Managing socio-ecological systems to achieve sustainability: A study of resilience and robustness

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Abstract: *Growing symptoms of the mis-management of socio-ecological systems (rangeland degradation, pollution of water bodies) show that the long term existence of those systems is threatened. SES management improvement is the aim of many policy measures. But how successful are these various simultaneous policy measures in achieving the sustainable management of SES? A framework for analysing policy measures and the management actions of land users was developed by Leach et al. (2010): the authors postulate that the sustainability of an SES depends on four system properties: stability, resilience, durability and robustness and that external shocks and stresses affect those properties differently. The aim of this contribution is to identify the strengths and weaknesses of the approach by applying it to three case studies in Namibia, in Patagonia and in West Sumatra, Indonesia. We found that (i) more actions were directed towards resilience and robustness than towards command-and-control; (2) actions directed at stability and durability were generally undertaken at the national level; (3) the introduction of the concept of robustness to illustrate the property of adaptability enables the identification of trade-offs among properties; but (4) issues of ecological degradation were difficult to address.*

Keywords: *resilience, robustness, socio-ecosystems, management, sustainability, arid rangelands, Lake Singkarak*

Introduction

Resource degradation and poverty are symptoms of the difficulties in the management of Socio-Ecological Systems (SES) and threaten their existence in the long term. While searching for immediate remediation strategies seems essential for maintaining the livelihoods of resource users, it is of equal importance to follow up with long term strategies for a sustainable management of the SES. Increasing globalisation has instigated increasingly control-oriented SES management strategies (e.g. Gomez-Baggethun et al., 2009). Command-and-control approaches differ from approaches promoting flexibility, in which the latter tend to enhance the resilience of the managed SES.

While a system's resilience does not necessarily imply its sustainability (Derissen et al., 2009), the capacity of a system to sustainably manage short disturbances (shocks) and long term pressures (stresses) is related to its properties, including the property of resilience. According to the Resilience Alliance, resilience comprises two properties: withstanding shocks (resilience in the structure of the SES) and adaptability (resilience of the SES in providing the function) (Walker et al., 2006). Yet, actions enhancing the ability of an SES to maintain its structure when facing a shock might in some cases counteract the adaptive capacity or transformability needed to sustain its function in the face of long term pressures (Walker et al., 2006, Scoones et al., 2007). Scoones et al. (2007) argue that distinguishing between the two properties in the analysis of SES is useful in the context of policy making. They develop a conceptual framework distinguishing between 'control and command management' measures vs. responses and defining the resilience property as the maintenance of the function and structure of an SES while robustness designates a change in the structure of the SES to maintain its function (Leach et al., 2010).

Specifically, our aim is to explore whether the use of a method distinguishing between resilience and robustness properties in SESs brings additional insights in taking effective management measures to achieve sustainability. In our search for patterns in the effectiveness of different measures in delivering sustainability by improving the resilience and/or robustness of SESs experiencing shocks and stresses, we formulate three hypotheses. The first one concerns the application of the framework to real case studies: (1) It is possible to distinguish between responses to stresses and responses to shocks. The two others concern the actual results of the analysis: (2) There will be tendencies for powerful actors to favour controlling actions; (3) Mitigating the impact of shock can sometimes exacerbate vulnerability to stress. The hypotheses are discussed thoroughly in the discussion. The relevance of this work lies in the applicability of the concept of SES resilience in the policy arena. The conceptual framework may help identify policy measures which have conflicting effects.

Yet, when moving from theoretical frameworks to operational tools, it is important to apply the framework to the analysis of very different systems in order to test its coherence and applicability to the evaluation of sustainability. In this respect, we selected cases according to their heterogeneity in i) political, economic and cultural characteristics; and ii) biophysical conditions and in productive systems. All cases are located in developing countries, where sustainability solutions are needed more urgently. As a result, the conceptual framework proposed by Leach and colleagues (2010) is applied to the analysis of the management of three SESs: a commercial farming region in southern Namibia, a smallholders region in Patagonia and a lake community in West Sumatra.

Theoretical foundations

Resilience of Social-Ecological Systems (SES)

An SES is an ecological system influenced by one or more social systems, where interdependencies among humans are influenced by biophysical and non-human biological units (Anderies et al., 2004). Establishing a diagnosis when faced with a problem in an SES requires the study of complex multivariable non-linear and cross-scale interactions, and the contemplation of how the system changes in time (Ostrom, 2007).

During the last ten years, the concept of resilience has been widely explored and case studies have shown the existence of relationships among resilience, diversity and sustainability in SES (Folke and Carpenter, 2002). Yet, definitions of SES resilience differ greatly in the conceptual frameworks for the landscape scale chosen in literature. A first group of studies defined resilience in opposition to vulnerability and as a key to sustainable SES (Dearing, 2008; Dougill et al., 2009; Elasha, 2005; Armitage and Johnson, 2006). This definition of resilience does not perfectly coincide with system thinking theory where resilience is a specific property of a system as mentioned above Another group of scholars, including the Resilience Alliance defines the resilience of an SES as the capacity of a system to experience shocks while retaining essentially the same function, structure, feedbacks, and therefore identity (Marshall and Marshall, 2007; Gunderson et al., 2006; Darnhofer, 2009; Folke et al., 2003 cited by Darnhofer, 2009). The key element here is whether a system maintains its control over its function: and by 'function' we mean the direction and nature of the feedbacks. A last group of authors retains the definition given for ecological systems (Holling, 1973; Gunderson and Holling, 2002) which states that resilience is the ability to maintain both structure and function, while adaptation (Leach et al., 2010) or transformability (Walker et al. 2006) assumes that only the function is maintained, possibly with a re-arrangement in the SES's structure.

Conceptual framework adopted

The method adopted here is the one proposed by Scoones et al. (2007) and Leach et al. (2010), which provides a clear framework to the interface of science and policy making. The conceptual framework proposes that in addition to the concept of resilience, the additional concept, of 'robustness' is needed to explicitly refer to the capacity of the system to adapt to long term stresses. They claim

that the distinction is useful because some policy measures may enhance resilience while at the same time undermining the robustness of the system. Walker et al. (2006), on the contrary, underline that efforts to deliberately enhance adaptability can (unintentionally) lead to loss of resilience.

This differentiation between resilience and robustness relies on a preliminary distinction among drivers between shocks and stresses (Elasha, 2005; Leach et al., 2010). Shocks are defined as 'transient disruption in an otherwise continuous trajectory' while stresses are 'enduring and pervasive cellular long run shifts' (Scoones et al., 2007). It is further hypothesized that (re)actions to shocks and to stresses generally aim at two different system properties, respectively resilience and robustness (fig. 1).

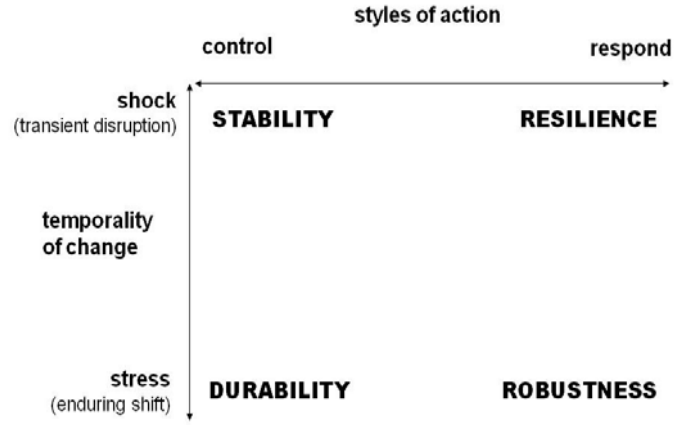

Figure 1. Dynamic property of sustainability (Leach et al., 2010).

The additional strength of this conceptual framework for policy making lies in the identification of several types of (re)actions in the face of drivers of change: reactions aiming at preventing or controlling variability, tagged as command-and control-strategies, are opposed to actions promoting flexibility and change, tagged as responses. While many of the policy measures in the last half century have focused on command-and-control, a departure from this position and towards a new way of thinking and of managing SES, focused on the concept of adaptive systems is emerging (Rammel et al., 2007).

Case study approach

We applied the resilience/robustness framework to three SES: two rangeland systems in Patagonia and Namibia and a lake system in Indonesia. This assured that diverse political, economic, socio-cultural and biophysical characteristics would be included in the study.

Arid southern rangelands

Both rangeland case studies were made in drylands. These locations are characterized by remoteness, low rainfalls, extreme temperatures and poor soils, all highly variable in space and time (Reynolds and Stafford Smith, 2002). Pastoralism with small stock is the main economic activity and is subject to prices set by the global market. Livestock production strongly relies on rangeland ecological dynamics. Experts agree that large rangeland areas have been degraded (Lund et al., 2007). In south Namibia, the study concerns a homogeneous 750 000ha sub-urban area around the town of Keetmanshoop in the Nama Karoo, characterized by summer rainfalls of 140 mm on average and recurring droughts. Large ranches of about 10 000 ha are managed by commercial farmers for the production of Karakul sheep skins, mutton and meat goats. Since 1994, a land reform has been slowly reorganising this structure of land ownership, inherited from the Apartheid (Tapia-Garcia,

2004). The Patagonian Western District is a winter rainfall area which occupies 3.5 million ha in the Río Negro province. The climate is dry and cold, with mean annual precipitation varying spatially from 300 to 150 mm (Prohaska, 1952, Paruelo et al., 1998). It snows frequently in the highlands. Most farms are held by smallholders, and reach 2500 ha of size on average (Easdale et al. 2009). They rely on family labor and produce Merino wool, Angora hair and meat.

Singkarak Lake in West Sumatra, Indonesia

Singkarak Lake and its catchment area are the location of a complex land use pattern, which ensures the livelihoods of about 400 000 people living on its shores and on the slopes of the surrounding hills. The inhabitants enjoy the benefits provided by the lake: irrigation, fishing, navigation, water supply and a hydroelectric power plant. Singkarak Lake is now facing many challenges including pollution, the degradation of water quality in the catchment, the depletion of water and eutrophication. Increased erosion in the catchment area has also accelerated sedimentation in the lake. The vicious degradation cycle is undermining all economic activities.

Methods

The method applied consists in the selection of relevant and typical drivers of change for the systems and in the documentation and analysis of the reactions of resource users and governments to drivers of change. First, we defined *drivers* as any change affecting the system considered, either endogenous or exogenous. For each case, we identified important drivers based on our expert knowledge and on literature and data sources documenting the functioning of the selected socio-ecological systems to change. Drivers were classified into shocks and stresses as defined by Scoones et al. (2007) according to the perceptions of the authors of the data sources or of the interviewees (table 1). Second, material used to document the reaction of the selected systems to the identified drivers and at the basis of the analysis included local magazine articles, local scientific journal articles, government communications, personal communication with farmers, with experts, with government members, local websites, data collected and observations made by the authors. Actions were classified as control measures when they aimed to act on the driver itself and as responsive measures when they acted on the SES or a part of it. Special attention was given to abiding by the intention of the actors – local users and governments – and by the opinion of the stakeholder/author in the classification of each reaction as controlling or responding.

Table 1. Shocks, stresses and their main impact on the SES in each case study.

	Driver	Impact on SES
Southern Namibian rangelands	Shock: Drought	Natural calamity: absence or extremely low amount of rainfall, occurring every 10 to 15 years and causing lack of biomass and water and the death of livestock or their forced sale.
	Stress 1: Increased land occupation	Continuous increase in the number of farms from colonial times to 1984, leading to the disappearance of emergency lands and fixing herds in space, thus causing reduced management options and a risk of degradation.
	Stress 2: Persistent market crash	Crash in the price of Karakul skins, sole product of southern pastoralism until 1979, leading to the loss of livelihoods of many farmers.
	Stress 3: Land Reform	Redistribution of land resources to previously disadvantaged Namibians. Results in a multiplication of small farm ownership and a turn-over in land ownership and social capital (especially knowledge and networks).
Northern Patagonian rangelands	Shock: Drought	Natural calamity: absence or extremely low amount of rainfall, occurring every 10 to 15 years and causing lack of biomass and water and the death of livestock or their forced sale.
	Stress 1: Increasing degradation	Loss of soil and vegetation cover leading to reduction of forage production due in part to overgrazing. Leads to long term loss of land productivity.
	Stress 2: Decreasing farm net margins	Due to decreasing wool prices on international markets and state economic choices. Leading to negative profits and a reduction of state social services and support.
Lake Singkarak, Indonesia	Shock: "*Bangai*"	Natural calamity (upwelling of low lake waters containing sulphuric acids, nitrates and ammonia) causing massive death of fish. Occurs every 10-15 years.
	Stress 1: Water pollution	Through pesticides, fertilizers, domestic and small scale industrial wastes. Impacts resource users' health and fish stocks
	Stress 2: Depletion and fluctuation of lake level	Associated with water usage by Hydro Electric Power Plant (HEPP), more variable rainfalls and erosion in the catchment. Affects fish reproduction and catch, and farming.
	Stress 3: Increasing number of fishermen	Decreases the available resource per head of user. May lead to overfishing and resource depletion or poverty.

Results

Figures 2, 3 and 4 display how measures taken in each country in the case of the identified stresses and shocks for each SES contribute to different properties of sustainability.

Resource users' level

In Indonesia, both responding and controlling options are used. Fishing communities build organizations, increase their power and manage to apply controlling measures on the driver which may even increase the resilience of the system (e.g. informal agreement on controlling fishing operations). In the rangelands of private ranches, controlling options are fewer as farmers are traditionally less organized. Yet in both cases, communities have formed to access emergency pastures as a response to shocks, or to improve sales prices or share costs to improve their control on their net margins. Nevertheless, responsive options are much more numerous than controlling ones in the rangelands.

Shocks

Both of the shocks under study are of an environmental nature and affect the ability of the farmers to generate income from their resources on the short term. Resource users opt for typical risk-reduction responses such as income diversification with off-farm income, livestock or fish diversification, or a switch to resistant livestock or fish. This last option has the particularity that while increasing the resilience of the SES, it also leads to resource depletion and to a loss in the long term resilience and in the robustness of the SES. In the rangelands, the immediate response is to sell stock and purchase fodder but enduring options consist in keeping a buffer of biomass on the farm and of cash at the bank at all times. Enduring options characterize farming systems which are

adapted to managing shocks. In Namibia, some farmers still benefit from an escape option by moving their stock to drought-spared areas belonging to friends or family.

Stresses

Most reactions to the various stresses are the same, be they environmental, (resource degradation), or socio-ecological (the increased land occupation), or economic (selling price reduction). Indeed, they all threaten the ability of the land users to survive without changing their livelihood strategy. In the case of rangelands, responses include income, livestock and, product diversification, improved land management techniques but also land abandonment, rural exodus and economy of scale by increasing farm size. While the first responses increase the robustness of the system, they do not automatically do so on the long term as they don't directly address the impact on the ecosystem and its degradation. The last responses reduce the stability of the farming community. As a too small population can be detrimental to agricultural (O'Farrell et al., 2008) and rural development, they may jeopardize long term robustness. The lake system presents the additional challenge of organizing resource use among different groups of users. Here, powerful users such as the government-owned Hydro-Electric Power Plant (HEPP) use control measures and may impose decisions on farmers at the downstream area. Yet, the fishing communities organize themselves which enables them to negotiate self-restrictive solutions in the interest of the group. As individuals, they also engage in diversification in both fishing (processing fish to increase the price) and non-fishing activities (migration, merchant, more intense farming).

Authorities' level

In Indonesia, government reactions were identified for only two of the 3 stresses identified, whereas in Namibia and Argentina, government measures were taken in reaction to all mentioned stresses. While, as we expected, the governments have made use of many more control measures than the resource users in all the case studies, they have also used an even greater number of responsive measures.

Shocks

In Indonesia, the government recently became active in the management of *Bangai* by combining the preventive response of investing in research and in monitoring the lake's condition with the controlling measure of prohibiting the fishing of endemic species sensitive to *Bangai*. The latter has a direct negative impact on fishermen's incomes and reduces their robustness. In the case of droughts in rangelands, the Patagonian government focuses on the income situation of the farmers and acts through measures alleviating the financial consequences of drought, which may increase the resilience of pastoralists on the short term but not on the long term, as they are made dependent on government aid. They subsidize post-drought restocking; yet if too early, restocking may lead to land degradation. In Namibia on the contrary, financial assistance and controlling options fell out of fashion under the new Drought Policy of 1997 after peaking during the drought of 1993 with the creation of more than a 100 boreholes throughout the country to increase water availability. Measures now aim at helping farmers increase their endurance to drought (that is their resilience) by promoting the conservative use of resources (land and water) and strengthening the economic environment of the SES (i.e. marketing channels, saving possibilities).

Stresses

When faced with (endogenous) environmental problems, governments make much use of responding measures including R&D to improve or transform the existing systems to stop the negative impact on the environment (re-forestation, improved grazing strategies) and also back up

the adoption of those strategies by enhancing knowledge transfer with extension services and the development of appropriate infrastructure with subsidies. This more systemic or holistic approach backs up controlling measures aiming at preventing immediate further degradation (e.g. prohibition of throwing waste in the lake, introducing conditionality in loans based on the land condition). Yet, in Indonesia, local initiatives in waste collection or income diversification or the prohibited use of explosives for fishing may fail due to lack of financial support from the government (no trucks to drive garbage to dumps, no alternatives to fishing). Insofar as the two rangelands are concerned, governments cope with economic or political stresses, usually external to the SES, through major interventions such as long term subsidies and even currency devaluation in Argentina to maintain the viability of land use activities, while investing in marketing structures or technological improvement. But no help is given to farmers in diversifying their income, although this is their own main adaptation response to the same stresses. However, in the special case of land reform in Namibia, the government has backed up many local initiatives by financing farmer knowledge exchange, by transparently monitoring the land reform process and by looking at alternative for more intensive uses of the land.

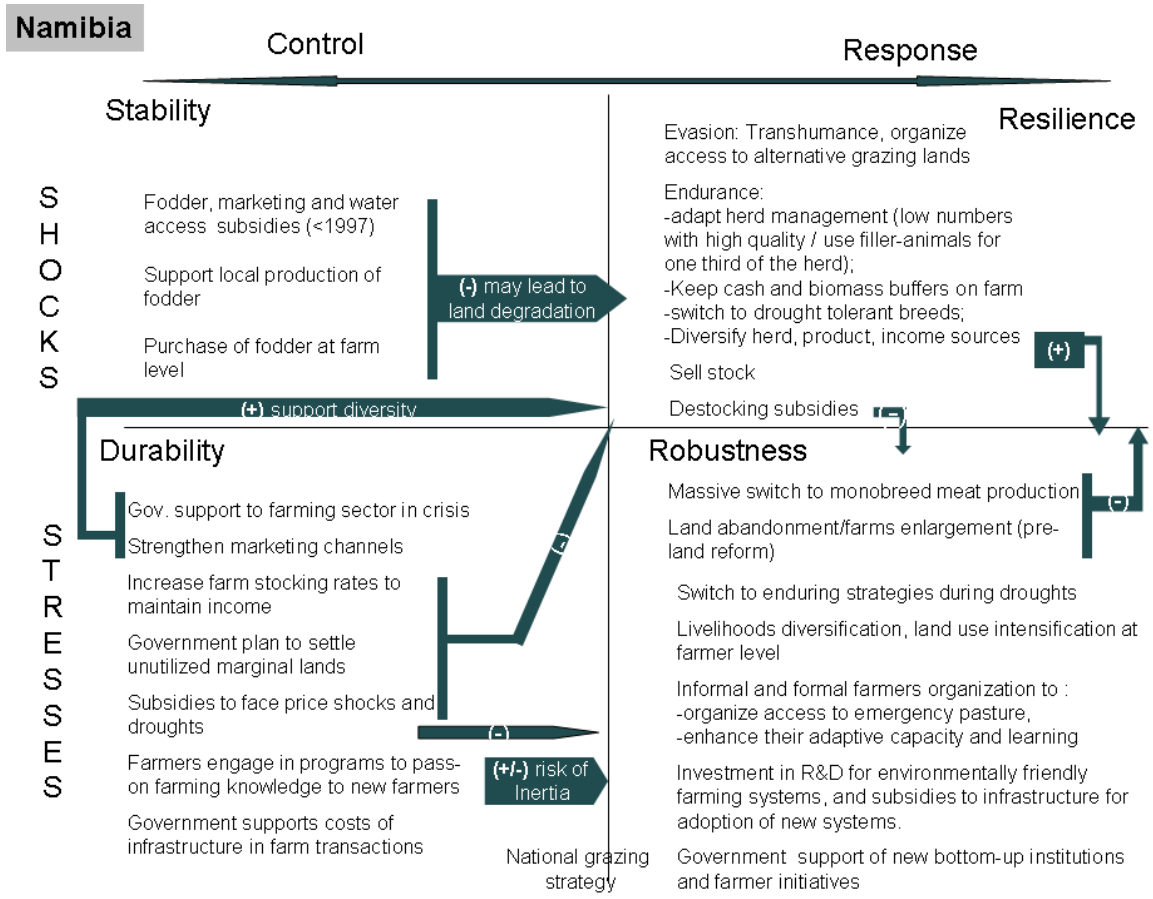

Figure 2. Main actions taken for the management of SES in the face of typical shocks and stresses, and relationships between actions in south Namibia. Data sources are listed in the annex.

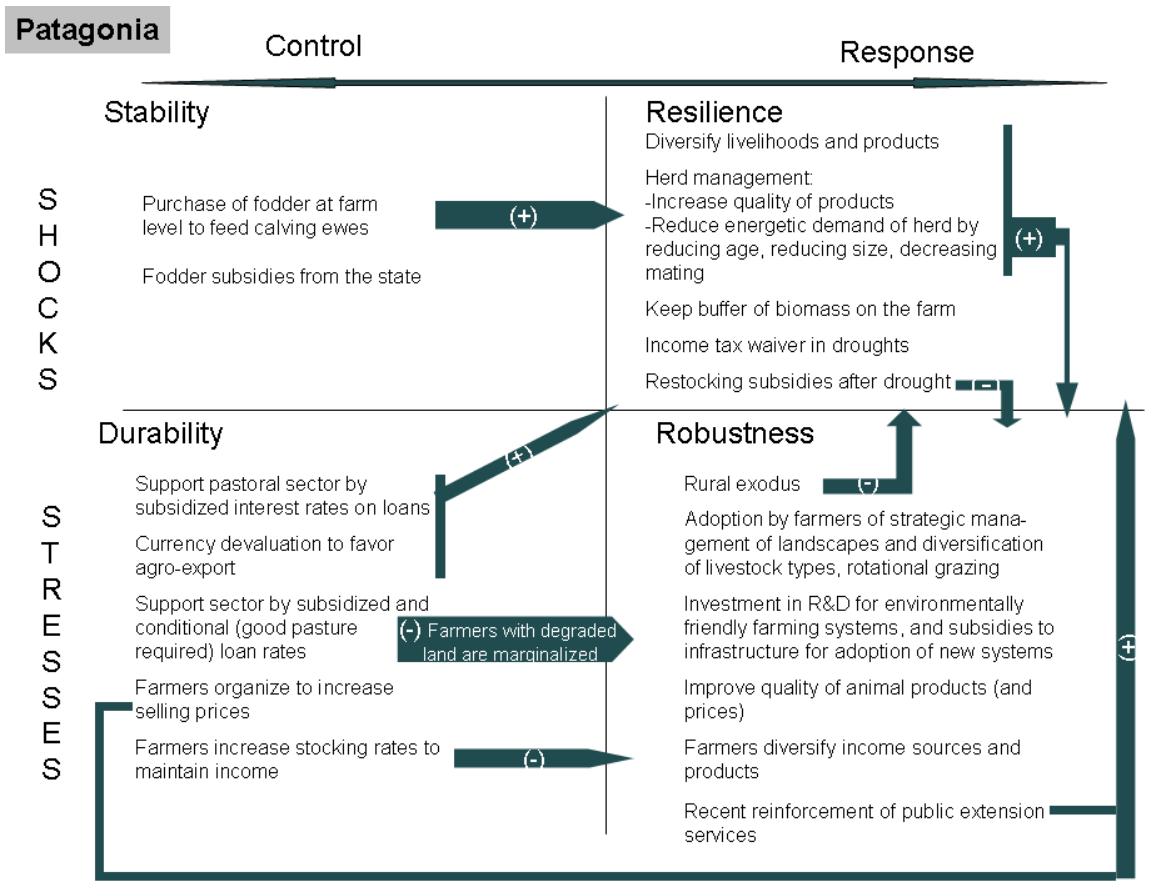

Figure 3. Main actions taken for the management of SES in the face of typical shocks and stresses, and relationships between actions in northern Patagonia. Data sources are listed in the annex.

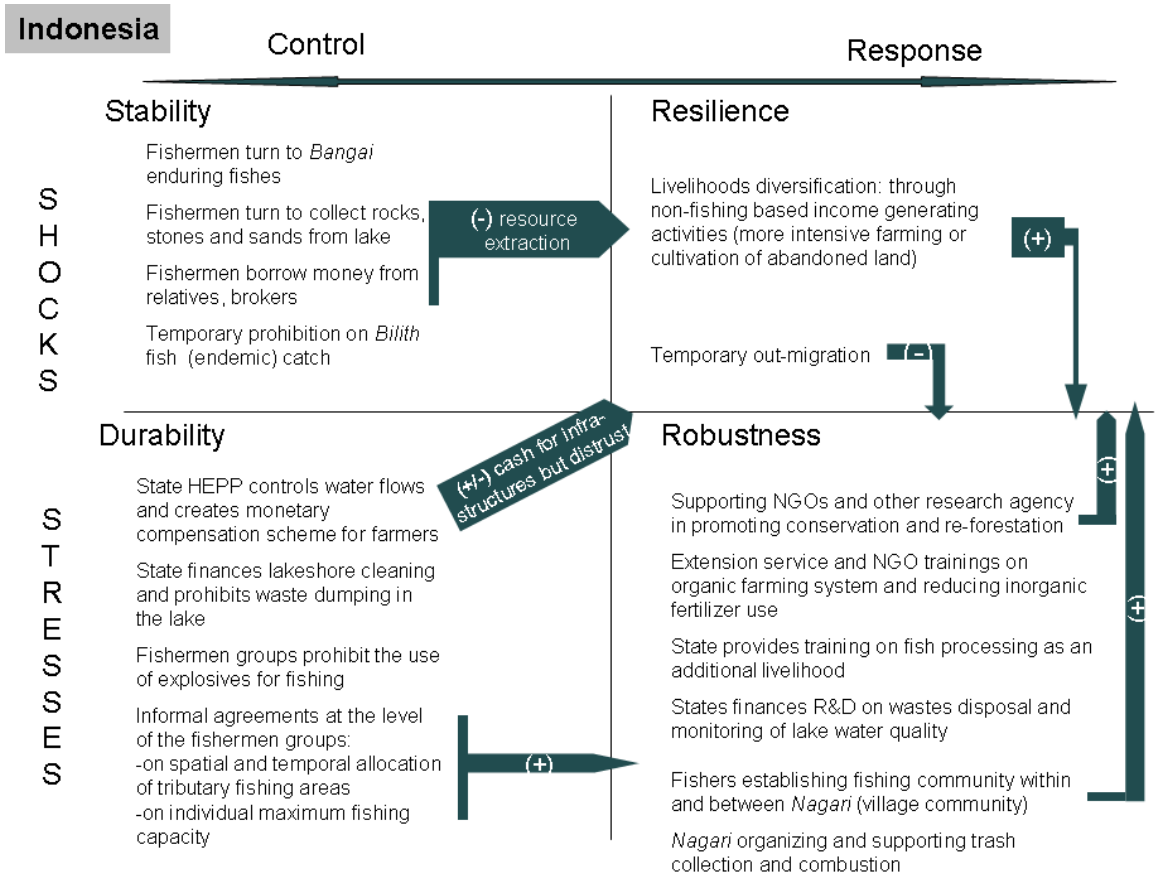

Figure 4. Main actions taken for the management of SES in the face of typical shocks and stresses, and relationships between actions in Indonesia. Data sources are listed in the annex.

Discussion

Hypotheses

We first proposed that it is possible and useful to distinguish between response to stresses and responses to shocks. The distinction was a challenging task as a shock can be the starting point of a long term stress such as an economic crisis or drought. Shocks may affect the system so deeply on the long term that adaptation strategies are needed to survive them. In the Namibian and Patagonian cases it appeared that stresses defined the changing background, constraining the reactions to shocks. In such cases, the discrimination between shocks and stresses does provide clarity in the analysis of the management of the SES. A second difficulty was that some responses to shocks appeared as both resilience and robustness seeking. Long term adaptations especially, aiming at mitigating recurrent shocks contribute to the robustness of the system by keeping possible development paths open. Yet, we could identify the following patterns: responses to shocks include buffering strategies, while responses to stresses include resource abandonment or diversification of livelihoods at the level of the resource user and pro-active research and development programs and accompanying financial- and capacity-building innovations on the part of the state.

Our second hypothesis argues that the mitigation of a shock may reduce the robustness of the system in case of stress. On the one hand, we have found evidence of this in the Namibian and Patagonian cases, where states try to increase the resilience of farming systems with destocking and restocking incentives, which increases the dependency of the farmers on state revenues and may lead to degradation (Illius and O'Connor, 1999). In the Indonesian case, the response of temporary migration may also be prejudicial to robustness because it may reduce the capacity of the human component of the SES to find solutions within the SES. While the actions mitigate the impact of the shock they do not favour an internal change in the farming system. Interestingly, we found evidence that adaptation strategies may not improve the resilience of the SES in each case study. Those responses include the switch from the use of one resource to another (another fish, another breed, another unique product) which do not increase either the economic or the ecological resilience to shocks, depleting a further resource. The question remains among the authors as to whether such an adaptation is really an adaptation or rather, a controlling action requiring nearly no change in the SES structure.

Our third hypothesis suggests that powerful actors favour controlling actions. We distinguished mainly between the scale of the resource user and the national scale. We found that in the rangeland cases, controlling actions fell more within the jurisdiction of the state, while individual farmers reacted with responses. In the case of the Lake SES, the social structure based on *nagari*[1] (village communities) and the further establishment of interest groups facilitated a concentration of power helpful in achieving control over certain stresses. This was found to a far lesser extent in the context of 'private' pastoralism.

Assessing sustainability

If we assume (i) that to be sustainable, policy measures need to be both controlling to deal with short term impact and responsive to enhance flexibility and long term adaptation; and (ii) that measures enhancing one property, which do not impact negatively on the three other system properties are more effective in reaching the aim of sustainable management, then the framework helps in evaluating the sustainability of the management of a given SES. Additionally, we found that the scheme can be applied to very different case studies. It revealed the existence of patterns in the type of action chosen depending on the type of actor and the social structure of the SES. This is an important methodological step since the lack of a standardized methodological tool remains the object of current conceptual developments and a bottleneck for sustainability discussions and assessments.

[1] *Nagari* is the name of the traditional village, pre-colonial political units of Minangkabau political organization (Benda-Beckmann, F. v. & Benda-Beckmann, K. v., 2001).

However, the framework does not allow differentiating between what we here call 'strong and weak sustainability'. Indeed, one adaptation strategy of people confronted with the degradation of their resources is to seek a livelihood source elsewhere, for instance in towns. While the strategy may prove successful we consider this SES to exhibit only weak sustainability, as natural resources are often exchanged for other resources in the search for livelihoods. Following Anderies et al. (2004), we feel that robust and sustainable adaptation strategies should only concern cases where both the social and the ecological systems are maintained within a SES (strong sustainability).

Limitations

Despite it being the aim of the framework, highlighting the conflicts or synergies between actions remains challenging. While criteria to classify an action aiming at resilience/robustness/ durability/stability are clear, the criteria to evaluate their impact on the other three system properties have not been defined, so that some conclusions are formulated at the juncture of knowledge and logical reasoning. For instance off-farm diversification could lead to the erosion of farmer knowledge and social networks, resulting in a loss in the adaptive capacity of the SES; but income diversification can also directly increase the robustness of the SES. Thus, the interpretation is largely based on (our) 'expert judgement', which constitutes the major weakness of the framework. A second limitation is that the framework does not provide help in visualizing interactions of subsytems within the SES. As an example, subsidies for restocking may increase the resilience of the economic subsystem while reducing that of the ecological one. Further, cross-scale interactions between actions do not appear explicitly. To consider the different scales of management more adequately, it is useful to consider using the method within a cross-scale framework which allows for the visualization of such interactions as suggested by Scoones et al. (2007).

Conclusion

This work is a contribution to the discussion highlighting the applicability of the concept of resilience of SES to the understanding of the dynamics and adaptive capacity of complex systems. The resilience/robustness conceptual framework developed by Leach et al. (2010) is applied to three social-ecological systems in order to evaluate its efficiency in analyzing the sustainable management of systems. By using the two concepts of robustness and resilience we address the notions of function and structure of SES separately (Stagl, 2009). The findings from the Namibian case study showed that Namibia is evolving towards a more pro-active management of rangelands where both ecological and social resilience and robustness are aimed at by both farmer organizations and government. In Patagonia, government actions have failed to address the degradation problem directly, except for the development of alternative grazing methods. An emerging public support throughout financial assistance and resurgence of extension services may reinforce SES robustness in a long run. As for Singkarak Lake fishing communities are moving to improve their resilience and robustness helped by a remarkable social capital; yet this strength has not been backed up by the government which has failed to simultaneously address the vulnerability and resource degradation issues.

Thus, if the analysis is carried out in the context of the historical, ecological and social background (esp. organization) of a given SES, the framework provides a global picture of the nature, coherence and sustainability of the measures taken to manage specific SES. By applying the framework at different institutional levels of management, comparisons can be made within one system as well as between systems. However, further developments would gain from addressing two identified limitations. First, actions mitigating impacts of shocks are not necessarily resilience seeking. Rather, they may contribute to robustness if shocks are regular. Second, socio-ecological interactions are not explicitly considered, which may render it difficult to evaluate the contribution of a particular action towards sustainable management of SES.

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