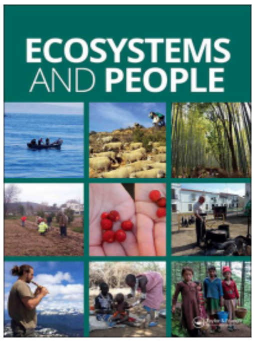

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RESEARCH

Nature's contribution to adaptation: insights from examples of the transformation of social-ecological systems

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ABSTRACT

Transformation of social-ecological systems due to climate change requires, transformative adaptation responses. We propose the concept of nature's contribution to adaptation (NCA; previously called adaptation services), to reveal properties of ecosystems that provide options for future livelihoods and adaptation to transformative change. Knowledge about the capacity of ecosystems to supply NCA can inform decisions by revealing options for adaptation. We analysed eight historical and contemporary case studies of transformative adaptation and found that the five cases with medium-high degree of adaptation and use of NCA showed evidence of participative learning and co-production of adaptation options, low values contestation, low power imbalances and well-developed governance arrangements. These variables indicated that communities engaged in adaptation had ownership and agency to change how they thought and acted to implement transformative adaptation. We found the use of NCAs enabled transformative adaptation by helping people overcome current decision constraints imposed by societal values, institutional rules, or knowledge deficits to create novel options and re-frame decision contexts. The NCA concept can be applied to (1) help resolve uncertainties about nature's contributions to people under environmental change; (2) reveal ecosystem properties of value for adaptation, but which are marginalised in current, dominant knowledge frameworks and decision-making; (3) act as a 'boundary object' for participative learning and co-production of adaptation options. Thus, the NCA concept represents a pragmatic, optimistic approach for societal adaptation to ecosystem transformation, countering feelings of despair that accompany the acceptance of irreversible, unavoidable loss of current ecosystem states and associated nature's contributions to people.

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1. Introduction

Rapid transformation of social-ecological systems due to climate change and other anthropogenic drivers is happening with increasing rates and magnitude (Steffen et al. 2018; Díaz et al. 2019). Such transformation involves biophysical changes to biota and ecological processes as well as adaptation responses by society to those changes. As ecosystems transform, so do the quality and quantity of ecosystem services on which humankind depends for livelihoods and wellbeing, as well as human-nature relations and thus people's perceptions of nature's contributions, and the ability to co-produce them. The impact of climate change on most types of ecosystem services is predominantly negative (Runting et al. 2017). Under ecosystem transformation, currently valued ecosystem services are replaced by new ones specific to transformed ecosystems, hence the need for transformative adaptation.

We define transformative adaptation as systemic changes to societal paradigms, visions, goals, rules and knowledge in response to actual or anticipated changes in driver variables that fundamentally change the properties of a social-ecological system (Díaz et al. 2019). In 2017 we published a framework to operationalise transformative adaptation that integrates the NCA concept (then called the adaptation services concept), the values-rules-knowledge perspective (cf. Section 5 below) and the adaptation pathways approach (Colloff et al. 2017).

At the scale of a landscape or region, climate change may have differential effects, with some ecosystems persisting (though with some changes in biophysical structure and processes) and even expanding, and others transforming (Chaplin-Kramer et al. 2019). Ecosystem transformation induced by climate change can be extensive, of relatively rapid onset (two to three decades), and is influenced by other drivers of global change such as human pressures on natural resources

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Supplemental data for this article can be accessed here.

Figure 1. Ecosystem transformations (see case studies in Table 1): (a) Lake faguibine, mali, with aquatic grasses and supporting fishing, lakeshore grazing and cropping and (b) after climatic drought and irrigation water diversions: dry lake bed with open forest of introduced mesquite *Prosopis juliflora*; (c) Hay plain, southern riverina, Australia, weeping myall *Acacia pendula* woodland and (d) chenopod shrubland after land clearing, to dryland salinity and repeated, severe droughts; (e) Arctic ice forms an extension of the land for transport and hunting and (f) water and land free of ice for extended periods due to global warming. Image credits: (a) Amadui kieta/IFAD; (b) Houria djoudi; (c, d) Murray fagg, Australian national botanic gardens; (e, f) Rorry macKinnon.

(Figure 1; Ostberg et al. 2015). For example, Lake Faguibine in Mali (ca. 600 km^2) supported diverse livelihoods based on fishing, cropping and grazing, but has dried almost permanently since the 1970 s and '80 s due to climatic drought and irrigation water diversions and been replaced by open forest (Djoudi et al. 2013; Brockhaus et al. 2013). In the Canadian Arctic, where ice formed an extension of the land for transport and hunting in the 1990 s, large areas are now ice-free for extended periods (Fawcett et al. 2018).

We may be approaching planetary thresholds for driver variables (Steffen et al. 2018), but discussions tend to focus on how to prevent transformation of social-ecological systems to undesirable states rather than what to do once thresholds are crossed. Consequently, adaptation has been mostly incremental rather than transformative (Wise et al. 2014). In a typology of climate change impacts and responses (Figure 2), assumptions of marginal change generate incremental options or favour perspectives based on resisting change in order to maintain the *status quo*. But the prospect of a + 2°C warmer world means such decision contexts become increasingly maladaptive as ecosystems undergo transformation (Stafford Smith et al. 2011), requiring transformative responses. The effects of ecosystem transformation may be seriously detrimental to human wellbeing, limiting options for the future. Under such circumstances, communities are faced with the stark choice of moving away or staying and trying to adapt and eke out a livelihood.

The ecosystem services concept was originally intended to highlight the consequences of environmental damage caused by unconstrained economic development. However, its dominant interpretation, based on an economic stock-and-flow framing with assumptions of marginal environmental change, is at odds with transformative changes that are occurring under climate change (Colloff et al. 2016a) and conceals the complexity of societal responses to these changes, which may constrain future options (Norgaard 2010). The ecosystem services concept has been a powerful metaphor of how humans depend on nature, but its application by policymakers and managers has tended to take a narrow instrumental framing of human-nature interactions and privileged a Western scientific-rationalist perspective that can exclude other systems of values, rules and knowledge (Muradian and Pascual

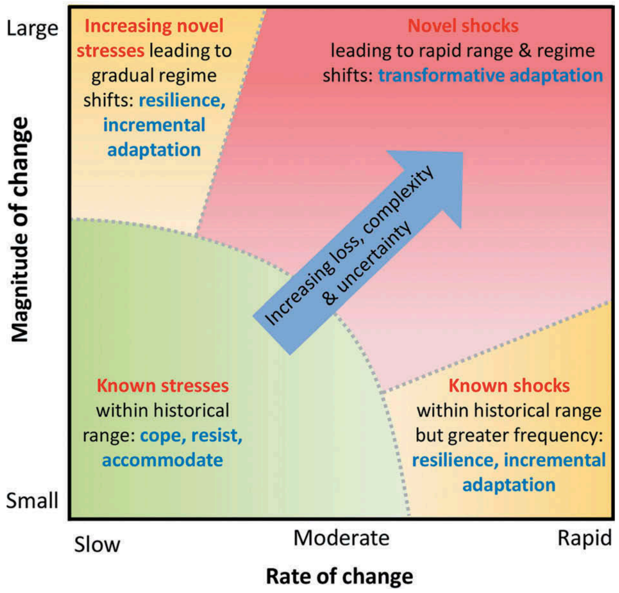

Figure 2. A typology of environmental change and adaptation responses based on rate and magnitude of change. Shocks are short-term extreme events of rapid onset and duration (e.g. bushfires), whereas stresses are longer-term continuous events (e.g. reduced rainfall). Shocks co-occur with stresses, but their risk and frequency increase with greater rate and magnitude of change.

2018; Ellis et al. 2019). In response to these perceived limitations, the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) proposed a framing based on 'nature's contributions to people' (Pascual et al. 2017; Díaz et al. 2018), which includes a plurality of human-nature relationships, allowing expression of different value and knowledge systems and ontological and epistemological framings, not found within the ecosystem services concept (Kadykalo et al. 2019). Such plurality is needed to integrate ecosystem transformation into adaptation thinking and action while engaging a diversity of actors with differing world views.

Under climate change, there is an important choice to be made. Researchers can refine the ecosystem services concept in the hope decision makers will embrace new ideas within the dominant neoliberal policy context, aligned with commodification of nature and economic rationalist decision-making (Pascual et al. 2017; Muradian and Pascual 2020). Alternatively, people can work with new and evolving ideas and framings that can enable inclusive understandings of human-nature relationships. We consider the latter is more useful and is the basis for this paper. Our rationale is centred on the principle that institutions (and their concepts) that were developed during times of stasis, or based on assumptions of marginal change, are likely to prove maladaptive under conditions of transformative change (Dryzek and Pickering 2019).

Accordingly, we frame the capacity of ecosystems under climate change to enable future human needs under the IPBES framework of nature's contributions to people (NCP) (Díaz et al. 2015, 2018; Pascual et al. 2017). We introduce the concept of *Nature's Contribution to Adaptation* (NCA) as a means to operationalise transformative adaptation, emphasising the need to create options for society to transform under ecosystem transformation. More specifically, the NCA concept is contained within the IPBES Conceptual Framework as NCP 18 (Díaz et al. 2018, supplementary material therein), which includes the maintenance of current and future options, i.e. nature's capacity to support ecosystem persistence and resilience and the ability of ecosystems to transform to novel states with new NCPs.

How can the NCA concept be applied by people engaged in adaptation activities, particularly where ecosystems have already transformed or are in the process of doing so, and livelihoods are under threat or no longer viable? To address this question we use historical and contemporary case studies of ecosystem transformation, examine how NCP have changed, the direct impacts of these changes on livelihoods and what people and communities have done to adapt to those changes. Our objectives in this paper are as follows: 1) to examine whether NCA had been used in case studies of transformative adaptation to ecosystem transformation; 2) to undertake a qualitative textual analysis of the major adaptation outcomes of the case studies and how these outcomes were achieved, or were being achieved, and 3) to clarify the processes used by people engaged in the transformative adaptation of their social-ecological systems, particularly in relation to re-framing and changing practices and livelihoods, participative learning and co-production of knowledge used in adaptation, as well as co-producing shared visions for the future and developing new governance arrangements for adaptation.

Below, we define the NCA concept and propose a typology of five NCA types. Next, we examine how the NCA concept can be applied to foster adaptation based on what we have learned from an analysis of the characteristics of the case studies. Then, we consider how the NCA concept can be made operational by changing the decision context for adaptation. Finally, we discuss the main implications of the NCA concept for environmental management and governance in the context of the impacts of climate change on ecosystems.

2. A typology of nature's contributions to adaptation

The idea of NCA was first conceived of as *adaptation services*: NCP that help protect society against the negative effects of climate change (Jones et al. 2012; Williams et al. 2012) and provide options as ecosystems undergo transformation (Williams et al. 2012). Lavorel et al. (2015) gave a broader definition of adaptation services as, 'the benefits to people from increased ability to respond to change, provided by the properties of ecosystems to moderate and adapt to climate change and variability.' This definition is consistent with the ecosystem services concept but the NCA concept emphasises developing options for adaptation, their evaluation and implementation, and involves more inclusive treatment of people's held values, relationships with nature, world views and knowledge than hitherto. Furthermore, the NCA concept goes further than the ecosystem services concept by including ecological mechanisms that support ecosystem persistence or transformation and how these outcomes can be managed for by society (Colloff et al. 2016a, Figure 5 therein). In an example of NCA thinking, Pramova et al. (2012) identified how forest-based NCAs support social adaptation to climate change and new governance arrangements by protecting and buffering coasts against more frequent and severe storms. Fedele et al. ((2017), (2018)) found communities in Indonesia responded to climate change-related rainfall variability and drought via adaptation strategies involving innovative uses of forest products and forming community associations to manage these.

Based on our previous research (Colloff et al. 2016a, 2016b; Lavorel et al. 2019), we identify five types of NCA (Figure 3b). When ecosystems persist under climate change there are: (1) NCAs in the form of ecological mechanisms that support ecosystem persistence and supply of current NCAs; for example, high response diversity of floodplain trees against extremes of flood and drought ensuring persistence of forests and livelihoods under a drying climate (Colloff et al. 2016a); and (2) regulating NCAs that are currently under-used or latent but could provide future benefits, such as coastal protection by mangroves or littoral forest from storm surges (Ahammad et al. 2013, Lavorel et al. 2015), or the insurance value of multiple benefits from high biodiversity (Baumgärtner 2007).

When ecosystems are transformed under climate change there are: (3) NCAs in the form of ecological mechanisms that support ecosystem transformation; for example, development of a mosaic of fire-tolerant vegetation communities in forest landscapes caused by altered fire regimes (Colloff et al. 2016b; Doherty et al. 2017); (4) novel NCAs from transformed ecosystems, such as fodder from grassland that transformed from forest (Colloff et al. 2016b); and (5) current NCAs for which supply is enhanced by ecosystem transformation, such as micro-climate regulation from more shade due to increased tree colonisation (Lavorel et al. 2019, cf. Table 1 for examples).

3. How are NCAs used? Evidence from eight case studies

3.1 Methodological approach

We identified eight case studies for analysis. Selection criteria were: 1) ecosystem transformation had occurred or was occurring (Figure 1, 3a); 2) ecosystem transformation resulted in transformative adaptation responses by the people directly affected; 3) use of any of the five types of NCAs could be identified as part of the transformative adaptation process; 4) examples of the use of NCAs included a range of different adaptation approaches and associated outcomes; 5) examples were drawn from a diversity of social, cultural, economic and environmental contexts; 6) case studies had been worked on by one or more of the authors (#1-3, 7, 8) or were well-documented (#4-6). Use of NCA was identified, mostly in retrospect, as part of transformative adaptation responses, mainly for new livelihoods when previous ones were no longer viable or in decline during and after ecosystem transformation (Table 1). In our retrospective identification of NCAs, it is important to note that the case studies (except #8) pre-dated both the NCA and adaptation services concepts.

Case studies were from the northern and southern hemisphere, temperate and tropical zones, coastal, arid inland and mountain regions (Table 1). Ecosystem transformations were: drought and water diversions leading to a drying lake and transformation from lake bed to open forest (#1); tree-clearing, increased rainfall variability and drought leading to dryland salinity and transformation from floodplain woodland to chenopod shrubland (#2); increased rainfall variability and drought leading to transformed land use from cropping systems to permaculture and forestry (#3); sea level rise and storm surges leading to salinity and large-scale erosion of coastal river deltas (#4); coastal fishery collapse caused by overharvesting of a keystone species (#5); increased temperatures reducing arctic snowfall and ice cover leading to open water and snow-free land for extended periods (#6); sea level rise leading to flooding and salinisation of soil and water of a coral atoll (#7) and increased temperatures and more variable precipitation causing glacier melt, droughts, heatwaves, shifts in alpine plant communities, landslides and erosion (#8).

We analysed the characteristics of each case study and the use of NCAs by local participants engaged in adaptation, as per the typology described above, based on textual analysis of the available literature on each case study, supplemented by our knowledge of and experience with the case studies (Table 2, Table S1; Supplementary Material S3). We summarised each case study according to: (1) the characteristics of ecosystem transformation; (2) the adaptation framework

Table 1. Examples of case studies where anthropogenic changes in ecosystem drivers have led to ecosystem transformation and transformative adaptation responses in which use of nature's contributions to adaptation (NCA) could be identified retrospectively (numbered in column 4 as per Figure 4). Case studies (except #8) pre-date the NCA concept. Examples are not restricted solely to effects of climate change, but include ecosystem transformation caused by other anthropogenic drivers (#2, 5), though for #2, extended climatic drought and rainfall variability are defining features of the social-ecological system (see supplementary material S3 for case study details).

#	Ecosystem transformation	Changes to livelihoods	Use of NCA	References
1	Declining river inflows due to climatic drought and irrigation water use caused drying of **Lake Faguibine**, Mali, and transformation of the lake bed to mesquite and acacia forest (Figure 1a,b)	Fishing, lakeshore cropping and floodplain grazing ceased	Charcoal and other products from new lake bed forests; shifts from sedentary to transhumant grazing (3,5)	Djoudi et al. 2013; Brockhaus et al. 2013
2	Land clearing caused dryland salinity & combined with rainfall variability & drought resulting in replacement of floodplain woodland with chenopod shrubland, **Southern Riverina**, Murray-Darling Basin, Australia (Figure 1c,d)	Existing grazing & cropping systems became non-viable; land was abandoned or barely used	Development of new drought-resistant grazing systems for saltbush lamb and wool production (2,3,5)	Wagg et al. 2007; Pearce et al. 2010; Colloff et al. 2016a
3	Increased variability of rainfall leading to soil water deficits during rice growing season, Central **Java & Kalimantan**, Indonesia	Agricultural production system based on dryland rice production on terraces increasingly unsustainable	Replacement of dryland rice system with agroforestry; harvesting of teak & rubber; greater use of existing forests; improved water quality, reduced erosion (1,2,3,5)	Fedele et al. 2017; 2018
4	Sea level rise, extreme weather & storm surges in the **Ganges-Brahmaputra-Meghna Delta** of Bangladesh have caused saline incursions of surface and groundwater and large-scale erosion	Cropping & livestock production declining; farming communities displaced	Mangrove restoration; new ecosystem-based livelihoods based on permaculture (1,3,5)	Rawlani and Sovacool 2011; Ahammad et al. 2013
5	Transformation of sub-littoral ecosystems due to over-harvesting of keystone shellfish species; collapse in fisheries resource stocks, **Coastal Chile**	Commercial harvesting of Chilean abalone ceased until stocks recovered	NCA of ecosystem recovery and persistence, supported by new law and fisheries governance rules (1,2,5)	Gelcich et al. 2010; 2017
6	Rise in surface temperatures causing ice to thaw in the **Canadian Arctic**, creating open water and snow-free land for extended periods of the year (Figure 1e,f)	Hunting large mammals for food and skins across open sea ice is in decline	Revival and re-invention of traditional arts & crafts; hunting adapted to open water; fishing & tourism (2,3,5)	Pearce et al. 2015 Fawcett et al. 2018
7	Sea level rise causing loss of land, flooding and salinisation of soil and water supply, **Ontong Java Atoll**, Solomon Islands	Decline in fishing and harvesting of bêche-de-mer. Migration to other islands has commenced	Adaptation to new livelihoods (e.g. permaculture) and use of novel NCA on other islands (3,5)	Bonie 2012; Marita and Manuari 2014; Bayliss-Smith et al. 2010
8	Higher temperatures causing reduced snowfall, shorter snow season, glacier melt, shifts in plant communities, drought, landslides, erosion, heatwaves, upper Romanche Valley, **French Alps**	Reduction in winter tourism activities; fodder production affected by increased climate variability & drought	NCA of drought-resistant fodder production; diversified summer tourism; new agricultural production systems (2,3,4,5)	Lavorel *et al.* (2919)

and strategies applied; (3) types of NCAs realised in adaptation; (4) characteristics of participative learning and knowledge co-production; (5) governance issue and arrangements; (6) power dynamics among participants and stakeholders and (7) interactions of held human values (V), societal rules (R) and scientific, experiential and local knowledge (K) that constrain or enable adaptation decision-making (cf. Section 5 below for more detail), by identifying pairwise interactions (VR, VK, RK), as described previously (Colloff et al. 2016b; Prober et al. 2017).

From the textual analysis, we identified four variables each for adaptation outcomes and for participative learning and knowledge co-production. Adaptation variables were: (1) degree of adaptation achieved, relative to the other case studies and/or stated objectives in the case study documentation (including shared visions for adaptation outcomes); (2) number and types of NCAs used; (3) whether VRK interactions enabled adaptation and use of NCAs; (4) adaptivity: the extent to which adaptation achieved is likely to sustain livelihoods and wellbeing under a changing climate into the future. Variables for knowledge co-production were: (5) whether means were developed and put in place for inclusive participation and reflexive learning; (6) whether a diversity of held values was recognised and processes existed to deliberate and negotiate contested values to develop a shared vision for the potential adaptation outcomes; (7) whether power imbalances between groups of participants or between decision-making bodies were explicitly recognised and attempts made to minimise these and (8) whether there were governance structures and processes in place to facilitate co-ordination, co-operation and communication among the different participants.

Each of the variables was ranked on a three-point interval scale (1–3 for low-medium-high), giving a maximum total score of 12 for each set of four variables (Table S2). Ranking was done initially by the lead author and then discussed and modified by co-authors and colleagues with experience of particular case studies. Criteria for ranking were as follows: for adaptation variables, 'low' (=1) indicated implementation of coping

Table 2. Characteristics that have contributed to realising nature's contributions to adaptation in the eight case studies of transformative adaptation. See supplementary material S3 for case study details.

#	Case study	Area of case study (km^2)	Approximate population involved	Period of ecosystem transformation	Adaptation framework	Participative learning and knowledge co-production	Governance issues and arrangements	Degree of adaptation achieved
1	Lake Faguibine, Mali	1,000[a]	1,700 [c]	1970-1980	Planned bottom-up, livelihood diversification	**Low**: via local associations & informal networks; low ownership of options & ideas	Local associations attempted to develop rules on resource use & tenure	**Medium**: some transformative adaptation as well as coping strategies
2	Southern Riverina, Australia	20,000	5,000[d]	1860-1900	Transformed production system via research & knowledge transfer: top-down & bottom-up	**High**: learning by doing via trial systems run by graziers; co-ordinated knowledge exchange and learning	Grazier networks supported by national-scale R&D investment & co-ordination	**Medium**: production system transformed and highly adaptive, livelihoods remain basically the same
3	Central Java & Kalimantan, Indonesia	500	8,000	1994-present	Planned bottom-up livelihood diversification by land use change	**Medium**: learning by doing: strong systems focus & local ownership	Decision making on land use change made at village scale and by local associations	**High**: production systems and land use transformed, livelihoods diversified
4	Ganges-Brahmaputra-Meghna Delta, Bangladesh	1,000	12,200	1980-present	Top-down implementation of adaptation schemes via national program: mix of 'hard' and 'soft' infrastructure	**Medium**: locals engaged in constructing systems and received training; medium ownership	Steering committees, local & national government engaged but not always linked to community organisations	**Medium**: coastal protection and livelihoods improved but may still be vulnerable to climate change
5	Coastal Chile	10,000	32,000	1975-1988	National-scale transformation of coastal fisheries governance: top-down & bottom-up	**High**: co-ordinated focus on influencing political processes and decision-makers	Comprehensive, inclusive, integrated across scales, backed by law, based on property rights	**High**: fishers empowered, governance transformed, resource stock sustainable
6	Nunavut, Canadian Arctic	1.8 mn	36,000	1980-present	Bottom-up adaptation strongly grounded in local traditional knowledge, customs, values and decision-making process	**Medium**: community-based adaptation builds on a history of community participative research and action	Local community and kin groups, co-operatives; limited engagement of regional and national agencies	**Medium**: though options are limited, new livelihoods have emerged and traditional ones adapted
7	Ontong Java Atoll, Solomon Islands	1,400[b]	3,000	1967-present[e]	Adaptation to achieve food security: some bottom-up, mostly top-down,. Relocation likely to be necessary but uncertain	**Low**: some engagement in permaculture; recent engagement in adaptation pathways planning	Local decision-making hierarchical via chief and council system, disconnected from regional & national governments	**Low**: limited options for adaptation; major constraints due to isolation
8	Pays de la Meije, France	45	1,200	1980-present	Bottom-up adaptation to achieve a vision for the future under climate change, based on adaptation pathways and services	**Medium**: researchers partnered with community actors to develop vision for region and adaptation pathways	Local focus groups linked with municipal government, national park authority, farmer collectives & extension services	**Low**: planning & implementation still in progress

[a]Area of lake bed is 590 km^2; the rest is former lakeshore and hinterland. [b]Includes land and sea area of entire atoll; total land area is 12 km^2. [c]Based on a mean population density of 1.7 per km^2 in the Goundham District (Djoudi et al. 2013). [d]Based on estimated population of graziers plus population dependent on grazing for income. [e]1967 was the year of Cyclone Annie, from which Ontong Javanese believe the soils and groundwater have never properly recovered.

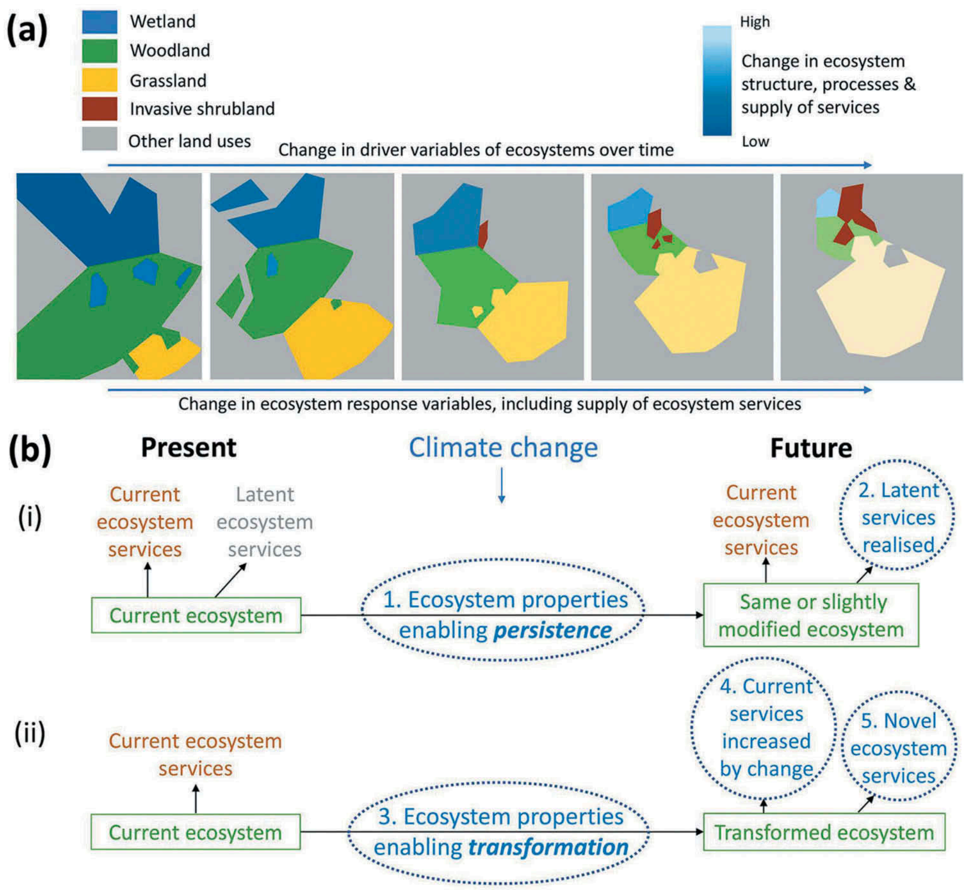

Figure 3. Ecosystem services change as ecosystems transform under climate change. (a) A conceptual time sequence shows transformative effects, including ecosystem fragmentation, invasive species and encroachment of managed land uses on natural ecosystems within a mixed-use landscape. (b) Typology of nature's contributions to adaptation (NCA; numbered). Ecosystems that persist provide ecosystem services currently used and valued (e.g. from woodlands in 3a), also latent services, not currently used but which may be important for adaptation (e.g. from expanded area of grassland in 3a); (ii) ecosystems that transform provide novel NCA (e.g. from invasive shrubland in 3a), plus NCA in the form of current ecosystem services which are enhanced by ecosystem transformation (e.g. from grassland or shrubland in 3a).

strategies with some transformative adaptation, low diversity of types of NCAs, VRK interactions that mostly constrained options (e.g. were limited by restrictive rules and lack of systems knowledge), and high uncertainty whether actions would be adaptive to future climate change; 'medium' (=2) indicated implementation of some transformative adaptation involving fundamental changes to production systems and livelihoods based on participants changing their paradigms, visions and objectives, moderate numbers and diversity of NCAs, VRK interactions both enabling and constraining of options, and a moderate likelihood that actions would be adaptive to future climate change; 'high' (=3) indicated transformative adaptation with fundamental changes in human-nature interactions (e.g. a shift from exploitation to stewardship; Muradian and Pascual 2018), high numbers and diversity of NCAs used, VRK interactions that mostly enabled adaptation options and a high likelihood of actions being strongly adaptive to future climate change.

For participative learning and co-production variables, 'low'(=1) indicated the existence of informal arrangements but no deliberate organisation, low unity of purpose, large power inequalities among stakeholders and lack of co-ordinating governance; 'medium' (=2) indicated some use of participative processes and co-ordination, typically in partnership with NGOs, researchers or government agencies and with indications of systems learning, as well as some degree of unity of purpose, plus some efforts to re-balance unequal power relations; 'high'(=3) indicated a relatively strong focus on learning-by-doing, reflexive systems learning and co-ordinated knowledge exchange linked to broader adaptation programmes and strong community ownership of ideas and objectives, a clear shared vision for the future and relatively high recognition and minimisation of power imbalances.

We then used a composite score of participative learning plus co-production of adaptation options as the independent variable and the composite score of adaptation and use of NCA, achieved to date and in progress, as the dependent variable, using linear regression to examine the relationship.

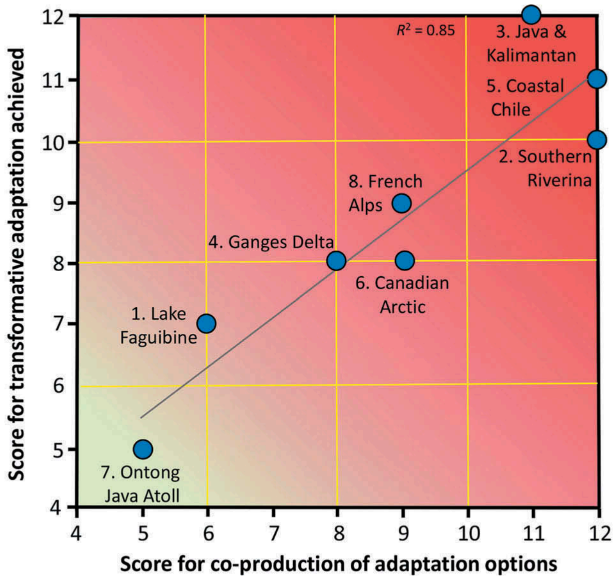

Figure 4. Relationship between composite scores for co-production of adaptation options and composite scores for adaptation achieved and in progress from eight case studies, with line of best fit (cf. text and Table S2 for details of scores and variables).

3.2 Findings from the case studies

We found evidence for the use of NCAs in all case studies. NCAs included examples of all five types shown in Figure 3b. A common assumption is that under climate change there will be fewer NCP available, especially material NCP (Dunford et al. 2015; Runting et al. 2017). However, in all case studies, we found the number of NCAs used or available for new livelihoods was equal to or greater than the number of provisioning services prior to ecosystem transformation (Table S2, Supplementary Material S3).

There was a statistically significant positive correlation between scores for transformative adaptation and participative learning and knowledge co-production (F = 33.3; 1,6 df; p = 0.0012; Figure 4). Case studies that had effective, co-ordinated partnerships between communities, NGOs and government agencies were associated with a medium-to-high degree of adaptation and use of NCAs, though one case study (#3) scored high for adaptation and was based on community-driven knowledge co-production. The two case studies that scored lowest for adaptation outcomes (# 1 and 7) lacked a shared vision for the future, processes and partnerships for participative learning and co-production, governance arrangements to co-ordinate adaptation and a lack of processes to address power imbalances. These variables scored medium-high for the other case studies.

The relative positions of case studies in Figure 4 may change over time as adaptation activities develop: implementation for #7 and #8 are in progress; others may move into new phases with increasing changes to social-ecological systems. Despite our analysis being based on only eight case studies, this number has proved sufficient to clarify the main elements that need to be considered in assessing transformative adaptation to ecosystem change and the application of the NCA concept.

In summary, our analysis indicates that participative learning and knowledge co-production are strongly associated with successful transformative adaptation outcomes and the realised or potential use of NCAs. Realising the use of NCAs for adaptation involved a strong focus on changing held values (#1, 5, 7) and societal rules and norms (#2, 3, 5) using the local and experiential knowledge base (#1, 2, 4, 7, 8) and creating novel production systems through learning by doing (# 2–4). Once revived, traditional knowledge and decision-making systems were important factors (#3, 6 and 8). The common feature of case studies with a medium-to-high degree of adaptation achieved was that the processes outlined above empowered communities and gave them agency by providing options, opportunities for innovation and changing the ways people conceptualised and acted on adaptation to ecosystem transformation. Our findings highlight the importance of participative learning and knowledge co-production of across different knowledge systems and transdisciplinary approaches as a means of achieving change through action and practice (Collins and Ison 2009; West et al. 2019).

In the following sections, we use examples from the case studies to illustrate how the NCA concept can contribute to adaptation science and practice; how the use of NCA can be enabled by changing the decision context for adaptation and the implications of the NCA concept for environmental management and governance.

4. Contributions of the NCA concept to adaptation science and practice

4.1 Revealing the importance of ecosystem properties for adaptation

The analysis of the case studies reveals the importance of ecosystem properties and the use of NCAs for adaptation to climate change, a central tenet of ecosystem-based adaptation (EbA; Jones et al. 2012; Pramova et al. 2012). Use of NCAs occurred in the case studies when participants identified new or previously unrecognised benefits and options from ecosystems that allowed modification of existing livelihoods through substitution of natural resources or development of new livelihoods. For example, in Lake Faguibine, *Prosopis* forests provided a new source of fodder from foliage, previously provided by lakeshore grasses, as well as new livelihoods from charcoal production (case study #1). In the Riverina, chenopod shrubland provided a fodder substitute for grassy myall woodland (#2). In the French Alps, *Patzkea paniculata* grasslands were previously considered undesirable for grazing but are proving to be a valuable drought-resistant fodder source (#8). On Ontong Java Atoll, where adaptation options are relatively few, new NCAs have begun to be realised via construction of novel permaculture systems to improve food security, using local materials such as coconut fibre and other plant residues to create organic substrates in which to grow crops (#7).

4.2 Creating options

Options are especially important during times of increasing variability and high uncertainty when costs and benefits of alternative actions are unclear (Mezey and Conrad 2010) and may include diversifying livelihoods by using a range of NCPs or NCAs (Baumgärtner 2007). Options provide a means for mitigating future risks by focussing on what ecosystems can provide and communities can use. For example, in Central Java co-production of rules for community-based forest conservation to provide for future NCA presented an alternative to clear-felling, even though the present value of timber is known and the future benefits of the forest for adaptation are uncertain (#3). The NCA concept thus highlights the options that ecosystems can keep open and the value this flexibility affords to people under transformative environmental change.

Realising benefits of NCAs through joint production with other forms of assets can create options and reduce risk (Palomo et al. 2016; Lavorel et al. 2020). For example, wood from forests at Lake Faguibine represents an NCA, but charcoal manufacture and its sale in urban markets require infrastructural, human, social and financial capital, and the use of this NCA is linked to a complex of adaptation actions (#1).

4.3 Reducing risks of maladaptation

Use of NCAs can be a means to avoid maladaptation. Provision of alternative resources can help avoid maladaptive risks that arise from trying to maintain a declining resource under ecosystem transformation. For example, in Central Java, establishing agroforestry gardens on rain-fed croplands with declining yields due to drought helped mitigate costs of additional water and labour that would be required to maintain crop production (#3). Avoiding maladaptive costs of soil erosion and landslides provides the impetus for maintaining terraces in the French Alps which then provide fodder and can be used to produce novel crops (#8).

However, NCAs can be maladaptive if used for short-term coping strategies that become locked in. For example, the urgent need to increase export earnings, driven by government policy, led to over-harvesting of abalone and collapse of Chilean coastal fisheries. Fish stocks only recovered after a transformation of governance regimes and establishment of rules for a sustainable coastal fishery (#5). As natural gas becomes more widely available, charcoal manufacture at Lake Faguibine may become maladaptive for communities that rely on charcoal as their main income source (#1).

Integration of new adaptation options with traditional knowledge can counter risks of maladaptation. For example, in the Canadian Arctic, production and international sale of arts and crafts, using traditional media of stone, skins, bone and walrus ivory, is a latent cultural NCA reprised and re-invented. It provides an alternative to adapting hunting methods in response to increasing scarcity of target animals. Art co-operatives aided skills exchange, learning about environmental change, creation of hybrid knowledge and maintaining cultural continuity (#6; Rathwell and Armitage 2016).

Finally, NCAs can synergise over space and time, potentially reducing the risk of maladaptation (Lavorel et al. 2020). For example, multiple benefits were realised from creating agroforestry systems on former farmland in central Java and Kalimantan to adapt to increased rainfall variability and drought (#3).

4.4 Facilitating participative learning and co-production of adaptation approaches

The NCA concept can be used as a boundary object for co-production of knowledge for adaptation. Boundary objects can be concepts, physical objects or tools that enable shared learning and collaboration on tasks such as adaptation planning by agents with very different knowledge and world views (Wallis et al. 2017). For example, development of a shared vision for the future (‘Seeds of Hope’) in the French Alps, has led to reflexive learning and co-production of knowledge that is helping actors reframe aims and interests and is revealing novel options for livelihoods (#8).

Political realist views of adaptation propose radical re-distribution of power and resources to create agency for social change (Gillard et al. 2016). We consider participative learning and knowledge co-production for adaptation is an important way to re-balance power relations and engender agency (Collins and Ison 2009). For example, learning-by-doing to develop new grazing systems on saline land placed graziers in positions of power and ownership in creating new knowledge (#2; Wagg et al. 2007). Conversely, in the Ganges-Brahmaputra-Meghna Delta, emphasis on capacity building and income generation risks creating winners and losers if power imbalances and inequities are not addressed through improved co-production processes (#4; Rawlani and Sovacool 2011): there is no automatic connection between capacity building and poverty reduction.

The application of the NCA concept is consistent with the idea that pluralistic approaches and the co-construction of shared conceptual frameworks (Newell 2012) can produce more ambitious visions of social change and 'encourage us to see social and ecological tensions as opportunities for thinking and acting differently rather than as mere technical problems to be solved' (Gillard et al. 2016). For example, after the Chilean coastal fisheries collapse, the co-production of a new governance regime based on territorial use rights has provided multiple benefits, including incentives for innovation and stewardship, conservation outcomes, territorial empowerment and the development of a sustainable fishery (#5; Gelcich et al. 2017)

5. Changing the decision context to enable transformative adaptation

Adaptation based on incremental change within existing institutional structures and arrangements involves path dependencies that can constrain options for adaptation to ecosystem transformation (Figure 2; Wise et al. 2014;). Institutional path dependency is caused by failure of governments, markets and organisations to adapt objectives and practices and change priorities in response to major changes to social-ecological systems (Dryzek and Pickering 2019, p. 27). These authors (2019, p. 35) proposed a cycle of what they call *ecological reflexivity* to counter path dependency and generate change by doing and being something different, rather than just doing something better. In this cycle, *recognition* of changes to social-ecological systems leads to *reflection*: the re-thinking of core practices and visioning possible futures, and *response*: the re-articulation of aims, values and discourses and reconfiguration of functions and practices.

We consider ecological reflexivity is a potentially powerful way of mobilising the NCA concept through processes of participative learning and knowledge co-production. In the case studies, transformative adaptation occurred in response to ecological transformation: actors had no choice but to respond by doing something different because they could not continue with existing practices and livelihoods. How to adapt, what options were available and what processes and resources were required then set the decision context for actors to organise and co-produce solutions.

But the scaling up of transformative adaptation requires anticipatory approaches to ecosystem transformation and use of NCAs, not just reactive ones. Here, the decision context is complicated because existing practices and livelihoods are still viable, even though there is recognition that the social-ecological system is transforming and will continue to do so. The tension between the need for transformative adaptation and the reluctance of actors to change then sets the decision context. The question then arises of how to change the decision context to enable anticipatory adaptation?

Decision contexts are set by the interacting systems of held human values (Schwartz 2012) and how values are expressed as preferences, as well as societal rules and norms and systems of scientific, local and experiential knowledge that decision makers deem credible, legitimate and important (Gorddard et al. 2016; Colloff et al. 2018). Power is exercised over which and whose values, rules and knowledge are included in decision-making. Introducing new adaptation options may be difficult if they conflict with dominant systems of values, rules and knowledge. Thus, changing the decision context for adaptation involves changing the VRK used by decision makers.

Changes to systems of VRK may typically involve contestation and power struggles. For example, in the case of Ontong Java Atoll, over whether to migrate or stay and adapt to sea level rise and try and address governance failures over use of resources (#7; Bayliss-Smith et al. 2010). Contestation can be addressed effectively through engagement of actors in reflexive practices such as collaborative conceptual modelling (Newell and Proust 2017), hence the positive association in case studies between transformative adaptation achieved and knowledge co-production.

Major changes in systems of VRK that enabled transformative adaptation could be identified in all case studies. For example, changes in values and rules to enable control by graziers over production of knowledge for sustainable grazing systems on saline land (#2; Wagg et al. 2007); development of new rules and knowledge for management of community forests (case study #3; Fedele et al. 2018) and governance systems for coastal fisheries (#5; Gelcich et al. 2010); changes in values and knowledge to adopt new food production systems (#4; Rawlani and Sovacool 2011; #7; Bonie 2012); shifts in values, rules and knowledge to produce, market and sell charcoal (#1; Djoudi et al. 2013), form co-operatives for sale of local arts and crafts into the international market (#6; Rathwell and Armitage 2016) and develop a shared community vision for the future (#8; Lavorel et al. 2019).

Changing the decision context and systems of VRK to enable adaptation is thus clearly possible. But in each case study, we do not know the specific details of which processes and practices worked well and which did not. Clarifying these issues is an important future task for case study research on transformative adaptation.

6. Implications of the NCA concept for environmental management and governance

The NCA concept is based on the prospect of both ecosystem persistence and transformation and can help overcome the tension between the need for transformative adaptation and the reluctance of actors to change. Understanding rates and extent of changes to ecosystems and their drivers and identifying alternative ecosystem states are vital to effective adaptation decision-making and options for management of NCAs (Lavorel et al. 2015; Colloff et al. 2016a, 2016b).

Responding to uncertain changes requires planning for a range of scenarios, participative learning, and 'no regrets' decision-making to avoid maladaptation (Stafford Smith et al. 2011). These requirements can be met by operationalising NCA using adaptation pathways (Colloff et al. 2017). An adaptation pathways approach can help decision makers identify and sequence options over time, based on continual monitoring and learning (Wise et al. 2014). Examples of adaptation pathways involving NCAs (then referred to as adaptation services) and changes in governance processes include the development of adaptation options for new forest-based livelihoods (Pramova et al. 2012), forest management and use (Colloff et al. 2016b; Doherty et al. 2017), multi-use woodland landscapes (Prober et al. 2017) agricultural systems (Panda 2018) and reconfiguration of the relationships between agriculture and tourism (Lavorel et al. 2019). Transformational changes in governance to address declining fisheries in Chile represent a compelling case of how generalised pathways for sustainable resource use can be developed and used (Gelcich et al. 2010).

Management for NCAs as part of transformative adaptation requires a fundamental re-think of governance for environmental management and sustained, legitimate opportunities for discourse to address differences and conflicts and engender change. Addressing conflict can be approached by framing management for transformative adaptation and NCAs not as a technical-political problem to be solved but as a 'mobilising idea' around which people can generate agency (Hulme 2009). To overcome contestation and the limits of the 'problem-solution' approach, we can use the concept and reality of ecosystem transformation imaginatively and deploy a diversity of innovative projects that address our cultural, material and spiritual needs and values.

7. Conclusions

Novel, uncertain environmental change can limit options for decision makers if their knowledge, rules and values about their social-ecological system are based on assumptions of low risks, marginal changes and negligible cross-scale effects. Incremental adaptation will not be enough where social-ecological systems are transforming. To address these issues we propose the NCA concept can support transformative adaptation, as applied to: (1) a re-framing of the ecosystem services concept that raises awareness and creates options for adaptation under ecosystem transformation; (2) a powerful metaphor to reveal ecosystem properties for adaptation, but which are not apparent in simple stock-and-flow framings of nature's contributions to people; (3) reducing the risks of maladaptation and (4) as a boundary object to facilitate learning and co-production of transdisciplinary knowledge for adaptation (Abson et al. 2014).

From the case studies of transformative adaptation, we found a significant positive relationship between co-production of adaptation options and the level of adaptation achieved. A medium-high degree of adaptation was associated with participative processes involving systems thinking and co-production of adaptation approaches, low levels of contestation over values and interests, low power imbalances and existence of co-ordinating governance arrangements. These variables indicated that communities were empowered to engage and had ownership and agency to change the ways they thought and acted to implement adaptation.

Reframing adaptation decision contexts to enable the use of NCAs aligns with the approach of IPBES, whereby relational and intrinsic values of human-nature interactions can be included along with instrumental values (Pascual et al. 2017). The interaction of different forms of values with similar pluralistic approaches to systems of knowledge and rules extends the possibilities for deliberation and decision-making on adaptation options (Colloff et al. 2017).

By creating novel options for the future, the NCA concept can help actors re-frame decision contexts for implementing transformative adaptation. We consider the NCA concept represents a pragmatic and optimistic approach to adaptation and ecosystem transformation that helps counter feelings of despair that accompany the acceptance of irreversible, unavoidable change and loss of current ecosystem states (Oakes et al. 2016). Furthermore, it helps reveals the importance of ecosystem properties for adaptation and the societal change processes in values, rules and knowledge that are required to enable transformative adaptation.

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References

Abson DJ, von Wehrden H, Baumgärtner S, Fischer S, Hanspach J, Härdtle W, Heinrichs H, Klein AM, Lang DJ, Martens P, et al. 2014. Ecosystem services as a boundary object for sustainability. Ecol Econ. 103:29–37.

Ahammad R, Nandy P, Husnain P. 2013. Unlocking ecosystem based adaptation opportunities in coastal Bangladesh. J Coastal Conserv. 17:833–840. doi:10.1007/s11852-013-0284-x.

Baumgärtner S. 2007. The insurance value of biodiversity in the provision of ecosystem services. Nat Resour Model. 20:87–127. doi:10.1111/j.1939-7445.2007.tb00202.x.

Bayliss-Smith T, Gough KV, Christensen AE, Kristensen SP. 2010. Managing ontong java: social institutions for production and governance of atoll resources in Solomon Islands. Singap J Trop Geogr. 31(1):55–69. doi:10.1111/j.1467-9493.2010.00385.x.

Bonie JM 2012. *A Report on Climate Change Adaptation Intervention in Pelau Island in the Ontong Java Atoll.* Pacific Adaptation to Climate Change (PACC) Project, Honiara.

Brockhaus M, Djoudi H, Locatelli B. 2013. Envisioning the future and learning from the past: adapting to a changing environment in northern Mali. Environ Sci Policy. 25:94–106. doi:10.1016/j.envsci.2012.08.008.

Chaplin-Kramer R, Sharp RP, Weil C, Bennett EM, Pascual U, Arkema KK, Brauman KA, Bryant BP, Guerry AD, Haddad NM, et al. 2019. Global modelling of nature's contributions to people. Science. 366 (6462):255–258. doi:10.1126/science.aaw3372

Collins K, Ison R. 2009. Jumping off arnstein's ladder: social learning as a new policy paradigm for climate change adaptation. Environ. Policy Governance. 19:358–373.

Colloff MJ, Doherty MD, Lavorel S, Dunlop M, Wise RM, Prober SM. 2016b. Adaptation services and pathways for the management of temperate montane forests under transformational climate change. Clim Change. 138(1–2): 267–282. doi:10.1007/s10584-016-1724-z.

Colloff MJ, Gorddard R, Dunlop M. 2018. The values-rules-knowledge framework in adaptation decision-making: a primer. Canberra: CSIRO Land and Water.

Colloff MJ, Lavorel S, Wise RM, Dunlop M, Overton IC, Williams K. 2016a. Adaptation services of floodplains and wetlands under transformational climate change. Ecol Appl. 26(4):1003–1017. doi:10.1890/15-0848.

Colloff MJ, Martín-López B, Lavorel S, Locatelli B, Gorddard R, Longaretti P-Y, Walters G, van Kerkhoff L, Wyborn C, Coreau A. 2017. An integrative research framework for enabling transformative adaptation. Environ Sci Policy. 68:87–96. doi:10.1016/j.envsci.2016.11.007.

Díaz S, Demissew S, Carabias J, Joly C, Lonsdale M, Ash N, Larigauderie A, Adhikari JR, Arico S, Báldi A. 2015. The IPBES conceptual framework—connecting nature and people. Curr Opinion in Environ Sustainability. 14:1–16.

Díaz S, Pascual U, Stenseke M, Martín-López B, Watson RT, Molnár Z, Hill R, Chan KMA, Baste IA, Brauman KA, et al. 2018. Assessing nature's contributions to people. Science. 359(6373):270–272. doi:10.1126/science.aap8826

Díaz S, Settele J, Brondízio E, Ngo HT, Guèze M, Agard J, Arneth A, Balvanera P, Brauman K, Butchart S. 2019. Summary for Policymakers of the Global Assessment Report on Biodiversity and Ecosystem Services of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services. IPBES Secretariat, Bonn.

Djoudi H, Brockhaus M, Locatelli B. 2013. Once there was a lake: vulnerability to environmental changes in northern Mali. Reg Environ Change. 13(3):493–508. doi:10.1007/s10113-011-0262-5.

Doherty MD, Lavorel S, Colloff MJ, Williams KJ, Williams RJ. 2017. Moving from autonomous to planned adaptation in the montane forests of southeastern Australia under changing fire regimes. Austral Ecol. 42 (3):309–316. doi:10.1111/aec.12437.

Dryzek J, Pickering J. 2019. The politics of the anthropocene. Oxford: Oxford University Press.

Dunford RW, Smith AC, Harrison PA, Hanganu D. 2015. Ecosystem service provision in a changing Europe: adapting to the impacts of combined climate and socio-economic change. Landsc Ecol. 30(3):443–461. doi:10.1007/s10980-014-0148-2.

Ellis E, Pascual U, Mertz O. 2019. Ecosystem services and nature's contribution to people: negotiating diverse values and trade-offs in land systems. Curr Opinion in Environ Sustainability. 38:86–94. doi:10.1016/j.cosust.2019.05.001.

Fawcett D, Pearce T, Notaina R, Ford JD, Collings P. 2018. Inuit adaptability to changing environmental conditions over an 11-year period in Ulukhaktok, Northwest Territories. Polar Rec. 54(2):119–132. doi:10.1017/S003224741800027X.

Fedele G, Locatelli B, Djoudi H. 2017. Mechanisms mediating the contribution of ecosystem services to human well-being and resilience. Ecosyst Serv. 28:43–54. doi:10.1016/j.ecoser.2017.09.011.

Fedele G, Locatelli B, Djoudi H, Colloff MJ. 2018. Reducing risks by transforming landscapes, cross-scale effects of land-use changes on ecosystem services. PLoS One. 13 (4):e0195895.

Gelcich S, Cinner J, Donlan J, Tapia-Lewin S, Godoy N, Castilla JC. 2017. Fishers' perceptions on the chilean coastal TURF system after two decades: problems, benefits, and emerging needs. Bulletin Marine Science. 93 (1):53–67. doi:10.5343/bms.2015.1082.

Gelcich S, Hughes TP, Olsson P, Folke C, Defeo O, Fernández M, Foale S, Gunderson LH, Rodríguez-Sickert C, Scheffer M. 2010. Navigating transformations in governance of chilean marine coastal resources. Proceedings of the National Academy of Sciences 107:16794–16799.

Gillard R, Gouldson A, Paavola J, Van Alstine J. 2016. Transformational responses to climate change: beyond a systems perspective of social change in mitigation and adaptation. WIREs Clim Change. 7:251–265. doi:10.1002/wcc.384.

Gorddard R, Colloff MJ, Wise RM, Ware D, Dunlop M. 2016. Values, rules and knowledge: adaptation as change in the decision context. Environ Sci Policy. 57:60–69. doi:10.1016/j.envsci.2015.12.004.

Hulme M. 2009. Why we disagree about climate change: understanding controversy, inaction and opportunity. Cambridge: Cambridge University Press.

Jones HP, Hole DG, Zavaleta ES. 2012. Harnessing nature to help people adapt to climate change. Nat Clim Chang. 2:504–509.

Kadykalo AN, López-Rodriguez MD, Ainscough J, Droste N, Ryu H, Ávila-Flores G, Le Clec'h S, Muñoz MC, Nilsson L, Rana S. 2019. Disentangling 'ecosystem services' and 'nature's contributions to people'. Ecosyst People. 15(1):269–287. doi:10.1080/26395916.2019.1669713.

Lavorel S, Colloff MJ, Locatelli B, Gorddard R, Prober SM, Gabillet M, Devaux C, Laforgue D, Peyrache-Gadeau V. 2019. Mustering the power of ecosystems for adaptation to climate change. Environ Sci Policy. 92:87–97. doi:10.1016/j.envsci.2018.11.010.

Lavorel S, Colloff MJ, McIntyre S, Doherty MD, Murphy HT, Metcalfe DJ, Dunlop M, Williams RJ, Wise RM, Williams KJ, et al. 2015. Ecological mechanisms underpinning climate adaptation services. Glob Chang Biol. 21(1):12–31. doi:10.1111/gcb.12689

Lavorel S, Locatelli B, Colloff MJ, Bruley E. 2020. Co-producing ecosystem services for adapting to climate change. Philos Trans R. Soc B. 375(1794):20190119. in press. doi:10.1098/rstb.2019.0119

Marita P, Manuari D. 2014. Vulnerability and adaptation (V&A) assessment for ontong java atoll, Solomon Islands. Apia (Samoa): Secretariat of the Pacific Regional Environment Programme.

Mezey EW, Conrad JM. 2010. Real options in resource economics. Annu Rev Resour Econ. 2:33–52.

Muradian R, Pascual U. 2018. A typology of elementary forms of human-nature relations: a contribution to the valuation debate. Curr Opinion in Environ Sustainability. 35:7–14. doi:10.1016/j.cosust.2018.10.014.

Muradian R, Pascual U. 2020. Ecological economics in the age of fear. Ecol Econ. 169(article):106499. doi:10.1016/j.ecolecon.2019.106498.

Newell B. 2012. Simple models, powerful ideas: towards effective integrative practice. Global Environ Change. 22(3):776–783. doi:10.1016/j.gloenvcha.2012.03.006.

Newell B, Proust K. 2017. Escaping the complexity dilemma. In: König A, Ravetz J, editors. Sustainability science: key issues. Abingdon: Routledge; p. 96–112.

Norgaard RB. 2010. Ecosystem services: from eye-opening metaphor to complexity blinder. Ecol Econ. 69:1219–1227.

Oakes LE, Ardoin NM, Lambin EF. 2016. "I know, therefore I adapt?" Complexities of individual adaptation to climate-induced forest dieback in Alaska. Ecol Soc. 21 (2):40.

Ostberg S, Schaphoff S, Lucht W, Gerten D. 2015. Three centuries of dual pressure from land use and climate change on the biosphere. Environ Res Lett. 10 (4):044011. doi:10.1088/1748-9326/10/4/044011.

Palomo I, Felipe-Lucia MR, Bennett EM, Martín-Lopez B, Pascual U. 2016. Disentangling the pathways and effects of ecosystem service co-production. Adv Ecol Res. 54:245–283.

Panda A. 2018. Transformational adaptation of agricultural systems to climate change. WIREs Clim Change. 9:e520. doi:10.1002/wcc.520.

Pascual U, Balvanera P, Díaz S, Pataki G, Roth E, Stenseke M, Watson RT, Başak Dessane E, Islar M, Kelemen E. 2017. Valuing nature's contributions to people: the IPBES approach. Curr Opinion in Environ Sustainability. 26:7–16.

Pearce KL, Norman HC, Hopkins DL. 2010. The role of saltbush-based pasture systems for the production of high quality sheep and goat meat. Small Ruminant Res. 91(1):29–38. doi:10.1016/j.smallrumres.2009.10.018.

Pearce T, Ford JD, Cunsolo Willox A, Smit B. 2015. Inuit traditional ecological knowledge (TEK) subsistence hunting and adaptation to climate change in the canadian arctic. Arctic. 68(2):233–245. doi:10.14430/arctic4475.

Pramova E, Locatelli B, Djoudi H, Somorin OA. 2012. Forests and trees for social adaptation to climate variability and change. WIREs Clim Change. 3:581–596.

Prober SM, Colloff MJ, Abel N, Crimp S, Doherty MD, Dunlop M, Eldridge DJ, Gorddard R, Lavorel S, Metcalfe DJ, et al. 2017. Informing climate adaptation pathways in multi-use woodland landscapes using the values-rules-knowledge framework. Agric Ecosyst Environ. 241:39–53. doi:10.1016/j.agee.2017.02.021.

Rathwell KJ, Armitage D. 2016. Art and artistic processes bridge knowledge systems about social-ecological change: an empirical examination with Inuit artists from Nunavut. Canada Ecol Soc. 21(2):21. doi:10.5751/ES-08369-210221.

Rawlani AK, Sovacool BK. 2011. Building responsiveness to climate change through community based adaptation in Bangladesh. Mitigation Adapt Strategies Global Change. 16(8):845–863. doi:10.1007/s11027-011-9298-6.

Runting R, Bryan BA, Dee LE, Maseyk FJF, Mandle L, Hamel P, Wilson KA, Yetka K, Possingham HP, Rhodes JR, et al. 2017. Incorporating climate change into ecosystem service assessments and decisions: a review. Glob Chang Biol. 23(1):28–41. doi:10.1111/gcb.13457

Schwartz SH. 2012. An overview of the Schwartz theory of basic values. Online Readings in Psychol Culture. 2 (1):11. doi:10.9707/2307-0919.1116.

Stafford Smith M, Horrocks L, Harvey A, Hamilton C. 2011. Rethinking adaptation for a 4°C world. Philos Trans Royal Soc A. 369:196–216. doi:10.1098/rsta.2010.0277.

Steffen W, Rockström J, Richardson K, Lenton TM, Folke C, Liverman D, Summerhayes CP, Barnosky AD, Cornell SE, Crucifix M. 2018. Trajectories of the earth system in the anthropocene. Proceedings of the National Academy of Sciences 115:8252–8259.

Wagg M, Lawson A, Pattinson R 2007. Land, water and wool: program management report. Land and Water Australia, Canberra.

Wallis PJ, Bosomworth K, Harwood A, Leith P. 2017. Charting the emergence of a 'knowing system' for climate change adaptation in Australian regional natural resource management. Geoforum. 84:42–50. doi:10.1016/j.geoforum.2017.06.002.

West S, van Kerkhoff L, Wagenaar H. 2019. Beyond "linking knowledge and action": towards a practice-based approach to transdisciplinary sustainability interventions. Policy Stud. 40(5):534–555. doi:10.1080/01442872.2019.1618810.

Williams KJ, Dunlop M, Bustamante RH, Murphy H, Ferrier S, Wise RM, Liedloff A, Skewes TD, Harwood TD, Kroon F. 2012. Queensland's biodiversity under climate change: impacts and adaptation–synthesis report. Canberra: CSIRO Climate Adaptation National Research Flagship.

Wise RM, Fazey I, Stafford Smith M, Park SE, Eakin HC, Archer van Garderen ERM, Campbell B. 2014. Reconceptualising adaptation to climate change as part of pathways of change and response. Global Environ Change. 28:325–336.