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Addressing the limits to adaptation across four damage–response systems

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ABSTRACT

Our ability to adapt to climate change is not boundless, and previous modeling efforts show that future policy decisions about climate change are affected when adaptation limits are exceeded. Adaptation limits are delineated by capacity thresholds, after which climate damages begin to overwhelm the adaptation response and net adaptation goes negative. The levels of such thresholds depend on the complex interaction of different environmental (climatic and ecological) and human response (technological and societal) systems. In this paper, the interactions among these sub-systems are explored and four novel archetypical climate damage and adaptation response systems are developed. These damage–response systems can be described by the level of their adaptation limits thresholds, the pathways of adaptation capacity degradation and failure, and the recoverability or permanence of such climate losses once the adaptation limits have been surpassed. Policy options upon reaching the limits to adaptation include investment in more of the same technology, implementation of new and more effective adaptation, or transformational adaptation that allows the damage–response system to become more resilient. Attention is drawn to the need for greater understanding of the uncertainties of adaptation limits, how to raise the effective capacities and lifetime ranges of adaptation (and thus delay adaptation failure), and what policy options exist when adaptation limits are breached.

1. Introduction

Our ability to adapt to climate change is not boundless, as each type of adaptation response has a limited capacity. The set of available adaptations encompasses a large array of strategies that are specific to particular economic sectors affected by climate change (for example, agriculture, transportation, infrastructure, energy) and types of climate damages that are faced (sea-level rise, droughts, floods, heat waves). The point at which each strategy reaches its limit will vary as well across these sectors facing different damages, where the maximum effectiveness of each response is constrained by the interaction of climatic, ecological, technological, and societal systems.

Over the long term, an effective response portfolio to climate change includes both mitigation and adaptation, as the two strategies are complementary tools of climate change risk management (Felgenhauer and Webster, 2013; IPCC, 2014). The relationship is summarized by Mastrandrea and Schneider (2010), ''what cannot be prevented through mitigation must be adapted to; what we cannot cope with by

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adaptation, we must prevent,'' and Oreskes et al. (2010), ''... the less we mitigate, the more we shall have to adapt. Furthermore, the less we mitigate, the more likely we are to face challenges that surpass our capacity to adapt without pain and suffering.'' Arguments for prioritizing adaptation comes from its supposed affordability, because there is a perception that it is too late for mitigation to be effective (Oreskes et al., 2010, 1017–1018), or because it is more politically feasible to implement at the local level because of its concentrated rather than global benefits. The pessimistic view is that while humans have always changed with their environment it is also true that environmental stressors have overwhelmed the ability of earlier societies to adjust, causing collapse (Diamond, 2005).[1] Humans have never experienced the speed of climate change that is expected to occur during this century (Rogelj et al., 2012). Absent aggressive global mitigation, the likelihood of meeting an internationally accepted global mean temperature change target of 2 °C continues to fall (Rogelj et al., 2012). A mean temperature change beyond this level, for instance a 4 °C change, will bring increasingly severe impacts that may surpass society's ability to adapt. A 6 °C global mean temperature change resulting from doubled atmospheric CO_2 concentrations and slow climate feedbacks would ''severely challenge the viability of contemporary human societies'' (Rockström et al., 2009). Responding to such extreme impacts will require ''fundamental socioeconomic and technological transformation, rather than adjustments [of existing systems]—assuming such transformations are achievable through planning at all'' (New et al., 2009). Adaptation limits, however, will become relevant before such extreme points are reached.

The Fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC AR5) finds that an adaptation limit is reached ''when adaptation efforts are unable to provide an acceptable level of security from risks to the existing objectives and values and prevent the loss of the key attributes, components or services of ecosystems'' (Klein et al., 2014). Relatedly, Moser and Ekstrom (2010) define limits as ''obstacles that tend to be absolute in a real sense: they constitute thresholds beyond which existing activities, land uses, ecosystems, species, sustenance or system states cannot be maintained, not even in a modified fashion.'' Building on Klinke and Renn (2002), Dow et al. (2013) define an adaptation limit as ''a point at which an actor can no longer secure valued objectives from intolerable risk through adaptive action.'' Preston et al. (2013) relatedly introduce the concept of an ''adaptation frontier'' defined as ''a socio-ecological system's transitional adaptive operating space between safe and unsafe domains,'' beyond which adaptation is limited. The limits to adaptation can also be seen through a sustainability lens (Eriksen et al., 2011), where sustainability means meeting ''the needs of the present without compromising the ability of future generations to meet their own needs'' (Brundtland Commission, 1987). Sustainable systems in a strict sense are those that continue to function through time as expected, while a system is unsustainable if at some point in the future it stops working in its current form.

In this paper, I define adaptation limits as the point at which the level of climate damages has surpassed the capacity of the current adaptation approach, and net adaptation (adaptation benefits minus damage costs) has dropped to zero. After this point, existing adaptation responses could still be providing damage-reducing benefits, but the total amount of damages will exceed the adaptive capacity. Adaptation limits matter for making policy decisions because they exist and will be surpassed, which will require that failing adaptation be replaced with other pre-existing policy responses or new approaches that have yet to be developed and tested. Results from integrated assessment models of the global climate and economy show that when adaptive capacity is overwhelmed it becomes costly to societal welfare, requiring substitution with other policy responses (Felgenhauer and Webster, 2014; de Bruin and Dellink, 2011). Adaptation limits have been recognized at the U.S. national policy level (U.S. EPA, 2010; Titus, 2011), and a National Research Council report called for more research into understanding the ''thresholds or tipping points for climate change impacts, which in turn helps to determine the limits of adaptation,'' as well as for contingency plans to be developed for times when adaptation limits have been reached (NRC, 2010, 205).

In order to understand adaptation limits within different damage–response systems, this paper looks at adaptation under assumed optimal decision-making conditions. Thus, adaptation proceeds if the resulting benefits from damage reduction outweigh the costs of implementation. Adaptation investment decisions are informed by uncertain expectations of climatic damages and associated vulnerabilities. Optimal implementation of an adaptive response means that it is not constrained by implementation, informational, or cognitive barriers (Oreskes et al., 2010; Moser and Ekstrom, 2010; Hulme et al., 2009; Moser, 2009; Inderberg and Eikeland, 2009; Eisenack et al., 2014). It is important to note that barriers are distinctly different from limits, though the two terms have been used interchangeably (e.g., Bardsley, 2014). Barriers to adaptation are obstacles that prevent implementation of a fully optimal adaptation response, such as inadequate information and experience, inadequate institutional support, lack of resources and technology, and behavioral impediments (NRC, 2010).[2]

In this paper, I outline a new framework for understanding the limits to climate change adaptation from a systems perspective. From Meadows (2008), a system is ''an interconnected set of elements that is coherently organized in a way that achieves something,'' often with the goal of ensuring ''its own perpetuation.'' I review the literature on human and natural systems, as well as the limits of adaptation in different damage sectors. What I call the climate damage–adaptation response (or damage–response) system is the dynamic space of possible climate impacts and human responses to those impacts. I develop four different archetypes of such systems that trace the pathways of adaptation degradation and failure in response to rising damage levels. Exploring the behavior of these damage–response systems can help to inform policy decisions when adaptation limits are approached and surpassed. The research motivation is to explore the factors that

[1] See the Electronic Supplementary Material (ESM) for additional background.

[2] For more on adaptation barriers, see the ESM.

determine adaptation limit thresholds, and better understand the implications for public policy when they are surpassed.

This paper contributes to an existing body of work looking at adaptation limits operating at the interaction between environmental and human systems. Meze-Hausken (2008) describes a stimulus-response framework in which a climate stimulus causes a default response that can be improved through adaptation, leading in turn to system outcomes that range from enhancement and stability to degeneration and crash. Systems are examined by Linkov et al. (2014), from a risk (low or high) and resilience (low or high) perspective where high resilience systems can recover relatively more quickly from climate shocks. Examples of four systems are presented by Preston et al. (2013) that are distinguished by different distances from their adaptation limits, with different speeds at which the limits are approached (the ''unsafe operating space''). The approach described in this paper is novel because it characterizes the adaptation degradation pathway, both before and after the adaptation limits are reached.

In Section 2, the components of the climate damage–adaptation response system and how they determine adaptation limits are presented, with a focus on the interactions between environmental impacts and human responses. Damage–response systems combine adaptation with different technological characteristics and the damages that are faced, and are distinguished across three attributes: the level of adaptation limit threshold for each sector, the pathways of adaptation degradation and failure over time (gradual or catastrophic), and whether the climate impacts suffered after adaptation limits have been surpassed are temporary (recoverable) damages or permanent losses. Viable policy options available to decision-makers upon reaching an adaptation limit are presented in Section 3. Such responses include additional investment in more adaptation, development and implementation of new and more effective adaptation, or a transformation of the damage–response system itself to create a more resilient system. Section 4 concludes with some potential options for policy officials as they consider responses to adaptation limits.

2. Adaptation limits within climate damage and adaptation response systems

The climate damage–response system is an example of a coupled human and natural system, characterized by nonlinear relationships, thresholds, feedbacks, legacy effects, and time lags (Liu et al., 2007). Related terminology includes ''natural and social systems'' (Dow et al., 2013), ''human-environment systems'' (Kates et al., 2012), ''socio-ecosystems'' (Bardsley, 2014), and ''socio-ecological systems'' (Adger et al., 2007; Preston et al., 2013). As depicted in the central shaded box of Fig. 1, the damage–response system is comprised of a complex interaction of environmental systems (climatic and ecological) with human adaptation responses (composed of technological and societal systems). As applied to the environmental sub-systems of the top row, Peterson (2009) describes the relationships between climatic and ecological systems where the ecological response depends on the dynamics of both systems, and both can exhibit either gradual or abrupt change. Climate damages derive from changes in the mean of climatic variables or to changes in their variability, which in turn affects the frequency and severity of extreme events. Resilient ecosystems are able to resist disruptions and changes such that little change will occur with gradual climate change, and in this sense they are adapting autonomously.

Even with such resilience, however, a threshold could still be breached, at which time a new ecological regime is entered. Abrupt ecological change can occur from linear or nonlinear pressures (Andersen et al., 2008). Indeed, a state shift in the global biosphere is possible with climate change as a contributing factor among others (Barnosky et al., 2012). Different thresholds mark the collapse of ecosystems such as rain forests, ice sheets, and coral reefs. Sea-level rise can lead to permanent inundation. Ecosystems can also collapse due to persistent drought, or to heat, either directly from the temperature exposure or indirectly from insect infestation or invasive species after a prolonged warming and drying period, such as with forests due to insect infestations and

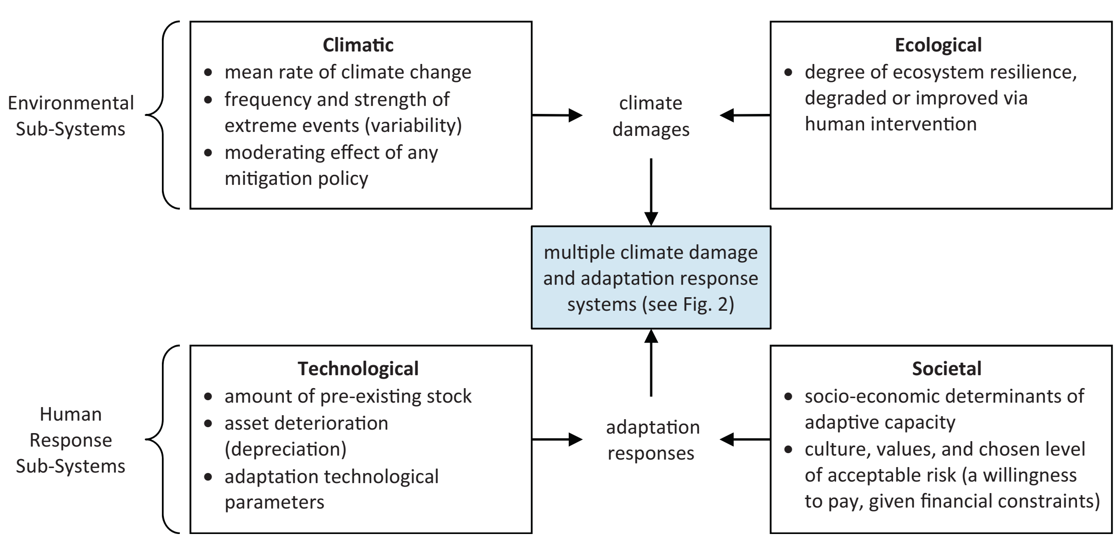

Fig. 1 – Key components of the climate damage–adaptation response system, with four sub-systems.

subsequent fires. The implication is that resilient ecosystems could also postpone a regime shift in the case of abrupt climate change. It is under a new regime that ecosystem services are impacted, an area where "...the majority of the impacts of climate change on human well-being may occur" (Peterson, 2009).

The climate–ecological system pairing is impacted by human response. In the bottom row, technological and societal characteristics and choices interact to describe the adaptation response to environmental changes. The technological characteristics and amount of adaptation determine its adaptation potential in isolation. However, adaptation responses are embedded within societies that choose how and where they are implemented. Societal vulnerability to climate change damages in turn depends on exposure to climate change, sensitivity to these changes, and coping capacity, where adaptation plays a role in the latter two determinants (Wilbanks et al., 2007a). Society can also choose how much of its limited resources to devote to climate change adaptation. Thus the limits can be values-driven, marked by a willingness to pay for a certain level of risk or damage reduction, given a certain cost. For example, the technology to adapt to coastal sea-level rise might be available, but the cost of such technology may be prohibitive for some communities (Reeder et al., 2009). Human influence is felt in all four subsystems, through conscious policy development, indirect impacts, or unwitting intervention.

Three system attributes characterize the behavior of the resulting climate damage and adaptation response systems. First, what determines the level of the adaptation limit threshold? Second, how does the investment in adaptation degrade in relation to its intended effective lifetime and periodic reinvestment. Does it fail gradually or catastrophically upon reaching and passing its limit? Third, after the adaptation limits have been surpassed, are the negative climate impacts recoverable damages or irreversible losses?

2.1. *Adaptation limits thresholds*

Adaptation limits are marked by thresholds that indicate where on its implementation pathway that adaptation begins to stop working, and it becomes infeasible or even impossible to prevent climate-related losses. As defined generally by Hulme et al. (2007), a threshold is "a state in sensitive ecological or physical systems beyond which change becomes irreversible." Social systems could be included as well. For climate change, a threshold can mean the point at which it becomes "dangerous," as with the UNFCCC (1992), but defining what "dangerous" means has been challenging (O'Neill and Oppenheimer, 2002; Oppenheimer, 2005; Dessai et al., 2004). Relatedly, "reasons for concern" about climate change have also undergone ongoing development (e.g., Yohe, 2010). Moellendorf (2011) stipulates that dangerous can only be defined normatively as something "too risky," which we would want to avoid. Narrowing further, the adaptation limit threshold is the "weakest link" in the chain of interconnected human and natural systems, and the line between two states separating when adaptation works and when it does not.

Adaptation limit thresholds depend in part on the intensity of the damages. On a scale of climate change severity developed by Travis (2010), the lower bound is the current climate while the upper bound marks the level of climate change that brings about ecological and societal collapse. With a rising climate severity, adaptation approaches evolve from expansions of current methods into fundamentally new responses. In an applied example, Hall et al. (2012) and Reeder et al. (2009) describe a scale of risk thresholds adopted by the UK Environment Agency's flood-risk management strategy for London and the Thames Estuary, in which risk is categorized into acceptable, tolerable, and intolerable levels. "Managed risk" is achieved when the risk pathways operates in the "acceptable" and "tolerable" zones, while risk becomes "unmanaged" when it exceeds these levels and becomes "unacceptable." At the highest level of risk it is considered impractical to intervene further to manage flooding through engineering, meaning an adaptation limit has been reached. A limit threshold can also be thought of as the maximum extent of a coping range (Jones and Mearns, 2005), within which systems are able to operate as before. As the climate warms, relevant variables such as temperature and precipitation move past the bounds of the coping range, making systems vulnerable. Adaptation then reduces the vulnerability by expanding society's coping range (Yohe and Tol, 2002; Carter et al., 2007), but a limited adaptation means that it can only be expanded to a finite amount.

One analytical challenge is that these thresholds can be defined in multiple ways. Understanding of technological thresholds can be relatively straightforward, such as the physical limits to the height of levees and seawalls or the diameter of culverts (NRC, 2010, 152). In addition to technical parameters, adaptation limits can also be determined by "individual and cultural values, and institutions and governance" (Adger et al., 2009b). Adger et al. (2009a) discuss how adaptation limits are mutable, dependent on societal norms, practices, and development pathways. They postulate that: (1) limits depend on the policy goals of the adaptation, as underpinned by diverse values; (2) adaptation need not be limited by uncertainties associated with foresight of future climate change; (3) adaptation is limited by social and individual factors such as risk perception, habit, social status, and age; and (4) systematic undervaluation of involuntary loss of places and culture disguises real and experienced but subjective limits to adaptation (Adger et al., 2007, 2009a). Relatedly, O'Brien (2009) argues that adaptation limits can be subjectively defined, as societal values determine the priorities for what is to be protected through adaptation. For example, it is up to society to decide upon goals to protect assets in an area from either a 1 in 500-year flood or a 1 in 1000-year flood, or a 1.5 m or 3 m sea-level rise. Human-defined climate thresholds are better seen as an uncertain transition zone, as they are determined by multiple climatic and human thresholds that are often subjective (Meze-Hausken, 2008).

The point at which adaptation limit thresholds are reached will vary depending on: (1) the characteristics of the damages, and (2) the characteristics of the affected economic sector. Damages may be distinguished by different types, such as impacts that are due to droughts, floods, heat waves, and sea-level rise. These damage types in turn will be felt at different rates and magnitudes (Stein et al., 2013). Drawing on NRC (2010), a selected subset of different economic sectors affected by climate change can be listed below, with assumptions on where the adaptation limit may be reached. In these cases, the adaptation limit has clearly been surpassed, even if the exact threshold is still uncertain.

- *Transportation and other infrastructure*: Extreme heat can deform and buckle roads, rails, and bridges, exceeding their designed engineering limits. The effect on roadways of increased freeze–thaw cycles exacerbated by climate change can increase their maintenance frequency and reduce the time until needed reconstruction (Mills et al., 2009; Picketts et al., 2013). Practical engineering limits exist on the height of seawalls and levees, or the size of storm sewers and culverts (NRC, 2010). Increasing frequency of coastal and riparian flooding can eventually lead to permanent inundation of transportation and other infrastructure, as levees and seawalls become ineffective at protecting these assets. At the opposite end of the scale, low water levels (e.g., in the U.S. Great Lakes) could eventually limit freight transport capacity (NRC, 2010).
- *Agriculture*: Climate change can affect agriculture in multiple ways, to the point where avoiding productivity declines or crop failures through adaptation becomes infeasible. While adaptation responses such as altering cropping species, their timing or location, or fertilizer and pest management practices can bring benefits, there are limits to the effectiveness of these methods with more severe climate change (Howden et al., 2007). Both extreme temperature thresholds as well as mean temperatures affect the productivity of crops at different periods in their growth cycles (Luo, 2011). Warren (2011) finds that a future 4 °C world would result in declining crop yields and large areas of cropland becoming unsuitable for cultivation. Either early heavy precipitation or prolonged drought can lead to crop failure. In an empirical example from Australia, Jones (2000) uses agricultural irrigation data to project when adaptation works below some critical threshold of water supply and fails after the threshold has been crossed. In the analysis, farmer adaptation was found to be feasible in the first half of the century while the limits of adaptation are likely exceeded in the second half of the century. Additionally, salt water intrusion from sea-level rise can ruin cropland.
- *Energy*: Electric power generation from hydropower, nuclear, and thermo-electric sources requires large amounts of water withdrawal and consumption to operate (Macknick et al., 2012), and low water levels can reduce production from these power plants. Additionally, rising water temperatures can warm the water for cooling to the point where it becomes too warm for efficient electricity generation (van Vliet et al., 2012), while sea-level rise can leave coastal power generation facilities unprotected (U.S. DOE, 2013).
- *Human health and well-being*: Rising persistency of droughts or floods could eventually reach a level that creates unsustainable living conditions in some areas. Given projections that global sea levels will rise by another 0.26–0.98 m by 2100 relative to 2005 (IPCC, 2013), some coastal settlements could face permanent inundation, requiring relocations. The habitability of some areas could be compromised from a new prevalence of heat-related diseases. Rising air temperatures in general could bring the habitability of some regions into question even with a much wider and largely impractical use of air conditioning (Sherwood and Huber, 2010). Indeed, extreme heat stress possible under current multi-century climate model predictions could be the ultimate upper bound to adaptation (Sherwood and Huber, 2010).

2.2. Pathway of adaptation degradation and failure

The pathway of adaptation capacity degradation and failure—whether gradual or catastrophic–is the second key characteristic of the damage–response system. The failure profile will depend on the characteristics of the particular adaptation type, as paired with the behavior of the damages it is trying to alleviate. Before failing, adaptation is more feasible when addressing moderate and gradual damages than it is with massive or abrupt damages (Wilbanks et al., 2007b). In practice, the damages will be perceived in the form of extreme events, as the mean shift in climate change is small (Trenberth, 2012). Such damages have different cost profiles. If the adaptive investment that is already in place still provides benefits even when its capacity is exceeded, then the additional new damages are incremental. An example would be a reservoir dam that is overtopped due to an extreme precipitation event—it still provides flood protection up to its original capacity even though additional flooding will occur downstream from the water that the reservoir cannot hold back. The problem is that, in this example, many water retention structures such as earthen levees have not been designed to be overtopped. When they are, it is only a short period of time from when the water flows over the structure and when it fails catastrophically, causing damages to spike. Examples of catastrophic adaptive failure include the failure of coastal barriers to prevent shoreline assets from completely washing away, or a complete loss of a season's crops that are planted from seeds that were modified for climate change. In these cases the adaptation has stopped working, nor will it work in the future if the damage trend continues.

Four different representative archetypes of damage–response systems are presented in Fig. 2, each of which derives directly from the shaded box of Fig. 1. Climate damages on the x-axes are paired with adaptation capacity on the y-axes. In the figure, damages and adaptation share the same units of measurement, where one unit of adaptive capacity addresses one unit of damages. Such units are difficult to describe in most cases, but the idea can be imagined with the overly simplified example of one foot of additional seawall height adapting to one foot of additional sea level rise. In other cases, as with new heat-tolerant agricultural hybrids developed for heat waves, the units are non-denominated units of adaptation capacity and damages. Gross adaptation is shown in solid (red) lines and net adaptation after damages is in dashed (red) lines. The upward-sloping diagonal dashed lines indicate the set of possible adaptation limit thresholds for each system, where the amount of gross adaptation exactly matches the climate damages ($a = d$), and net adaptation is zero. Above this threshold line net adaptation is positive and an adaptation surplus exists, while below it net adaptation has gone negative and there is an adaptation deficit (Burton, 2004). Adaptation and damages balance off of each other. On the positive side of the ledger are the amount of adaptive capacity initially built,

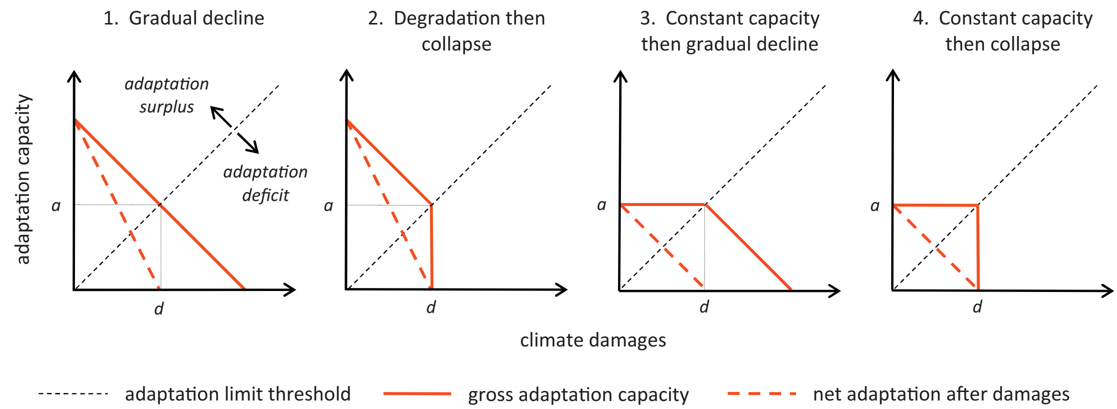

Fig. 2 – Four climate damage–adaptation response system archetypes.

retrofits to that capacity, and new investments in adaptation and on the negative side are the depreciation and degradation of these investments as they operate against rising climate damages. The timing of when limits are met is determined in part by the pace at which adaptation drops relative to the rate of climate damages, and limits are surpassed when adaptive capacity is less than the damages. The assumption is that climate decision makers strive to maintain adaptation surpluses (net adaptation >0). For ease of comparison each system is shown meeting its adaptation limit at the same point on the threshold line, and with the same maximum levels of climate damages that can be addressed through adaptation. The depictions are static, but if we assume that climate damages rise over time then a progression can occur through each system, moving from left to right along the adaptation lines until the adaptation response is overwhelmed at the limit threshold.

The four systems are distinguished by their different paths of adaptation degradation and failure. In system #1, as damages rise adaptive capacity degrades gradually and continues to decline after the adaptation has begun to fail. Such would be the case with crop yield declines over time due to changing mean temperatures. Adaptation capacity also declines in system #2 but here the adaptation limit example would be a managed forest that gradually weakens due to drought and insect infestation and then collapses from a debilitating fire. System #3 shows constant adaptive capacity that falls off gradually with after the adaptation limit threshold is passed. An example of this would be coastal infrastructure, initially outside of the flood zone, that suffers increasingly frequent flooding events once it is in the flood zone. System #4 demonstrates a constant adaptation capacity in relation to damages, which collapses suddenly after the limits are surpassed. The catastrophic failure of a flood protection levee is an example of this system. Note that in systems #1 and #3, the remaining adaptation is still providing some benefit even though it is overwhelmed by the damages.

2.3. *Losses and damages*

A third way to distinguish the damage–response systems is to ask if reaching the limits of adaptation creates irrecoverable losses or recoverable and temporary damages. Dividing negative climate impacts into this loss and damage framework was proposed by Huq et al. (2013) and has been adopted in the Warsaw Mechanism for Loss and Damages (UNFCCC, 2013). Some damages are reversible, such as a one-time crop failure due to a year of extreme climatic events, or damages to urban structures from flooding. In these instances, full (though expensive) recuperation can occur—the crops can be replanted and the buildings can be repaired or rebuilt. In contrast, other damages cause irreversible losses, such that recovering what is lost is practically infeasible on human timescales. Examples are the destruction of man-made cultural landmarks like Venice or natural assets like vulnerable coral reefs. Irreplaceable losses can be prevented through adaptation, as with the successful relocation of the Cape Hatteras Lighthouse in North Carolina, which was moved inland before being washed away at the eroding shoreline. However, once these types of losses occur recovery is either very difficult or impossible (steps can also be taken to make Venice and coral reefs more resilient). Thus, the more irreversible the climate damages are the more negative are the consequences of any adaptation failure

In the representation of damage–response systems from Fig. 2, the x-axis is the level of damages rather than the damages through time. However, assuming that climate change only worsens in the near term before any possible mitigation begins to take effect, then gross damages will only rise and the system status can only move from left to right. The implication is that any reversibility of net damages will depend on additional types of adaptation, as discussed in the next section. In this way, the system could move from states of adaptation surplus, to adaptation deficit, and back to a surplus again, even as gross damages continue to rise.

3. Policy options once an adaptation limit is surpassed

Adaptation limits are important because they will be reached, and in some parts of the world this is already happening (Huq et al., 2013). When this happens, policymakers will need to decide how to respond, either with higher levels of existing responses or new approaches in order to avoid suffering higher levels of climate damages. Over the long term mitigation works to reduce the likelihood that adaptation limits are reached, as over long timeframes mitigation and adaptation are complementary tools of climate change risk management. However, mitigation and adaptation are not perfect policy substitutes because climatic inertia significantly delays mitigation's climate-related benefits relative to those of adaptation. The asynchronous scales of climate policy effectiveness mean that current mitigation is thus not a credible near-term response to adaptation that is failing now (Felgenhauer and Webster, 2013). Furthermore, a strategy focused on the mitigation of short-lived climate forcers such as methane and black carbon is judged to bring only modest climate benefits, at best (Smith and Mizrahi, 2013). Another option is a climate intervention (geoengineering) approach such as stratospheric sulfate aerosol injection, which could potentially limit the global mean temperature rise (Keith, 2013) within a relatively short timeframe. But the uncertainties associated with such a strategy are huge, and it would not independently control both precipitation and temperature (Barrett et al., 2014)—thus it would likely be unable to be focused on climate damages at the smaller scale of an adaptation response. What options are available then as a near term response to adaptation failure? The four developed archetypical climate damage and adaptation response systems can help to assess and inform climate change decision making.

The most straightforward approach to implement upon adaptation failure may be investing in additional adaptation, i.e., adapt "more." This approach holds two assumptions: first, that repeated investments accumulate upon themselves, and second, that the challenge faced is merely one of additional needed adaptation quantity rather than quality. Adaptation investment decisions will be repeated through time within each affected sector. In theory the optimizing policymaker will purchase adaptation up to the point where its falling marginal benefits equal its rising marginal costs (Hall et al., 2012), and net adaptation benefits drop to zero at the point where the limits threshold is breached (Fig. ESM1 presents this process graphically). Additional adaptation can have a range of effective design lifetimes, whether it is shorter term "flow" responses or longer lived "stock" responses that need replenishment less frequently. With sea-level rise, additional beach renourishment could replace sand that washed away, the height of seawalls could be raised to prevent overtopping, or levees and other coastal engineering could be extended. For agriculture, additional irrigation water could be supplied if it exists. Finally, homes could be retrofitted with more insulation and more powerful air conditioners.

A second option when adaptation limits are reached is not to adapt with more of the same but instead with a new approach that is independent of previous efforts, with innovative technologies that might need to be developed and tested. The new approach could be welfare-enhancing, with the new adaptation reducing rising damages more effectively than even when the previous adaptation was working. Alternatively, the new adaptation could instead be a coping approach, working better than the previously failed adaptation but not as well as when the earlier response was working. Applying a modified version of the AD-DICE integrated assessment model (de Bruin et al., 2009) that disaggregates adaptation into short-lived "flow" and long-lived and depreciable "stock" types, Felgenhauer and Webster (2014) find that the degree of substitutability between adaptation types is a key factor in determining the amount that other adaptation types can "ramp up" if one type of adaptation fails.

As an example from the agricultural sector, a farmer may have a set of available adaptation options and technologies in order of rising costs—e.g., changing planting and harvesting times, intensifying irrigation, switching to new heat or drought-resistant seed varieties, or changing crops altogether. Such movement up an "adaptation response ladder" (Felgenhauer and Webster, 2013) assumes that alternative and new adaptation approaches are available, and that they can substitute for earlier ones that have reached their limit, in a sequence until options no longer exist (Fig. ESM2 depicts this process where new adaptation approaches replace previous ones that have stopped working, or become too costly.).

The third option available to policymakers when adaptation limits are reached is transformational adaptation, which means *changing the climate damage–response system* rather than changing or adding to the adaptation response. For example, it would be useful to operate within a system where adaptation degrades gradually rather than collapsing suddenly. Kates et al. (2012) contrast transformational adaptation with incremental adaptation, where the former includes such approaches as a dramatically enlarged scale of current adaptations, new adaptations, and moving vulnerable assets to new locations. Transformational adaptation involves the creation of new and better systems, where for instance in agriculture the desired goals and location of the system may change (Rickards and Howden, 2012). In the framework outlined here, new and larger scale adaptation is not transformational unless it changes the behavior of the system in fundamental and non-linear ways (Pelling et al., 2014). Transformational adaptation could be initiated in anticipation of expected adaptation failures, but in practice it may be done as a last resort when all other adaptation options have been exhausted. Indeed, "The key tension appears to be whether actors choose to transform or have transformation forced upon them" (Preston et al., 2013).

In changing the system's behavior rather than the adaption, successful transformational adaptation changes the calculus of all future adaptation decisions. Some examples of transformational adaptation fall under the "retreat or abandon" rubric, such as rolling easements for sea-level rise (Titus, 2011), the creation of tourist islands on the North Carolina Outer Banks with the demise of its road system (Riggs et al., 2011), or migration away from hazardous areas (McLeman and Smit, 2006). Bardsley (2014) argues that such adaptation needs to be embedded within a larger societal transformation away from unsustainable practices. Among other ideas involving extensive efforts at transformational adaptation are building underground or constructing sea walls around entire communities (Travis, 2010). In the agricultural sector, transformational adaptation could mean land abandonment and moving farms to new areas. The farmer could abandon the land and re-establish operations elsewhere, but the transition and absolute costs of such a move would likely be higher than leaving farming altogether.

Fig. 3 depicts the four damage–response systems from Fig. 2, now with different adaptation responses that a policymaker might take to address impending adaptation limits before they are reached. Pre-existing pathways of gross adaptation paired with damages across the four systems are in solid red, as before. Single dashed blue lines show a new investment in more adaptation, implemented in response to higher damages. For consistency across the four systems, the timing and relative initial amounts of the new adaptation are the same. The new adaptation investment is of the same type as the previous (red) adaptation, and it degrades and fails in the same manner—there is just more of it now. In double green lines, the policymaker implements more adaptation, but with a new technology type that degrades less rapidly than the previous approach did. Finally, in double purple dashed lines are transformational adaptation responses (systems #2 and #4) that convert these damage–response systems from those exhibiting sudden adaptive capacity collapse to a gradual decline (The green ''more and better'' adaptation response is not shown in system #4.). In the figure, the decision to invest in more adaptation is taken when 20% of the original net adaptation capacity remains before the limit is reached, and the amount of new adaptation brings total adaptive capacity up to a level that is double that of the damages faced.

We see across the four climate damage–adaptation response systems that both *more* and *better* adaptation are able to maintain and extend an adaptation surplus, depending on the behavior of adaptation decline and failure in the damage–response systems. Transformational adaptation, while not preventing damages, has the possibility of creating a new system with a gentler failure path than could previously be achieved. Such adaptation would likely be helpful in all scenarios. However, large expected transactional and opportunity costs of transformational adaptation (Rickards and Howden, 2012), along with the challenge of overcoming policy inertia to achieve such change, may mean that this option may only be applied after other adaptation strategies have reached their limits.

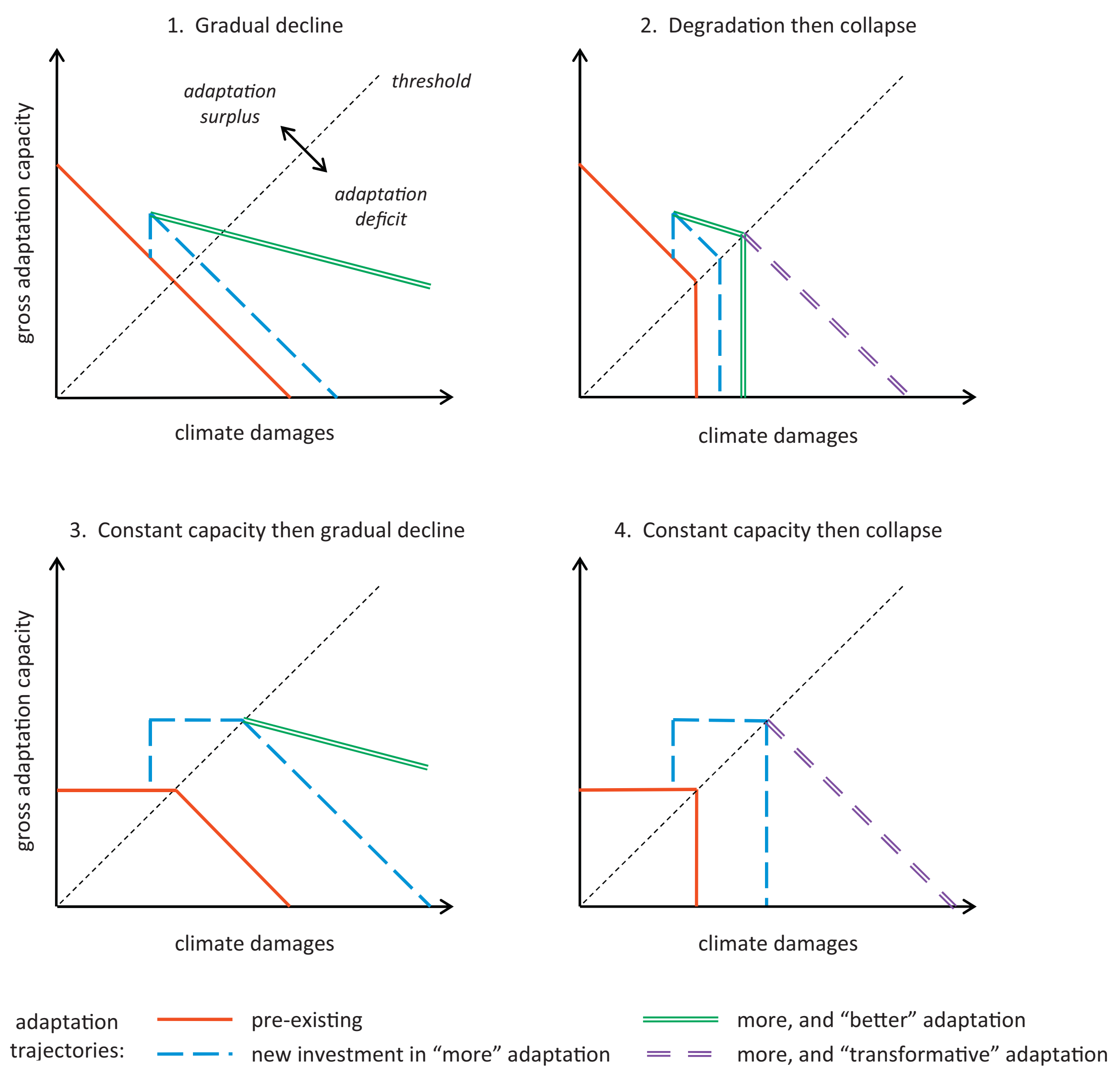

Fig. 3 – New adaptation implemented to address rising climate impacts, in four different damage–response systems.

4. Conclusions and future research

Given the projected trajectories of long-term climate change and the existence of adaptation limits, it is an open question as to whether it is possible to achieve "sustainable" adaptation that can operate both now and in the future. The implications of adaptation limits and associated uncertainty means that further research in this area has the potential to improve future decisions made at local, state, and national levels on how to respond to climate change. There are three general areas where future research would be beneficial:

- *Understand how to raise the effective capacities and lifetime ranges of adaptation, and thus delay adaptation failure.*

This can be done in three ways. First, following Fankhauser et al. (1999), a subset of current climate-exposed adaptation stock can be retrofitted to adapt to expected climate change damages, while the rest is better scrapped and replaced with new adaptation investments. Understanding the optimal portfolio mix of retrofits and new capital investments is a key question. Second, increasing the substitutability of adaptation activities under different levels of climate damages – by exploring new technologies and policies – would create additional and alternative responses when one adaptation type fails. Third, in some cases, some investment in "option stock" adaptation now may allow for the opportunity to delay higher levels of adaptation spending, learn about future damages, and implement cheaper adaptation in the future if it is needed (Felgenhauer and Webster, 2013).

- *Learn more about the uncertainties of adaptation limits—their level and timing.*

Reducing this uncertainty now can help policymakers to prepare for inevitable policy disruption in the future. Indeed, the IPCC AR4 lists the limits to adaptation among several key uncertainties and research priorities (Wilbanks et al., 2007b). Understanding these limits thresholds could allow for the possibility of early warning and the opportunity to undergo planned (rather than emergency) transformational adaptation (NRC, 2010).

- *Develop a better understanding of the available response options when adaptation limits are breached.*

Several areas of research can be pursued. An understanding of appropriate responses to adaptation limits requires knowledge of the type of likely adaptation failure (gradual or catastrophic) and the feasibility of responding with new, better, or transformational adaptation. Without the effects of mitigation, policymakers can do little to change the character of climate damages that we will face in the near term. However, interchangeability between these various adaptation types may be receptive to human influence. If certain categories of adaptation can more easily substitute for others when they inevitably fail, this may help to reduce losses due to climate damages.

Disclaimer

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