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COMMENTARY
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Advancing the Understanding of Adaptive Capacity of Social-Ecological Systems to Absorb Climate Extremes

Kirsten Thonicke[1], **Michael Bahn**[2], **Sandra Lavorel**[3], **Richard D. Bardgett**[4], **Karlheinz Erb**[5], **Mariasilvia Giamberini**[6], **Markus Reichstein**[7], **Björn Vollan**[8], **and Anja Rammig**[1,9]

[1]Research Department 1 "Earth System Analysis", Potsdam Institute for Climate Impact Research (PIK), Member of the Leibniz Association, Potsdam, Germany, [2]Department of Ecology, University of Innsbruck, Innsbruck, Austria, [3]Laboratoire d'Ecologie Alpine, UMR 5553, CNRS-Université Grenoble Alpes-Université Savoie Mont-Blanc, Grenoble, France, [4]Department of Earth and Environmental Sciences, The University of Manchester, Manchester, UK, [5]Institute of Social Ecology, University of Natural Resources and Life Sciences Vienna, Vienna, Austria, [6]Institute of Geoscience and Earth Resources, National Research Council (CNR), Pisa, Italy, [7]Max-Planck-Institute for Biogeochemistry, Jena, Germany, [8]School of Business and Economics, Philipps-Universität Marburg, Marburg, Germany, [9]TUM School of Life Sciences Weihenstephan, Technical University of Munich, Freising, Germany

Key Points:

- Climate extremes impact the resilience of social-ecological systems; their adaptation requires knowledge on ecological and social mechanisms
- Relevant ecological and social variables document the impact of climate extremes on the coupling flows, enabling management options
- Three challenges remain to advance our understanding on adapting social-ecological systems for a resilient and sustainable future

Supporting Information:

- Supporting Information S1

Correspondence to:
K. Thonicke,
kirsten.thonicke@pik-potsdam.de

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Author Contributions:
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Abstract Enhancing the capacity of social-ecological systems (SES) to adapt to climate change is of crucial importance. While gradual climate change impacts have been the main focus of much recent research, much less is known about how SES are impacted by climate extremes and how they adapt. Here, based on an advanced conceptualization of social-ecological resilience, performed by an interdisciplinary group of scientists, we outline three major challenges for operationalizing the resilience concept with particular focus on climate extremes. First, we discuss the necessary steps required to identify and measure relevant variables for capturing the full response spectrum of the coupled social and ecological components of SES. Second, we examine how climate extreme impacts on coupling flows in SES can be quantified by learning from past societal transitions or adaptations to climate extremes and resulting changes in ecosystem service supply. Last, we explore how to identify management options for maintaining and enhancing social-ecological resilience under a changing regime of climate extremes. We conclude that multiple pathways within adaptation and mitigation strategies which enhance the adaptive capacity of SES to absorb climate extremes will open the way toward a sustainable future.

Plain Language Summary Ecosystems and society are closely coupled and are both affected by climate change. Climate extremes are expected to occur more often and/or get more intense under climate change. We ask the following question: How can ecosystems and society, which can be described as so-called social-ecological systems, withstand climate extremes and can therefore become more resilient? To achieve this, we use the concept of social-ecological resilience and identify three challenges that scientists, decision makers, and practitioners need to work on to improve the adaptive capacity of social-ecological systems to climate extremes. We need to describe and measure the main drivers of climate extremes that impact ecosystems and society and those variables that describe the adaptive capacity and all possible responses of ecosystems and society. Ecosystems and society are coupled: Ecosystems provide ecosystem services to society, and society manages ecosystems. These coupling flows also change under the impact of climate extremes. We still do not fully understand how climate extremes impact these coupling flows or how they can be measured. Because society has influenced ecosystems for many centuries and millennia in many regions of the world, these coupling flows also often have a long history; as such we cannot expect ecosystems and society to adapt to climate extremes separately. We can learn about impacts from past extreme events to continuously improve the management of ecosystems and increase the adaptive capacity of social-ecological systems. Such management options range from adaptations of land management to institutional practices which are often necessary in order to be useful in helping the affected region immediately after a climate extreme event.

1. Introduction

Recent and projected increases in climate variability and the occurrence of climate extremes pose a profound challenge to society and the biosphere (Bowman et al., 2017; Harrington et al., 2016; Ummenhofer & Meehl,

D. Bardgett, Karlheinz Erb, Markus Reichstein, Björn Vollan, Anja Rammig
Visualization: Kirsten Thonicke, Anja Rammig
Writing - original draft: Kirsten Thonicke, Michael Bahn, Anja Rammig
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2017). Climate extremes can affect natural and managed ecosystems more severely and abruptly than gradual climate change (e.g., Reyer et al., 2013). The ability of ecosystems to resist and recover from climate extremes is of fundamental societal importance given the critical role of ecosystems in supplying ecosystem services (ES) such as food, water, climate regulation, feed, and fiber (Hassan et al., 2005). Society in turn manages land and water which affect ecosystem processes (Steffen et al., 2004), thereby actively shaping ecological responses to climate extremes. Thus, ecological and socioeconomic responses to climate extremes are tightly coupled, consistent with the conceptualization of social-ecological systems (SES; see Figure 1) (Haberl et al., 2016; Liu et al., 2007; Ostrom, 2009). A SES is a complex system of nested interactions between societal and ecological processes. Society purposely intervenes in ecological structures and processes by management. Ecosystems and society are coupled by the flow of ES from ecosystems to society (e.g., material, energy), and vice versa by various forms of human and social resources or capital, expressed in technologies and practices (Figure 1; Erb, 2012; Hummel, 2008; Liehr et al., 2017). A detailed definition of the SES concept is provided in the supporting information Text S1, including a glossary of key words (Table S1).

To ensure human well-being in the face of climate extremes, it is crucial to enhance the resilience of coupled SES across spatial, temporal, and institutional scales (Anderies et al., 2004; Carpenter et al., 2012; Cote & Nightingale, 2012). Such enhanced resilience is especially relevant to achieve the UN Sustainable Development Goals (Biermann et al., 2017; Liu et al., 2015). Stakeholders and decision makers, such as resource and hazard managers, land users, and landscape and conservation planners need an improved knowledge base on potential impacts and responses to climate extremes for better informed decision making (Kates et al., 2001; Reid et al., 2010; Turner et al., 2007). Specifically, the cultural context of knowledge production and of power structures across institutional scales influences decision making and how rules and norms change in adaptation dynamics (Cote & Nightingale, 2012). However, there is a lack of systematic, conceptual-theoretical, and empirical research specifically addressing the impacts of climate extremes on coupled SES (Carpenter et al., 2014; Carpenter et al., 2012). Concepts such as vulnerability and adaptive capacity have concentrated on gradual changes in ecosystems (Folke et al., 2005; Schroter et al., 2005; Turner et al., 2003). But they need to be developed further to incorporate interacting ecological and social impacts of climate extremes and their legacy and indirect effects (Bahn et al., 2014; Frank et al., 2015) for improved adaptation and mitigation policies and decisions (e.g., Kythreotis et al., 2013).

Social-ecological resilience (SER, e.g., Folke et al., 2016) describes a socio-ecosystem capacity to withstand the impacts (i.e., resistance) of "unfamiliar, unexpected events and extreme shocks" such as climate extremes or disturbances, to reduce their severity, to recover endogenously from such impacts to initial SES patterns and functions, or to transform to alternative social-ecological states (Figure 2 and Text S2). While a resilient SES is able to recover ecosystem functioning and ES supply, and also to restore the affected sectors, infrastructure and institutions, a tipped SES has to cope with a changed portfolio of ES and sometimes a breakdown of other sectors, infrastructure, and institutions that requires deeper changes in management and institutions (see Text S2 on details of SER definition). Building on earlier work on robustness (Anderies et al., 2004) or resource use affecting social and ecological resilience (Adger, 2000), the concept of SER has evolved, but its operationalization still poses significant challenges. It requires the integration of ecological resilience (Gunderson, 2000; Hodgson et al., 2015) and of transformational processes of society (Carpenter et al., 2012; Folke et al., 2005). The precise definition of relevant SES attributes (i.e., SES state variables in Figure 2 and examples in Table 1, second column), however, remains open, and significant challenges persist as to the operationalization of the SER concept. In particular, understanding and enhancing social-ecological adaptive capacity to climate extremes is a significant challenge.

Climate extremes change ecological patterns and processes, and thus ES supply, thereby challenging decision making and management (Hummel, 2008; Liehr et al., 2017). Society adapts to climate extremes through postevent analysis and adjusts regulation, technology, and practices to enhance urban and disaster resilience before the next event strikes (Davidson et al., 2016). Adaptive strategies to alleviate impacts of climate extremes on SES depend on the socioeconomic, cultural, technological, and institutional context (Berkes & Jolly, 2001; Carpenter et al., 2012; Cote & Nightingale, 2012), which often require communication and decision making across state boundaries (Garrick et al., 2018). SER is enhanced by management practices that alleviate the drivers, pressures, and impacts of climate extremes, which in turn influence patterns and processes in ecosystems and thus the supply of related ES.

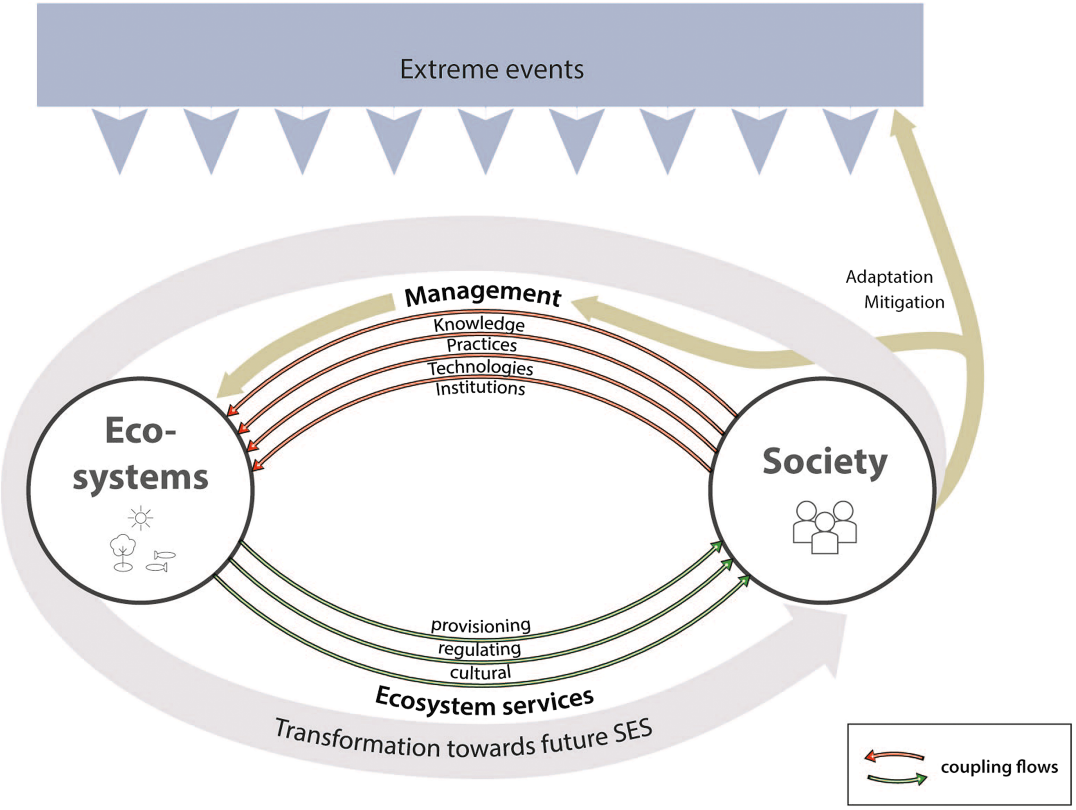

Figure 1. Simplified concept of a social-ecological system (SES) where ecosystems provide ecosystem services to society. Society, in turn, manages ecosystems through its knowledge, practices, technologies and institutions. Management and ecosystem services constitute coupling flows between the two. Climate extremes impact both, ecosystems and society. Society can directly adapt to and mitigate climate extremes but can also adjust management in order to reduce impacts on ecosystems which then maintain their supply of ecosystem services to society. This circle results in the dynamic transformation to future, sustainable SES. The concept integrates key elements of similar approaches (Erb, 2012; Hummel, 2008; Liehr et al., 2017). A detailed definition of the SES is provided in the supporting information.

In this paper, we review current literature and elaborate on SES and SER definitions for their application to climate extremes. We outline three major research challenges to be addressed to advance understanding and enhance the adaptive capacity of SES to absorb and cope with climate extremes.

2. Challenges for Operationalization of the SER Concept

2.1. Challenge 1: Identify and Measure the Relevant Driver and System Variables Based on SER Definition

Current literature focuses on the long-term transformation of SES to maintain their resilience and enhance sustainability (Folke et al., 2016; Olsson et al., 2014). Understanding SER to climate extremes requires a better description of the coupling flows and mechanisms in SES, which are mainly defined by the flows and other interactions between ecosystems and society (Figure 1). In this context, methods need to be further developed to incorporate the response and adaptive capacity of SES to climate extremes under future global change. The first issue is *to identify and measure relevant driver and SES state variables in response to climate extremes* that describe the resilience of SES structure and function and how it is perceived and valued by individuals and institutions (e.g., Allen et al., 2018). It includes identification and quantification of SES state variables based on a clear SER definition (see Text S2). We provide some examples for such an assessment in Table 1 and possible indicators describing SES state variables (Figure 2). For example, improving water management to reduce pressure on water resources and thereby reduce drought impact (Table 1) might alleviate pressure on ES supply and support sustainable SES transformation. Society has the potential to actively learn from experience by improving hazard response systems and to integrate knowledge of future projections

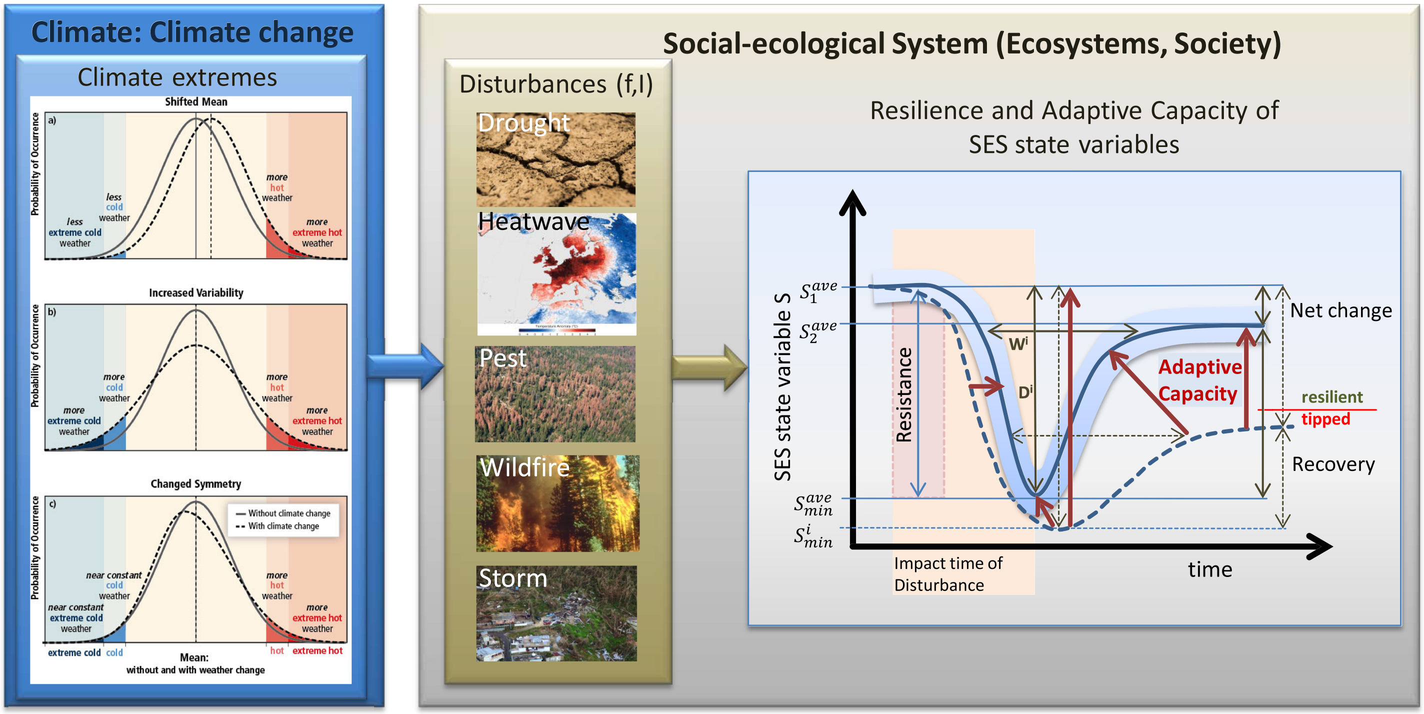

Figure 2. Concept of impacts of climate extreme under climate change on social-ecological resilience. Changes in climate extremes influence frequency (*f*) and intensity (*I*) of disturbances. The impact of and recovery from single climate extremes (events) via disturbances (drought, heatwave, pest, wildfire, and storm) on social-ecological systems (SES) state variables can be quantified by comparing two system states S_1 and S_2 (solid vs. dashed lines). The social-ecological resilience (SER) of a SES state variable *S* is challenged under climate change increasing the depth of the impact (*D*) or recovery time which increases the basin width *W*. The impact time of a driving factor might include a resistance phase until the impact reaches its maximum damage (depth *D* of impact basin). Recovery is different after each event, leading to a range of net changes. However, a state has to reach at a certain level of the preimpact state to maintain SER. Adaptive capacity can increase SER by delaying the impact, thus increasing resistance, and by reducing *D* and *W*, thus the net change. Note that the scale of the time axis may be strongly influenced by the state variable in question and the type and intensity of climate extremes. Inserted illustration showing changes in climate extremes taken from IPCC (2012). Pictures: drought—pixabay; heatwave (Wikimedia, 2018); pest (flickr, 2016); wildfire (Wikimedia, 2008); storm (Wikipedia, 2017).

(e.g., early warning systems) and thereby increase preparedness for future events and thus also adaptive capacity (Olsson et al., 2014; Tompkins & Adger, 2004). By acknowledging a range of responses to climate extremes (Figure 2), the modularity versus connectivity of the SES subcomponents need to be quantified to better describe how climate extremes lead to direct and indirect impacts in the SES (Allen et al., 2018; Carpenter et al., 2012, see Table S1 for definitions). This implies that recoverable and irreversible thresholds and processes need to be identified that (a) determine when, how fast, and to what degree ecosystems can recover and reestablish the functions and community composition of their preimpact state (Bahn & Ingrisch, 2018; Bahn et al., 2014); and b) describe social adaptive capacity, specifically how institutions, innovation and social capital respond and adapt in society (Allen et al., 2016, 2018; Tompkins & Adger, 2004). A quantification of lagged and legacy effects (see Table S1 for definitions) is required for relating short-term responses to extreme events to long-term ecosystem dynamics (Frank et al., 2015; Kayler et al., 2015) and thus their ES supply for society. Specifically, cooperation (Anderies et al., 2004; Garrick et al., 2018), trust (Carpenter et al., 2012), and integration of traditional knowledge (Berkes & Jolly, 2001) characterize the social capital that can enhance SER. The relationship of knowledge, institutions, and power structure can strongly influence the way past experiences of climate extreme impacts is used to enhance SER, posing the question of which social groups can benefit from increasing adaptive capacity (Cote & Nightingale, 2012). Climate extremes can affect society by impacting ES, infrastructure, energy, and transport (Figure 1). These impacts can disrupt services within society but also influence the functioning of ecosystems, for example, when built infrastructure reduces the natural inundation area in flood plains (Markolf et al., 2018; Miller et al., 2018).

Table 1

Examples of Changes in SES State or Function (cf. SES State Variable in Figure 2) Caused by Different Types of Climate Extremes, Mechanisms to Describe Recovery From Extreme Impact, and Options to Increase the Adaptive Capacity of Ecosystems and Society

Type of climate extreme	Examples of affected SES state or function in ecosystems	Ecological mechanisms or properties of AC in ecosystems	Affected ecosystem service supply, including negative effects (*n*)	Ecological indicators to quantify AC	Observational system/SDG indicator	Management options to increase adaptive capacity in society to climate extremes	Societal indicator to describe adaptive capacity
Drought	Soil water storage	Community reassembly across trophic levels and succession to drought-adapted species (e.g., Ratcliffe et al., 2017)	Water supply, flood control (e.g.,Ford et al., 2011), increased fire risk (*n*)	Biomass recovery, species abundance, soil moisture (e.g., Gouveia et al., 2012)	EBV, GEOSS, soil profiles, NDVI/NWDI/EVI as indirect measure of plant water stress, water balance models for watersheds	Improve water management: increase size of retention areas and water use efficiency (e.g., irrigation), improve management of critical soil properties: organic matter, structure, soil biodiversity, increase water use efficiency (precision farming etc.)	Water management regulations established or adapted, water consumption per sector and time unit, efficiency of water retention (water retention effect per input, e.g., energy, time, technology, capital), transboundary institutional arrangements (Garrick et al., 2018)
	Crop yield	Plant plasticity to drought of crop variety (e.g., Koevoets et al., 2016; Walter et al., 2011)	Food, feed fiber and fuel supply	Growth rate, yield, cover crops (Kaye & Quemada, 2017)	FAO, national statistics, SDG indicator 2.a.1	Improve water management, including irrigation, investment in drought-adapted crop varieties, improve water supply/reduce losses; introduce landscape elements (e.g., trees for shading)	Regulation of water management changed, crop harvest, water use efficiency, the use of traditional/indigenous knowledge to maintain crop yield in variable climates (Cote & Nightingale, 2012)
Fire (indirect climate extreme)	Carbon stored in biomass and soil	Community reassembly across trophic levels and succession close to preimpact state (e.g., Silva et al., 2013); recovery of nutrients (e.g., Pellegrini et al., 2018)	Carbon sequestration, microclimate regulation, erosion risk (*n*)	Biomass recovery rate, vegetation structure, species abundance (e.g., Berenguer et al., 2018; Loiola et al., 2015; Staver et al., 2011)	Fire monitoring system, EBV, LTER, NEON, ECZO observatories, forest inventories, GEOSS, SDG indicator 15.1.1	Reduce human-caused fires, financial capital to improve fire monitoring and fire-fighting, adjust management to allow for disturbance response diversity (e.g., Silva et al., 2014), cautious fire prevention that reduces impact of episodic events, introduction of fire-prone tree species	Money spent for fire monitoring system and educational programs, socioeconomic costs of fire prevention and fire damage, casualties
	Timber volume	Natural recovery, reforestation	Timber production	Biomass recovery, tree height, growth rate (e.g., Lindner et al., 2010)	Forest inventory, SDG indicator 15.2.1	Diversification of commercial tree species with respect to fire adaption or low flammability (e.g., Doherty et al., 2017)	Money spent in reforestation and forest conversion to balance fire-adapted and low-flammable species, financial capital invested in specific forestry programs
Heat wave	Increased water temperature in lakes	Community reassembly across trophic levels, regulation of water quality (nutrients and sediments)	Regulation: microclimate, disease; supply: food (fish), clean water	Water temperature, algae growth rate, oxygen and nutrient content in water bodies	ECV, EBV, GEOSS	Improve water management including irrigation (e.g., Abel et al., 2016)	Regulation of water management changed, expenses for water management adapted
	Nighttime temperature in urban areas (Dousset et al., 2011; Ward et al., 2016)	n.a.	Microclimate regulation (Li & Bou-Zeid, 2013)	Amount of green spaces and water bodies, fresh air circulation (e.g, Bowler et al., 2010)	ECV, GEOSS	Urban planning system adapted, introduce green spaces in urban areas, climate-proof building (e.g., passive energy houses)	Financial and human capital, educational program to change human behavior, SDG indicator 11.5.1 heat-related mortality reduced (Norton et al., 2015)

Table 1
(continued)

Type of climate extreme	Examples of affected SES state or function in ecosystems	Ecological mechanisms or properties of AC in ecosystems	Affected ecosystem service supply, including negative effects (*n*)	Ecological indicators to quantify AC	Observational system/SDG indicator	Management options to increase adaptive capacity in society to climate extremes	Societal indicator to describe adaptive capacity
Storm	Carbon stored in forests	Community reassembly across trophic levels and succession close to preimpact state (e.g., Negron-Juarez et al., 2018)	Regulation: disease, microclimate; supply: timber, carbon sequestration, habitat (Fisk et al., 2013; Xu et al., 2013)	Biomass recovery, vegetation structure, species abundance	EBV, LTER, NEON, SDG indicator 15.2.1	Proactive management for natural hazards: weather forecast and early warning system improved, diversification of tree age in forest management plans incorporated	Adjusted forestry program, financial capital invested in specific forestry program; impacts from climate extremes considered in management plan (Markolf et al., 2018; Miller et al., 2018)
	Coastal infrastructure affected	Community reassembly and succession of coastal communities	Flood protection, food supply (fish)	Recovery of coastal ecosystems (Long et al., 2016)	EBV, GEOSS	Weather forecast and early warning system improved, ecosystem-based adaptation versus hard infrastructure	Financial and human capital, educational program to change human behavior, climate change and fail-safe strategies considered in infrastructure design (Markolf et al., 2018; Miller et al., 2018); considered in size and structure of actor network to engage stakeholders across scales and sectors (Tompkins & Adger, 2004) and traditional knowledge (Berkes & Jolly, 2001), SDG indicator 11.5.2

Note. Platforms such as GEOSS, specifically GEO BON for ecosystem services (Balvanera et al., 2017), should help to monitor indicators that quantify SES recovery relative to their preimpact state. Monitoring systems include Essential Climate Variables (ECV, Bojinski et al., 2014; Buchwitz et al., 2017), Essential Biodiversity Variables (EBV, Pereira et al., 2013; Proenca et al., 2017; Schmeller et al., 2018), and open data repositories such as LTER-DEIMS (https://data.lter-europe.net/deims/) and National Ecological Network (NEON, Lowman et al., 2009). The Sustainable Development Goals (SDG) indicator eBook (https://unstats.un.org/wiki/display/SDGeHandbook) is a new compilation of distributed data sources aiming at reporting the status of achieving the SDGs (Editorial, 2018). NDVI = normalized differentiated vegetation index; NDWI = normalized differential water index; EVI = enhanced vegetation index.

The second issue is to *systematize observations to obtain a coherent description of climate extreme impacts on all SES components* using the resilience properties of Olsson et al. (2014). To meet such demands, detailed observational systems are required to produce corresponding data and knowledge (see examples in Table 1). Qualitative and participatory methodologies (surveys, interviews, and experimentation) provide rigorous data to describe knowledge systems, institutional change as well as values, and different perspectives of SES agents (Garrick et al., 2018; Stone-Jovicich et al., 2018; Tompkins & Adger, 2004). Social science can contribute with quantitative and qualitative analysis of actors and institutions (Allen et al., 2018). Existing cross-disciplinary or interdisciplinary SER approaches need to be further developed and applied to describe society′s reflection and adaptation specifically to climate extremes to map the adaptive capacity of (local) communities, institutions, and governance (see Berkes & Jolly, 2001), which build on critical thresholds when the limits of adaptive capacity are exceeded (Nelson et al., 2007). The adaptation pathways that are discussed for climate change conditions (e.g., Tompkins & Adger, 2004) need to be specifically examined in regard to their robustness to increase resistance and decrease the impact of climate extremes, such as drought (e.g., Garrick et al., 2018).

Socioeconomic data are monitored at one specific point in time using survey techniques and are in many cases not continuous. Integrating qualitative and survey data in the assessment might pose a challenge when quantifying short-term responses of society to climate extremes, especially if the data have long intervals (≥ 5 years) between measurements. Respective indicators (Table 1) need to be assessed immediately after a climate extreme to allow the comparison to their preimpact status, making the measurement of preimpact and postimpact conditions essential (Figure 2). The adaptive capacity of society also depends on the social capital (Garrick et al., 2018; Lin, 2001; Putnam, 2000; Tompkins & Adger, 2004). Bonding social capital enables actors to manage risky environments and recover from disasters. Social networks enable comanagement and contribute to improved adaptation to climate extremes and ecosystem resilience (Tompkins & Adger, 2004). Bridging social capital, characterized by linkages spanning segregated communities, may facilitate innovation and growth which are also integral parts of adaptive capacity (Henry & Vollan, 2014). For example, Ambrus et al. (2014) showed that localized social networks in Peruvian villages allow for risk sharing and that socially closer agents better insure each other against risk; similar results were found by Agder et al. (2003) in Vietnam. Methods to complement existing observation strategies for society have to be developed further to close these knowledge gaps that arise from discrete data acquisition and to connect these data with ecosystem measurement to identify the full response spectrum of the coupled SES to climate extremes.

2.2. Challenge 2: Quantify Climate Extreme Impacts on Coupling Flows in SES

Given the long history of human intervention in nature in many regions worldwide, the mutual interdependence, and the complexity of human-nature interactions (i.e., a high modularity, see Table S1), an interdisciplinary approach is required to describe how impacts of climate extremes affect the coupling flows between ecosystems and society. Human society fundamentally depends on the ES supply: a process that intensified in many regions millennia ago (Ellis et al., 2013). In recent times, demand for ES such as food, feed, and fiber has grown at an unprecedented pace (Steffen et al., 2004). As a consequence, more than three quarters of the terrestrial surface is currently used by humans, resulting in a wide range of managed ecosystems where coupling flows have established a long time ago thereby affecting the response of SES to climate extremes (Ellis, 2011).

Resilience indicators illustrating the state variable over time (e.g., Ingrisch & Bahn, 2018; Scheffer et al., 2015) may be computed for simulated and observational data, which also capture possible feedback loops and make it possible to focus on critical SES components (Carpenter et al., 2012). Such approaches are extended to society with the SER concept to describe climate extreme impacts also on management, for example, institutions (Figure 1), based on measuring impacts on social capital and communities (Olsson et al., 2014). Society is not purely passively adapting to natural dynamics, including climate extremes, but actively alters ecosystem processes and structures and, in consequence, also the coupling flows in their entirety (Fischer-Kowalski & Weisz, 2016; Godelier, 1986). Societal transformations require individual or institutional decision making, that is, actor-based transitions, to achieve a specific goal or to recover from climate extremes (Nelson et al., 2007; Pelling, 2011). Gained knowledge and experience after climate extremes create the possibility to constantly adjust regulations, management, or technologies resulting in SES transformation (Olsson et al., 2015) toward sustainability (see Figure 1). However, power relations between local communities, access to knowledge, or representation in institutions play an important role in understanding when and how knowledge is used in decision making or social learning (Cote & Nightingale, 2012). From such past societal transitions or adaptations we can quantify past climate extreme impact on society, which resulted in changed ES supply (e.g., Dearing et al., 2012). Also, during climate extremes the capacity of institutions to monitor impacts and enforce regulations may be limited, for instance, due to less funding being available or there being less commitment to law enforcement. A growing body of evidence shows, for example, that climate extreme events increase the likelihood of violent conflict in societies (Hsiang et al., 2013), for example, indirectly through shocks in livestock prices (Maystadt & Ecker, 2014). Violent conflict is, of course, an extreme example. Many effects of climate extremes may manifest themselves in less drastic but nevertheless severe ways, such as declines in food production or food security which results in migration (Dovers & Hezri, 2010; Hunter et al., 2015). When analyzing the drivers and impacts of climate extremes, it is therefore crucial to recognize the transformability of society. Learning from past events will help to proactively take measures to be prepared for future events.

The challenge is now to quantify climate extreme impacts on the coupling flows from society to ecosystems (Figure 1). This involves (a) identifying changes in decision making (policies, regulations, and incentives); (b) describing feedbacks among critical components to avoid crossing critical thresholds; (c) evaluating changes in rules in communities as a result from learning, experience, and active participation; and (d) recognizing updates in responsibilities and regulations in institutions to adapt governance (cf. Olsson et al., 2014; Pahl-Wostl, 2009).

2.3. Challenge 3: Identify Management Options and Institutional Changes to Maintain or Enhance SER

The third major challenge is to identify land use options that allow mitigating detrimental impacts that allow keeping developments within critical thresholds, thereby ensuring ES supply and increasing SER. This can be achieved in three ways: (i) by reducing dependence on single ES and achieving equity in access to ES benefits; (ii) by improving adaptive capacity of SES to reduce impacts of climate extremes; and (iii) by considering the combined effects of gradual climate change and land degradation in combination with climate extremes.

In the first case, alternative income possibilities, emerging for instance as a result from education and development of the private sector and cross-sectoral activities, reduce the direct dependency of communities on natural resources and the increasing variability of their delivery with climate change (e.g., Berkes & Jolly, 2001), thereby reducing pressure on local ecosystem functioning and ES supply. However, the social-ecological and geographical context determines if the integration of the local into a market economy helps to alleviate pressure on local ES supply and increases SER to climate extremes which might be different in tropical island SES (see Tompkins & Adger, 2004). Additionally, the integration into the market economy and international trade may potentially come at the expense of enhanced telecoupled land systems (Liu et al., 2018; Schröter et al., 2018). Such an alternative might be favorable if certain land uses are shifted to other regions less prone to climate extremes, but this calls for the assessment of large-scale SER. A quantification of drivers and the respective impacts of climate extremes on the SES components and their interactions should document the level of spatial organization at which they are occurring and valid (ecosystems: landscape to biome; socioeconomic: local to global markets and institutions, respectively; see Table 1). This allows mapping the institutional responsibility concomitantly to maintain or enhance adaptive capacity of the affected SES or one of its components.

Second, to fully capture and assess the adaptation potential of the SES to climate extremes, two types of analysis methods need to be bridged: (a) system dynamic methods and indicators to describe SER (cf. Text S2 and Table 1) and (b) actor-based methods to describe management of climate extreme impacts in society (Allen et al., 2018; Stone-Jovicich, 2015). Based on such two-way knowledge generation, *management and planning procedures to increase adaptive capacity of the SES* can be adjusted (see examples in Table 1). Furthermore, mapping the networks of actor groups and institutions describes mechanisms by which actors and institutions interact and contribute to increasing the adaptive capacity of an SES (Anderies et al., 2004; Tompkins & Adger, 2004). By understanding these mechanisms, actor groups and institutions can better target inflection points that help to reduce the impact from climate extremes, enhance recovery rates of affected

SES components, and thus reduce potential net changes (Figure 2). Decision-making processes not only need to take adaption to climate change into account but also adaptation to alleviate impacts from climate extremes. Impacts from climate extremes might require that adaptation response options be changed much earlier than would result from the mean climate trajectory alone (Stafford Smith et al., 2011). The severe impacts of past climate extremes such as hurricanes and wildfires emphasize the growing need for constant readjustment of practices, improved institutional communication across scales and the design of cross-sectoral management plans, and above all for adapting the infrastructural design to ongoing climate change (Markolf et al., 2018; Miller et al., 2018). Such adaptations in society strongly depend on the social capital among policy makers across institutional scales and the degree to which they can form coalition networks (Henry et al., 2010).

Third, impacts of climate extremes can be amplified due to changes in land use and land management as seen in pastoral systems (see Linstädter et al., 2016). Resilience of such SES could be stabilized via changes in management based on an improved knowledge base, institutional changes, and improved practices for sustainable development (Anderies et al., 2004; Reynolds et al., 2007). Globally, multiple socioeconomic and ecological drivers can lead to regime shifts in terrestrial, coastal, and aquatic ecosystems (Rocha et al., 2015), which in turn feeds back to society. We therefore need a better understanding of how future changes in the frequency and intensity of climate extremes will compound with these gradual environmental changes and might jointly impact ES supply and thus SER. We also need more knowledge on when and how drivers could combine and amplify climate extreme impacts inducing multivariate cascading effects in SES. First-hand evidence on the different dynamics of climate extremes versus gradual climate change is starting to emerge (Laliberté & Tylianakis, 2012; Pescaroli & Alexander, 2016), for instance, also for droughts in cross-boundary river catchments (Garrick et al., 2018). However, a more systematic empirical, observational, and modeling evidence of drivers and effects along climatic and land use intensity gradients that involve climate extremes is required.

Given a conceptual, modeling, and monitoring basis, a constant revision of suggested solutions is required to ensure the SES transformation is on a desired path (Haasnoot et al., 2013; Wise et al., 2014). With increasing experience of climate extreme impacts on the SES, conditions need to be identified that allow exploitation of a window of opportunity during and after climate extremes that can help society to correct transformation pathways to ensure SER. The implementation of such a strategy will be a formidable challenge for transdisciplinary and interdisciplinary research (Kramm et al., 2017). It starts with the integration of ecological and social science perspectives on SER (Stone-Jovicich, 2015) and should continue to integrate methodologies from material flow analysis, life cycle analysis, industrial ecology, environmental impact assessment, industrial safety engineering, and institutional and stakeholder analysis but also extend to sectors such as economy, political ecology, and urban and landscape planning.

3. Expected Societal Impact

Finding solutions to the above challenges will be essential for strengthening SER to climate extremes under ongoing and future climate change. Improved understanding for sustainable management is to be expected from advances in monitoring, modeling, and survey techniques. Gained knowledge and methodologies on SER need to be integrated into decision-making processes to identify leverage points and relevant actors to better understand option spaces for adaptation and mitigation and hence contribute to the enhancement of SER (Abson et al., 2017). Building on these developments, society could further profit from enhanced empowerment and a greater contribution to decision making which could help to support achieving Sustainable Development Goals and the 2° climate target of the Paris Agreement. Exploring multiple pathways to enhance the adaptive capacity of SES to absorb climate extremes and implementing these pathways in adaptation and mitigation strategies will slow down critical SES transitions and facilitate transformation toward sustainable future SES.

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