

Earth's Future

COMMENTARY

10.1029/2019EF001221

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

Citation:

Thonicke, K., Bahn, M., Lavorel, S., Bardgett, R. D., Erb, K., Giamberini, M., et al. (2020). Advancing the understanding of adaptive capacity of social-ecological systems to absorb climate extremes. *Earth's Future*, 8, e2019EF001221. <https://doi.org/10.1029/2019EF001221>

Received 26 MAR 2019

Accepted 3 JAN 2020

Accepted article online 8 JAN 2020

Author Contributions:

Conceptualization: Kirsten Thonicke, Michael Bahn, Sandra Lavorel, Richard D. Bardgett, Karlheinz Erb, Mariasilvia Giamberini, Markus Reichstein, Björn Vollen, Anja Rammig

Investigation: Kirsten Thonicke, Michael Bahn, Sandra Lavorel, Richard D. Bardgett, Karlheinz Erb, Mariasilvia Giamberini, Markus Reichstein, Björn Vollen, Anja Rammig

Methodology: Kirsten Thonicke, Michael Bahn, Sandra Lavorel, Richard D. Bardgett, Karlheinz Erb, Mariasilvia Giamberini, Markus Reichstein, Björn Vollen, Anja Rammig

©2020 The Authors.

This is an open access article under the terms of the Creative Commons Attribution License, which permits use, distribution and reproduction in any medium, provided the original work is properly cited.

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

Kirsten Thonicke¹, Michael Bahn², Sandra Lavorel³, Richard D. Bardgett⁴, Karlheinz Erb⁵, Mariasilvia Giamberini⁶, Markus Reichstein⁷, Björn Vollen⁸, and Anja Rammig^{1,9}

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

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

Writing - review & editing: Kirsten Thonicke, Michael Bahn, Sandra Lavorel, Richard D. Bardgett, Karlheinz Erb, Mariasylvia Giamberini, Markus Reichstein, Björn Vollan, Anja Rammig

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.

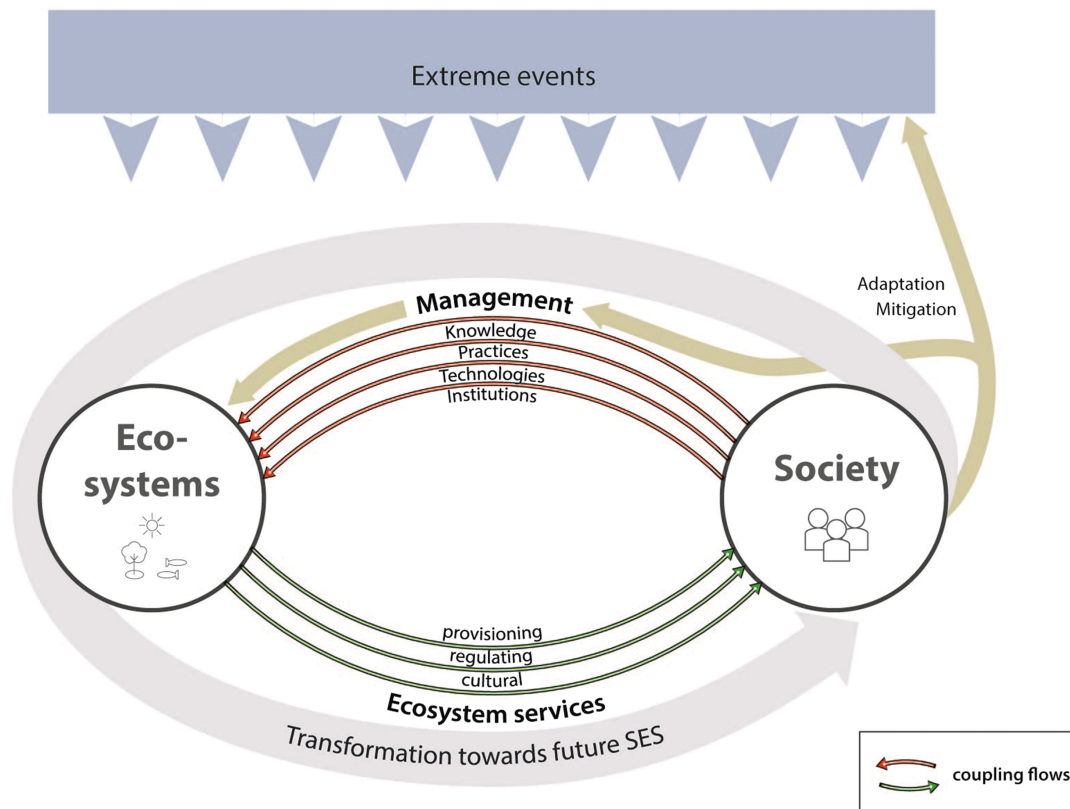


Figure 1. Simplified concept of a social-ecological system (SES) where ecosystems provide ecosystem services to society. Society, in turn, manages ecosystems through its knowledge, practices, technologies and institutions. Management and ecosystem services constitute coupling flows between the two. Climate 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

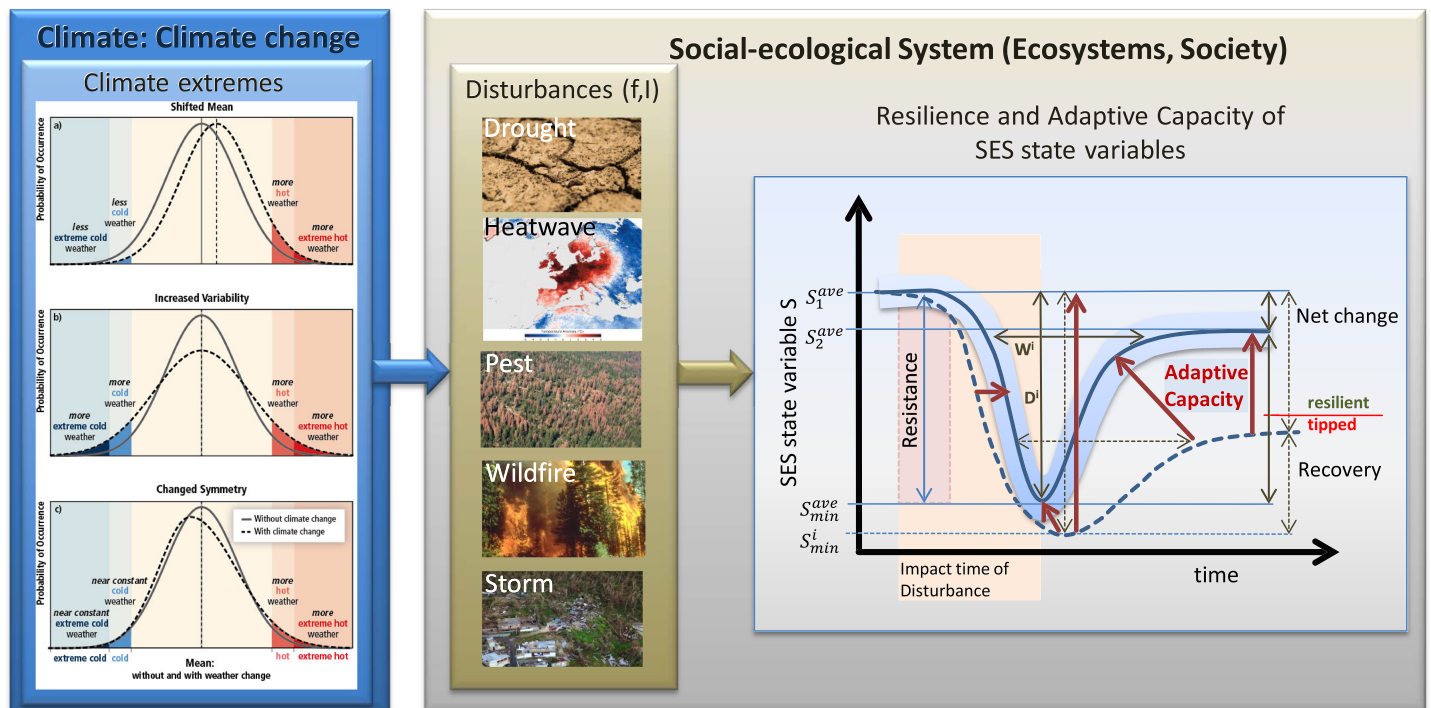


Figure 2. Concept of impacts of climate extreme under climate change on social-ecological resilience. Changes in climate extremes influence frequency (f) and intensity (I) of disturbances. The impact of and recovery from single climate extremes (events) via disturbances (drought, heatwave, pest, wildfire, 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 (<i>n</i>)	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 (<i>n</i>)	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 (<i>n</i>)	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 adaptation 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 (<i>n</i>)	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., Negrón-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/SDGHandbook>) 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 pre-impact 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 co-management 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.

References

- Abel, N., Wise, R. M., Colloff, M. J., Walker, B. H., Butler, J. R. A., Ryan, P., et al. (2016). Building resilient pathways to transformation when "no one is in charge": Insights from Australia's Murray-Darling Basin. *Ecology and Society*, 21(2), art23. <https://doi.org/10.5751/ES-08422-210223>

Acknowledgments

The paper was kicked off at the Future Earth workshop "Cross community workshop on Extreme Events and Environments from Climate to Society (E3S)" in Berlin, 14–16 February 2016. We thank Jasper Bloemen, Stanislava Brnkalakova, Simone Gingrich, Stefan Liehr, Ilan Chabay, Rebecca Oliver, and all participants of the workshop for their thoughtful comments and contributions which laid the foundation of this work. M.B. acknowledges funding from the Austrian Academy of Sciences projects "ClimLUC: Climate extremes and land-use change: effects on ecosystem processes and services" and "ClimGrassHydro". K. H. E acknowledges funding from the Austrian Academy of Sciences, project "Clim-LUC", and the links provided by the project H2020-EO-2014-640176 (BACI). B. V. acknowledges funding from Robert Bosch Stiftung, project "The shadow of the future and the shadow of the past: Studying the impact of climate change on human behavior," Grant 32.5.F082.0001.0/MA01. A. R. and K. T. acknowledge funding from the BMBF- and Belmont Forum-funded project "CLIMAX: Climate services through knowledge co-production: A Euro-South American initiative for strengthening societal adaptation response to extreme events", FKZ 01LP1610A. A. R. acknowledges funding from the Bavarian Ministry of Science and the Arts in the context of the Bavarian Climate Research Network (bayklif) and from the ERA-Net "Sumforest" project "Forests and extreme weather events: Solutions for risk resilient management in a changing climate" (FOREXCLIM).

- Abson, D. J., Fischer, J., Leventon, J., Newig, J., Schomerus, T., Vilsmaier, U., et al. (2017). Leverage points for sustainability transformation. *Ambio*, 46(1), 30–39. <https://doi.org/10.1007/s13280-016-0800-y>
- Adger, W. N. (2000). Social and ecological resilience: Are they related? *Progress in Human Geography*, 24(3), 347–364.
- Allen, C. R., Angeler, D. G., Cumming, G. S., Folke, C., Twidwell, D., & Uden, D. R. (2016). Quantifying spatial resilience. *Journal of Applied Ecology*, 53(3), 625–635. <https://doi.org/10.1111/1365-2664.12634>
- Allen, C. R., Birge, H. E., Angeler, D. G., Arnold, C. A., Chaffin, B. C., DeCaro, D. A., et al. (2018). Quantifying uncertainty and trade-offs in resilience assessments. *Ecology and Society*, 23(1), 23. <https://doi.org/10.5751/es-09920-230103>
- Ambrus, A., Mobius, M., & Szeidl, A. (2014). Consumption risk-sharing in social networks. *American Economic Review*, 104(1), 149–182.
- Anderies, J. M., Janssen, M. A., & Ostrom, E. (2004). A framework to analyze the robustness of social-ecological systems from an institutional perspective. *Ecology and Society*, 9(1), 18.
- Bahn, M., & Ingrisch, J. (2018). Accounting for complexity in resilience comparisons: A reply to Yeung and Richardson, and further considerations. *Trends in Ecology & Evolution*, 33(9), 649–651. <https://doi.org/10.1016/j.tree.2018.06.006>
- Bahn, M., Reichstein, M., Dukes, J. S., Smith, M. D., & McDowell, N. G. (2014). Climate-biosphere interactions in a more extreme world. *New Phytologist*, 202(2), 356–359. <https://doi.org/10.1111/nph.12662>
- Balvanera, P., Quijas, S., Karp, D. S., Ash, N., Bennett, E. M., Boumans, R., et al. (2017). Ecosystem services. In M. Walters, & R. J. Scholes (Eds.), *The GEO handbook on biodiversity observation networks* (pp. 39–78). Cham: Springer International Publishing.
- Berenguer, E., Malhi, Y., Brando, P., Cordeiro, A. C. N., Ferreira, J., Franca, F., et al. (2018). Tree growth and stem carbon accumulation in human-modified Amazonian forests following drought and fire. *Philosophical Transactions of the Royal Society, B: Biological Sciences*, 373(1760), 20170308. <https://doi.org/10.1098/rstb.2017.0308>
- Berkes, F., & Jolly, D. (2001). Adapting to climate change: Social-ecological resilience in a Canadian western Arctic community. *Conservation Ecology*, 5(2), 18.
- Biermann, F., Kanieh, N., & Kim, R. E. (2017). Global governance by goal-setting: The novel approach of the UN sustainable development goals. *Current Opinion in Environmental Sustainability*, 26–27, 26–31. <https://doi.org/10.1016/j.cosust.2017.01.010>
- Bojinski, S., Verstraete, M., Peterson, T. C., Richter, C., Simmons, A., & Zemp, M. (2014). The concept of essential climate variables in support of climate research, applications, and policy. *Bulletin of the American Meteorological Society*, 95(9), 1431–1443. <https://doi.org/10.1175/bams-d-13-00047.1>
- Bowler, D. E., Buyung-Ali, L., Knight, T. M., & Pullin, A. S. (2010). Urban greening to cool towns and cities: A systematic review of the empirical evidence. *Landscape and Urban Planning*, 97(3), 147–155. <https://doi.org/10.1016/j.landurbplan.2010.05.006>
- Bowman, D., Williamson, G. J., Abatzoglou, J. T., Kolden, C. A., Cochrane, M. A., & Smith, A. M. S. (2017). Human exposure and sensitivity to globally extreme wildfire events. *Nature Ecology & Evolution*, 1(3), 6. <https://doi.org/10.1038/s41559-016-0058>
- Buchwitz, M., Lavender, S., & Chuvieco, E. (2017). Special issue on earth observation of essential climate variables. *Remote Sensing of Environment*, 203, 1–1. <https://doi.org/10.1016/j.rse.2017.09.001>
- Carpenter, S., Arrow, K., Barrett, S., Biggs, R., Brock, W., Crépin, A.-S., et al. (2012). General resilience to cope with extreme events. *Sustainability*, 4(12), 3248–3259. <https://doi.org/10.3390/su4123248>
- Carpenter, S., Walker, B., Anderies, J. M., & Abel, N. (2014). From metaphor to measurement: Resilience of what to what? *Ecosystems*, 4(8), 765–781. <https://doi.org/10.1007/s10021-001-0045-9>
- Cote, M., & Nightingale, A. J. (2012). Resilience thinking meets social theory: Situating social change in socio-ecological systems (SES) research. *Progress in Human Geography*, 36(4), 475–489.
- Davidson, J. L., Jacobson, C., Lyth, A., Dedekorkut-Howes, A., Baldwin, C. L., Ellison, J. C., et al. (2016). Interrogating resilience: Toward a typology to improve its operationalization. *Ecology and Society*, 21(2), art27. <https://doi.org/10.5751/es-08450-210227>
- Dearing, J. A., Yang, X., Dong, X., Zhang, E., Chen, X., Langdon, P. G., et al. (2012). Extending the timescale and range of ecosystem services through paleoenvironmental analyses, exemplified in the lower Yangtze basin. *Proceedings of the National Academy of Sciences of the United States of America*, 109(18), E1111–E1120. <https://doi.org/10.1073/pnas.1118263109>
- Doherty, M. D., Lavorel, S., Colloff, M. J., Williams, K. J., & Williams, R. J. (2017). Moving from autonomous to planned adaptation in montane forests under changing fire regimes: A case study from SE Australia. *Austral Ecology*, 42, 309–316.
- Doussot, B., Gourmelon, F., Laaidi, K., Zeghnoun, A., Giraudet, E., Bretin, P., et al. (2011). Satellite monitoring of summer heat waves in the Paris metropolitan area. *International Journal of Climatology*, 31(2), 313–323. <https://doi.org/10.1002/joc.2222>
- Dovers, S. R., & Hezri, A. A. (2010). Institutions and policy processes: The means to the ends of adaptation. *Wiley Interdisciplinary Reviews: Climate Change*, 1(2), 212–231. <https://doi.org/10.1002/wcc.29>
- Editorial (2018). Tracking progress on the SDGs. *Nature Sustainability*, 1(8), 377–377. <https://doi.org/10.1038/s41893-018-0131-z>
- Ellis, E. C. (2011). Anthropogenic transformation of the terrestrial biosphere. *Philosophical Transactions of the Royal Society a-Mathematical Physical and Engineering Sciences*, 369(1938), 1010–1035. <https://doi.org/10.1098/rsta.2010.0331>
- Ellis, E. C., Kaplan, J. O., Fuller, D. Q., Vavrus, S., Goldewijk, K. K., & Verburg, P. H. (2013). Used planet: A global history. *Proceedings of the National Academy of Sciences of the United States of America*, 110(20), 7978–7985. <https://doi.org/10.1073/pnas.1217241110>
- Erb, K.-H. (2012). How a socio-ecological metabolism approach can help to advance our understanding of changes in land-use intensity. *Ecological Economics*, 76, 8–14.
- Fischer-Kowalski, M., & Weisz, H. (2016). The archipelago of social ecology and the island of the Vienna school. In H. Haberl, M. K. F. Fischer-Kowalski, & V. Winiwarter (Eds.), *Social Ecology, Human-Environment Interactions* (Vol. 5, pp. 3–28). Cham, Switzerland: Springer International Publishing. https://doi.org/10.1007/978-3-319-33326-7_1
- Fisk, J. P., Hurr, G. C., Chambers, J. Q., Zeng, H., Dolan, K. A., & Negron-Juarez, R. I. (2013). The impacts of tropical cyclones on the net carbon balance of eastern US forests (1851–2000). *Environmental Research Letters*, 8(4), 6. <https://doi.org/10.1088/1748-9326/8/4/045017>
- flicker (2016). pest. Dead trees on a parched landscape. Aerial detection survey photo of dead and dying trees on the Sequoia and Sierra National forests, August 2016 under CC BY 2.0). Date, <https://www.flickr.com/photos/usfsregion5/30896474392>.
- Folke, C., Biggs, R., Norström, A. V., Reyers, B., & Rockström, J. (2016). Social-ecological resilience and biosphere-based sustainability science. *Ecology and Society*, 21(3). <https://doi.org/10.5751/es-08748-210341>
- Folke, C., Hahn, T., Olsson, P., & Norberg, J. (2005). Adaptive governance of social-ecological systems. *Annual Review of Environment and Resources*, 30(1), 441–473. <https://doi.org/10.1146/annurev.energy.30.050504.144511>
- Ford, C. R., Laseter, S. H., Swank, W. T., & Vose, J. M. (2011). Can forest management be used to sustain water-based ecosystem services in the face of climate change? *Ecological Applications*, 21(6), 2049–2067. <https://doi.org/10.1890/10.1890/10-2246.1>
- Frank, D., Reichstein, M., Bahn, M., Thonicke, K., Frank, D., Mahecha, M. D., et al. (2015). Effects of climate extremes on the terrestrial carbon cycle: Concepts, processes and potential future impacts. *Global Change Biology*, 21(8), 2861–2880. <https://doi.org/10.1111/gcb.12916>

- Garrick, D. E., Schlager, E., De Stefano, L., & Villamayor-Tomas, S. (2018). Managing the cascading risks of droughts: Institutional adaptation in transboundary river basins. *Earth's Future*, 6(6), 809–827. <https://doi.org/10.1002/2018ef000823>
- Godelier, M. (1986). *The mental and the material. Thought, economy and society*. oxford: Blackwell Verso.
- Gouveia, C. M., Bastos, A., Trigo, R. M., & DaCamara, C. C. (2012). Drought impacts on vegetation in the pre- and post-fire events over Iberian Peninsula. *Natural Hazards and Earth System Sciences*, 12(10), 3123–3137. <https://doi.org/10.5194/nhess-12-3123-2012>
- Gunderson, L. H. (2000). Ecological resilience—In theory and application. *Annual Review of Ecology and Systematics*, 31, 425–439.
- Haasnoot, M., Kwakkel, J. H., Walker, W. E., & Maat, J. (2013). Dynamic adaptive policy pathways: A method for crafting robust decisions for a deeply uncertain world. *Global Environmental Change*, 23, 485–498.
- Haberl, H., Fischer-Kowalski, M., Krausmann, F., & Winiwarter, V. (Eds) (2016). *Social Ecology, Society-Nature Relations across Time and Space, Human-Environment Interactions* (Vol. 5). Cham, Switzerland: Springer International Publishing. <https://doi.org/10.1007/978-3-319-33326-7>
- Harrington, L. J., Frame, D. J., Fischer, E. M., Hawkins, E., Joshi, M., & Jones, C. D. (2016). Poorest countries experience earlier anthropogenic emergence of daily temperature extremes. *Environmental Research Letters*, 11. <https://doi.org/10.1088/1748-9326/11/5/055007>
- Hassan, R., Scholes, R., & Ash, N. (Eds) (2005). Ecosystems and human well-being: Current state and trends. In *Findings of the Condition and Trends Working Group of the Millenium Ecosystem Assessment* (p. 917). Washington: Island Press.
- Henry, A., & Volland, B. (2014). Networks and the challenge of sustainable development. *Annual Review of Environment and Natural Resources*, 39, 583–610.
- Henry, A. D., Lubell, M., & McCoy, M. (2010). Belief systems and social capital as drivers of policy network structure: The case of California regional planning. *Journal of Public Administration Research and Theory*, 21(3), 419–444. <https://doi.org/10.1093/jopart/muq042>
- Hodgson, D., McDonald, J. L., & Hosken, D. J. (2015). What do you mean, 'resilient'? *Trends in Ecology & Evolution*, 30(9), 503–506. <https://doi.org/10.1016/j.tree.2015.06.010>
- Hsiang, S. M., Burke, M., & Miguel, E. (2013). Quantifying the influence of climate on human conflict. *Science*, 341(6151), 1235367. <https://doi.org/10.1126/science.1235367>
- Hummel, D. (Ed) (2008). *Population dynamics and supply systems: A transdisciplinary approach*, 295 pp. Frankfurt, New York: Campus Verlag.
- Hunter, L. M., Luna, J. K., & Norton, R. M. (2015). The environmental dimensions of migration. *Annual Review of Sociology*, 41, 377–397. <https://doi.org/10.1146/annurev-soc-073014-112223>
- Ingrisch, J., & Bahn, M. (2018). Towards a comparable quantification of resilience. *Trends in Ecology & Evolution*, 33(4), 251–259. <https://doi.org/10.1016/j.tree.2018.01.013>
- IPCC (2012). Summary for policymakers. In C. B. Field et al. (Eds.), *Managing the risks of extreme events and disasters to advance climate change adaptation* (pp. 1–19). Cambridge, UK, and New York, NY, USA: Cambridge University Press.
- Kates, R. W., Clark, W. C., Robert, C., Michael Hall, J., Jaeger, C. C., Lowe, I., & McCarthy, J. J. (2001). Sustainability science. *Science*, 292(5517), 641–642. <https://doi.org/10.1126/science.1059386>
- Kaye, J. P., & Quemada, M. (2017). Using cover crops to mitigate and adapt to climate change. A review. *Agronomy for Sustainable Development*, 37(1), 1–17. <https://doi.org/10.1007/s13593-016-0410-x>
- Kayler, Z. E., De Boeck, H. J., Faticchi, S., Grünzweig, J. M., Merbold, L., Beier, C., et al. (2015). Experiments to confront the environmental extremes of climate change. *Frontiers in Ecology and the Environment*, 13(4), 219–225. <https://doi.org/10.1890/140174>
- Koevoets, I. T., Venema, J. H., Elzenga, J. T. M., & Testerink, C. (2016). Roots Withstanding their environment: Exploiting root system architecture responses to abiotic stress to improve crop tolerance. *Frontiers in Plant Science*, 07. <https://doi.org/10.3389/fpls.2016.01335>
- Kramm, J., Pichler, M., Schaffartzik, A., & Zimmermann, M. (2017). Societal relations to nature in times of crisis—Social ecology's contributions to interdisciplinary sustainability studies. *Sustainability*, 9(7), 1042. <https://doi.org/10.3390/su9071042>
- Kythreotis, A. P., Mercer, T. G., & Frostick, L. E. (2013). Adapting to extreme events related to natural variability and climate change: The imperative of coupling technology with strong regulation and governance. *Environmental Science & Technology*, 47(17), 9560–9566. <https://doi.org/10.1021/es4014294>
- Laliberté, E., & Tylianakis, J. M. (2012). Cascading effects of long-term land-use changes on plant traits and ecosystem functioning. *Ecology*, 93(1), 145–155. <https://doi.org/10.1890/11-0338.1>
- Li, D., & Bou-Zeid, E. (2013). Synergistic Interactions between urban heat islands and heat waves: The impact in cities is larger than the sum of its parts*. *Journal of Applied Meteorology and Climatology*, 52(9), 2051–2064. <https://doi.org/10.1175/jamc-d-13-02.1>
- Liehr, S., Röhrig, J., Mehring, M., & Kluge, T. (2017). How the social-ecological systems concept can guide transdisciplinary research and implementation: Addressing water challenges in central northern Namibia. *Sustainability*, 9(7), 1109. <https://doi.org/10.3390/su9071109>
- Lin, N. (2001). *Social capital: A theory of social structure and action*. New York: Cambridge Univ. Press.
- Lindner, M., Maroschek, M., Netherer, S., Kremer, A., Barbati, A., Garcia-Gonzalo, J., et al. (2010). Climate change impacts, adaptive capacity, and vulnerability of European forest ecosystems. *Forest Ecology and Management*, 259(4), 698–709. <https://doi.org/10.1016/j.foreco.2009.09.023>
- Linstädter, A., Kuhn, A., Naumann, C., Rasch, S., Sandhage-Hofmann, A., Amelung, W., et al. (2016). Assessing the Resilience of a Real-world Social-ecological System: Lessons from a Multidisciplinary Evaluation of a South African Pastoral System. *Ecology and Society*, 21(3). Accessed January 22, 2020. www.jstor.org/stable/26269980
- Liu, J., Dietz, T., Carpenter, S. R., Alberti, M., Folke, C., Moran, E., & Pell, A. N. (2007). Complexity of coupled human and natural systems. *Science*, 317(5844), 1513–1516. <https://doi.org/10.1126/science.1144004>
- Liu, J., Dou, Y., Batistella, M., Challies, E., Connor, T., Friis, C., et al. (2018). Spillover systems in a telecoupled Anthropocene: Typology, methods, and governance for global sustainability. *Current Opinion in Environmental Sustainability, System dynamics and sustainability*, 33, 58–69. <https://doi.org/10.1016/j.cosust.2018.04.009>
- Liu, J., Mooney, H., Hull, V., Davis, S. J., Gaskell, J., Hertel, T., et al. (2015). Sustainability. Systems integration for global sustainability. *Science*, 347(6225), 1258832. <https://doi.org/10.1126/science.1258832>
- Loiola, P. P., Scherer-Lorenzen, M., & Batalha, M. A. (2015). The role of environmental filters and functional traits in predicting the root biomass and productivity in savannas and tropical seasonal forests. *Forest Ecology and Management*, 342, 49–55. <https://doi.org/10.1016/j.foreco.2015.01.014>
- Long, J., Giri, C., Primavera, J., & Trivedi, M. (2016). Damage and recovery assessment of the Philippines' mangroves following Super Typhoon Haiyan. *Marine Pollution Bulletin*, 109(2), 734–743. <https://doi.org/10.1016/j.marpolbul.2016.06.080>

- Lowman, M., D'Avanzo, C., & Brewer, C. (2009). A national ecological network for research and education. *Science*, 323(5918), 1172–1173. <https://doi.org/10.1126/science.1166945>
- Markolf, S. A., Chester, M., Eisenberg, D. A., Iwaniec, D. M., Davidson, C. I., Zimmerman, R., et al. (2018). Interdependent infrastructure as linked social, ecological, and technological systems (SETs) to address lock-in and enhance resilience. *Earth's Future*, 6(12), 1638–1659. <https://doi.org/10.1029/2018EF000926>
- Maystadt, J.-F., & Ecker, O. (2014). Extreme weather and civil war: Does drought fuel conflict in somalia through livestock price shocks? *American Journal of Agricultural Economics*, 96(4), 1157–1182. <https://doi.org/10.1093/ajae/aa010>
- Miller, T. R., Chester, M., & Munoz-Erickson, T. (2018). Rethinking infrastructure in an era of unprecedented events. *Issues in Science and Technology*, 34(2), 47–58.
- Negron-Juarez, R. I., Holm, J. A., Marra, D. M., Rifai, S. W., Riley, W. J., Chambers, J. Q., et al. (2018). Vulnerability of Amazon forests to storm-driven tree mortality. *Environmental Research Letters*, 13(5), 054021. <https://doi.org/10.1088/1748-9326/aabe9f>
- Nelson, D. R., Adger, W. N., & Brown, K. (2007). Adaptation to environmental change: Contributions of a resilience framework. *Annual Review of Environment and Resources*, 32(1), 395–419. <https://doi.org/10.1146/annurev.energy.32.051807.090348>
- Norton, B. A., Coutts, A. M., Livesley, S. J., Harris, R. J., Hunter, A. M., & Williams, N. S. G. (2015). Planning for cooler cities: A framework to prioritise green infrastructure to mitigate high temperatures in urban landscapes. *Landscape and Urban Planning*, 134, 127–138. <https://doi.org/10.1016/j.landurbplan.2014.10.018>
- Olsson, L., Jerneck, A., Thoren, H., Persson, J., & O'Byrne, D. (2015). Why resilience is unappealing to social science: Theoretical and empirical investigations of the scientific use of resilience. *Science Advances*, 1(4), e1400217. <https://doi.org/10.1126/sciadv.1400217>
- Olsson, P., Galaz, V., & Boonstra, W. J. (2014). Sustainability transformations: A resilience perspective. *Ecology and Society*, 19(4). <https://doi.org/10.5751/es-06799-190401>
- Ostrom, E. (2009). A general framework for analyzing sustainability of social-ecological systems. *Science*, 325(5939), 419–422. <https://doi.org/10.1126/science.1172133>
- Pahl-Wostl, C. (2009). A conceptual framework for analysing adaptive capacity and multi-level learning processes in resource governance regimes. *Global Environmental Change*, 19(3), 354–365.
- Pellegrini, A. F. A., Ahlstrom, A., Hobbie, S. E., Reich, P. B., Nieradzik, L. P., Staver, A. C., et al. (2018). Fire frequency drives decadal changes in soil carbon and nitrogen and ecosystem productivity. *Nature*, 553(7687), 194–198. <https://doi.org/10.1038/nature24668>
- Pelling, M. (2011). *Adaptation to climate change: From resilience to transformation*, (p. 202). London and New York: Taylor&Francis Group.
- Pereira, H. M., Ferrier, S., Walters, M., Geller, G. N., Jongman, R. H. G., Scholes, R. J., et al. (2013). Essential biodiversity variables. *Science*, 339(6117), 277–278. <https://doi.org/10.1126/science.1229931>
- Pescaroli, G., & Alexander, D. (2016). Critical infrastructure, panarchies and the vulnerability paths of cascading disasters. *Natural Hazards*, 82(1), 175–192. <https://doi.org/10.1007/s11069-016-2186-3>
- Proenca, V., Martin, L. J., Pereira, H. M., Fernandez, M., McRae, L., Belnap, J., et al. (2017). Global biodiversity monitoring: From data sources to essential biodiversity variables. *Biological Conservation*, 213, 256–263. <https://doi.org/10.1016/j.biocon.2016.07.014>
- Putnam, R. (2000). *Bowling alone: The collapse and revival of American community*. New York: Simon & Schuster.
- Ratcliffe, S., Wirth, C., Jucker, T., van der Plas, F., Scherer-Lorenzen, M., Verheyen, K., et al. (2017). Biodiversity and ecosystem functioning relations in European forests depend on environmental context. *Ecology Letters*, 20(11), 1414–1426. <https://doi.org/10.1111/ele.12849>
- Reid, W. V., Chen, D., Goldfarb, L., Hackmann, H., Lee, Y. T., Mokhele, K., & Ostrom, E. (2010). Earth system science for global sustainability: Grand challenges. *Science*, 330(6006), 916–917. <https://doi.org/10.1126/science.1196263>
- Reyer, C. P. O., Leuzinger, S., Rammig, A., Wolf, A., Bartholomeus, R. P., Bonfante, A., et al. (2013). A plant's perspective of extremes: Terrestrial plant responses to changing climatic variability. *Global Change Biology*, 19(1), 75–89. <https://doi.org/10.1111/gcb.12023>
- Reynolds, J. F., Smith, D. M. S., Lambin, E. F., Turner, B. L., Mortimore, M., Batterbury, S. P. J., et al. (2007). Global desertification: Building a science for dryland development. *Science*, 316(5826), 847–851. <https://doi.org/10.1126/science.1131634>
- Rocha, J. C., Peterson, G. D., & Biggs, R. (2015). Regime shifts in the anthropocene: Drivers, risks, and resilience. *PLoS ONE*, 10(8), e0134639. <https://doi.org/10.1371/journal.pone.0134639>
- Scheffer, M., Carpenter, S. R., Dakos, V., & van Nes, E. H. (2015). Generic indicators of ecological resilience: Inferring the chance of a critical transition. In D. J. Futuyma (Ed.), *Annual Review of Ecology, Evolution, and Systematics* (Vol. 46, pp. 145–167). Palo Alto: Annual Reviews.
- Schmeller, D. S., Weatherdon, L. V., Loyau, A., Bondeau, A., Brotons, L., Brummitt, N., et al. (2018). A suite of essential biodiversity variables for detecting critical biodiversity change. *Biological Reviews*, 93(1), 55–71. <https://doi.org/10.1111/brv.12332>
- Schroter, D., Cramer, W., Leemans, R., Prentice, I. C., Araujo, M. B., Arnell, N. W., et al. (2005). Ecosystem service supply and vulnerability to global change in Europe. *Science*, 310(5752), 1333–1337. <https://doi.org/10.1126/science.1115233>
- Schröter, M., Koellner, T., Alkemade, R., Arnhold, S., Bagstad, K. J., Erb, K.-H., et al. (2018). Interregional flows of ecosystem services: Concepts, typology and four cases. *Ecosystem Services*, 31(Part B), 231–241. <https://doi.org/10.1016/j.ecoser.2018.02.003>
- Silva, D. M., Batalha, M. A., & Cianciaruso, M. V. (2013). Influence of fire history and soil properties on plant species richness and functional diversity in a neotropical savanna. *Acta Botânica Brasileira*, 27(3), 490–497. <https://doi.org/10.1590/s0102-33062013000300005>
- Silva, F. R. Y., Martinez, J. R. M., & Gonzalez-Caban, A. (2014). A methodology for determining operational priorities for prevention and suppression of wildland fires. *International Journal of Wildland Fire*, 23(4), 544–554. <https://doi.org/10.1071/wf13063>
- Stafford Smith, M., Horrocks, L., Harvey, A., & Hamilton, C. (2011). Rethinking adaptation for a 4°C world. *Philosophical Transactions. Series A, Mathematical, Physical, and Engineering Sciences*, 369(1934), 196–216. <https://doi.org/10.1098/rsta.2010.0277>
- Staver, A. C., Archibald, S., & Levin, S. (2011). Tree cover in sub-Saharan Africa: Rainfall and fire constrain forest and savanna as alternative stable states. *Ecology*, 92(5), 1063–1072.
- Steffen, W., Sanderson, A., Tyson, P. D., Jäger, J., Matson, P. A., Moore, B. III, et al. (2004). *Global change and the earth system. A planet under pressure*. Berlin: Springer.
- Stone-Jovicich, S. (2015). Probing the interfaces between the social sciences and social-ecological resilience: Insights from integrative and hybrid perspectives in the social sciences. *Ecology and Society*, 20(2), 23. <https://doi.org/10.5751/es-07347-200225>
- Stone-Jovicich, S., Goldstein, B. E., Brown, K., Plummer, R., & Olsson, P. (2018). Expanding the contribution of the social sciences to social-ecological resilience research. *Ecology and Society*, 23(1), 8. <https://doi.org/10.5751/es-10008-230141>
- Tompkins, E. L., & Adger, W. N. (2004). Does adaptive management of natural resources enhance resilience to climate change. *Ecology and Society*, 9(2), 10.

- Turner, B. L., Kasperson, R. E., Matson, P. A., McCarthy, J. J., Corell, R. W., Christensen, L., & Eckley, N. (2003). A framework for vulnerability analysis in sustainability science. *Proceedings of the National Academy of Sciences of the United States of America*, 100(14), 8074–8079. <https://doi.org/10.1073/pnas.1231335100>
- Turner, B. L., Lambin, E. F., & Reenberg, A. (2007). The emergence of land change science for global environmental change and sustainability. *Proceedings of the National Academy of Sciences of the United States of America*, 104(52), 20,666–20,671. <https://doi.org/10.1073/pnas.0704119104>
- Ummenhofer, C. C., & Meehl, G. A. (2017). Extreme weather and climate events with ecological relevance: A review. *Philosophical Transactions of the Royal Society, B: Biological Sciences*, 372(1723), 13. <https://doi.org/10.1098/rstb.2016.0135>
- Walter, J., Nagy, L., Hein, R., Rascher, U., Beierkuhnlein, C., Willner, E., & Jentsch, A. (2011). Do plants remember drought? Hints towards a drought-memory in grasses. *Environmental and Experimental Botany*, 71(1), 34–40. <https://doi.org/10.1016/j.envexpbot.2010.10.020>
- Ward, K., Lauf, S., Kleinschmit, B., & Endlicher, W. (2016). Heat waves and urban heat islands in Europe: A review of relevant drivers. *Science of the Total Environment*, 569, 527–539. <https://doi.org/10.1016/j.scitotenv.2016.06.119>
- Wikimedia (2008). Canadian wildfire. Date accessed: 25. August 2018, https://commons.wikimedia.org/wiki/File:Wildfire_in_California.jpg
- Wikimedia (2018). Europe 2006 heatwave. Europe 2006 Heatwave.png English: July 2006 land surface temperature anomaly wrt 2000–2012 derived from Modis Terra data. Date accessed: 25 August 2018, https://upload.wikimedia.org/wikipedia/commons/7/7b/Europe_2006_Heatwave.png
- Wikipedia (2017). Hurrican Maria, Puerto Rico. Date accessed: 25 August 2018, [https://en.wikipedia.org/wiki/Hurricane_Maria#/media/File:Hurricane_Maria_\(2017\)_170923-H-NI589-0007_\(36602415074\).jpg](https://en.wikipedia.org/wiki/Hurricane_Maria#/media/File:Hurricane_Maria_(2017)_170923-H-NI589-0007_(36602415074).jpg)
- Wise, R. M., Fazey, I., Smith, M. S., Park, S. E., Eakin, H. C., Garderen, E. R. M. A. V., & Campbell, B. (2014). Reconceptualising adaptation to climate change as part of pathways of change and response. *Global Environmental Change*, 28, 325–336.
- Xu, X. J., Zhou, G. M., Liu, S. G., Du, H. Q., Mo, L. F., Shi, Y. J., et al. (2013). Implications of ice storm damages on the water and carbon cycle of bamboo forests in southeastern China. *Agricultural and Forest Meteorology*, 177, 35–45. <https://doi.org/10.1016/j.agrformet.2013.04.005>

References From the Supporting Information

- Biggs, R., Schlter, M., Biggs, D., Bohensky, E. L., BurnSilver, S., Cundill, G., et al. (2012). Toward principles for enhancing the resilience of ecosystem services. *Annual Review of Environment and Resources*, 37(1), 421–448. <https://doi.org/10.1146/annurevenviron051211123836>
- IPCC (2014). Summary for policymakers. In C. B. Field, V. R. Barros, D. J. Dokken, K. J. Mach, M. D. Mastrandrea, T. E. Bilir, M. Chatterjee, et al. (Eds.), *Climate change 2014: Impacts, adaptation, and vulnerability. Part A: Global and sectoral aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* (pp. 1–32). Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press.
- Matin, N., Forrester, J., & Ensor, J. (2018). What is equitable resilience? *World Development*, 109, 197–205. <https://doi.org/10.1016/j.worlddev.2018.04.020>
- Mori, A. S., Furukawa, T., & Sasaki, T. (2013). Response diversity determines the resilience of ecosystems to environmental change. *Biological Reviews*, 88(2), 349–364. <https://doi.org/10.1111/brv.12004>
- Reichstein, M., Bahn, M., Ciais, P., Frank, D., Mahecha, M. D., Seneviratne, S. I., et al. (2013). Climate extremes and the carbon cycle. *Nature*, 500(7462), 287–295. <https://doi.org/10.1038/nature12350>
- Sakschewski, B., von Bloh, W., Boit, A., Poorter, L., Pena-Claros, M., Heinke, J., Joshi, J., et al. (2016). Resilience of Amazon forests emerges from plant trait diversity. *Nature Climate Change*, 6(11), 1032–+. <https://doi.org/10.1038/nclimate3109>
- Seneviratne, S. I., Nicholls, N., Easterling, D., Goodess, C. M., Kanae, S., Kossin, J., Luo, Y., et al. (2012). Changes in climate extremes and their impacts on the natural physical environment. In C. B. Field et al. (Eds.), *Managing the risks of extreme events and disasters to advance climate change adaptation* (pp. 109–230). Cambridge, UK, and New York, NY, USA: Cambridge University Press.
- Tomimatsu, H., Sasaki, T., Kurokawa, H., Bridle, J. R., Fontaine, C., Kitano, J., et al. (2013). Sustaining ecosystem functions in a changing world: A call for an integrated approach. *Journal of Applied Ecology*, 50(5), 1124, n/a–1130. <https://doi.org/10.1111/1365-2664.12116>