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Transformative adaptation to climate change for sustainable social-ecological systems

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ABSTRACT

In the face of major shifts in temperature and precipitation, some conventional strategies that help people to cope or incrementally adapt to climate change may become inappropriate in the long-term. Transformative adaptation, i.e. fundamental systems' changes that address root causes of vulnerability may be needed. However, we have a limited understanding of what transformative adaptation looks like in social-ecological systems and when it can be implemented. We applied an interdisciplinary perspective to describing social-ecological shifts driven by climate change. We reviewed 80 recent conceptual publications about responses of social, ecological, and social-ecological systems to climate change. Our review suggests that transformative adaptation is characterized as being restructuring, path-shifting, innovative, multiscale, systemwide, and persistent. Despite several barriers to implement transformative adaptation, policy makers and practitioners should consider this option in adaptation plans to help societies to anticipate, guide, or recover from radical climate change impact. Using transformative adaptation to navigate shifts driven by climate change can increase the efficiency and sustainability of climate solutions.

1. Introduction: Climate change impacts and the need for adaptation

Societies and ecosystems around the world are increasingly being impacted by rising temperatures, changing rainfall patterns and frequent or severe extreme weather events and will require support to adapt to these changes. Both people and ecosystems have been adapting to these climate-driven changes. Examples of societal responses to climate change include farmers who have increasingly subscribed to crop insurance against extreme weather in China (Jianjun et al., 2015), low lying cities that have built walls and planned relocations due to recurrent floods in the Netherlands (Edelenbos et al., 2017), and coastal communities that have migrated inland due to sea level rise in the Mekong Delta (Smajgl et al., 2015), among others. Examples of ecological responses driven by climate change include plants that have shifted their distribution towards higher altitudes in European mountains (Gottfried et al., 2012), birds and plants that have shifted their breeding or flowering periods around the world (Walther et al., 2002), and corals that have expelled their symbiotic algae causing coral bleaching in the Great Barrier Reef (Hughes et al., 2017).

However, conventional coping strategies and incremental adaptation to climate change may not always be effective at helping people or ecosystems to reduce their vulnerabilities to severe climatic changes. For example, in response to climate change-driven floods, people can borrow money to repair houses or replant damaged crops in the same location. These coping responses may not be enough to protect communities from floods that are increasingly severe and frequent, and affect large areas (Adger and Jordan, 2009; Kim et al., 2012). People can also incrementally adapt to the floods by building higher dams or elevating their houses. This type of adaptation modifies the social or ecological system to accommodate changes but does not alter the fundamental characteristics of the social-ecological system, so people may remain vulnerable to future floods. Instead of these incremental adaptations, people can also respond to floods by transforming their social-ecological system, for example by relocating houses or crop fields to safer areas or restoring previously degraded wetlands upstream. 'Transformative adaptation' therefore refers to these changes that fundamentally alter the entire system's ecological and/or social properties and functions. It aims to reduce the root causes of vulnerabilities to climate change (Future Earth, 2015; Kates et al., 2012), such as social,

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cultural, economic, environmental, and power relations, by transforming them into more just, sustainable, or resilient states.

Although there is increasing interest in the concept of transformative adaptation (Feola, 2015 and Patterson et al., 2017), transformative adaptation is rarely considered in adaptation projects, plans or policies to reduce the impacts of climate change. Very few studies of climate change adaptation have reported the implementation of transformative adaptation, even though some promising studies have started, such as those in Eastern Indonesia (Butler et al., 2016), the French Alps (Lavorel et al., 2019), and the city of Rotterdam (Hölscher et al., 2019). For example, a review of Africa adaptation projects to reduce farmer vulnerabilities to climate change, found that most adaptation interventions were incremental adjustments of livelihoods (Mapfumo et al., 2017). In the United States, proposed adaptation projects in the agricultural and water sectors were mostly related to slight modifications of existing adaptation strategies with the exception of a few cases, such as a reform in the water rights system and water allocation mechanisms that fundamentally changed current institutional arrangements (Kates et al., 2012). In cities around the world, a review of the adaptation plans to heat stress and infrastructure damages showed that they mostly focused on increasing resilience, e.g. through resistant buildings, but rarely included actions with transformative potential such as the development of new land-use plans that restricted the use of areas with high risks and mitigation potential (Revi et al., 2014).

There are many more barriers for the implementation of transformative adaptation (Fig. 1) compared to the implementation of coping responses or incremental adaptation (Chung Tiam Fook, 2017; Kates et al., 2012; Rickards and Howden, 2012). Transformative adaptation may receive less social or political support because of the particularly high investments that may be required (human, financial, and time) and the long time needed for the benefits to manifest themselves (Adger et al., 2005; Kuntz and Gomes, 2012). There is a tendency to adapt through incremental adaptation or business-as-usual strategies that do not challenge the status-quo of the current system because of a lack of familiarity with transformative adaptation, constraining funding structures for such strategies, or narrow mandates of the institutions planning these interventions (Abson et al., 2017; Gibson et al., 2016; Thornton and Comberti, 2017). Power imbalances and inequalities can also hinder transformative adaptation because dominant actors who benefit from the status-quo may be in a position to block such changes (Colloff et al., 2017a; Pelling et al., 2015; Tschakert et al., 2013). In addition, transformative adaptation may be discouraged by the need to involve multiple stakeholders, sectors, and governance levels with potentially different interests (Meadowcroft, 2011; Van den Bergh, 2011). Transformative adaptation may also need to reconcile different future visions (e.g. economic growth versus low carbon emissions) and reconnect local service producers with regional or global beneficiaries (e.g. through fair-trade sustainable food supply chains, water or carbon Payments for Ecosystem Services). These barriers increase the degrees of uncertainty and risks associated with transformative adaptation (Blythe et al., 2018). Another set of barriers for transformative adaptation are complex ethical and distributional questions that need to be clarified prior to its implementation, such as the deliberate choice to support certain values (Biermann et al., 2012; Gorddard et al., 2016), governance structures (Colloff et al., 2017a; Fazey et al., 2018), and vested interests in particular outcomes (Stirling, 2014; Wise et al., 2014).

Transformative adaptation is emerging in the scientific and sustainable development debates as both a necessity and an opportunity, but it is a complex concept that remains poorly defined in practice. Researchers have described the distinction between transformative adaptation and other responses aimed at coping with climate change impacts or incrementally adapting to these changes (for reviews, see Feola, 2015 and Patterson et al., 2017). However, there is little information on what transformative adaptation entails, what this type of adaptation looks like in social-ecological systems, and when to consider implementing it (Moore et al., 2014; Patterson et al., 2017; Rickards and Howden, 2012). Policy-makers have started recognizing that climate change responses might need to go beyond business-as-usual to be effective (Mapfumo et al., 2017; O'Brien, 2012), but rarely consider transformative adaptation as a potential solution. References to transformative adaptation are found, for example, in the SDGs preamble ("*transformative steps […] to a sustainable and resilient path*) (UN, 2018), in the Green Climate Fund mandate ("*paradigm shift towards […] climate-resilient development pathways*") (UNFCCC, 2012), and in the Paris Agreement Article 7 ("*greater adaptation needs can involve greater adaptation costs*") (UN, 2015). In all those strategic documents, it is clear that without considering transformative adaptation as a response to climate change, we may not only fail to reduce the vulnerabilities of both ecological and social systems, but also increase the costs and delay the implementation of sustainable and long-term solutions (Adger and Jordan, 2009; Pelling et al., 2015; Rickards and Howden, 2012).

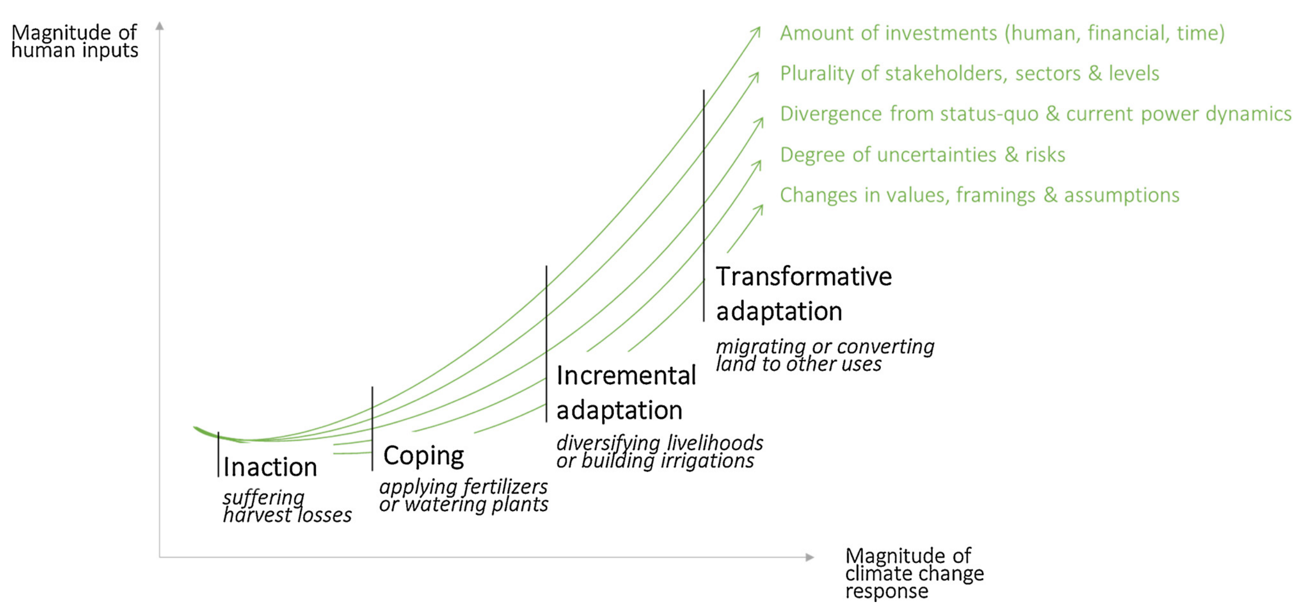

Fig. 1. Types of strategies for reducing the impact of climate change on social-ecological systems, with examples from agriculture, along a gradient of increasing magnitude of responses.

In this study, we provide an overview of what transformative adaptation is in coupled social-ecological systems, highlight the characteristics of this type of adaptation, and explore opportunities for helping to operationalize the implementation of transformative adaptation as part of the set of adaptation options. We adopt an interdisciplinary perspective to transformative adaptation that includes aspects related to both the social and ecological systems, as well as their interactions. We review the recent conceptual literature (80 publications in total) describing major changes and responses to climate change in social, ecological, and social-ecological systems to identify common characteristics of transformative adaptation (see Methods and Annex). We then discuss how an improved understanding of these characteristics can help decision makers consider transformative adaptation in programs, plans, and processes, including National Adaptation Plans, Nationally Determined Contribution, and Ecosystem-based Adaptation projects. Finally, we discuss when transformative adaptation may be an appropriate response to climate change instead of coping or incremental options. By understanding what transformative adaptation entails and when it should be considered in practice, we can be better prepared to develop climate solutions that follow more sustainable development pathways.

2. Theory: Types of adaptation in social-ecological systems

Responses to the adverse impacts of climate change can be categorized into three major types: coping responses, incremental adaptation, and transformative adaptation (Fig. 2 from left to right). Because social and ecological systems are tightly interconnected (Berkes and Folke, 1998), an alteration in one sub-system likely leads to modifications in the other. Climate change can affect ecosystems on which people depend for their livelihoods (CBD, 2009); these communities, in turn, can respond by altering land management to adapt the social-ecological systems (Pramova et al., 2012; Sudmeier-Rieux et al., 2009). For example, decreasing precipitation and droughts in Sub-Saharan Africa have been reducing maize, banana, and cacao yields (Rippke et al., 2016; Ruf et al., 2015). Depending on the magnitude of the impacts of climate change on agricultural systems (zig-zag arrows in Fig. 2) and their capacities to respond, famers can modify the system in different ways to maintain food security under these changing conditions (dotted arrows in Fig. 2). For example, farmers can replant damaged crops (a coping strategy), build irrigation to reduce future risks of crop failure (incremental adaptation), or fundamentally change the characteristics and properties of the land use through the adoption of agroforestry or reforestation (transformative adaptation).

Coping strategies are strategies that people use to resist the impacts from climate change and maintain the affected social-ecological system in a similar state or business-as-usual functioning (Kates et al., 2012; Perrings, 2006). The use of coping strategies usually does not alter the existing ecological or social characteristics and functions of the system. Coping strategies are often reactive and may be applied when the impacts are not intense, when people do not have the technical or financial capacity to respond in a different way, or when they do not recognize any need for changes. Examples of coping responses include small-holder farmers in Indonesia or Madagascar replanting crops that were damaged due to floods or looking for wild vegetables or other edible forest products to maintain food security following climate-driven extreme weather events (Fedele et al., 2016; Rakotobe et al., 2016).

A second type of response to climate change is incremental adaptation, which includes strategies to continue to provide benefits by accommodating changes. Incremental adaptation strategies drive minor and small-scale adjustments to current social-ecological systems and focus on building their resilience to climate change impacts (Adger and Jordan, 2009; Kates et al., 2012). Incremental adaptation tends to be more anticipatory than coping strategies. For social-ecological systems, examples of incremental adaptations include adjusting agricultural or land management practices, such as building irrigation systems, reducing livestock numbers or cultivated areas, increasing use of fertilizers or pesticides, or using new crop varieties, among others, to adapt the agroecological system to climate change impacts (Ash et al., 2012; Nguyen et al., 2013; Nhemachena and Hassan, 2007).

Transformative adaptation is the third type of potential response to climate change. Transformative adaptation is a strategy that aims to reduce the root causes of vulnerability to climate change in the long-term by shifting systems away from unsustainable or undesirable trajectories (O'Brien, 2012; Olsson et al., 2014). It relates to fundamental systemic changes that create new states and interactions within social-ecological systems (Adger and Jordan, 2009; Feola, 2015; O'Brien, 2012; Wahid et al., 2017). It can be driven directly by radical shifts in either ecosystems or societies in response to observed or expected climate change, or indirectly through an accumulation of incremental adaptation or changes (Adger et al., 2011; Kates et al., 2012). In social-ecological systems, examples of transformative adaptation include the revitalization of rivers and relocation of human activities in flood plains (as opposed to building channels and dikes), the shift from fossil fuels towards clean energy production, or the creation of multi stakeholders' committees for managing water use quotas during scarcity (compared to top-down decisions), among others.

3. Methods

To help understand transformative adaptation in social, ecological, and social-ecological systems, we reviewed literature that described major changes in systems driven by climate change and adaptation responses and explored what transformative adaptation, if any, had occurred. We identified conceptual papers on transformative adaptation by using Web of Science and Google Scholars (through the combination of the following words: "transform* adaptation" AND "climate change" AND "social" OR "ecological" "system"). We searched all papers published by December 2017. We reviewed a total of 80 relevant

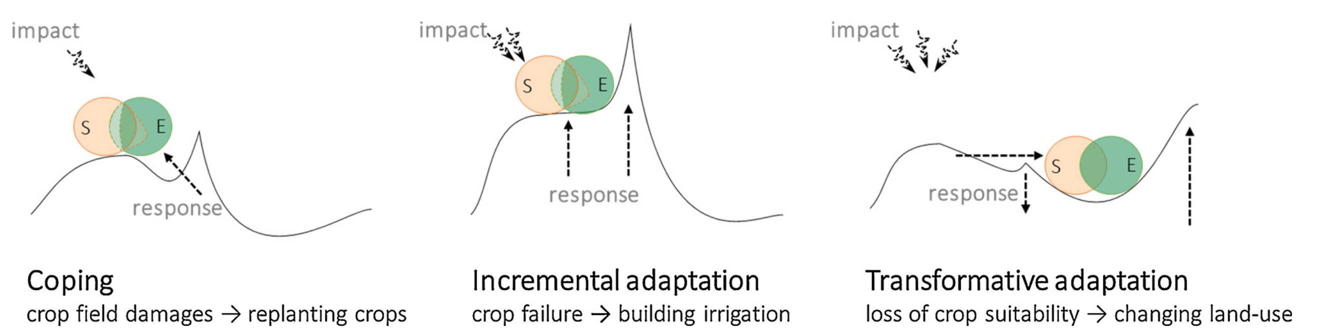

Fig. 2. Three possible ways for a social-ecological system (SES) to respond to the perceived or expected impact of climate change. The climate change impacts (zigzag arrows) drive coping, incremental adaptation, or transformative adaptation responses (dotted arrows) that increasingly alter the original system's properties and function.

publications that included theoretical descriptions of transformative adaptation and compared transformative adaptation with other types of adaptation. We focused on descriptions of transformative adaptation that included comparisons with other types of adaptation, but additional insights could have been gained by specifically analyzing definitions of incremental adaptation. The papers included a mix of social, ecological and interdisciplinary studies that varied in their definition of the term 'transformative adaptation'. This plurality of definitions allowed us to explore different perspectives on the concept and advance the understanding of transformative adaption with an interdisciplinary perspective.

To identify the characteristics of transformative adaptation, we analyzed each publication to understand how they used the term 'transformative adaptation' and to identify the key characteristics of this type of adaptation. In an interactive process we grouped similar elements found in the descriptions of transformative adaptation in each publication. Recurrent elements or parallels in the descriptions of transformative adaptation mentioned across the social, ecological, and social-ecological literature represented the characteristics of transformative adaptation. Subsequently, we assigned the element of the description of transformative adaptation in each paper to the matching characteristic (see Appendix A). We analyzed the frequency of each characteristic across the publications and recorded the type of system in which this adaptation had occurred (i.e. either ecological, social, or social-ecological system).

4. Results

4.1. Characteristics of transformative adaptation

In the reviewed literature, transformative adaptation has been described with specific terminology and different emphasis depending on the social or ecological disciplinary perspective used (see Table 1 and Appendix A). However, there are several parallels across the social and ecological literature. In the literature on social-ecological systems, transformative adaptation was mentioned in relation to 'sustainability issues', 'resilience pathways', and productive system transitions, such as agriculture, forestry, fisheries, and water management (Enfors, 2013; Hatakenaka et al., 2011; Ramankutty and Coomes, 2016). In the literature on ecological systems, transformative adaptation was mentioned in the context of 'regime shifts', 'tipping points', 'ecological transitions', and 'resilience', especially for marine ecosystems (Bennett et al., 2009; Crépin et al., 2013; Keith et al., 2015). In the literature on social systems, transformative adaptation was mentioned in association with the concepts of 'social innovation', 'transitions of socio-technical systems', and political or power shifts, such in energy production, governance institutions, and economic activities (Geels and Schot, 2007; Gillard et al., 2016; Patterson et al., 2017).

We identified six recurring characteristics of transformative adaptation based on the literature review of 80 ecological, social and social-ecological studies (see Table 1 for summary and Appendix A for full analysis). Across the reviewed papers, transformative adaptation was generally characterized as being restructuring, path-shifting, innovative, multiscale, systemwide, and persistent (Fig. 3). Transformative adaptation is 'restructuring' in that it involves major shifts in fundamental properties, functions, or interactions within the social, ecological, or social-ecological system (Fazey et al., 2018; Mapfumo et al., 2017; Matyas and Pelling, 2015). For example, farmers who depend on agriculture for their livelihoods can decide to abandon some fields and start working off-farm in response to decreasing land productivity due to climate change. Transformative adaptation is often 'path-shifting' because it alters the systems' current trajectory by pushing it towards an alternative direction, e.g. from a landscape dominated by oil palm monocultures - to one with mixed trees species- (Dakos et al., 2015; Hahn and Nykvist, 2017; Pelling et al., 2015). It is 'innovative' because it often changes systems to new states that have

Table 1
Six common characteristics of transformative adaptation in ecological, social, and social-ecological systems based on the review of 80 conceptual papers. The percent of references (% ref) refers to the percent of the 80 papers that mentioned this characteristic in their description of transformative adaptation. The footnotes refer to illustrative references that report on these characteristics (complete list of references in Appendix A).

Characteristic	% ref.	Ecological	Social	Social-ecological
Restructuring	90%	substantive re-structure of ecosystem states (species abundance and diversity, ecological functions)[5,6]	fundamental social shift (values, norms, knowledge, power relations, ways of thinking, business processes) [8, 3, 4]	radical alteration of interactions between people and nature (livelihoods, ecosystem services, land uses, environmental values/ knowledge,)[7, 17]
Path-shifting	80%	ecosystem shift toward an alternative "stable" state[1, 6]	shift toward alternative development pathways [20,8]	shift toward different pathways of sustainability, resilience, vulnerability, or equity [16, 13]
Innovative	70%	new species or variety compositions in the ecosystem [6, 2]	social and technical innovation, learning and novel behaviors [7, 11]	re-evaluation and innovation in the relations between people and nature [10, 13]
Multiscale	70%	at multiple trophic levels and spatial scales[1, 12]	across jurisdictional and societal levels[9, 7, 8]	at multiple systems' scales (spatial, governance, sectors) [10, 18]
Systemwide	60%	in large areas of ecosystems or landscapes [6]	widespread in societies and geographies[22]	at large-scale or systemic [10, 16]
Persistent	40%	hard to reverse (without human inputs)[1]	persistent (over several generations)[8]	future-oriented and long-term but not necessarily irreversible [14, 16]

[1]Andersen et al., 2009, [2]Biggs et al., 2010, [3]Colloff et al., 2017a, [4]Pelling et al., 2015, [5]Scheffer, 2012, [6]Crépin et al., 2013, [7]Folke et al., 2010, [8]Geels and Schot, 2007, [9]Holling, 2001, [10]Kates et al., 2012, [11]Klein et al., 2007, [12]Lees et al., 2006, [13]Moore et al., 2014, [14]Moser and Ekstrom, 2010, [15]Mustelin and Handmer, 2013, [16]O'Brien, 2012, [17]Thornton and Comberti, 2013.

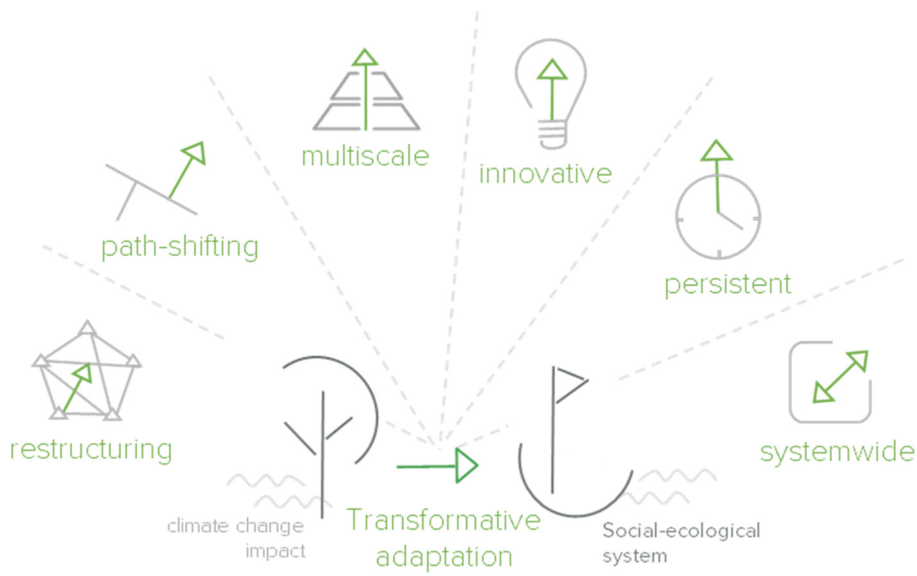

Fig. 3. Six characteristics of transformative adaptation in social-ecological systems. The original social-ecological system (tree) under the impact of climate change (waves) undergoes transformative adaptation shifting toward another state with different properties and functions (boat).

Table 2
An example of transformative adaptation (the conversion of unproductive croplands to agroforestry systems due to reduced rainfall) that illustrates the six characteristics of transformative adaptation.

	Transformative adaptation: the conversion of unproductive cropland to agroforestry systems in response to reduced rainfall		
Characteristics of transformative adaptation	Ecological changes	Social changes	Social-ecological transformative adaptation
Restructuring	Soils with high moisture → soils with low moisture	Little work/time needed for crop productivity → More work/time needed for ensuring crops productivity (watering and fertilizing)	Transformative adaptation changes livelihoods from undiversified to diversified (from rice farmers to farmers with agroforestry and off-farms activities)
Path-shifting	Crop-dominated land → tree-dominated lands	Populated rural villages with rice farming opportunities → migration and less populated villages with fewer rice farming opportunities	Transformative adaptation leads to a shift from drought-sensitive rice monocultures to a more drought-resilient mix of crops and trees
Innovative	More drought sensitive vegetation (crops) → more drought resistant vegetation (trees)	Low farmer awareness of climate change impact on land productivity → higher awareness among farmers	Transformative adaptation reverses a decades-long trend of losses in forest cover in a region
Multiscale	Simple food web in cropland (few trophic levels) → complex food web in a tree-dominated landscape (multiple trophic levels)	Rice produced by local farmers → rice produced by/bought from farmers in other regions	Transformative adaptation impacts people at different scales by affecting water availability for downstream users
Systemwide	Abundant water in a region → widespread scarce water in an entire region	Few villages in a region with low rice productivity → several villages in entire region with low rice productivity	Transformative adaptation modifies rural landscapes across the entire region
Persistent	Forested land often changed to cropland → long-term forested land maintained through natural regeneration	Limited yearly variations in rice harvest and income → lasting reduction of rice harvest and income across seasons and years	Transformative adaptation provides lasting benefits for rural livelihoods

not previously existed in that area thanks to new knowledge, policies, or technologies (Biggs et al., 2010; Feola, 2015; Suding et al., 2004). For example, through learning from the impact of climate change, farmers might convert cropland to agroforestry systems, or city planners replace infrastructure with new green spaces in flood prone areas. Transformative adaptation is 'multi-scale' in that it has impacts across multiple scales (e.g. trophic, spatial, jurisdictional, or sectoral scales) (Biggs et al., 2010; Gillard et al., 2016; Lin and Petersen, 2013). For example, farmers' conversion of croplands to forests can lead to increases in both species richness and erosion control with a positive impact on people downstream. Transformative adaptation is also 'system-wide', i.e. it occurs at large-scale and leads to systemic changes across whole regions, ecosystems, landscapes, or communities (Douxchamps et al., 2017; Gillard et al., 2016; Ostberg et al., 2013). Finally, transformative adaptation is often a 'persistent' shift with long-term impacts, although not necessarily irreversible (Crépin et al., 2013; Feola, 2015; Rippke et al., 2016). For example, farmers may switch to new livelihoods that are expected to provide them with food or income for a long-time frame and may find it difficult to later revert to their previous agroecological system (Table 2).

Table 3
The six characteristics of transformative adaptation highlight opportunities to catalyze transformative adaptation in the design and implementation of responses to climate change.

Characteristic	Opportunity to catalyze transformative adaptation	References
Restructuring	identify leaders and key agents to promote deep social changes that lead to transformative adaptation, as well as identify power dynamics that might prevent its implementation; engage with bridging organizations to facilitate sharing of knowledge that increase awareness on behavioural changes for transformative adaptation;	Folke et al., 2010; Patterson et al., 2017; Múnera and van Kerkhoff, 2019
Path-shifting	re-evaluate current assumptions on dominant values, rules, practices to promote new adaptation options; facilitate multi-loop learning approaches that questions current world visions and open opportunities for alternative adaptation; take advantage of windows of opportunities, such as extreme climate hazards, political reforms, new technologies to re-direct development pathways;	Wise et al., 2014, Colloff et al., 2017b; Olsson et al., 2018, Medema et al., 2014; Westley et al., 2013
Innovative	invest in research and experimentation on new adaptation options, including transformative adaptation; learn through long-term Monitoring & Evaluation and impact evaluation to avoid ineffective adaptation;	Loorbach, 2010; Wyborn et al., 2016, Fazey et al., 2018
Multiscale	create cross-scale partnerships to implement transformative adaptation; engage with multiple levels of governance to spread transformative adaptation; consider entire commodity chains (from producers to consumers);	Holling, 2001, Ekstrom and Moser, 2014; Sayer et al., 2013, Abel et al., 2016; Bennett et al., 2009; Crépin et al., 2013
Systemwide	foster multi stakeholders & cross-sectoral collaborations; apply landscape and participatory approaches; expand progressively successful strategies	O'Neill and Hulme, 2009, Stirling, 2014; Chapin et al., 2010, Sayer et al., 2013
Persistent	institutionalize new practices and regulatory frameworks; secure political and funding support to long-term actions	Mapfumo et al., 2017, Olsson et al., 2018

5. Discussion

5.1. Opportunities for transformative adaptation in responses to climate change

Transformative adaptation has started being described through different disciplinary perspectives, but there are six recurring characteristics that span across social, ecological, and social-ecological studies. Each characteristic can be related to a specific change in a system that is adapting. For instance, the re-structuring characteristic can refer to either the ecological structure of ecosystems (e.g. species diversity), the social structure of communities (e.g. power dynamics), or the structure of social-ecological interactions (e.g. land uses). These similarities suggest that transformative adaptation is likely to alter both social and ecological processes and thus re-define entire systems (Adger et al., 2009; Feola, 2015; O'Brien, 2012). Therefore, transformative adaptation should be approached holistically by integrating multiple disciplinary perspectives (Colloff et al., 2017b; Fazey et al., 2018).

The six characteristics of transformative adaptation identified in the review can help policy makers and implementers to create opportunities to catalyze this type of adaptation (Table 3). Abson et al. (2017) recognized that several changes to social structures or values, goals and world views of actors (i.e. "deep leverage points") are more effective than many other small changes to parameters or system feedbacks (i.e. "shallow leverage points"). The characteristics of transformative adaptation also highlight the high magnitude of changes required in such strategies, which can hinder their implementation. Designing transformative adaptation strategies considering the six characteristics can help identify opportunities to drive major changes in entire systems. Opportunities to facilitate transformative adaptation include identifying key actors that can help spread new practices (e.g. bridging organizations or local leaders) and help re-structuring systems (e.g. Patterson et al., 2017). Another opportunity for catalyzing transformative adaptation is creating safe-spaces to question current dominant values, power, knowledge systems (e.g. learning and re-evaluation workshops) that help shift away from current development pathways (e.g. Múnera and van Kerkhoff, 2019; Wise et al., 2014). In addition, investing in research and Monitoring & Evaluation can help identifying innovative adaptation (e.g. Fazey et al., 2018). Transformative adaptation can also be catalyzed by fostering partnerships and polycentric governance structures (e.g. commodity chains, mixed management committees) that connect multiple spatial and jurisdictional scales (e.g. Abel et al., 2016). Another opportunity is promoting participatory approaches and collaboration among multiple stakeholders, such as researchers, communities, practitioners, and policy makers (e.g. through knowledge brokers or multi-stakeholders' fora) that can help reach consensus for system-wide actions (e.g. Lavorel et al., 2019; Sayer et al., 2013). Moreover, an opportunity for transformative adaptation is in promoting long-term investments (e.g. by institutionalizing processes or increasing commitments duration) that support persistent impact (e.g. Mapfumo et al., 2017).

Managers and policy maker should identify opportunities to consider transformative adaptation early in the selection of an adaptation strategy, e.g. as part of vulnerability or risk assessments. Vulnerability assessments can provide information about the potential of a system to undergo changes related to the six characteristics of transformative adaptation and thus guide the selection of adaptation strategy. Integrated social-ecological assessments of past, current, and future vulnerability can reveal whether certain types of adaptation can be appropriate in the long-term (Colloff et al., 2017b). For example, using climate and land-use scenarios in vulnerability assessments help anticipating potential changes that can influence what type of adaptation is likely to be successful in the long-term (Ash et al., 2012; Lavorel et al., 2019). Similarly, using historical analysis can reveal attempts at incremental adaptation that need to be either scaled-up because they are promising or abandoned because are failing (Dearing et al., 2010; Fedele et al., 2018).

5.2. Navigate climate-driven changes with transformative adaptation

The review of the characteristics and associated social-ecological processes leading to transformative adaptation highlighted the need to strategically consider and plan for this type of adaptation. Policy makers and practitioners should better acknowledge and carefully plan for transformative adaptation as option to respond to climate change impact. Compared to coping or incremental adaptation strategies, transformative adaptation may be a more suitable strategy when the severity of climate change impacts is expected to dramatically and rapidly increase (Pelling et al., 2015; Wise et al., 2014), when current adaptation strategies are reaching their limits (Ash et al., 2012; Dow et al., 2013), or when radical changes in social or ecological systems driven by climate have already happened (Colloff et al., 2016a; Gunderson et al., 2017; Pelling et al., 2015). In these cases, policy makers and practitioners should consider transformative adaptation in projects or plans in order to: i) anticipating changes by planning transformative adaptation, ii) redirecting changes by assisting autonomous transformative adaptation, or iii) recovering from changes by implementing climate-forced transformative adaptation (see following paragraphs).

i. Anticipating changes by planning transformative adaptation. In areas expected to be severely affected by climate change, adaptation projects and plans must consider transformative adaptation to adequately manage the anticipated impacts (Moore et al., 2014; O'Brien, 2012; Ramankutty and Coomes, 2016). Areas expected to be severely impacted by climate change include costal zones, coral reefs and fishing areas around small islands, grasslands in arid regions, wetlands, and forested floodplains, among others (IPCC 2014, IPBES 2018, Keith et al., 2015). In these areas, coping or incremental adaptation should be carefully evaluated and possibly avoided because of the high likelihood of not being effective in the long-term with the risk of just postponing unavoidable change (Colloff et al., 2017b). An example of likely unsuccessful strategy is expanding a protected area as an incremental adaptation to better preserve a declining threatened bird population, which also provides eco-tourism opportunities, where the suitability of habitat for the birds is declining due to drier climate. In this case, planning transformative adaptation is likely needed. A possible transformative adaptation could be re-thinking the management of protected areas to promote the transitions to an alternative ecosystem state that minimize species loss, while create new habitat in regions expected to become suitable for the birds as the climate changes. Another example is expanding seawalls to protect coastal communities from floods and storms (as an incremental adaptation) in places expected to be submerged due to sea level rise caused by climate change. In this example, plans that include transformative adaptation, such as relocation of people or restoration of forests in different areas would have been more likely to succeed than coping strategies and incremental adaptation.

ii. Redirecting changes by assisting autonomous transformative adaptation. Where the impacts of climate change are already threatening the well-being of ecosystems or people that are struggling to adapt, assisted transformative adaptation can guide ongoing shifts in social or ecological systems towards less vulnerable states. People and ecosystems may reach their adaptation limits or have insufficient capacities to adapt, requiring transformative adaptation to further reduce ongoing impact of climate change (Ash et al., 2012; Feola, 2015; Few et al., 2017; Preston et al., 2013). Example of such cases are remote communities highly dependent on natural resources, settlements on landslide-prone slopes, farmers in marginal rural agricultural lands, vegetation in permafrost and forests in mountains due to rising temperature, and coastal or low-land communities under flood risk (IPCC 2014, IPBES 2018). In these cases, relying on coping responses or incremental adaptation may not be enough or result in maladaptation. The use of coping strategies or incremental adaptation can compromise future options because they exacerbate environmental degradation and let the next generations bear the costs (Abel et al., 2016). For example, providing support to coffee farmers with conventional agricultural inputs (pesticides, seeds, or farming techniques) in areas that are already facing climate-driven declines in production is likely to be an unsuccessful adaptation strategy (Verburg et al., 2019). Instead, the use of climate-driven transformative adaptation strategies such as the support for alternative land uses (agroforestry or new crops that would not require the expansion of agricultural land) may be more appropriate. Such strategies could help shift the coffee systems toward a more sustainable alternative pathway (Colloff et al., 2017a; Fazey et al., 2018; O'Brien and Wolf, 2010).

iii. Recovering from changes by implementing climate-forced transformative adaptation. In places where radical changes in either ecological or social systems have already happened or are unavoidable due to climate change, transformative adaptation could be the only viable solution to shift the affected systems towards a more desirable new state, which can continue to support ecosystem and/or people well-being. In these severely affected places, recovering viable ecological or social conditions from the impact of climate change will likely require transformative adaptation (Gunderson et al., 2017; O'Brien, 2012; Suding et al., 2004). Examples of places under severe impact of climate change are submerged coastal areas, degraded ecosystems or agricultural land, dry grasslands under desertification or alien species encroachment, as well as eutrophic or dried out lakes and rivers (IPCC, 2014, Brockhaus et al., 2013). Because the recovery to the previous conditions may not fully possible (Suding et al., 2004), a shift toward alternative desired states should be initiated. In these cases, transformative adaptation can build on the new ecosystem states and services to help people and species to adapt in new ways (Colloff et al., 2016b; Lavorel et al., 2015) and take advantage of the new opportunities (Park et al., 2012; Rickards and Howden, 2012). Examples of climate-forced transformative adaptation include land-use changes in large areas where people move away from food insecurity situations caused by increasing dry conditions due to climate change. This has been happening for the regreening of the Sahel with multipurpose trees (Sendzimir et al., 2011), the establishment of domestic forests mixing crops and trees in unproductive agricultural land in Southeast Asia (Michon et al., 2007; van Noordwijk et al., 2014), and the restoration of grassland to improve water availability by re-introducing native vegetation and removing alien species in USA or South Africa (Keith et al., 2013; Suding et al., 2004).

6. Conclusion

Our review provides an interdisciplinary overview of what transformative adaptation involves, how it is characterized, and when it may be an appropriate or necessary response to climate change. Response strategies to climate change can be loosely categorized in coping, incremental adaptation, or transformative adaptation that require increasing human inputs and system re-organization. Transformative adaptation, which fundamentally changes systems and addresses root causes of vulnerability, usually has six characteristics: it is restructuring, innovative, path-shifting, multiscale, systemwide, and persistent. Transformative adaptation may be an appropriate response to climate change when the severity of climate change impacts is expected to considerably increase, when current adaptations are reaching limits, or when radical climate-driven changes have already happened. In these cases, transformative adaptation may be planned, assisted, or forced, respectively. With a better understanding of what transformative adaptation entails and when it should be implemented, policy makers and practitioners can be better prepared to consider transformative adaptation as an option within the portfolio of adaptation strategies.

A greater consideration of transformative adaptation in responses to climate change can help reach an impact that is commensurate to the extent of the issue, as well as avoid costs and delays due to failures of coping or incremental adaptation. Although still hard to design and implement, transformative adaptation may be the only suitable response to climate change and other complex global environmental issues in certain cases. However, in transformative adaption is particularly important to evaluate weather this type of adaptation leads to desired development outcomes by different actors with limited capacity or agency. Effective responses might not come from business-as-usual perspectives and approaches that contributed to build these issues. Therefore, transformative adaptation is key for managing severe climate change impacts in social-ecological systems and decrease vulnerabilities in the long-term. Transformative adaptation can help us shift from accommodating change to embracing them and deliberately implementing more sustainable strategies to respond to climate change.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at https://doi.org/10.1016/j.envsci.2019.07.001.

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