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Research

Resilience principles and a leverage points perspective for sustainable woody vegetation management in a social-ecological system of southwestern Ethiopia

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ABSTRACT. Addressing ecosystem destruction and unsustainable development requires appropriate frameworks to comprehensively investigate social-ecological systems. Focusing on woody plant management in southwestern Ethiopia, we combined social-ecological resilience and a leverage points perspective to (1) assess how stakeholders perceive and operationalize resilience principles; (2) investigate resilience challenges and solutions across different levels of systemic depth; and (3) assess how different stakeholder groups noted challenges and solutions at different levels of system depth. Data were collected in focus group discussions with multiple types of stakeholders and analyzed via quantitative content and descriptive analysis. All stakeholder groups identified two principles currently applied in the landscape, while other principles were not currently applied widely. In total, we identified 37 challenges and 44 solutions to resilience, mainly focused on "deeper" systemic change. This trend was noted across stakeholder groups, but particularly by local people. Based on our work, we suggest to foster bottom-up changes in system goals, rules, paradigms, and intent, drawing explicitly on local people and their knowledge. More broadly, we suggest that further research on combining social-ecological resilience and leverage points perspectives could be helpful to better navigate and transform social-ecological systems.

Key Words: *leverage points; resilience principles; smallholder farming landscapes; social-ecological systems; sustainability transformation; woody vegetation diversity management*

INTRODUCTION

Land-use change, particularly deforestation, forest degradation, agricultural expansion and intensification, and urbanization, affect most terrestrial ecosystems (Ellis et al. 2010, Foley et al. 2011, Steffen et al. 2015). Rapid and large-scale land-use change has impacted the state and functioning of the entire Earth system, and ultimately could trigger far-reaching, non-linear, and irreversible changes that may devastate a variety of ecosystem services (Steffen et al. 2015, Díaz et al. 2019, IPBES 2019) and other aspects of nature's contributions to people (Díaz et al. 2018, Riechers et al. 2020).

Addressing ecosystem destruction (Rockström et al. 2009, WWF 2020) and unsustainable development pathways (White 2017, O'Neill et al. 2018, Brand et al. 2021) requires urgent and fundamental transformative change (e.g., Fazey et al. 2020, Vogel and O'Brien 2022). However, enacting such transformative change remains a challenge because of its political and normative character, as well as the inherent complexities and uncertainties in social-ecological systems (SES; see Blythe et al. 2018, Chaigneau et al. 2022). Hence, it is vital to find appropriate frameworks to comprehensively analyze transformational processes in SES in order to identify interventions with transformative potential.

Transformation processes can be assisted by embracing systems thinking (Ostrom 2007, Meadows 2009, Scoones et al. 2020). Systems thinking is an analytical perspective to study and manage the emergent behavior of complex and interlinked social-ecological system elements (Ostrom 2007, Meadows 2009). Within systems thinking, two complementary perspectives have emerged that can help to facilitate better and more sustainable management of SES. First, a resilience perspective is interested in how systems can cope with shocks and continue to develop (Folke et al. 2010). More specifically, this perspective emphasizes human-nature relations and adaptive management. The resilience perspective views humans as part of nature, and human-nature interactions form the core of SES (Berkes et al. 2003, Folke 2006). The resilience of SES can be enhanced by applying established principles that are widely recognized to foster social-ecological resilience (Biggs et al. 2012; see Table 1).

In addition to the resilience perspective, a leverage points perspective can also be useful to improve SES management (Meadows 1999, Abson et al. 2017, Fischer and Riechers 2019). Leverage points are specific places within a complex system where relatively small interventions can lead to substantial change (Meadows 1999). A leverage points perspective conceptualizes interventions in systems as acting on different levels of systemic depth, from the relatively shallow levels of parameters and feedbacks to the deeper levels of system design and intent (Abson et al. 2017), and thereby helps to identify potential interventions that could help bring about transformative change (Fischer and Riechers 2019; see Table 2 for details and examples). Interventions at shallow levels (e.g., allocating budgets for tree planting or increasing the size of a protected area) of a given system will be ineffective, or unfeasible, if such interventions are constrained by deeper level system characteristics (e.g., authoritarian regimes that resist institutional change or a system with core goals related

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Table 1. Contemporary principles for building resilience of social-ecological systems (SES), and their relation to the management of woody vegetation as discussed in this paper. E = primarily ecological aspects; S = primarily social aspects. E and S were differentiated for some principles for ease of discussion with local stakeholders; we are acutely aware that E and S aspects are tightly interrelated. Adapted from Biggs et al. 2012.

P1. Maintain diversity and redundancy	P1E: Maintaining ecological diversity and redundancy Diversity refers to diversity of woody plant species, habitats, and ecosystems. Redundancy is functional replication of species in SES that can provide options for responding to change and adapting to uncertainty, thereby building resilience. P1S: Maintaining social diversity and redundancy Diversity refers to diversity of social actors. Redundancy relates to the functional replication of social actors in SES and can provide options for responding to change and adapting to uncertainty, thereby building resilience.
P2. Manage connectivity	P2E: Managing ecological connectivity Ecological connectivity—that is, the way in which resources, e.g., seeds, disperse, species migrate, or interact with each other across patches, habitats, or ecosystems—helps to maintain diversity and is key for resilience. P2S: Managing social connectivity Social connectivity—that is, the way in which multiple social actors interact with each other and collaborate across social structures and domains—helps to maintain diversity and is key for resilience. Notably, too much connectivity can cause rigidity.
P3. Manage slow variables and feedbacks	P3E: Managing ecological slow variables and feedbacks Managing ecological, slowly changing variables as well as the feedbacks that influence the configuration and dynamics of a given SES is important to avoid crossing possible thresholds into undesired states. P3S: Managing social slow variables and feedbacks Managing social, slowly changing variables as well as the feedbacks that influence the configuration and dynamics of a given SES is important to avoid crossing possible thresholds into undesired states.
P4. Foster an understanding of SES as complex adaptive systems	Complex adaptive systems thinking helps to make sense of SES dynamics and to manage SES for multiple ecosystem services in an integrated way, across multiple temporal and spatial scales.
P5. Encourage learning and experimentation	The uncertain and dynamic nature of complex SES requires continuous learning via adaptive management, co-management, and collaborative governance.
P6. Broaden participation	Active participation of stakeholders in the management and governance process enhances collective action for resilience.
P7. Promote polycentric governance systems	Governance systems in which various interacting governing bodies have autonomy to make and enforce rules can enhance resilience by improving connectivity, participation, and adaptive learning.

to production-oriented rather than sustainability). Moreover, interventions need to account for possible interactions among system characteristics across multiple levels of systemic depth (e.g., Manlosa et al. 2019a, Jiren et al. 2021).

The study presented here is an empirical exploration that combines resilience principles (Biggs et al. 2012) with the notion of leverage points across multiple levels of systemic depth (i.e., system parameters, feedbacks, design, and intent; Table 2; Abson et al. 2017). Specifically, we investigated at which depth within a complex SES key challenges and opportunities occurred for applying resilience principles. Our case study focused specifically on the management of woody plant diversity for improved social-ecological resilience and well-being in a smallholder farming landscape in southwestern Ethiopia. Woody plant diversity, in this system, is central to both biodiversity and people's livelihoods (Rodrigues et al. 2018, Shumi et al. 2019a). The region is also a part of the eastern Afromontane biodiversity hotspot (Mittermeier et al. 2011) and the center of origin and diversity of Arabica coffee (*Coffea arabica*; Anthony et al. 2002).

Drawing on the rationale outlined above, we aimed to do the following:

1. Assess how different stakeholders perceive resilience principles and operationalize them, including perceptions of the current social-ecological situation, and barriers and opportunities of applying resilience principles in the context of woody vegetation diversity management;
2. Investigate and characterize the perceived resilience challenges and solutions across different levels of systemic depth, from the relatively shallow levels of parameters and feedbacks to the deeper levels of system design and intent; and
3. Assess whether or not different stakeholder groups noted challenges and solutions at different levels of system depth.

In doing so, our study can contribute to better understanding how various stakeholders perceive the sustainability of their system, including its current situation as well as barriers and opportunities to resilience building. This, in turn, can help to identify places of intervention to improve resilience in the study region. Some of the findings may also be helpful for other similar settings, especially in bioculturally diverse parts of the Global South. The insights obtained are particularly important for the local community within our study area who greatly depend on, and have close ties to, nature. The local people have built a wealth of traditional ecological knowledge and experience, but are often marginalized by top-down and sectoral policies. Indirectly, our study thus also contributes to the better recognition of local people, and their livelihood and nature stewardship needs, local knowledge, and experiences. To this end, the outcomes of this study were summarized in a non-technical manual for how to build resilience within our study region in the context of woody vegetation management. This manual was produced in both English and the local language, so that it, too, can be used beyond the study area as appropriate (Shumi and Fischer 2023a, b).

Table 2. System characteristics as defined by Abson et al. (2017) and leverage points by Meadows (1999), with increasingly deep (i.e., influential) leverage points toward the bottom of the table.

System characteristics			Leverage points	
Effectiveness	Type	Description		
Shallow leverage points	Parameters	The relatively mechanistic characteristics or physical elements typically targeted by policy makers (or environmental managers in our case)	12.	Constants, parameters, numbers (such as subsidies, taxes, standards);
			11.	The sizes of buffers and other stabilizing stocks, relative to their flows;
			10.	The structure of material stocks and flows (such as transport networks, population age structures);
	Feedbacks	Interactions between elements within a system that drive internal dynamics	9.	The lengths of delays, relative to the rate of system change;
			8.	The strength of negative feedbacks, relative to the impacts they are trying to correct against;
			7.	The gain around driving reinforcing feedback loops;
Deep leverage points	Design	The social structures and institutions that manage feedbacks and parameters	6.	The structure of information flows (who does and does not have access to what kinds of information);
			5.	The rules of the system (such as incentives, punishments, constraints);
			4.	The power to add, change, evolve, or self-organize system structure;
	Intent	The underpinning values, goals, and worldviews of actors that shape the emergent direction to which a system is oriented	3.	The goals of the system;
			2.	The mind-set or paradigm out of which the system, its goals, structure, rules, delays, parameters, arises;
			1.	The power to transcend paradigms;

Finally, collaborative multi-stakeholder field days were organized to kick-start the implementation of some of the resilience principles prioritized by local stakeholders.

CONCEPTUAL FRAMEWORKS

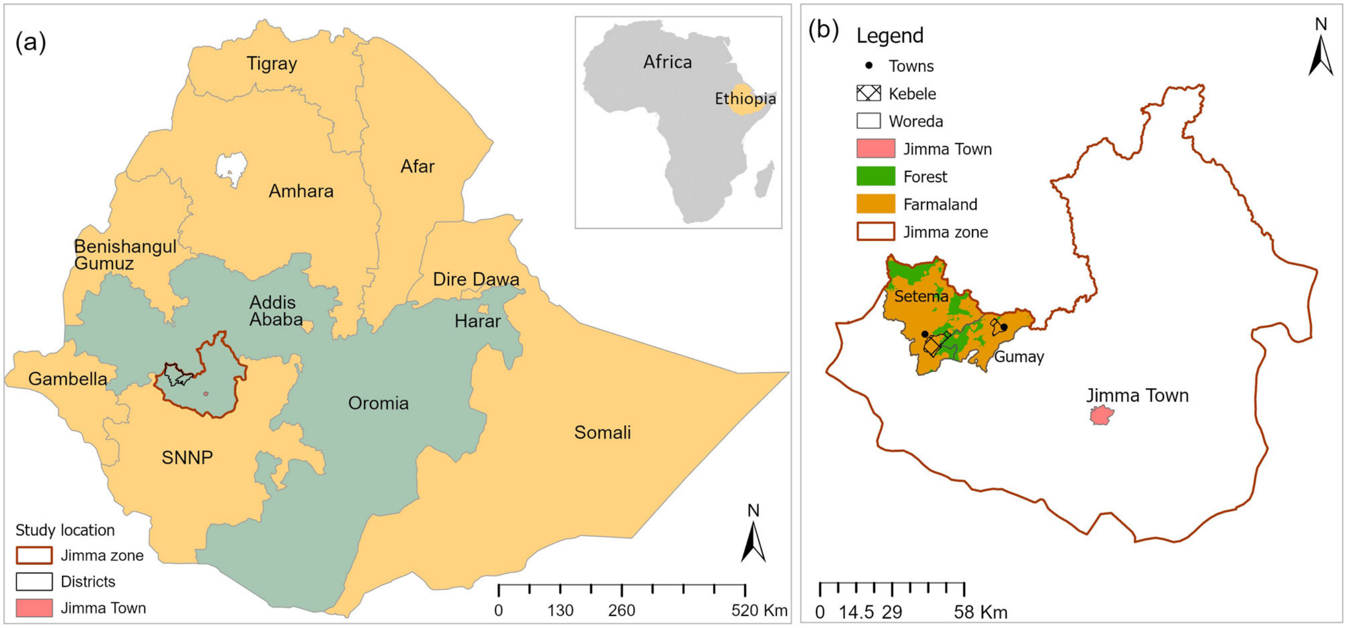
The concept of resilience, as defined above, was introduced by Holling (1973) in a seminal paper describing nonlinear ecosystem dynamics. Since then, resilience has become a dominant concept in SES research (Folke et al. 2004). Because many contemporary social and ecological challenges are complex and intertwined (Donohue et al. 2016), systems thinking can contribute to finding solutions to such multifaceted and interconnected systems' problems (Ostrom 2007, Meadows 2009).

To this end, a social-ecological resilience perspective recognizes the strong impact and reliance of humanity on nature as well as possible non-linearities arising from human impact. This perspective can be used to explore and understand the current status and spatial-temporal dynamics of SES (e.g., see Fischer et al. 2015, Dugo 2019). Further, some principles seem to generally support the sustainable management of a given system, that is, applying these principles can help the system remain adaptable and avoid undesirable shifts into degraded system states (e.g., see Biggs et al. 2012). Biggs et al. (2012) identified seven generic principles through an assessment of the scientific literature, a survey of leading resilience experts, and a mock court workshop. The identified principles are listed in Table 1. In this article, as indicated in Table 1, we differentiated ecological and social aspects for each of the first three principles and considered them separately to avoid ambiguity as well as ease the discussion with local stakeholders.

The first three resilience principles focus on general SES properties and processes to be managed (diversity, redundancy, connectivity, slow variables, and feedbacks), while the remaining four principles relate to aspects of SES governance (Biggs et al. 2012). Overall, all principles are intended together as a guide to ensure a continuous flow of desirable ecosystem services (Biggs et al. 2012). Because these principles were first generated, there have been several attempts to apply them to diverse contexts, including ecological restoration (Krievins et al. 2018) and water management (Reilly et al. 2021), among others.

Applying resilience-fostering principles in real world landscapes, particularly in smallholder farming landscapes, remains challenging because of the prevalent production-oriented green revolution discourse (IPBES 2019, Grass et al. 2020). Operationalizing resilience principles to maintain resilient SES requires radical transformational change. A radically transformed system would place sustainability at the core of personal and societal value and belief systems and elevate it to the top of political agendas (Osborne et al. 2021, McPhearson et al. 2021). Fostering such transformative change hinges on identifying suitable interventions within a given system. This, in turn, can be facilitated by a leverage points perspective. In a landmark essay, Meadows (1999) identified a hierarchy of 12 leverage points—places of interventions—in complex systems. Meadows (1999) differentiated between leverage points at which interventions are simple but restricted in their potential to bring about transformative change (i.e., shallow leverage points) and leverage points at which interventions are more difficult but have great potential to bring about transformative change (i.e., deep leverage points). Building on the work by Meadows (1999), Abson et al. (2017) summarized the 12 leverage points into four main areas of leverage, and surmised that increasingly deep or influential areas of leverage would be associated with changes in parameters, feedbacks, system design, and the intent encapsulated by a given system (Table 2).

Fig. 1. Location of (a) study area in Ethiopia, Oromia Regional State, Jimma Zone; (b) the two kebeles (Gido Bere in Setema district, Kuda Kofi in Gumay district), two district towns (black dots, namely Gatira in Setema district and Toba in Gumay district), and Jimma town.



A leverage points perspective recognizes the link between causal and teleological explanations of system change, that is, change is perceived to arise from variables influencing one another as well as from how human intent traces and shapes the trajectory of a system (Fischer and Riechers 2019). System change can also arise from interactions among system characteristics across multiple levels of systemic depth (Fischer and Riechers 2019, Manlosa et al. 2019a, Jiren et al. 2021).

Combining a resilience perspective with a leverage points perspective could be useful to facilitate a better understanding of the depth within a system at which resilience challenges and solutions occur; and thereby, identify possible interventions that are needed to more fully apply or operationalize resilience principles in a given system. In our context, challenges were defined as actions, processes, or structures that hinder the application of resilience principles and thus, transformation to sustainability. Solutions were defined as actions, processes, or structures that could facilitate the application of resilience principles.

METHODS

Study area

Our study was conducted in Jimma Zone, within Oromia National Regional State, in southwestern Ethiopia. In this region, we engaged stakeholders selected from two kebeles (the smallest administrative unit), namely Gido Bere and Kuda Kofi; from the two districts that these two kebeles are located within, namely Gumay and Setema; and from Jimma town also (Fig. 1). We selected the kebeles and districts based on our previous work experience in the study area (Shumi et al. 2018, Shumi et al. 2019a, Shumi et al. 2021), which suggests that these kebeles and districts are broadly representative of the typical social-ecological characteristics of the broader region.

The study area is characterized by a mosaic of forest, farmland (arable land, grazing land, and home gardens), and settlements. The forest in the area is moist evergreen Afromontane forest. Woody plants are rich and abundant in the forest-agriculture mosaic of the region. Dominant woody plant species include *Olea welwitschii*, *Pouteria adolfi-friederici*, *Schefflera abyssinica*, *Prunus africana*, *Albizia* spp., *Syzygium guineense*, *Cordia africana*, *Croton macrostachyus*, and *Coffea arabica* (Shumi et al. 2019a).

Woody plants have important ecosystem functions and contribute critically to local biodiversity (Engelen et al. 2017). They also provide multiple ecosystem services, e.g., including soil fertility maintenance for agricultural production or livestock and honey production, and local people strongly depend on these services for their day-to-day livelihoods (Ango et al. 2014).

Subsistence agriculture, including cropping and livestock keeping, is the main source of livelihoods (Manlosa et al. 2019b). Coffee and to a lesser degree honey are economically important non-timber forest products in the area (Ango et al. 2014). Coffee is widely managed at altitudes between 1500 and 1800 m asl, within its ecological optimum, generally under a canopy of native shade trees (Teketay 1999). The largest ethnic group in the region is the Oromo, while Amhara, Keffícho, and Tigre people are minorities (Shumi et al. 2019a).

Data collection

We chose focus group discussions to collect empirical data on perceptions and operationalization of the resilience principles. Focus groups can help to generate a joint understanding of complex social-ecological system issues, with participants being informed and stimulated in their thinking by the discussion points of others. Because of this, we selected this tool over other, more individually focused tools, such as key informant interviews (Hennink 2014). Focus group discussions were guided by prompting questions on how stakeholders perceived established resilience principles (sensu Biggs et al. 2012; see Table 1), and how they might or might not operationalize them in the context of woody vegetation management in southwestern Ethiopia.

For this, we first systematically grouped relevant stakeholders, from local to zonal levels, based on their likely similar backgrounds, shared experiences, ages, and wealth or social status (Hennink 2014). Grouping of stakeholders into separate discussion groups was done to minimize potential effects of unequal power relations and fundamentally differing perceptions of key issues, and to allow the emergence of different perspectives and discussions within and between groups. Accordingly, at the local level, stakeholders in each kebele were divided into five groups, namely (a) model farmers (i.e., those who usually adopt new agricultural technologies and have close contact or link to extension agents or experts and researchers), (b) low-income farmers, (c) women, (d) elders, and (e) a group that comprised elementary school teachers, students (including graduated and jobless youngsters), and development agents. At the district level, stakeholders in each district were divided into two groups, specifically (a) experts from the agricultural office (i.e., crop, coffee, livestock, extension, and natural resource management department) and the Oromia Wildlife and Forest Enterprise (OFWE), and (b) experts from different administration offices (i.e., district-admin, security, cooperatives, tourism, marketing, and financial experts) and district-level experts of non-governmental organizations (NGOs). At the zonal level, we divided stakeholders into three main groups, namely (a) experts from the agricultural office (i.e., crop, coffee, livestock, extension, and natural resource management experts) and from OFWE, (b) experts from the administration (i.e., zone-admin, security, cooperatives, tourism, marketing, and financial experts) and from zonal NGOs, and (c) lecturers and researchers from Jimma University and the Biodiversity Research Institute.

Then, for each of the 17 groups, 10–12 participants were selected purposefully and further divided into two sub-groups comprising 5–6 discussants each (a suitable size for focus group discussions; Hennink 2014), which also helped to align our work with local SARS-CoV-2 regulations at the time, resulting in 34 individual group discussions. To limit the time spent in the group discussions, one sub-group then discussed resilience principles P1, P3, P6, and P7, while the other sub-group discussed P2, P4, P5, and P6 (see Table 1 for a list of the principles). Before we started each focus group discussion, we introduced the objectives of our study and informed the discussants about the voluntary nature of participation in the focus group discussion. A poster illustrating all seven resilience principles (in general terms) and a set of open-ended guiding questions in the local language (Oromifaa) were used to stimulate and guide the focus group discussions for each principle. Within each focus group discussion, participants were first briefed about each resilience principle. Then, participants were asked to discuss the principles in relation to woody vegetation management. They were encouraged to explicitly articulate how they understand each principle, that is by describing their current social-ecological situation with respect to the resilience principle and were asked whether they apply a given principle or not, and to list possible barriers and opportunities for applying each principle in the context of woody vegetation management within the study landscape.

Thus, in total, we conducted 34 separate focus group discussions from March to April 2021. All were conducted in the local language Oromifaa and moderated by local experts and supervised by the lead author.

Data analysis

The qualitative data obtained from the focus group discussions were transcribed and coded using MAXQDA 2020 software. Data were coded mainly deductively based on the resilience principles, as well as inductively, meaning that additional coded categories were developed for each principle based on the responses of discussants.

Quantitative content analysis (Mayring 2000) was used to assess how different stakeholders perceived and operationalized resilience principles (aim 1). To this end, we analyzed the frequency of statements on the social-ecological situation, challenge, and opportunity or solution (related to a given resilience principle) across stakeholder groups or the percentage of groups articulated these statements. We chose to analyze the data quantitatively because the frequency or percentage of mentions provides an indicator of how prevalent a given understanding was of the current situation, challenges to, and solutions for, increasing social-ecological resilience, both within and across different stakeholder groups. Further, we identified the resilience principles that were linked to many challenges, as well as suggested solutions that would address multiple challenges at the same time.

To investigate and characterize the perceived resilience challenges and solutions across system characteristics (aim 2), we classified the coded categories of challenges and solutions of each resilience principle across levels of systemic depth, namely system parameters, feedbacks, design, and intent (see Table 2 for system characteristics and specific leverage points). The classification into leverage points was based on Meadows (1999) and Abson et al. (2017), combined with our experiences of the study area (e.g., Fischer et al. 2021), and was undertaken independently by three of the co-authors and then synthesized. Using the frequencies of challenges and solutions mentioned in relation to a given resilience principle, we generated Sankey diagrams in R software (R Core Team 2022) to visualize how resilience challenges and solutions linked to each level of systemic depth.

Finally, to assess whether different stakeholder groups focused on challenges or solutions at different systemic depths (aim 3), we determined the frequency of resilience challenges and solutions across parameters, feedbacks, design, and intent system level by each stakeholder group. We produced histograms to visualize the results using R software (R Core Team 2022).

RESULTS

Perceived current resilience situation, challenges and solutions

Perceived current resilience situation

All 17 stakeholder groups agreed on the existence and benefit of various direct and indirect ecosystem services of diverse tree and shrub species (P1E; Table S1). Similarly, a large majority of groups, (16 or 94%) and (13 or 77%), perceived benefits from the existence of connectivity among different habitats (P2E) via vegetation strips/corridors and steppingstones in the landscape (Table S1).

However, almost all (16 or 94%) groups noted an absence of local social networks (P1S) for tree management in the landscape (Table S1). A majority of groups (15 or 88%) also perceived an absence of social connectivity or collaboration among stakeholders (P2S) across scales. Similarly, all 17 groups perceived steadily ongoing degradation of land and water resources, including biodiversity and ecosystem services, as well as changes in the climate (P3E). All groups also agreed on the presence of slow social drivers, namely ongoing human population growth, deterioration of traditional social norms, values, cultures, and institutions; and 14 or 82% of groups reported growing poverty (P3S; Table S1). All 17 groups perceived absence of genuine participation or local self-organization (P6) in tree or forest management and voiced a lack of decision-making powers by local people and their social networks. Instead, 16 or 94% of groups revealed that tree/forest management related decision-making powers across the landscape were exerted exclusively by government actors, namely by local administration, and agricultural or OFWE experts (P7). About half of the groups (9 to 10 groups) voiced absence of understanding of SES as complex adaptive systems (CAS; P4), and absence of learning and experimentation processes (P5) in the context of tree/forest management (Table S1).

Perceived resilience challenges and solutions

In total, 37 different challenges were identified that could hinder the application of at least one resilience principle. Identified challenges were most numerous for applying P6, i.e., participation (24 challenges), P1S, i.e., social diversity and redundancy (22 challenges), P7, i.e., encouraging polycentric governance (22 challenges), and P5, i.e., continuous learning and experimentation (20 challenges; Table S2).

The most commonly mentioned challenges were the following: individualism and an absence of commitment or care (85 instances out of a possible 170, namely 17 focus groups by 10 specific principles), lack of awareness and experience sharing (82), weak government performance or policy implementation (36), and failure to recognize and prioritize local people and their needs and experiences (32). Challenges that were perceived most consistently throughout all principles were lack of awareness and experience sharing, individualism and absence of commitment or care, lack of monitoring, absent or weak support and supply of materials (e.g., seedlings), absent or weak tree/forest management and maintenance, and weak government performance or policy implementation (Table S2). Box 1 summarizes the key challenges that need attention in the study area.

Box 1: Key challenges (in decreasing frequency of total mentions summed across all individual groups and principles) that hinder the application of resilience principles to the management of woody plant diversity in smallholder faming landscapes of southwestern Ethiopia (cf. Table S2, for complete list of challenges).

1. Individualism and absence of commitment, responsibility, care, and respect
2. Lack of awareness and experience sharing
3. Weak government performance and policy implementation
4. Failure to recognize and prioritize local people and their needs and experiences
5. Deforestation/tree clearing for land-use expansion and intensification, and overutilization
6. Lack of or weak monitoring
7. Lack of or fake participation, only for political/reporting purposes
8. Corruption
9. Absence of or weak trees/forest planting, management, maintenance, and governance
10. Predominance of inequality and unfairness
11. Lack of or weak support and supply of materials (e.g., seedlings)
12. Predominance of human-wildlife conflict
13. Dependency on or waiting for government for tree/forest management
14. Lack of or fake collaboration: connectivity among stakeholders across scales
15. Lack of or weak local social network and collaboration in trees/forest management
16. Lack of coordination or predominance of diverging values, knowledge, needs, and interests
17. Lack of responsible unit or institution
18. Loss of local social norms, values, cultures, institutions, and bylaws (customary laws)
19. Power of political elite: local people are afraid to stand up for their rights
20. Predominance of mistrust/doubt, and absence of interest, motivation, and willingness in trees/forest management

As to solutions, 44 different types of solutions were identified to help facilitate the application of at least one of the resilience principles (Table S3) in the context of woody vegetation diversity management. The most frequently named solutions were:

enhancing awareness and experience sharing (72 instances out of a possible 170 mentions [17 groups by 10 principles]), connectivity among stakeholders across multiple units and levels (71), adaptive co-management and governance of trees and forest (68), enacting local social networks and collaboration legally (60), genuine participation or self-mobilization of local people (41), strengthening government structures and policy performance (41), and enhancing equity and roles of stakeholders (30; Table S3). Among the solutions that could improve the operationalization of most resilience principles simultaneously were the above-mentioned solutions, as well as enhancing laws and law enforcement, support and supply of materials, e.g., tree seedlings, and monitoring of the entire system (Table S3). Box 2 lists the most prominently suggested solutions for better resilience management for our study system.

Box 2: Suggested solutions (in decreasing frequency of total mentions summed across all individual groups and principles) that could help facilitate the application of resilience principles to the management of woody plant diversity in smallholder faming landscapes of southwestern Ethiopia (cf. Table S3, for complete list of suggested solutions).

1. Enhance awareness creation and experience sharing
2. Enhance connectivity among stakeholders across units and levels
3. Enhance adaptive co-management and governance of trees/forest
4. Enact and enhance local social network and collaboration legally
5. Enhance genuine participation or local self-mobilization
6. Strengthen government structures and policy performance
7. Enhance equity and roles of stakeholders, particularly local groups
8. Avoid individualism, and enhance care, responsibility, and respect
9. Restore and enhance local cultures, norms, values, institutions, and bylaws
10. Empower local people and their social networks/institutions
11. Enhance support and supply of materials (e.g., seedlings)
12. Recognize and prioritize local people, their needs and experiences
13. Enhance NGOs/projects and their performance
14. Enhance family planning services
15. Enhance law, legislation, and proclamation as well as its enforcement
16. Enhance monitoring
17. Recognize local people trees/forest ownerships and use rights
18. Enhance soil and water conservation practices
19. Enhance transparency and freedom of speech or expression
20. Enhance job creation/suitable poverty reduction strategy
21. Stop corruption

Resilience challenges and solutions across system characteristics

Relatively few resilience challenges and solutions were associated with the shallow levels of system parameters (Fig. 2) and feedbacks (Fig. 3). In contrast, many perceived resilience challenges and solutions occurred at the deeper levels of system design (Fig. 4) and intent (Fig. 5).

As to differences among stakeholder groups, administration staff, expert, researcher, and model farmer stakeholder groups articulated resilience challenges and solutions that occurred across all system levels, including shallow levels of system parameters and feedbacks (Fig. S1, S2, S3 and S4). In contrast, local stakeholder groups, including low-income farmers, perceived resilience challenges and solutions that occurred predominantly at the deeper levels of system design and intent (Fig. S3 and S4).

DISCUSSION

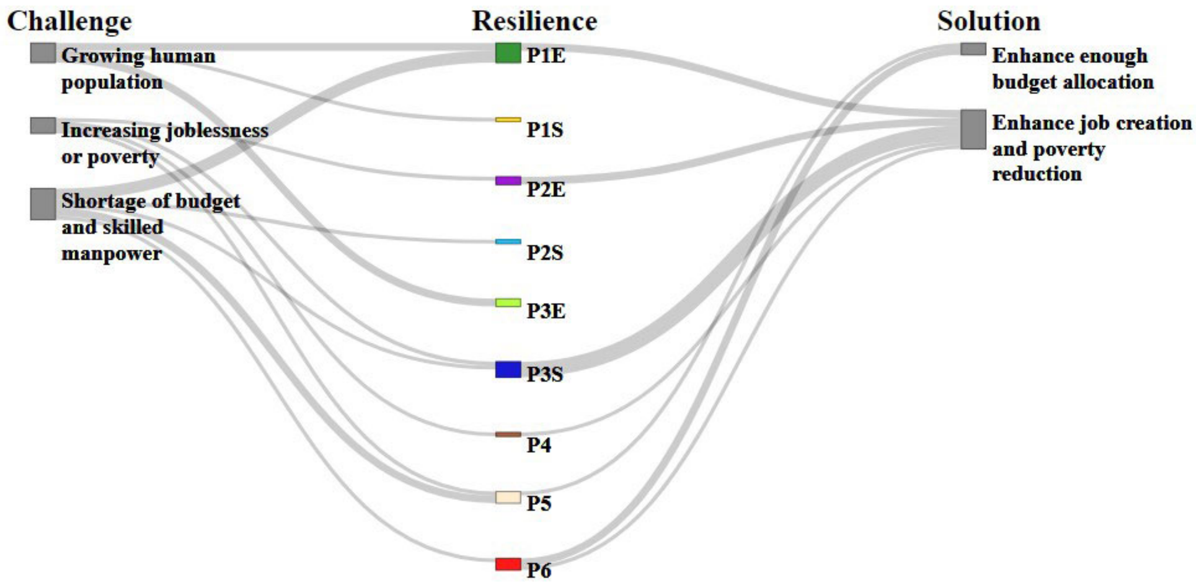
We combined two perspectives on complex SES, namely a social-ecological resilience perspective and a leverage points perspective. First, we documented stakeholders' understanding of the resilience principles, and identified numerous challenges and suggested solutions to building resilience. Second, we uncovered linkages from resilience challenges and solutions to many different leverage points, ranging from parameters to intent. Third, we noted divergence among local and other stakeholder groups in their perceptions, in that most local stakeholder groups perceived resilience challenges and solutions that were associated predominantly with deeper systemic levels, while higher-level stakeholders also (and sometimes primarily) considered relatively more shallow levels of the social-ecological system.

In the following, we discuss these findings with respect to (a) applying resilience principles, and particularly why applying some principles remains challenging in the Global South; and (b) the importance of the deeper systemic levels of system design and intent to guide interventions. Finally, (c) we reflect on the possible utility of combining the two perspectives used here (a resilience perspective and a leverage points perspective) in other SES contexts.

Applying resilience principles

Our findings showed widespread management of woody plant diversity and redundancy (P1E) and ecological connectivity (P2E) in the study area. A possible reason for this could be that the culture of local people and farmers is to manage trees and favor agrobiodiversity (Altieri 2009, Jiren et al. 2018a, Shumi et al. 2021) in spite of agricultural intensification policies (Kassa et al. 2016) and a highly hierarchical food security and biodiversity conservation governance in the region (Jiren et al. 2018b). A likely additional reason is that local communities directly depend on

Fig. 2. Sankey diagram of perceived challenges for and solutions to resilience, at the systemic level of parameters. The width of lines in the diagram denotes the number of stakeholder groups asserting the challenge or solution. For details of resilience principles, see Table 1.



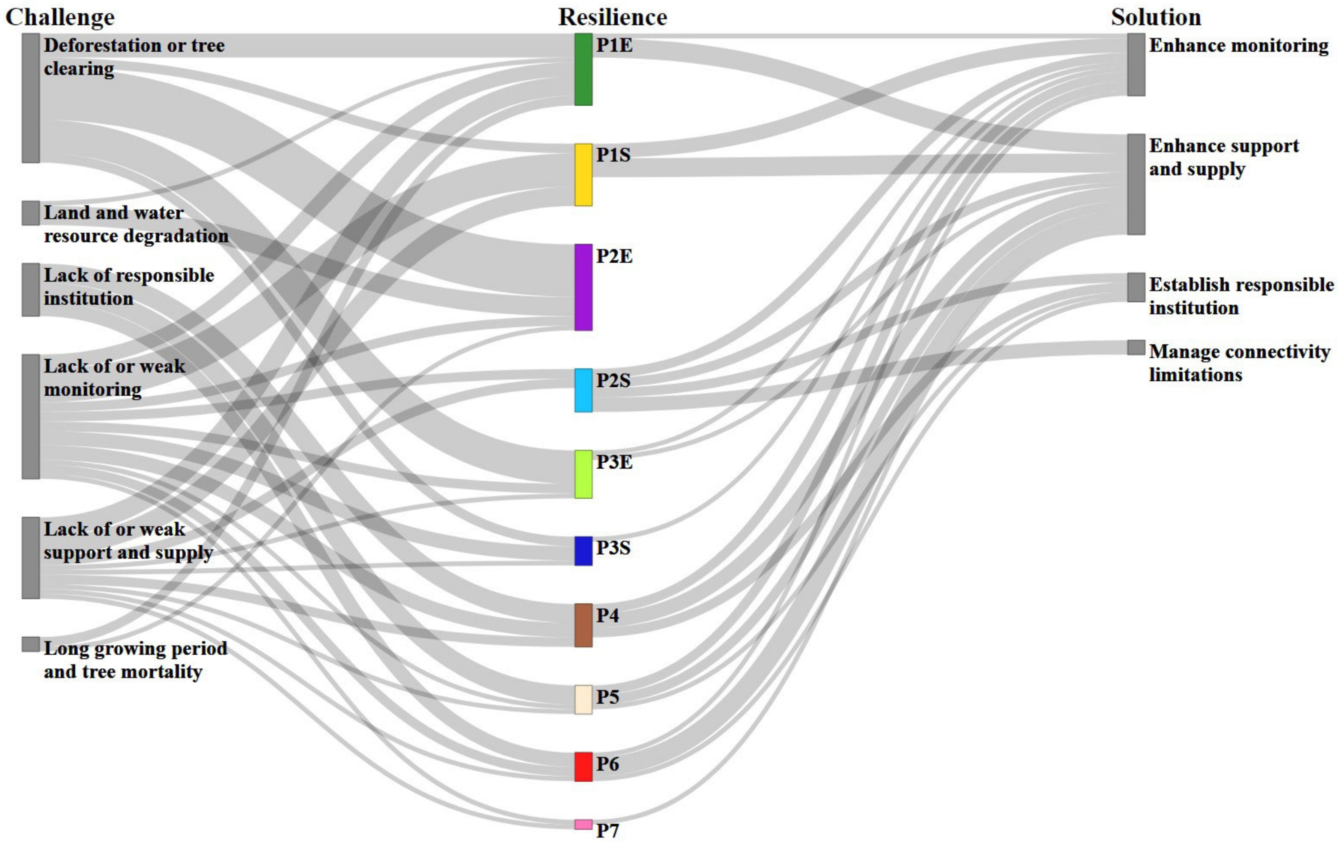
and have close ties to nature, and especially woody vegetation and their associated ecosystem services, for their livelihoods in the area (Shumi et al. 2019b), similarly to other SES within the Global South (e.g., Samberg et al. 2016, Pehou et al. 2020, Gitz et al. 2021). Managing diverse tree and shrub species across the landscape can also facilitate ecological connectivity, as corroborated by other studies (e.g., Bailey 2007, Saura et al. 2014), which is vital for the maintenance of local and regional biodiversity, ecosystem integrity, and ecological functions.

In contrast, our findings also uncovered the widespread lack of application of many other resilience principles, such as managing social diversity and redundancy (P1S), managing social connectivity (P2S), managing slow ecological variables and feedbacks (P3E) and slow social variables and feedbacks (P3S), understanding of SES as complex adaptive systems (CAS; P4), adaptive learning and experimentation processes (P5), participation (P6), and polycentric governance (P7). This may be due to deep-rooted, expert-driven, top-down command and control economic development strategies (Holling and Meffe 1996, Jiren et al. 2018b, Reed et al. 2020) that are typified by strong power hierarchies and asymmetries (Armitage et al. 2009, Foli et al. 2018), which is common in many parts of the Global South (e.g., see Faye 2017, Mustalahti et al. 2020, Zafra-Calvo et al. 2020). Linked to this is the possible marginalization of local people, their traditional knowledge, social networks, norms, and lifestyles (Megerssa and Kassam 2020, van Noordwijk 2020, Zinngrebe et al. 2020), which could eventually lead to a deterioration of their relationship with nature (Faye 2017, White 2017, Lyver et al. 2019). For example, empirical findings by Jiren et al. (2018b) in our study area and by Mustalahti et al. (2020) in Mexico, Nepal, and Tanzania revealed highly hierarchical natural resource governance that favors only few powerful stakeholders and functions without adequate legitimacy of deprived social groups and their livelihoods (Faye 2017, Salomon et al. 2018).

The issues mentioned above may explain our findings regarding the difficulty of pursuing participatory management (P6), social diversity and redundancy (P1S), polycentric or decentralized governance (P7), and adaptive learning and experimentation (P5) in our study area. Our findings concur explicitly with study by Ruiz Agudelo et al. (2020) who documented difficulties in the application of these principles in the Amazon basin, as well as with other studies from other countries that show widespread absence of political recognition of social groups and absence of decentralized governance (e.g., see Scheba and Mustalahti 2015, Faye 2017, Mustalahti et al. 2020). Applying these key principles therefore may be hampered by strong prevailing political power differences as well as by reductionist views (Béné et al. 2009, Scheba and Mustalahti 2015), lack of political willingness, bureaucratic institutions, and social-political reluctance for change in natural resource governance (Brockhaus and Angelsen 2012, Foli et al. 2018).

Despite many challenges, our findings also highlighted possible solutions, including enhancing awareness and experience sharing, connectivity among stakeholders across scales and levels, adaptive co-management and governance of woody vegetation, enacting local social networks and collaboration, genuine participation of local people, strengthening government structures and policy performance, and enhancing equity, all of which can facilitate resilience building in the study region. Furthermore, often these interventions were understood as contributing simultaneously to multiple resilience principles (see Fig. 4 and 5; Table S3). Our empirical findings concur with studies, by e.g., Waters et al. (2022) and Chavez-Miguel et al. (2022), that provide insights into the importance of contextualized, locally based initiatives for SES resilience building. Importantly, they have clear parallels with recent recommendations for reconciling resilience and well-being (Chaigneau et al. 2022), for social-

Fig. 3. Sankey diagram of perceived challenges for and solutions to resilience at the systemic level of feedbacks. The width of lines in the diagram denotes the number of stakeholder groups asserting the challenge or solution. For details of resilience principles, see Table 1.



ecological transformation (e.g., see Visseren-Hamakers et al. 2021, Fougères et al. 2022), and for supporting the pluriverse, that is, pluralistic, culturally, and contextually specific solutions (Escobar 2018).

Interventions at deep leverage points: system design and intent

Several recent studies have emphasized the need for working with deep leverage points (system design and intent) to instigate system-wide transformative change (e.g., Dorninger et al. 2020 in energy and food systems, or Ives et al. 2020 for inner sustainability). Because there are interactions and interlinkages among leverage points, deeper system design and intent interventions might also facilitate interventions at more shallow leverage points, and vice versa (Manlosa et al. 2019a, Fischer and Riechers 2019, Riechers et al. 2021). Empirically, our findings uncovered the occurrence of a majority of both challenges and solutions at relatively deep leverage points (see Fig. 4 and 5); that is, effectively operationalizing resilience principles in smallholder faming landscapes likely entails deep interventions, such as changes in system goals, rules, values, self-organizing structures, paradigms, and intents (Abson et al. 2017, Ives et al. 2020). In line with our findings, the study by Fischer et al. (2022), for example, reveals the manifestation of resilience challenges (mainly triggered by the global green revolution discourse) at system design and intent levels in highly divergent SES of south-eastern Australia, central Romania, and southwestern Ethiopia. Thus, to address sustainability challenges or to enact effective solutions and foster diverse and fair futures for human and nonhuman life on Earth, paradigm shifts are needed (Patterson et al. 2017, Fougères et al. 2022).

In pursuing such paradigm system shifts, recognizing and aligning with indigenous peoples and local communities, and their multiple worldviews could help to facilitate social-ecological transformation (Fernández-Llamazares et al. 2021, Tynan 2021), particularly in the Global South (Escobar 2016, Megerssa and Kassam 2020, Martin et al. 2022). Our findings that most local stakeholder groups perceived that challenges and solutions occurred at deep leverage points (see Fig. S3 and S4) indicates a strong potential of local thought and action for transformative change and fundamentally improving social-ecological resilience (Ives et al. 2020, Molnár and Babai 2021, Fernández-Llamazares et al. 2021). Nevertheless, in many cases both Western and non-Western modernist practitioners (i.e., those who focus on the green revolution or growth-based development, and often have an intent to dominate or control other humans and nature), policy makers, and researchers neglect local communities and their livelihoods, complex systems of knowledge, cultures, and norms (Arora 2019, Lyver et al. 2019, Fernández-Llamazares et al. 2021).

Fig. 4. Sankey diagram of perceived challenges for and solutions to resilience at the systemic level of design. The width of lines in the diagram denotes the number of stakeholder groups asserting the challenge or solution. For a complete list of perceived challenges for and solutions to resilience for the design system level, see Tables S2 and S3. For details of resilience principles, see Table 1.

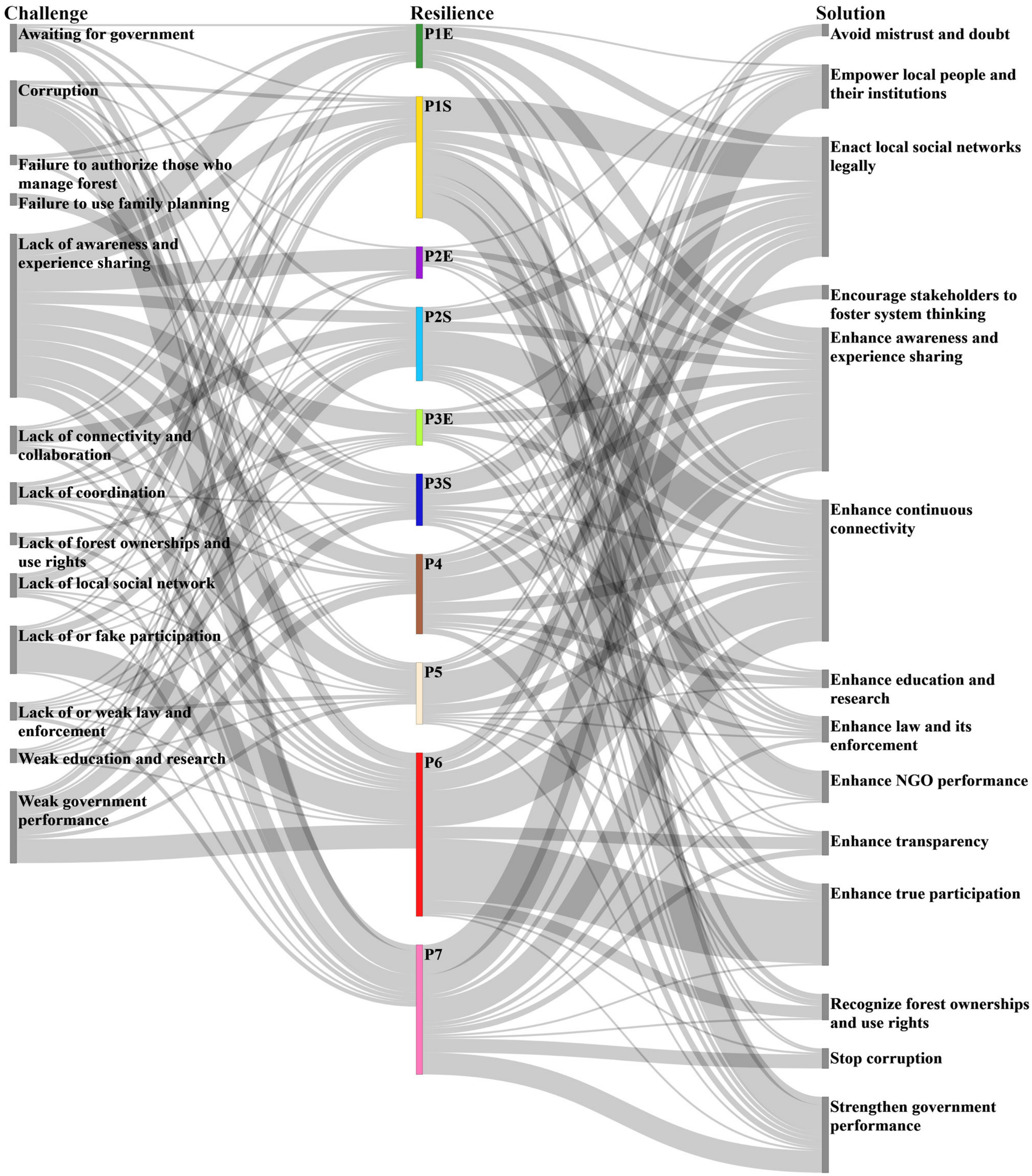
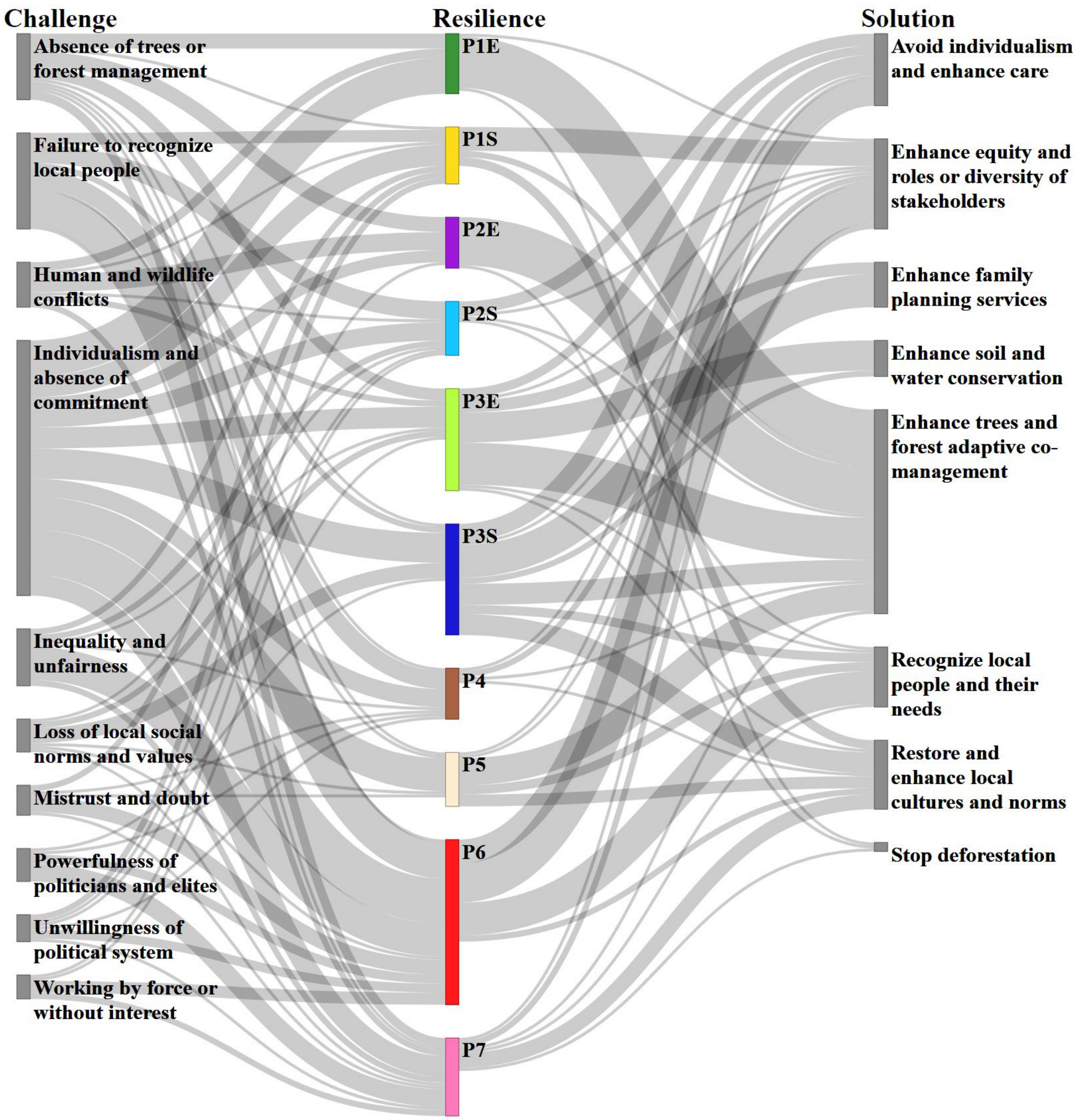


Fig. 5. Sankey diagram of perceived challenges for and solutions to resilience at the systemic level of intent. The width of lines in the diagram denotes the number of stakeholder groups asserting the challenge or solution. For a complete list of perceived challenges for and solutions to resilience for at intent system level, see Tables S2 and S3. For details of resilience principles, see Table 1.



Modernist thinking can "inferiorize" local people and their long-standing practices as "primitive," "irrational," or "unproductive" (Arora 2019, Megerssa and Kassam 2020). Because of this, even though local people perceive and are affected by a loss of resilience, they do not have the power to use their experiences to reverse the situation (e.g., see Jacobi et al. 2017, Zikargie and Cochrane 2022, Hartel et al. 2023). Our findings therefore add to the growing recognition of the importance of facilitating resilience by drawing on deeper place-based local knowledge, including the people, culture, and norms that produce such knowledge (see also Hernández 2020, Thomas 2021, Tynan 2021).

Combining social-ecological resilience and leverage points perspectives

Many land-use models (e.g., land-sharing/-sparing analyses of landscapes for ecosystem services and biodiversity conservation; Grass et al. 2019) and social-ecological system studies (e.g., on woody plant conservation and ecosystem services; Dugo 2019) primarily consider the material characteristics of SES, without due consideration of immaterial system feedbacks, design, and intent (e.g., Fischer et al. 2014, Fischer et al. 2022, Riechers et al. 2022). Such models and studies are likely limited in their ability to address sustainability problems, because deep-rooted dominant worldviews, power structures, institutions, and technologies favor intensification for material production and consumption (Beddoe et al. 2009, Blythe et al. 2018, Knutti 2019), but are outside the scope of many existing investigations.

By combining the social-ecological resilience and leverage points perspectives, our research revealed the current state of social-ecological resilience, as well as context-specific resilience challenges and solutions for transformative change toward sustainability. This combination of perspectives can help to shed light on the places to intervene in the system, and in our case, clearly underlined the need to draw on the deep knowledge of local people to overcome current challenges. Our research thus suggests that combining social-ecological resilience and leverage points perspectives can provide a useful framing for revealing and understanding context-specific challenges and solutions for transformative change toward sustainability in complex SES. Applying a similar approach could therefore also be useful in other types of SES.

Finally, the findings discussed above depend entirely on the empirical data gathered from focus group discussions with various stakeholders, and therefore may be limited by our accuracy of understanding the points made by discussants, as well as by the accuracy of our coding these data. The study may also be limited by a certain degree of subjectivity in classifying the generated codes into levels of systemic depth, namely system parameters, feedbacks, design, and intent. Nevertheless, we suggest future studies should also attempt to combine a social-ecological resilience perspective and with a leverage points perspective, because this may be a promising way to generate new insights for how to better navigate and transform SES.

CONCLUSION

Addressing ecosystem destruction and unsustainable development pathways requires appropriate frameworks to comprehensively investigate complex and interlinked social and ecological processes. Such approaches are key to identifying interventions that can facilitate transformation to sustainability. Yet, much work is still needed to link suitable approaches to concrete, local transformative change. In this study, by combining a social-ecological resilience perspective and a leverage points perspective, we documented evidence of stakeholders' understanding of currently applied approaches to building SES resilience. In addition, we documented numerous challenges, and suggested solutions for further building SES resilience. Many resilience challenges and solutions were related to deeper systems properties, such as institutional structures and rules (system design) and the worldviews, system goals, and underpinning paradigms that shape the governance of SES (system intent). Especially community level stakeholders perceived resilience challenges and solutions as being associated predominantly with these deeper systemic levels.

Our results and approach could be useful well beyond our study area, especially because in 2021 the IPBES launched its new call for a "Transformative Change Assessment" with the aim to understand and identify factors in SES that may be leveraged to bring about transformative change (IPBES 2021). To enhance transformative change and resilience management in the landscapes of southwestern Ethiopia and other similar parts of the globe, we suggest (a) to foster bottom-up changes in system goals, rules, paradigms, and intent, drawing explicitly on local people and their knowledge; and (b) more specifically to recognize local people, mainly farmers, and their livelihoods, long-aged traditional ecological knowledge, and practices.

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Data Availability:

The empirical data that support the findings of this study are also available on request.

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Appendix 1. Supplementary Materials

Table S1. Stakeholder groups articulated social-ecological system current situations and their possible link to system level characteristics and specific leverage point – place of intervention in a system in the context of woody vegetation management in the landscape of southwestern Ethiopia. For details of resilience principles and system characteristics and leverage points, see Table 1 and Table 2 in the method section of the main text, respectively). Note that stakeholder groups are GBG1MF = Model farmers from Gido Bere; GBG2PF = Low-income farmers from Gido Bere; GBG3W = Women from Gido Bere; GBG4E = Elders from Gido Bere; GB5TSDA = Teachers, students and development agents (DA) from Gido Bere; KKG1MF = Model farmers from Kuda Kofi; KKG2PF = Low-income farmers Kuda Kofi; KKG3W = Women from Kuda Kofi; KKG4E = Elders from Kuda Kofi; KKG5TSDA = Teachers, students and development agents (DA) from Kuda Kofi; SG1AdmNGO = Admin and None Governmental Organization (NGO) experts from Setema district; SG2AgriOFWE = Agricultural and Oromia Forest and Wildlife Enterprise (OFWE) experts from Setema district; GG1AdmNGO = Admin and NGO experts from Gumay district; GG2AgriOFWE = Agricultural and OFWE experts from Gumay district; JG1AdmNGO = Admin and NGO experts from Jimma Zone; JG2AgriOFWE = Agricultural and OFWE experts from Jimma Zone; and JG3JURE = Lecturers and researchers from Jimma University and Biodiversity Research Institute. Note also that frequency denotes the number of stakeholder groups and the number in bracket the percentage of stakeholder groups articulating the respective current resilient situation.

Stakeholder group involved	Perceived current situation	Frequency (%)	Narrated resilience principle	Likely system level (Abson et al. 2017)	Specific leverage point – place of intervention (Meadows 1999)	Remark
GBG3W, KKG1MF, KKG2PF, KKG5TSDA, GG1AdmNGO, SG2AgriOFWE, JG2AgriOFWE, JG3JURE	Local people separately manage trees/forest on their own, leading to stakeholder fragmentation in trees/forest management in the landscape	8 (47)	P1S	Design	The structure of information flows	
GG2AgriOFWE	In some cases, religious institutions manage trees/forest by their own initiative in the landscape	1 (6)	P1S	Design	The rules of the system (informal institutions – weak informal rules)	Stated only by district government actors or experts
GB5TSDA, KKG1MF, KKG3W, KKG4E, KKG5TSDA, GG1AdmNGO, GG2AgriOFWE, SG1AdmNGO, JG1AdmNGO, JG2AgriOFWE, JG3JURE	In some cases, associations/forest user groups manage trees/forest in the landscape	11 (65)	P1S	Design	The structure of information flows	Stated mainly by government actors or experts
GB5TSDA, KKG1MF, KKG3W, KKG4E, KKG5TSDA, GG1AdmNGO, GG2AgriOFWE, SG1AdmNGO, JG1AdmNGO, JG2AgriOFWE, JG3JURE	Government/OFWE manage trees/forest	11 (65)	P1S	Design	The power to add, change, evolve, or self-organize system structure	Stated mainly by government actors or experts
GB5TSDA, KKG3W, KKG4E, GG1AdmNGO, GG2AgriOFWE,	NGO (SLM, REDD+, CALM & Green legacy) manage trees/forest in	10 (59)	P1S	Design	The structure of information flows	Stated mainly by government actors

SG1AdmNGO, SG2AgriOFWE, JG1AdmNGO, JG2AgriOFWE, JG3JURE	the landscape					or experts
GBG4E, KKG2PF, SG1AdmNGO	Politically imposed local social networks manage trees/forest but they are weak	3 (18)	P1S	Design	The power to add, change, evolve, or self-organize system structure	
SG2AgriOFWE, JG2AgriOFWE	In some cases, informal local social networks manage trees/forest by their own initiative	2 (12)	P1S	Design	The rules of the system but weak informal rules	Stated only by government actors or experts
GBG1MF, GBG2PF, GBG3W, GBG4E, GB5TSDA, KKG1MF, KKG2PF, KKG3W, KKG4E, KKG5TSDA, GG1AdmNGO, GG2AgriOFWE, SG1AdmNGO, SG2AgriOFWE, JG1AdmNGO, JG3JURE	Informal local social networks do not manage trees/forest or have no trees/forest management roles legally, leading to absence of diverse local groups that manage trees/forest in the landscape	16 (94)	P1S	Design	Rules of the system	Stated by almost all stakeholders
GBG1MF, GBG2PF, GBG3W, GBG4E, SG2AgriOFWE	There is no formal local social network that manage trees/forest in the landscape	5 (29)	P1S	Design	The power to add, change, evolve, or self-organize system structure	Stated mainly by local stakeholders
GBG1MF, GBG2PF, GBG3W, GBG4E, KKG2PF	Government/OFWE does not manage trees/forest practically, leading to weak management and policy performance	5 (29)	P1S	Design	The power to add, change, evolve, or self-organize system structure	Stated by local stakeholders
GBG1MF, GBG2PF, GBG3W, GBG4E, GB5TSDA, KKG1MF, KKG2PF, KKG3W, KKG4E, KKG5TSDA, GG1AdmNGO, GG2AgriOFWE, SG1AdmNGO, SG2AgriOFWE, JG1AdmNGO, JG2AgriOFWE, JG3JURE	Certain tree species provide a stock for direct benefit	17 (100)	P1E	Parameters	The structure of material stocks and flows and nodes of interaction	Stated by all stakeholders
GBG1MF, GBG2PF, GBG3W, GBG4E, GB5TSDA, KKG1MF, KKG2PF, KKG3W, KKG4E, KKG5TSDA, GG1AdmNGO, GG2AgriOFWE, SG1AdmNGO, SG2AgriOFWE, JG1AdmNGO, JG2AgriOFWE, JG3JURE	Certain tree species provide a stock for indirect benefit	17 (100)	P1E	Parameters	The structure of material stocks and flows and nodes of interaction	Stated by all stakeholders
GBG1MF, GBG2PF, KKG1MF, GG2AgriOFWE, SG1AdmNGO, JG2AgriOFWE	The abundance of some native tree species in the landscape is declining	6 (35)	P1E	Feedback	The gain around driving positive feedback loops	
GBG1MF, JG1AdmNGO	Nowadays, some native tree species are found only in the forest	2 (12)	P1E	Feedback	The gain around driving positive feedback loops	
SG1AdmNGO, JG1AdmNGO	Nowadays, the number of Eucalyptus plantations in the landscape is increasing	2 (12)	P1E	Parameters	The size of buffers and other stabilizing stocks, relative to their flows	Stated only by admin experts – government actors

GBG4E, KKG2PF, KKG5TSDA, GG1AdmNGO, GG2AgriOFWE, SG2AgriOFWE, JG1AdmNGO, JG2AgriOFWE, JG3JURE	Connectivity/collaboration among stakeholders exists for trees/forest management in the landscape	9 (53)	P2S	Design	The structure of information flows	Stated mainly by experts or government actors
GBG1MF, GBG2PF, GBG3W, GBG4E, GB5TSDA, KKG1MF, KKG2PF, KKG3W, KKG4E, KKG5TSDA, GG1AdmNGO, SG1AdmNGO, SG2AgriOFWE, JG1AdmNGO, JG3JURE	Connectivity/collaboration among stakeholders does not exist, leading to lack of information flow for/in trees/forest management in the landscape	15 (88)	P2S	Design	The structure of information flows	Stated by almost all stakeholders
GBG1MF, GBG2PF, GBG4E, GB5TSDA, KKG1MF, KKG2PF, KKG3W, KKG4E, KKG5TSDA, GG1AdmNGO, GG2AgriOFWE, SG1AdmNGO, SG2AgriOFWE, JG1AdmNGO, JG2AgriOFWE, JG3JURE	Connectivity among habitats in the landscape exists via vegetation strips/corridors	16 (94)	P2E	Parameters	The structure of material stocks and flows and nodes of interaction	Stated by almost all stakeholders
GBG1MF, GBG2PF, GBG4E, GB5TSDA, KKG1MF, KKG3W, KKG4E, KKG5TSDA, GG1AdmNGO, SG1AdmNGO, SG2AgriOFWE, JG1AdmNGO, JG2AgriOFWE	Connectivity among habitats in the landscape exists via steppingstones/scattered trees	13 (77)	P2E	Parameters	The structure of material stocks and flows and nodes of interaction	
GBG1MF, GBG2PF, GBG3W (2), GBG4E, GB5TSDA, KKG1MF, KKG2PF, KKG3W (2), KKG4E, KKG5TSDA, GG1AdmNGO, GG2AgriOFWE, SG1AdmNGO, SG2AgriOFWE (2), JG1AdmNGO (2), JG2AgriOFWE, JG3JURE	Currently, there is a cascade of land & water resources/biodiversity & ecosystem service degradation/loss	4 (24) (P3S), & 17 (100) (P3E)	P3S & P3E	Feedback	The gain around driving positive feedback loops	Stated by all stakeholders for P3E
SG1AdmNGO	There is an outmigration	1 (6)	P3S	Parameters	The structure of material stocks and flows and nodes of interaction	Stated only by district admin experts
GG2AgriOFWE	Livestock population is increasing	1 (6)	P3S	Parameters	The structure of material stocks and flows and nodes of interaction	Stated only by district experts
GG2AgriOFWE, JG2AgriOFWE, JG3JURE	Lawlessness is increasing, leading to lack of social order or violence	3 (18)	P3S	Design	Rules of the system	Stated only by experts
GBG1MF, GBG2PF, GBG3W, GBG4E, GB5TSDA, KKG1MF, KKG2PF, KKG3W, KKG4E, KKG5TSDA, GG1AdmNGO, GG2AgriOFWE, SG1AdmNGO, SG2AgriOFWE, JG1AdmNGO, JG2AgriOFWE, JG3JURE	Human population is growing	17 (100)	P3S	Parameters	Constants, parameters, numbers	Stated by all stakeholders
GBG1MF, GBG2PF, GBG3W, GBG4E, GB5TSDA, KKG1MF, KKG2PF, KKG4E, KKG5TSDA, GG1AdmNGO,	Poverty is increasing due to human population growth, inequality and natural resources degradation	14 (82)	P3S	Parameters	Constants, parameters, numbers	Stated by almost all stakeholders

SG1AdmNGO, SG2AgriOFWE, JG1AdmNGO, JG2AgriOFWE						
GBG1MF, GBG2PF, GB5TSDA (2), KKG2PF, KKG3W (2), KKG4E, KKG5TSDA, GG1AdmNGO, SG1AdmNGO, SG2AgriOFWE, JG1AdmNGO	Deforestation/tree clearing for farmland/settlement expansion, tree use & land–use intensification in the landscape is increasing	2 (12) (P3S), & 11 (65) (P3E)	P3S & P3E	Feedback	The gain around driving positive feedback loops	
GBG1MF, GBG2PF, GBG3W, GBG4E, GB5TSDA, KKG1MF, KKG2PF, KKG3W, KKG4E, KKG5TSDA, GG1AdmNGO, GG2AgriOFWE, SG1AdmNGO, SG2AgriOFWE, JG1AdmNGO, JG2AgriOFWE, JG3JURE	There is a tendency of loss of local social norms/values & cultures, leading to loss of local social capital or local people ability to self-organize and enhance sustainable trees/forest management in the landscape	17 (100)	P3S	Design	The power to add, change, evolve, or self-organize system structure	Stated by all stakeholders
GBG2PF, GBG4E, GB5TSDA, KKG3W, GG1AdmNGO	Individualism, and absence of commitment/ responsibility & care/respect is increasing, leading to uncontrolled personal behavior and mindset/paradigm out of which unsustainable system arises	5 (29)	P3S	Intent	Mindset/paradigm out of which system arises	Stated by almost local stakeholders
GBG1MF, GBG2PF, GBG3W, GBG4E, GB5TSDA, KKG1MF, KKG2PF, KKG3W, KKG4E, KKG5TSDA, GG1AdmNGO, GG2AgriOFWE, SG1AdmNGO, SG2AgriOFWE, JG1AdmNGO, JG2AgriOFWE, JG3JURE	Nowadays climate change is experienced locally due to both local and global factors, e.g., deforestation	17 (100)	P3E	Feedback	The gain around driving positive feedback loops	Stated by all stakeholders
KKG2PF, SG1AdmNGO, JG3JURE	NGO actors recognize & use system thinking for trees/forest management	3 (18)	P4	Design	The structure of information flows	
GBG2PF, KKG2PF, KKG4E, GG1AdmNGO, GG2AgriOFWE, SG1AdmNGO, JG1AdmNGO, JG2AgriOFWE	Local people/farmers recognize & use system thinking for trees/forest management self-initiatively	8 (47)	P4	Intent	The mindset or paradigm out of which the system arises	Stated by almost admin/NGO experts and local people
KKG2PF, KKG4E, G1AdmNGO, GG2AgriOFWE, SG1AdmNGO, JG1AdmNGO, JG2AgriOFWE, JG3JURE	Government actors & policy makers recognize & use system thinking for trees/forest management	8 (47)	P4	Design	The power to add, change, evolve, or self-organize system structure	
GBG1MF, GBG2PF, GBG3W, GBG4E, GB5TSDA, KKG1MF, KKG3W, KKG5TSDA, SG2AgriOFWE	There is no stakeholder that recognize & use system thinking for trees/forest management, leading to extremely reductionist/sectorial thinking	9 (53)	P4	Intent	Mindset/paradigm out of which system arises	Stated by almost local stakeholders
GBG1MF, GBG4E, KKG2PF, GG2AgriOFWE, SG2AgriOFWE, JG2AgriOFWE, JG3JURE	There is field day/agroforestry/farm visit & experience sharing process, but weak	7 (41)	P5	Design	The structure of information flows	
GBG2PF, GBG3W, GB5TSDA, KKG1MF, KKG3W, KKG4E, KKG5TSDA, GG1AdmNGO, SG1AdmNGO,	Continuous learning & experimentation processes do not exist, leading to absence of	10 (59)	P5	Design	The structure of information flows	Stated by almost local people and admin/NGO experts

JG1AdmNGO	trees/forest adaptive, co-management, monitoring and governance in the landscape					
GG2AgriOFWE, SG2AgriOFWE	Local people/farmers have customary law for experience sharing/learning among themselves	2 (12)	P5	Design	The rules of the system (weak informal rules)	Stated by district experts
SG1AdmNGO, SG2AgriOFWE	There is participation, e.g., in soil & water conservation, but weak	2 (12)	P6	Design	The power to add, change, evolve, or self-organize system structure	
GBG1MF, GBG2PF, GBG3W, GBG4E, GB5TSDA, KKG1MF, KKG2PF, KKG3W, KKG4E, KKG5TSDA, GG1AdmNGO, GG2AgriOFWE, SG1AdmNGO, SG2AgriOFWE, JG1AdmNGO, JG2AgriOFWE, JG3JURE	There is no true participation/local people self–mobilization in trees/forest management leading to the detachment of local people from nature & its benefits due to fortress conservation ahead of people approach	17 (100)	P6	Design	The power to add, change, evolve, or self-organize system structure	Stated by all stakeholders
GBG2PF	Politically imposed local social networks make decision on trees/forest management/uses	1 (6)	P7	Design	Rules of the system	Stated by poor farmers
GBG1MF, GBG2PF, GBG4E, GB5TSDA, KKG1MF, KKG2PF, KKG3W, KKG4E, KKG5TSDA, GG1AdmNGO, GG2AgriOFWE, SG1AdmNGO, SG2AgriOFWE, JG1AdmNGO, JG2AgriOFWE, JG3JURE	Admin, government & OFWE actors make decision at local & district/woreda levels on trees/forest management and uses	16 (94)	P7	Design	Rules of the system	Stated by almost all stakeholders
SG1AdmNGO	In some cases, elders make decision at community level on trees/forest management and uses	1 (6)	P7	Design	The rules of the system (weak informal rules)	Stated only by admin/NGO experts
GBG1MF, GBG5TSDA, KKG2PF, JG1AdmNGO	Local people are prohibited from accessing/using native trees/forest leading to absence of or limited trees/forest related benefits or ecosystem services to local people	4 (24)	P7	Design	Rules of the system	
GBG1MF, GBG2PF, GBG3W, GBG4E, GB5TSDA, KKG1MF, KKG2PF, KKG3W, KKG4E, KKG5TSDA, GG1AdmNGO, GG2AgriOFWE, SG1AdmNGO, SG2AgriOFWE, JG1AdmNGO, JG2AgriOFWE, JG3JURE	There is no decision-making power to local people & their social networks	17 (100)	P7	Design	The power to add, change, evolve, or self-organize system structure	Stated by all stakeholders

Table S2. Perceived challenges; their system level characteristics; and leverage points in applying resilience principles to woody vegetation diversity management in stallholder farming landscape of southwestern Ethiopia. For details of resilience principles and system characteristics and leverage points, see Table 1 and Table 2 in the method section of the main text).

Perceived resilience challenge	**Frequency of challenge**	**Hindered resilience principle**	**System level (Abson et al. 2017)**	**Specific leverage point – place of intervention (Meadows 1999)**
Land and water resource/ecosystem service degradation/loss	5	P1E, P2E	Feedback	The gain around driving positive feedback loops
Long gestation/growing period & mortality of native species	3	P1E, P2E	Feedback	The length of delays, relative to the rate of system change/and the gain around driving positive feedback loops
Growing human population	5	P1S, P1E, P3E	Parameters	Constants, parameters, numbers
Absence of/weak NGO performance	3	P1S, P3E	Design	Structure of information flow
Deforestation/tree clearing for farmland/settlement expansion, tree use-overutilization & land-use intensification, e.g., due to growing human population	27	P1S, P1E, P2E, P3S, P3E	Feedback	The gain around driving positive feedback loops
Failure to use/absence of family planning services	6	P3S	Design	Structure of information flow
Conflict among local people & investors–land grabbing	1	P4	Design	Rules of the system
Failure to encourage/authorize those who manage trees/forest	5	P1S, P1E, P5	Design	Structure of information flow
Increasing joblessness/poverty–inappropriate poverty reduction strategy	4	P2E, P3S, P4, P5	Parameters	Constants, parameters, numbers
Absence of/weak continuous learning & experimentation processes	3	P5	Design	Structure of information flow
Lack of/weak education, research & scientific information	7	P1S, P2S, P2E, P3E, P4, P5, P6	Design	Structure of information flow
Shortage/limitation of budget & lack of skilled manpower	8	P1E, P2S, P3S, P5, P6	Parameters	Constants, parameters, numbers
Lack of coordination or diverging values/knowledge, needs & interests	11	P1S, P2S, P2E, P3S, P4, P5, P6	Design	Rules of the system/structure of information flow
Lack of responsible unit/institution, e.g., that facilitate/monitor participation, continues learning processes, system thinking	11	P4, P5, P6	Feedback	The strength of negative feedback loops, relative to the impacts they are trying to correct against
Weak government performance/policy implementation	36	P1S, P1E, P2S, P2E, P3S, P4, P5, P6	Design	The power to add, change, evolve, or self-organize system structure
Lack of/weak local social network & collaboration	12	P1S, P1E, P2S, P3E, P5, P6, P7	Design	The power to add, change, evolve, or self-organize system structure
Loss of local social norms/values, cultures & institutions/bylaws (customary laws) – aggravated by reductionist approach	11	P2S, P3S, P3E, P5, P6, P7	Intent	The mindset or paradigm out of which the system–its goals, structures, rules, delays, parameters–arises
Lack of/fake participation–only for political/reporting purposes	24	P1S, P1E, P2S, P3S, P3E, P6, P7	Design	The power to add, change, evolve, or self-organize system structure
Lack of/weak monitoring, e.g., monitoring of trees/forest management, connectivity, slow variables	26	P1S, P1E, P2S, P2E, P3S, P3E, P4, P5, P6, P7	Feedback	The strength of negative feedback loops, relative to the impacts they are trying to correct against
Absence of/weak trees/forest planting,	22	P1S, P1E, P2E,	Intent	The goals of the system

management & maintenance, leading to loss of biodiversity and ecosystem services degradation in the landscape		P3S, P3E, P4, P5, P6, P7		
Failure to recognize and prioritize local people and their needs & experiences	32	P1S, P2S, P3S, P4, P5, P6, P7	Intent	The power to transcend paradigms
Lack of clearly defined local people trees/forest ownerships & use rights	6	P3E, P6, P7	Design	Rules of the system
Lack of/weak support & supply	17	P1S, P1E, P2S, P3S, P3E, P4, P5, P6, P7	Feedback	The strength of negative feedback loops, relative to the impacts they are trying to correct against/ or the gain around driving positive feedback loops
Powerfulness of politicians/elites–local people are afraid/quit to ask for their rights	11	P3S, P4, P6, P7	Intent	Mindset/paradigm out of which system arises
Prevalence of mistrust/doubt & absence of interest/motivation/willingness	10	P1S, P4, P5, P6, P7	Intent	Mindset/paradigm out of which system arises
Working by force/without interest–command & control approach	6	P2S, P3E, P6, P7	Intent	Mindset/paradigm out of which system arises
Lack of awareness & experience sharing	82	P1S, P1E, P2S, P2E, P3S, P3E, P4, P5, P6, P7	Design	Structure of information flow
Unwillingness (of politicians) & instability of political systems to institutional change that local people desire or transformation to sustainability	9	P1S, P2S, P2E, P4, P6, P7	Intent	The goal of the system
Predominance of inequality/unfairness	19	P1S, P2S, P3E, P4, P6, P7	Intent	Mindset/paradigm out of which system arises
Human–wildlife conflict	15	P1S, P1E, P2S, P2E, P3E, P7	Intent	The goals of the system
Corruption	23	P1S, P2E, P3S, P4, P5, P6, P7	Design	Rules of the system
Lack of/weak law/proclamation & enforcement	9	P2S, P3S, P3E, P4, P5, P6, P7	Design	Rules of the system
Dependency on/awaiting for government–prevalence of trees/forest to government notion	14	P1S, P1E, P2S, P3E, P5, P6, P7	Design	The power to add, change, evolve. Or self-organize system structure
Individualism & absence of commitment/responsibility & care/respect	85	P1S, P1E, P2S, P2E, P3S, P3E, P4, P5, P6, P7	Intent	Mindset/paradigm out of which system arises
Lack of/fake connectivity/social network–collaboration among stakeholders	14	P1S, P1E, P2S, P4, P6, P7	Design	Structure of information flow
Fake/wrong or political trees/forest management & use/governance decision–making	3	P7	Design	The power to add, change, evolve, or self-organize system structure
Lack of transparency	1	P7	Design	The power to add, change, evolve, or self-organize system structure

Table S3. Perceived solutions to resilience; their system level characteristics; and leverage points in applying resilience principles to woody vegetation diversity management in stallholder farming landscape of southwestern Ethiopia. For details of resilience principles and system characteristics and leverage points, see Table 1 and Table 2 in the method section of the main text, respectively).

Perceived solution to resilience	Frequency of solution	Targeted resilience principle	System level (Abson et al. 2017)	Specific leverage point – place of intervention (Meadows 1999)
Encourage and involve investors in trees/forest management	3	P1S	Design	The power to add, change, evolve, or self-organize system structure
Encourage local people to consent with government/NGO structures	1	P1S	Design	The power to add, change, evolve, or self-organize system structure
Stop exerting power/being powerful on/to local people	1	P2S	Intent	Mindset/paradigm out of which system arises
Strengthen politically imposed local social networks	3	P1S, P2S	Design	Power to change system structure or self-organize
Enhance technology innovation	1	P2E	Intent	Goals of the system
Enhance changes/transformations in political systems, e.g., paradigm change from top-down to bottom-up approaches, change in institutions/rules	1	P3S	Intent	The power to transcend paradigms
Enhance ethics or raise children ethically	2	P3S	Intent	Mindset/paradigm out of which system arises
Manage connectivity limitations/conflicts/problems	3	P2S	Feedback	The strength of negative feedback loops, relative to the impacts they are trying to correct against
Distinct trees/forest management practices from politics	2	P1S, P3E	Design	Rules of the system
Enhance productivity via agricultural intensification, that might commodify smallholder farming (forest-agricultural mosaic) landscape	3	P3S, P3E	Intent	Goals of the system
Enhance family planning services	15	P3S, P3E	Intent	Goals of the system
Enhance soil and water conservation practices to mitigate land and water resource degradation	12	P3S, P3E	Intent	Goals of the system
Enhance organic farming approaches such as crop rotation & organic fertilizers	3	P3E	Intent	The power to transcend paradigm
Enhance coordination of diverging ideas/views & interests	4	P1S, P2S, P3E, P4	Design	Structure of information flow
Encourage stakeholders to foster & use system thinking for trees/forest management	7	P4	Design	Structure of information flow
Enhance education & research that fit into local/landscape context	9	P2E, P3S, P4, P5	Design	Structure of information flow
Resolve human–wildlife conflict	2	P2E, P5	Intent	Goals of the system
Enhance trees/forest adaptive, co–planting, management & maintenance/governance in the landscape	68	P1S, P1E, P2S, P2E, P3S, P3E, P4, P5, P7	Intent	Goal of the system
Authorize & strengthen those who manage trees/forest	5	P1E, P5	Design	Rules of the system
Avoid mistrust/doubt & enhance trust/interest/willingness	6	P4, P5, P6	Design	The power to add, change, evolve, or self-organize system structure
Enhance enough budget allocation/saving	3	P5, P6	Parameters	Constants, parameters, numbers
Enhance job creation/suitable poverty	10	P1E, P2E, P3S,	Parameters	Constants, parameters, numbers

reduction strategy		P4, P6		
Avert dependency on/awaiting for government	2	P3E, P6	Design	The power to add, change, evolve, or self-organize system structure
Define government & religious institutions' roles clearly	1	P6	Design	Rules of the system
Enhance monitoring, e.g., of trees/forest management, social and ecological connectivity	13	P1S, P1E, P2S, P3S, P3E, P4, P5, P6	Feedback	The strength of negative feedback loops, relative to the impacts they are trying to correct against
Establish responsible unit/institution, e.g., for owning and facilitating participation, continues learning processes, system thinking	6	P2S, P4, P5, P6	Feedback	The strength of negative feedback loops, relative to the impacts they are trying to correct against
Enhance true participation/local people self–mobilization in trees/forest management	41	P1S, P2S, P3S, P3E, P5, P6, P7	Design	The power to add, change, evolve, or self-organize system structure
Stop deforestation/illegal settlement/encroachment & logging – foster social-ecological resilience management	3	P1E, P2E, P7	Intent	Goal of the system
Enhance NGOs/projects & their performance	16	P1S, P1E, P2S, P4, P7	Design	Structure of information flow
Restore & enhance local cultures/norms, values & institutions/bylaws (customary laws) – to confront the current paradigms, e.g., reductionist approach	23	P1S, P3S, P3E, P4, P5, P6, P7	Intent	The mindset or paradigm out of which the system–its goals, structures, rules, delays, parameters–arises
Enhance transparency & freedom of speech/expression	12	P1S, P2S, P5, P6, P7	Design	The power to add, change, evolve, or self-organize system structure
Empower local people and their social networks/institutions	22	P1E, P2S, P2E, P3S, P5, P6, P7	Design	The power to add, change, evolve, or self-organize system structure
Prioritize/recognize local people, their needs & experiences than conservation or development fortress – a paradigm that persist for more than 100 years – leading to paradigm shift from top-down to bottom-up approaches	20	P2S, P3S, P3E, P5, P6, P7	Intent	The power to transcend paradigms
Enhance awareness creation & experience sharing	72	P1S, P1E, P2S, P2E, P3S, P3E, P4, P5, P6, P7	Design	Structure of information flow
Enhance support & supply, e.g., of seeds, seedlings or technical and material support	21	P1S, P1E, P2S, P3E, P4, P5, P6, P7	Feedback	The strength of negative feedback loops, relative to the impacts they are trying to correct against/ or the gain around driving positive feedback loops
Recognize local people tree/forest ownerships & use rights	13	P1S, P2S, P3E, P6, P7	Design	Rules of the system
Avoid individualism & enhance care/responsibility & respect – fostering transformative changes	24	P2S, P3S, P3E, P4, P5, P6, P7	Intent	Mindset/paradigm out of which system arises
Stop corruption	10	P1S, P2E, P6, P7	Design	Rules of the system
Strengthen government structures & their policy performance	41	P1S, P1E, P2S, P3S, P3E, P4, P5, P6, P7	Design	The power to add, change, evolve, or self-organize system structure
Enhance law/legislation/proclamation & its enforcement – strengthening constitutionality	13	P1S, P1E, P2S, P2E, P3S, P4, P5, P7	Design	Rules of the system

Enact and enhance local social networks, their leaders & collaboration legally	60	P1S, P1E, P2S, P3S, P3E, P4, P5, P6, P7	Design	The power to add, change, evolve, or self-organize system structure
Enhance continuous connectivity/collaboration among stakeholders for trees/forest management	71	P1S, P1E P2S, P2E, P3S, P3E, P4, P5, P6, P7	Design	Structure of information flow
Enhance equity & roles/diversity of stakeholders/local groups	30	P1S, P1E, P2S, P3S, P3E, P4, P5, P6, P7	Intent	Mindset/paradigm out of which system arises
Specify local people's & government powers clearly	1	P7	Design	Rules of the system

Fig. S1. Frequency of perceived challenges and solutions to resilience at parameters system level by stakeholder group. Note that stakeholder groups are GBG1MF = Model farmers from Gido Bere; GBG2PF = Low-income farmers from Gido Bere; GBG3W = Women from Gido Bere; GBG4E = Elders from Gido Bere; GB5TSDA = Teachers, students and development agents (DA) from Gido Bere; KKG1MF = Model farmers from Kuda Kofi; KKG2PF = Low-income farmers Kuda Kofi; KKG3W = Women from Kuda Kofi; KKG4E = Elders from Kuda Kofi; KKG5TSDA = Teachers, students and development agents (DA) from Kuda Kofi; SG1AdmNGO = Admin and None Governmental Organization (NGO) experts from Setema district; SG2AgriOFWE = Agricultural and Oromia Forest and Wildlife Enterprise (OFWE) experts from Setema district; GG1AdmNGO = Admin and NGO experts from Gumay district; GG2AgriOFWE = Agricultural and OFWE experts from Gumay district; JG1AdmNGO = Admin and NGO experts from Jimma Zone; JG2AgriOFWE = Agricultural and OFWE experts from Jimma Zone; and JG3JURE = Lecturers and researchers from Jimma University and Biodiversity Research Institute.

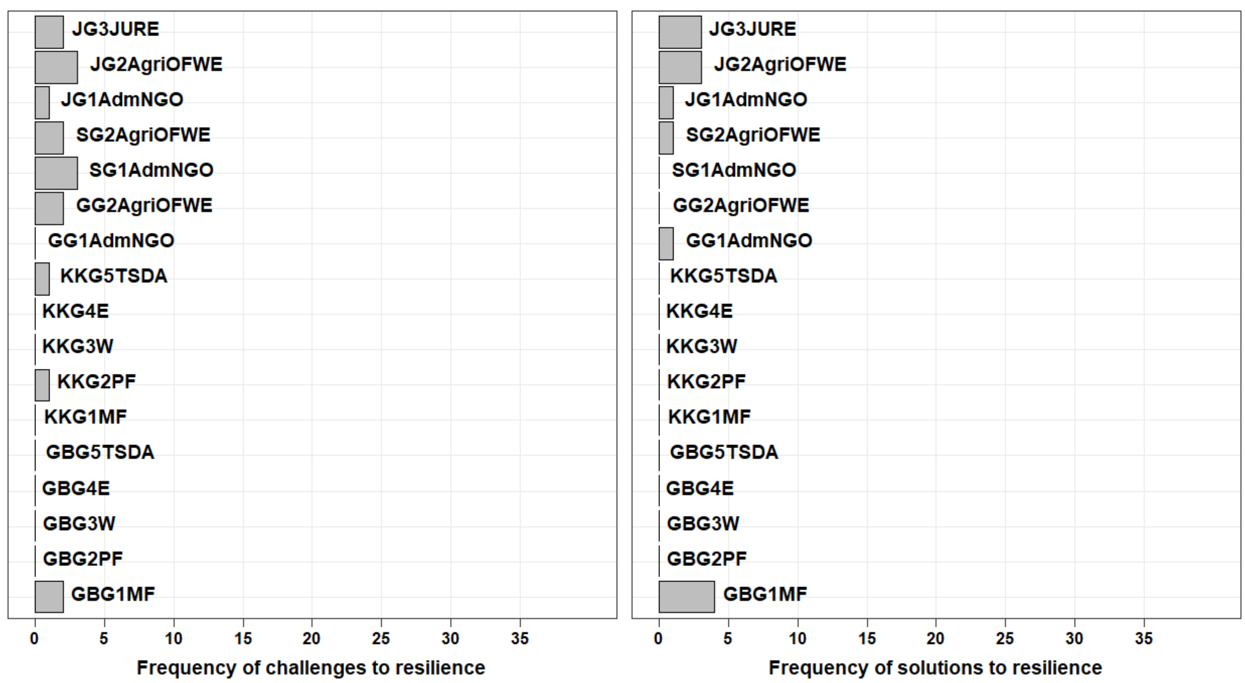

Fig. S2. Frequency of perceived challenges and solutions to resilience at feedbacks system level by stakeholder group. For types of stakeholder groups, see the caption of Fig. S1.

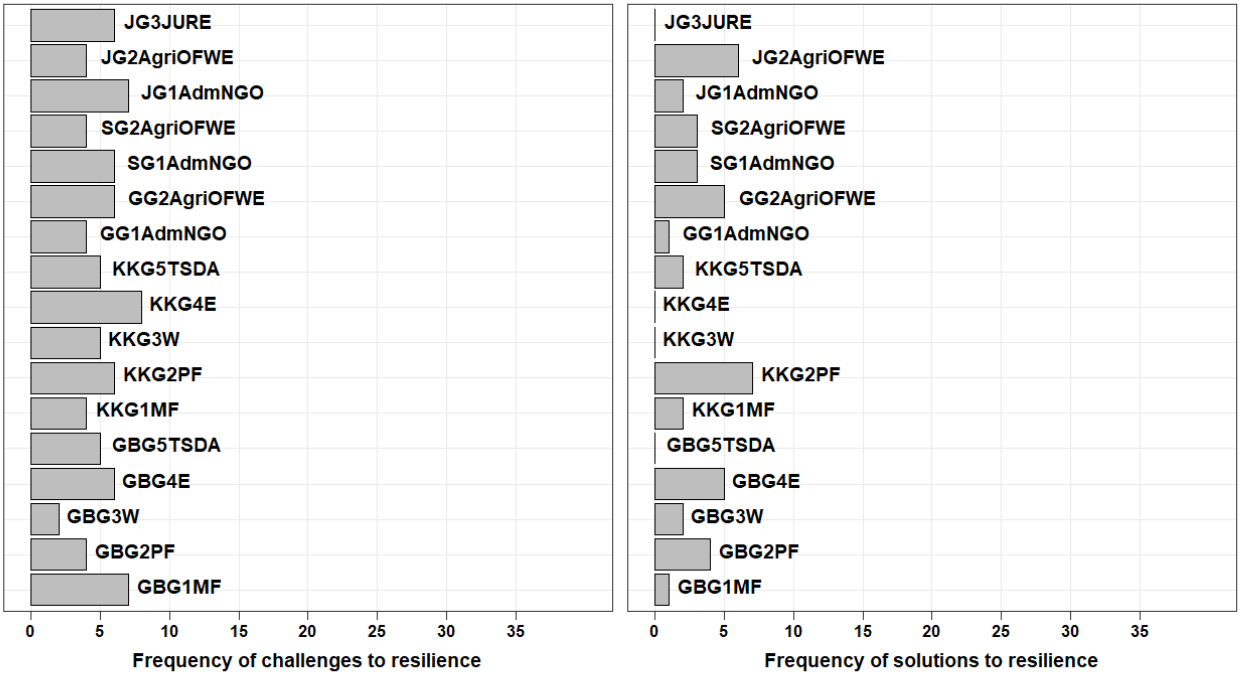

Fig. S3. Frequency of perceived challenges and solutions to resilience at design system level by stakeholder group. For types of stakeholder groups, see the caption of Fig. S1.

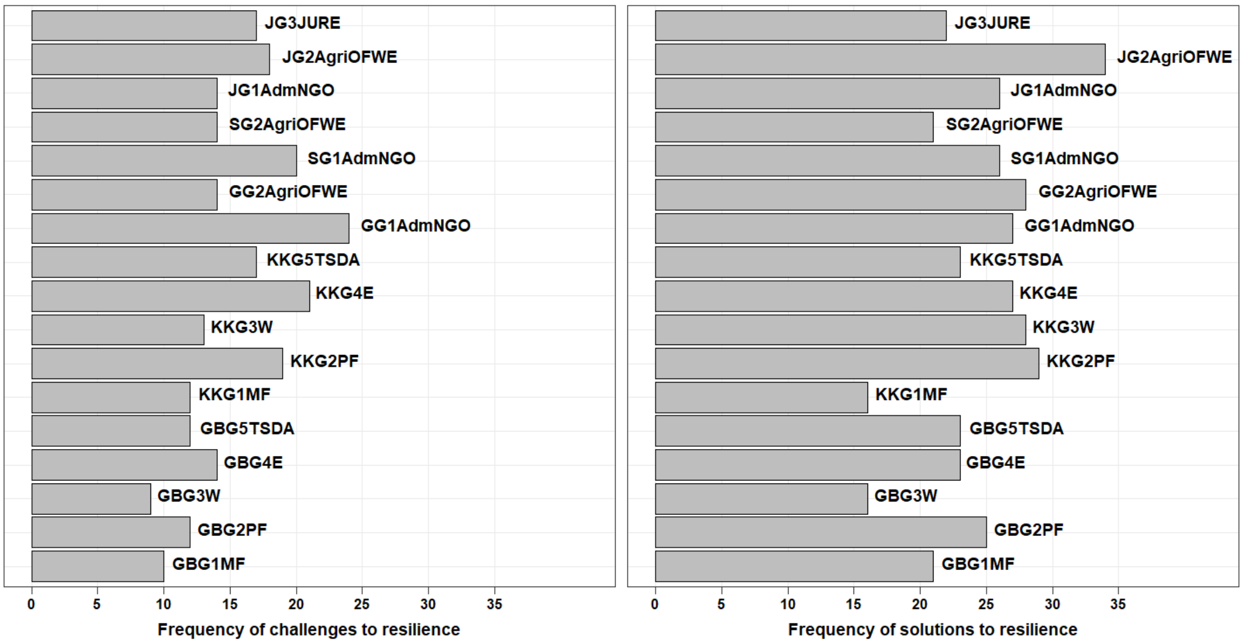

Fig. S4. Frequency of perceived challenges and solutions to resilience at intent system level by stakeholder group. For types of stakeholder groups, see the caption of Fig. S1.