node is the cause and condition for the emergence of adjacent nodes. We assumed that an LP in such a complex network could be defined in terms of the characteristics of the nodes, which were new or existing nodes in the network that, by forming links with other nodes, caused significant changes in the structure of the network, in whole or in part. The loss of a node that becomes an LP or the loss of a link to another node leads to a major change in the structure of the network. Thus, in a causal network of autonomous innovation that is already producing outcomes, the LP can be an existing node with significant overall or local influence. Based on these assumptions, we examined the theoretical definition of an LP.

Alexandridis et al. [37] studied the network structure of knowledge on natural resource management in SESs and found that the knowledge network had two characteristics, scale-free networks and small world networks, and that the network dynamically changes through collapse and reorganization. In such knowledge networks, there are groups of nodes that exert a large influence locally or globally, and the network centrality indices of the nodes included in these groups are higher than those of other nodes (Figure 1; [35]). Therefore, we assumed that the network centrality indices could be used as a cue to construct a theoretical definition of LPs.

Based on the assumption that a node that can become an LP is one with both local and global influences, we defined an LP using network centralities as a measure of such influence. We used betweenness centrality (BWC) as a measure of system-wide influence and leverage centrality (LVC) as a measure of local influence.

BWC is the probability that any node is included in the shortest paths between any two nodes in the network. Therefore, the loss of a node with high BWC has a significant impact on the entire network. The BWC of node i is given by Equation (1) [38].

$$BWC_i = \sum_{s \neq i \neq t}^{b} \sigma_{st}(i)/\sigma_{st} \tag{1}$$

where σ_{st} is the total number of shortest paths from node s to node t and $\sigma_{st}(i)$ is the number of shortest paths from node i that pass through the node. The higher the probability of the shortest path passing through each node, the higher the BWC of that node.

LVC is the relative value of the number of connections of any node to other nodes and the number of connections of nodes adjacent to that node to other nodes. It is higher for a node that is connected to more nodes in the network than its adjacent nodes. Thus, a node with a high leverage centrality has greater local influence over its neighbors. LVC is a relative value of the degree of a node (k_j) and the degree of each of its adjacent nodes (k_i), averaged over all neighboring nodes (N_i), and is defined as in Equation (2) [39].

$$LVC_i = (1/k_i \sum_{N_i})(k_i - k_j)/(k_i + k_j) \tag{2}$$

LVC can be positive or negative, and a node with a positive LVC is an important node that strongly influences its neighbors. A node with a negative LVC is strongly influenced by its neighbors [39].

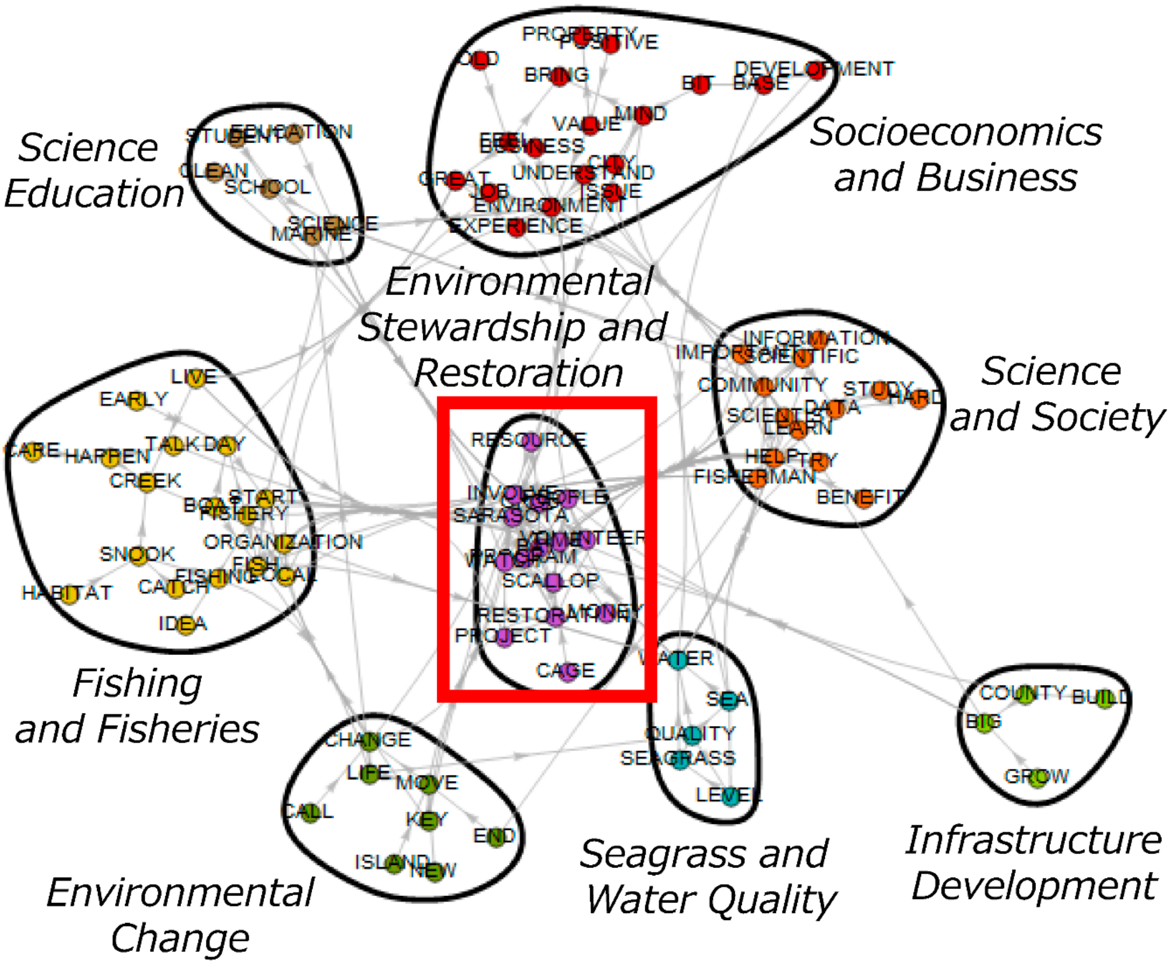

Figure 1. An example of a network structure of knowledge about natural resource management in a social-ecological system. This network has both small world network and scale-free network characteristics, with a central cluster (red box) having a large influence on the entire network, and the nodes in that cluster have high values of network centralities (Alexandridis, Takemura, et al. [35]; modified from Figure 14).

Of the two network centrality indices used to define an LP, the higher the value of *BWC*, the more likely it is to be a hub of the entire network. Therefore, when identifying LPs, we decided that any node with *BWC* above a certain threshold was an LP. We did not attempt to categorize LPs using *BWC*. *LVC* takes positive and negative values, but nodes with a large local impact are those with positive values. Therefore, we decided LPs to be those with positive *LVC* values. However, since the causal network of autonomous innovation is a directed network, the links that connect one node to its adjacent nodes have inputs and outputs. Therefore, it is possible to compute the *LVC* separately for inputs (in) and outputs (out) [39]. We attempted to categorize LPs by computing *in_LVC* and *out_LVC* for each node.

We used the igraph package (version 1.3.3; Csardi and Nepusz [40]) and the centiserve package (version 1.0.0; Jalili et al. [41]) from R (version 4.2.0; R Core Team [42]) to perform the network analysis.

2.3. Case Studies

We described the causal networks of emergence processes of autonomous innovations in the real world for the two cases in the developing countries shown in Figure 2 and drew causal networks using Cytoscape (version 3.8.1; Shannnon et al. [43]). Figure 2a shows a case study (Case 1) of the creation of satoumi-like fishing grounds in Chembe village, Malawi (Tajima et al. [33]; Table 1, No. 19: Efforts by fishers to create satoumi-type fishing grounds). Figure 2b shows the location of the case study (Case 2) of the improvement of cacao quality to achieve value-added supply (Tajima et al. [33]; Table 1, No. 2: Improving the quality of cacao raw materials and high value-added distribution) in Polewali, Indonesia. We classified the leverage points (LPs) identified for these cases using the methods described in the above section and compared their characteristics across cases. We attempted to elucidate the characteristics of LPs that lead to the emergence of autonomous innovations and transformation of the social-ecological systems (SESs) through an analysis of the emergence processes of innovations in the real world.

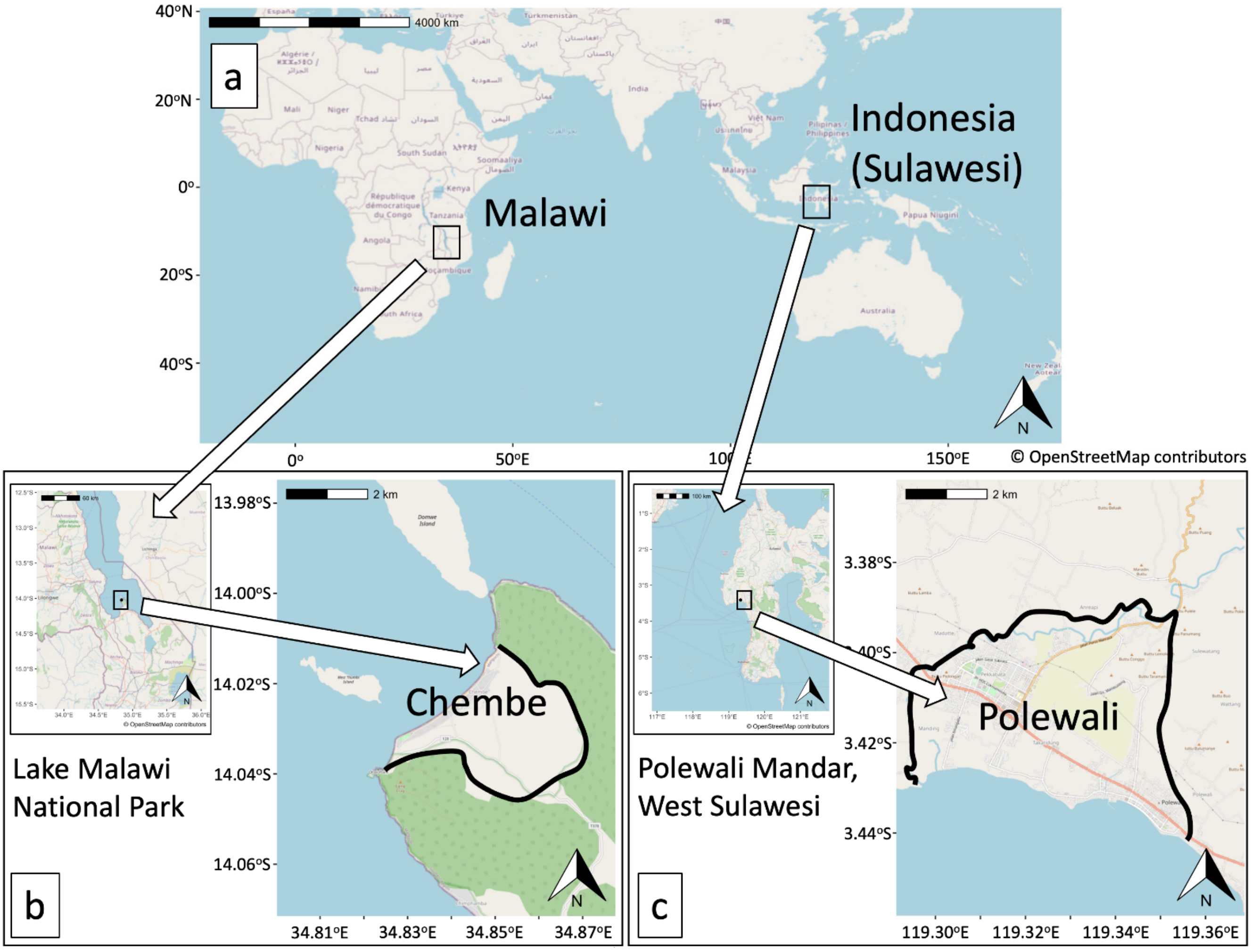

Figure 2. A map of the case study sites: (**a**) Malawi and Indonesia (Sulawesi); (**b**) Lake Malawi National Park and Shembe Village; (**c**) Polewali City, Polewali Mandal Province, West Sulawesi.

The village of Chembe, Malawi, in Case 1, is located within Lake Malawi National Park, a World Natural Heritage Site, and is estimated to have a population of more than 15,000 people. The village is a mixture of a tourism area and a traditional fishing village. The main livelihoods in the communities are fishing, agriculture, tourism, and the processing and distribution of agricultural and fishery products. Although tourism is a new livelihood option, fishing remains an important basis for people's livelihoods. This study analyzed efforts to sustainably use fishery resources through the creation of satoumi-like fishing grounds (Chirundu) led by local fishers.

Case 2, Polewali, Indonesia, is located in Polewali Mandal Province, West Sulawesi. The main livelihoods in the region are agriculture, including rice, cacao, and coconut;

fishing; and agro-industry. Cacao is distributed internationally as a raw material for chocolate, supporting the livelihoods of many farmers. The population of Polewali city is 58,190 (2018). This study analyzed local farmer-led efforts to improve the quality of cocoa raw materials and high value-added distribution.

3. Results

3.1. Emergence Processes of Autonomous Innovations: Initial Conditions, Outcomes, and Challenges

Figure 3a,b show the causal networks of the emergence processes of autonomous innovations in the two case studies (Case 1, Chembe, and Case 2, Polewali). The part starting from the oldest node in time to the feedback loop (red) represents the initial conditions for the emergence process. The feedback loops (green and yellow) represent the process by which the outcomes of autonomous innovation have been created. The open-ended areas (gray) are challenges that have not been resolved at that point in time. Leverage points (LPs), described in Section 3.2 below, are the nodes circled. We defined the part of the feedback loop representing the shortest path that includes all LPs as the main loop and the feedback loops that branch off from the main loop as sub loops. The main loop constitutes the central part of the network and can be considered the central outcome of autonomous innovation. Sub loops represent secondary outcomes derived from the main loop. The causal networks drawn in this way show how multiple feedback loops are created through the emergence of autonomous innovations, dynamically transforming the social-ecological systems (SESs). By visualizing such networks, the initial conditions, outcomes, and challenges of the emergence processes of autonomous innovations could be extracted and clearly visualized on the network. Simultaneously, we could visualize the processes of the dynamic transformations of the SESs through the creation of multiple feedback loops.

3.2. Theoretical Definition and Classification of Leverage Points

We assumed that a node that is a leverage point (LP) in a causal network must have betweenness centrality (*BWC*) above a certain threshold. As noted above, *BWC* represents the node's influence on the entire network. We also calculated three types of leverage centrality (*all_LVC*, *in_LVC*, and *out_LVC*). *All_LVC* was calculated using the sum of the node's indegrees and outdegrees. *In_LVC* was only calculated for indegrees, while *out_LVC* was only calculated for outdegrees. Here, the indegree represents the number of links going to a node, and the outdegree represents the number of links leaving a node. Thus, we can think of *all_LVC* as representing the overall magnitude of the node's local influence, of *in_LVC* as representing the node's ability to integrate influence from adjacent nodes, and of *out_LVC* as representing the node's ability to influence its neighbors. Since *all_LVC* had positive and negative values, we considered that a node was performing its function when the values were positive.

LPs could be defined as in Equation (3) using the values of *BWC* and *all_LVC* for node *i* calculated using Equations (1) and (2) of the method (Section 2.2).

$$BWC\_rank_i \leq \ \alpha \wedge \ all\_LVC_i > 0 \tag{3}$$

where BWC_rank_i indicates that BWC_i is within the top α% of *BWC*s for all nodes. all_LVC_i is the value of *all_LVC* for node i, which must be positive for LPs. We tentatively set α to 30% in this study. We adopted this value to eliminate nodes close to the average value and to ensure that sufficient nodes were detected as candidates for LPs.

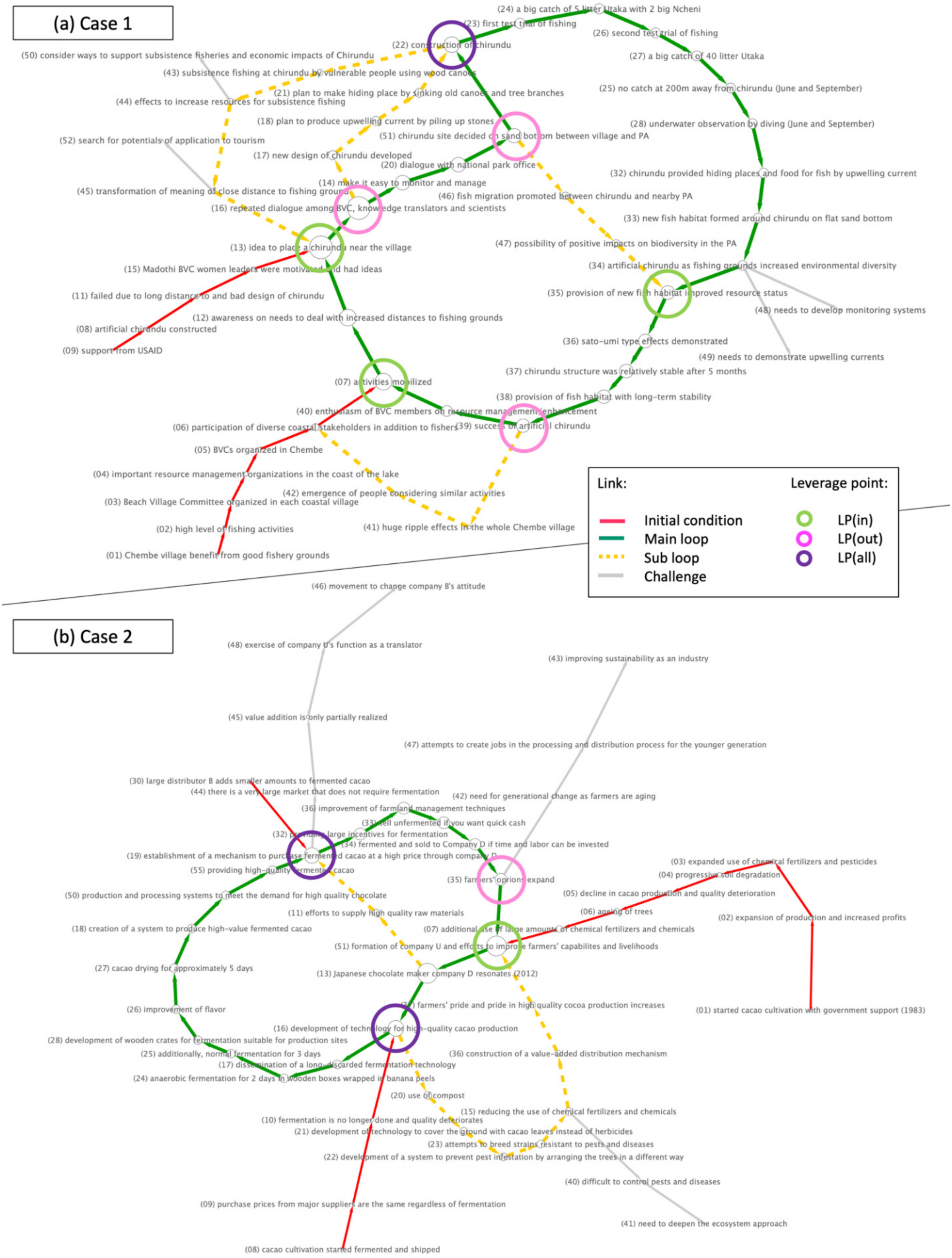

Figure 3. Causal networks and leverage points of autonomous innovation emergence processes: (**a**) Chembe, Malawi; (**b**) Polewali, Indonesia.

We could classify the LPs extracted using Equation (3) into three types with Equations (4)–(6) using the values of *in_LVC* and *out_LVC*, where in_LVC_i is the value of *in_LVC* of node i and out_LVC_i is the value of *out_LVC* of node i.

$$\mathrm{LP(in)}:\ in\_LVC_i > 0 \wedge\ out\_LVC_i < 0 \tag{4}$$

$$\mathrm{LP(out)}\ :\ in\_LVC_i < 0 \wedge\ out\_LVC_i > 0 \tag{5}$$

$$\mathrm{LP(all)}:\ in\_LVC_i > 0 \wedge\ out\_LVC_i > 0 \tag{6}$$

A node classified as LP(in) is considered an LP that integrates various components since only *in_LVC* is positive; a node classified as LP(out) is considered an LP that provides various components to adjacent nodes since only *out_LVC* is positive; and a node classified as LP(all) is considered an LP that combines the characteristics of LP(in) and LP(out) since *in_LVC* and *out_LVC* are both positive and aggregates the influences from adjacent nodes to generate new influences. Based on the above results, we derived the following hypotheses regarding the characteristics of the three types of LPs in the causal network of autonomous innovations. Note that all of these LPs have *BWC* above a threshold value and that *all_LVC* is positive:

1. LP(in): An LP that incorporates and integrates new components of knowledge into the emergence processes of autonomous innovations;
2. LP(out): An LP that creates new knowledge components from the emergence processes of autonomous innovations;
3. LP(all): An LP that supports the emergence of autonomous innovations through the integration and creation of new knowledge components.

3.3. Characteristics of Leverage Points That Led to the Transformation of the Social-Ecological Systems

We could identify seven LPs in Case 1 (Chembe) and four in Case 2 (Polewali) from the causal network of emergence processes of autonomous innovations, using a new definition of leverage points (LPs) based on graph theory. Table 1 shows the names of the identified LPs, the values of the network centralities on which the identifications were based, and the types of LPs. Nodes with BWC_rank_i below 30% had a *BWC* significantly larger than the average (Table 1). For these nodes, three types of LPs were extracted in both cases. However, only two types of LPs were extracted in both cases for nodes with *BWC_rank* of 10% or less. These results confirm that the *BWC* threshold set in this study ($BWC\_rank_i \leq 30\%$) is appropriate as a condition for excluding nodes with *BWC* close to or below the average and for extracting all three types of LPs.

The analysis of these 11 LPs allowed us to test the hypotheses about the characteristics of the three types of LPs derived in Section 3.2.

In Case 1 (Figure 3a), nodes 7, 13, and 35 were classified as LP(in). In Case 2 (Figure 3b), node 51 was classified as LP(in). These LPs(in) were located in the network diagram where the initial condition was integrated into the main loop and where sub loops that branched off from the main loop were reintegrated into the main loop. These results indicated that LP(in) integrated the conditions of the communities, challenges, and actors inside and outside the communities (components of initial conditions), as well as innovation outcomes, technology produced, new knowledge, and new human networks (components of sub loops) into the emergence and operating processes of autonomous innovations.

The nodes classified as LP(out) were nodes 16, 39, and 51 in Case 1 (Figure 3a) and node 39 in Case 2 (Figure 3b). These LPs(out) were located where sub loops diverged from the main loop or where challenges arose from the main loop. Thus, they were LPs that created practices (components of sub loops) for new outcomes and manifested new challenges in the emergence and operating processes of autonomous innovations. Additionally, the new challenges thus manifested could generate new practices to solve the challenges.

Table 1. Leverage points of the cases in Malawi and Indonesia. Nodes with BWC_rank_i within 30% and positive *all_LVC* were selected as leverage points (LPs) and classified as LP(in), LP(out), or LP(all) according to *in_LVC* and *out_LVC* values.

Case	Node Name	*BWC*	*BWC_rank* (%)		*all_LVC*	*in_LVC*	*out_LVC*	Type
No. 19 (Chembe)	(13) idea to place a chirundu near the village	1	1	(2%)	0.238	0.5	−0.333	LP(in)
	(16) repeated dialogue among BVC, knowledge translators, and scientists	0.995	2	(4%)	0.086	−0.5	0.333	LP(out)
	(07) activities revitalized	0.710	3	(6%)	0.133	0.167	0	LP(in)
	(22) construction of chirundu	0.656	5	(11%)	0.286	0.333	0.333	LP(all)
	(51) chirundu site decided on sand bottom between village and PA	0.598	8	(17%)	0.086	0	0.167	LP(out)
	(35) provision of new fish habitat improved resource status	0.569	9	(19%)	0.086	0.333	0	LP(in)
	(39) success of artificial chirundu	0.549	13	(28%)	0.200	0	0.333	LP(out)
	N	47						
	Average	0.333			−0.062	0.041	0.023	
	SD	0.260			0.218	0.271	0.246	
No. 2 (Polewali)	(51) formation of company U and efforts to improve farmers' capabilities and livelihoods	1	1	(2%)	0.238	0.5	−0.333	LP(in)
	(16) technology development for high-quality cacao production	0.774	3	(7%)	0.286	0.333	0.333	LP(all)
	(19) establishment of a mechanism to purchase fermented cacao at a high price through company D	0.756	4	(9%)	0.476	0.667	0.333	LP(all)
	(35) farmers' options expand	0.557	9	(20%)	0.086	0	0.333	LP(out)
	N	46						
	Average	0.299			−0.055	0.031	0.05	
	SD	0.254			0.200	0.298	0.314	

Node 22 in Case 1 (Figure 3a) and nodes 16 and 19 in Case 2 (Figure 3b) were classified as LP(all). These LPs(all) integrated initial conditions and sub loops into the main loop, while branching out new sub loops and challenges from the main loop. Thus, LP(all) was an LP that dynamically transformed the emergence and operating processes of autonomous innovations through the integration of various knowledge components (initial conditions and sub-loop outcomes) into the processes of innovations and that stimulated the emergence of new practices and the manifestation of challenges. These results were well aligned with the hypothesized characteristics of the three types of LPs that we theoretically constructed.

4. Discussion

By representing the emergence processes of autonomous innovations as a causal network, we could extract the initial conditions of innovations, the outcomes achieved, and the remaining challenges and visualize them as a causal network. By using graph theory to theoretically define the leverage points (LPs) that promote the essential transformation of social-ecological systems (SESs), we classified LPs into three types, LP(in), LP(out), and LP(all), and developed a theoretical hypothesis regarding the function of each type in the emergence processes of autonomous innovations. By testing the theoretical functions of the three types of LPs using the causal networks of real-world cases of autonomous innovations, we postulated that the overall functioning of LPs with different characteristics in the emergence processes of autonomous innovations is important as a mechanism for the transformation of SESs.

The originality of the methodology we used in this study is that by constructing a new definition of LPs and by applying network analysis to the emergence processes of innovations in the real world, we could simultaneously identify the initial conditions, outcomes, and challenges of innovations, as well as three types of LPs. These approaches are important in examining which parts of the system can be effectively intervened upon for the transformation of the SES. So far, the concept of LP has been discussed as a point of intervention for the transformation of the system [26,27]. All three types of LPs used in this study had high *BWC*; therefore, they had a high impact on the overall system. Enhancing the functioning of these LPs would strengthen the impacts of autonomous innovations on the entire SES. The loss or reduced functioning of these LPs would mean the loss or reduction of the impacts of innovation through the drastic changes in causal networks. Therefore, strengthening or transforming the functions of these LPs would facilitate the transformation of the SES as a whole.

How, then, can we enhance or transform the functioning of the three types of LPs? The initial conditions for autonomous innovation are the parts of a complex system where intervention is relatively easy and by adding new initial conditions to a particular LP, new components of knowledge can be integrated into the system. For the open-ended parts of the system that remain challenges, the emergence of new practices that solve those challenges, and the formation of new feedback loops linking those outcomes to other LPs, would strengthen and transform the functioning of the LP. The characteristics of the three types of LPs would change dynamically by adding links from new initial conditions and new practices. If a new link connects to LP(in) or LP(all), its function is strengthened, and if it connects to LP(out), it can transform into LP(all) and assume a new function. The formation of a new link from a challenge changes the path of the main loop through the creation of a new feedback loop. This may cause a node that was previously an LP to cease to be an LP, or a new LP to emerge. Thus, it is relatively easy to intervene upon the initial conditions or challenges outside existing feedback loops, and such indirect interventions may lead to the enhancement or transformation of LP functions. Direct interventions, such as removing specific LPs, often lead to system collapse; direct enhancements to the functioning of LPs are possible and would strengthen existing feedback loops, but in many cases, they would not lead to significant system-wide changes. Forming new links from specific LPs could bring about significant changes in the system, but such direct intervention is not easy in complex SESs. Our results suggested that the three types of LPs contributed to the emergence of innovations in different ways and that their integrated functions dynamically transformed the emergence processes of autonomous innovations, leading to the transformations of the SESs. This study also specifies the possibility that the type and function of an LP can change dynamically through indirect interventions to initial conditions and challenges. One of the major outcomes of this study is the proposal of a mechanism for the transformation of an SES by promoting a synergetic and dynamic change in LP types and functions through indirect interventions.

In this study, we developed a methodology to visualize the causal networks of complex autonomous innovations with simple rules with initial conditions, outcomes (main and sub-loops), challenges, and three types of LPs. The proposed methodology is capable of uniquely defining initial conditions, outcomes, challenges, and three types of LPs for any causal network. The graphically represented causal network diagrams are expected to have the credibility, salience, and legitimacy [30] not only for researchers but also for innovators in the community and supporting agencies of autonomous innovations, including government agencies (mainly local), NGOs, international donors working in local settings, and transdisciplinary researchers, such as ourselves, who share the respect for the innovators in the communities and share the values of their autonomous innovations, to promote collective thinking and mutual learning on the transformation processes of complex socio-ecological systems. Therefore, the causal network diagram, which graphically represents the processes and outcomes of transdisciplinary collaboration among diverse stakeholders, can be rephrased as a boundary object for diverse actors participating in the emergence of autonomous innovations to share the path of transformation of complex socio-ecological systems.

Several studies have indicated the potential of LPs as boundary objects [26–28,44]. This study successfully graphically represented three types of LPs using causal network analyses. The causal network of autonomous innovation emergence is an intuitive and easy-to-understand graphical representation of the transformation processes of complex SESs. The structure of feedback loops and the characteristics and functions of the underlying LPs are also easy to understand. Tajima et al. pointed out that the emergence of synergies among different resource management practices is important for the transformation of SESs through integrated natural resource management, and they identified examples of synergies being realized in autonomous innovation around the world [33]. It is not easy for innovators and actors that produce innovations in the community to understand the mechanisms and pathways by which synergies among different resource management practices are realized in complex SESs. The causal network developed in this study could help innovators and other diverse actors share the pathways to realize new synergies through an intuitive grasping of the complex synergy emergence process and understanding the functions of the three types of LPs supporting synergies. The causal network is a graphical representation of autonomous innovation with credibility, salience, and legitimacy, which are indispensable requirements for boundary objects [30]. For integrated natural resource management to achieve the sustainability of various natural resources to transform SESs with uncertainty, it is necessary for innovators and diverse actors to support innovations and for researchers from different disciplines to engage in a series of transdisciplinary dialogues to share perceptions of challenges, map out venues for solutions, and identify new challenges. A causal network can certainly serve as an effective boundary object in such a dialogue. We hope that this research study and the proposed concepts of LPs can stimulate transdisciplinary research using boundary objects to promote collective actions toward social-ecological transformation through the transdisciplinary collaboration of diverse actors.

5. Conclusions

To address the challenges arising in complex social-ecological systems (SESs) in developing countries, this study used network theory to analyze the emergence of autonomous innovations from socially vulnerable people to identify initial conditions, outcomes, and challenges. To understand the transformation mechanisms of SESs, we developed a new definition of leverage point (LP) using graph theory and classified LPs into three types: LP(in), LP(out), and LP(all). We analyzed the characteristics and functions of these three types of LPs in the causal networks of emergence processes of autonomous innovations and examined the characteristics of LPs as the basis for innovations in the real world. As a result, the possibility emerged that indirect interventions on the initial conditions and challenges of autonomous innovation could lead to a synergetic enhancement or changes in the functions of the three types of LPs, thereby realizing transformations of the SESs. The results also suggest that the causal network developed in this study is effective as a boundary object in driving the transdisciplinary processes toward integrated natural resource management and the transformation of SESs.

To obtain more generalizable knowledge about the mechanisms of transformations, we conducted qualitative and quantitative analyses of the emergence mechanisms of autonomous innovations and enablers of social-ecological transformations using the cases of autonomous innovations that we accumulated [33,45]. To understand the emergence mechanism of autonomous innovations toward social-ecological transformations, research is needed to theoretically and mathematically explore the dynamics and factors that cause the transformation of systems through interventions on the initial conditions and challenges of innovation by understanding the time-series changes in the causal network. To deepen our understanding of the nature of interventions for the transformation of complex networks consisting of many LPs, modeling research would certainly be helpful to clarify the potential benefits derived from the interventions based on the analysis and identification of LPs for different actors conducting interventions on a system with diverse societal positions.

To further enhance the effectiveness of causal networks as boundary objects, we are working with innovators in the community to develop an application that automatically draws the network diagrams with LPs. This application allows users to visualize and share the process of interventions on the network causing dynamic changes in the system by manipulating nodes and links on the screen. We hope that further progress in research derived from this paper deepens our understanding of the emergence mechanisms of autonomous innovations that can transform SESs. The outcomes of these studies would also promote transdisciplinary collaboration among societal stakeholders and scientists to contribute to solutions to the complex and difficult challenges that humanity faces toward sustainable futures.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/su141912054/s1, Table S1. Nodes and links extracted from the narratives in the toolbox of Case 1: Efforts by fishers to create satoumi-type fishing grounds in Chembe, Malawi). Table S2. Nodes and links extracted from the narratives in the toolbox of Case 2: Improving the quality of cacao raw materials and high value-added distribution in Polewari, Indonesia. Table S3. List of causal relations (edge list) of Case 1. Table S4. List of causal relations (edge list) of Case 2.

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