Chapter 16. Adaptation Opportunities, Constraints, and Limits

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Executive Summary

Risk-based approaches to decision-making provide a useful foundation for assessing the potential opportunities, constraints, and limits associated with adaptation of human and natural systems (*high agreement, medium evidence*). Risk management frames the consequences of climate change and potential adaptation responses in the context of actors' values, objectives, and planning horizons as they make decisions under uncertainty. Adaptation planning and implementation are therefore contingent on actors' perceptions of risk. Some risks may be routine and/or the consequences so minor that they are accepted. Other risks may be judged intolerable because they pose fundamental threats to actors' objectives or the sustainability of natural systems. A key objective of adaptation is to avoid such intolerable risks. Yet, the capacity of societal actors and natural systems to adapt is finite, and thus there are limits to adaptation. [16.2; 16.3.2; 16.4; Box 16-1]

Understanding of how the adaptive capacity of societal actors and natural systems influences the potential for adaptation to effectively manage climate risk has improved since the AR4 (*very high confidence*). Adaptive capacity is influenced by actors' abilities to capitalize on available opportunities that ease the planning and implementation of adaptation as well as constraints that make adaptation processes more difficult for both human and natural systems. Opportunities and constraints are unevenly distributed among global regions, communities, sectors, ecological systems, and species as well as across different time periods. Recent studies have provided greater recognition of the role of private businesses in facilitating adaptation. However, much of current knowledge about adaptation opportunities and constraints is dominated by insights from public institutions and community-based case studies. [16.2; 16.3; 16.4; 16.5; Box 16-1]

Opportunities exist to enable adaptation planning and implementation for actors across all sectors and geographic regions (*very high confidence*). Adaptation guidance, information, and tools are increasingly available to practitioners operating in different sectoral, regional and organizational contexts. Enhancing the awareness of individuals, organizations, and institutions about climate change vulnerability, impacts and adaptation can help build individual and institutional capacity for adaptation planning and implementation. However, addressing knowledge deficits alone is not sufficient to achieve successful adaptation. The development and provision of tools for risk and vulnerability assessment as well as decision-support tools and early warning systems can help actors prioritize adaptation needs and identify options that reduce vulnerability. Opportunities can also arise as actors learn from experience with climate variability and incorporate consideration for long-term climate change into disaster risk reduction efforts. Formal policies regarding infrastructure design standards or spatial planning can trigger adaptation

action. However, many adaptation opportunities arise as ancillary benefits of actions implemented for reasons other than climate change. [16.2 16.3.1; 16.5; Table 16-1; Table 16-3; Box 16-1; Box 16-2; Box CC-EA]

A range of biophysical, institutional, financial, social, and cultural factors constrain the planning and implementation of adaptation options and potentially reduce their effectiveness (*very high confidence)*. Adaptation of both human and natural systems is influenced by the rate of climate change as well as rates of economic development, demographic change, ecosystem alteration, and technological innovation. Adaptation planning and implementation may require significant inputs of knowledge as well as human, social, and financial capital. Real or perceived deficiencies in access to such resources can and do constrain adaptation efforts in both developing and developed nations. Public and private institutions influence the distribution of such resources as well as the development of policies, legal instruments, and other measures that facilitate adaptation. Therefore, institutional weaknesses, lack of coordinated governance, and conflicting objectives among different actors can constrain adaptation. Cultural characteristics including age, gender, and sense of place influence risk perception, entitlements to resources, and choices about adaptation. Societal actors and natural systems may experience multiple constraints that interact. [16.2; 16.3.2; 16.5; Table 16-2; Table 16-3; Box 16-1; Box 16-3]

Limits to adaptation can emerge as a result of the interactions among climate change and biophysical and socioeconomic constraints (*high agreement, medium evidence*). An adaptation limit occurs due to the inability to avoid an intolerable risk to an actor's objectives and/or to the sustainability of a natural system. Understanding of limits is informed by historical and recent experience where limits to adaptation have been observed, as well as by limits that are anticipated to arise as a consequence of future global change. Recent studies have provided valuable insights regarding global 'tipping points', 'key vulnerabilities', or 'planetary boundaries' as well as evidence of climate thresholds for agricultural crops, species of fish, forest and coral reef communities, and humans. However, for most regions and sectors, there is a lack of empirical evidence to quantify magnitudes of climate change that would constitute a future adaptation limit. Furthermore, economic development, technology, and cultural norms and values can change over time to enhance or reduce the capacity of systems to avoid limits. As a consequence, some limits may be considered 'soft' in that they may be alleviated over time. Nevertheless, some limits may be 'hard' in that there are no reasonable prospects for avoiding intolerable risks. Recent literature suggests that incremental adaptation may not be sufficient to avoid intolerable risks, and therefore transformational adaptation may be required to sustain some human and natural systems. [16.2; 16.3; 16.4; 16.5; 16.6; 16.7; Table 16-3; Box 16-1; Box 16-4]

Greenhouse gas mitigation can reduce the rate and magnitude of future climate change and therefore the likelihood that limits to adaptation will be exceeded (*high agreement, medium evidence*). Adaptation and greenhouse gas mitigation are complementary risk management strategies. However, residual loss and damage will occur from climate change despite adaptation and mitigation action. Knowledge about limits to adaptation can inform the level and timing of mitigation needed to avoid dangerous anthropogenic interference with the climate system. For example, the level of effort needed to adapt to a 4°C increase in global mean temperature would be significantly greater than that needed to adapt to lower magnitudes of temperature increase. Mitigation can reduce the likelihood of 4°C of warming and therefore the likelihood of exceeding limits to adaptation of natural and human systems. However, the empirical evidence needed to identify limits to adaptation of specific sectors, regions, ecosystems, or species that can be avoided with different greenhouse gas mitigation pathways is lacking. [16.3.2.2; 16.6; Box 16-3]

The selection and implementation of specific adaptation options has ethical implications (*very high confidence*). Adaptation decision-making involves the reconciliation of legitimate differences about how adaptation resources are distributed and the values that adaptation seeks to protect. For example, the costs and benefits of different adaptation options, such as insurance schemes or large-scale infrastructure projects, may be inequitably distributed among different actors and stakeholders. Such inequities may generate ethical questions regarding who is advantaged or disadvantaged by adaptation actions. In addition, awareness that climate change may exceed the capacity of actors to adapt may have ethical implications for decisions regarding mitigation and climate targets as well as investments in greenhouse gas mitigation policies and measures. National and international law as well as decision-making at regional and local scales among both public and private actors will influence distributive and procedural justice in adaptation planning and implementation. [16.3.3.8; 16.6; 16.7; Table 16-4; Box 16-4]

Successful adaptation requires not only identifying adaptation options and assessing their costs and benefits, but also exploiting available mechanisms for expanding the adaptive capacity of human and natural systems (*high agreement, medium evidence*). Since the AR4, a growing body of literature provides guidance on how enabling conditions for adaptation can be developed and how constraints can be reduced. Continued development of this knowledge through research and practice could accelerate more widespread and successful adaptation outcomes. However, seizing opportunities, overcoming constraints, and avoiding limits can involve complex governance challenges and may necessitate new institutions and institutional arrangements to effectively address multi-actor, multi-scale risks. [16.2; 16.3; 16.5; 16.8; Table 16-1; Box CC-EA]

16.1. Introduction and Context

Since the IPCC's *Fourth Assessment Report* (AR4), demand for knowledge regarding the planning and implementation of adaptation as a strategy for climate risk management has increased significantly (Preston *et al.*, 2011a; Park *et al.*, 2012). This chapter assesses recent literature on the opportunities that create enabling conditions for adaptation as well as the ancillary benefits that may arise from adaptive responses. It also assesses the literature on biophysical and socioeconomic constraints on adaptation and the potential for such constraints to pose limits to adaptation. Given the available evidence of observed and anticipated limits to adaptation, the chapter also discusses the ethical implications of adaptation limits and the literature on system transformational adaptation as a response to adaptation limits.

To facilitate this assessment, this chapter provides an explicit framework for conceptualizing opportunities, constraints, and limits (16.2). In this framework, the core concepts including definitions of adaptation, vulnerability, and adaptive capacity are consistent with those used previously in the AR4 (Adger *et al.*, 2007). However, the material in this chapter should be considered in conjunction with that of other complementary AR5 WGII chapters. These include Chapter 14 (*Adaptation Needs and Options*), Chapter 15 (*Adaptation Planning and Implementation*), and Chapter 17 (*Economics of Adaptation*). Material from other WGII chapters is also relevant to informing adaptation opportunities, constraints, and limits, particularly Chapter 2 (*Foundations for Decision-Making*) and Chapter 19 (*Emergent Risks and Key Vulnerabilities*). This chapter also synthesizes relevant material from each of the sectoral and regional chapters (16.5).

In order to enhance its policy relevance, this chapter takes as its entry point the perspective of actors as they consider adaptation response strategies over near, medium, and longer terms (Eisenack and Stecker, 2012; Dow *et al.*, 2013a, b). Actors may be individuals, communities, organizations, corporations, NGOs, governmental agencies, or other entities responding to real or perceived climate-related stresses or opportunities as they pursue their objectives (Patt and Schröter, 2008; Blennow and Persson, 2009; Frank *et al.*, 2011). These actors may seek to navigate near-term constraints to implement adaptation while simultaneously working to alleviate those constraints to enable greater flexibility and adaptive capacity in the future. Therefore, it is necessary to consider diverse timeframes for possible social, institutional, technological and environmental changes. These timeframes also differ in the types of uncertainties that are relevant, ranging from those of climate scenarios and models, possible system thresholds, nonlinear responses or irreversible changes in social or environmental systems, and the anticipated magnitude of impacts associated with higher or lower levels of climate change (Meze-Hausken, 2008; Hallegatte, 2009; Briske *et al.*, 2010).

To provide further background and context, this chapter proceeds by revisiting relevant findings on adaptation opportunities, constraints, and limits within the AR4 and the more recent IPCC *Special Report on Managing the Risks of Extreme Events and. Disasters to Advance Climate Change Adaptation* (SREX) (IPCC, 2012). The chapter then presents a framework for adaptation, opportunities, and limits with an emphasis on explicit definitions of these concepts to facilitate assessment. Key components of this framework are assessed in subsequent chapter sections including the synthesis of how these components are treated among the different sectoral and regional chapters of the AR5 WGII report. The chapter subsequently assesses relationships between mitigation and adaptation opportunities, constraints, and limits as well as their ethical implications. The chapter concludes with discussion of key pathways forward for research and practice to seize opportunities, overcome constraints, and avoid limits.

16.1.1. Summary of Relevant AR4 Findings

The AR4 *Summary for Policymakers* of Working Group II concluded that there are "*formidable environmental, economic, informational, social, attitudinal and behavioural barriers to the implementation of adaptation*" and that "*availability of resources and building adaptive capacity are particularly important*" (IPCC, 2007a, pg. 19). These findings were based primarily on Chapter 17, *Assessment of Adaptation Practices, Options, Constraints and Capacity* (Adger *et al.*, 2007). The key conclusion from Adger *et al.* (2007, pg. 719), as relevant to this chapter, was as follows: "*There are substantial limits and barriers to adaptation (very high confidence)*". The authors go on to discuss biophysical and technological limits to adaptation as well as barriers arising from technological, financial, cognitive and behavioral, and social and cultural factors. The authors also noted both significant knowledge gaps and impediments to the sharing of relevant information to alleviate those gaps.

These findings were further evidenced by the sectoral, and particularly, regional chapters of the AR4 WGII report. For example, the chapters assessing impacts and adaptation in Africa, Asia, and Latin America collectively emphasized the significant constraints on adaptation in developing nations. Meanwhile, the chapter on Small Islands by Mimura *et al.* (2007) identified several constraints to adaptation including limited natural resources and relative isolation. Finally, in the chapter on Polar Regions, Anisimov *et al.* (2007) noted that indigenous groups have developed resilience through sharing resources in kinship networks that link hunters with office workers, and even in the cash sector of the economy. However, they concluded that such responses may be constrained by social, cultural, economic, and political factors. For all of these regions, adaptation constraints are linked to governance systems and the quality of national institutions as well as limited scientific capacity and ongoing development challenges (e.g., poverty, literacy, and civil and political rights).

The AR4 also provided evidence that constraints on adaptation are not limited to the developing world. For example, Hennessy *et al.* (2007) reported that while adaptive capacity in Australia and New Zealand has strengthened over time, a number remain including access to tools and methods for impact assessment as well as appraisal and evaluation of adaptation options. They also note weak linkages among the various strata of government regarding adaptation policy and skepticism among some populations toward climate change science. For North America, Field *et al.* (2007) identify a range of social and cultural barriers, informational and technological barriers, and financial and market barriers. The chapter on Europe mentions the limits faced by species and ecosystems due to lack of migration space, low soil fertility and human alternations of the landscape (Alcamo *et al.*, 2007).

Several other AR4 chapters assessed literature relevant to this chapter. Chapter 18, *Inter-Relationships between Adaptation and Mitigation* (Klein *et al.*, 2007) discussed the possible effect of mitigation on adaptation (an issue also considered by the AR4 Working Group III, in particular by Fisher *et al.* (2007) and Sathaye *et al.* (2007). Finally, Chapter 19, *Assessing Key Vulnerabilities and the Risk from Climate Change* (Schneider *et al.*, 2007) outlined how the presence of adaptation constraints and limits is a contributing factor to vulnerability. Chapters that address similar themes also appear in the AR5, and cross-references are provided in this chapter to this more recent material.

16.1.2. Summary of Relevant SREX Findings

The IPCC's SREX report assesses a broad array of literature on climate change, extreme events, adaptation, and disaster risk reduction. A central framing concept for the SREX was the assertion that (Lavell *et al.*, 2012; pg. 37),

> *" . .while there is a longstanding awareness of the role of development policy and practice in shaping disaster risk, advances in the reduction of the underlying causes – the social, political, economic, and environmental drivers of disaster risk – remain insufficient to reduce hazard, exposure, and vulnerability in many regions (UNISDR, 2009, 2011) (high confidence)."*

This summary of the relevant SREX material focuses on how the key findings of the SREX provide insights relevant to the treatment of opportunities, constraints and limits in this chapter.

With respect to opportunities, the linkages between development and disaster risk reduction provide a number of avenues for enhancing societal resilience to natural disasters and climate change. For example, the SREX highlights the benefits of considering disaster risk in national development planning if strategies to adapt to climate change are adopted (Lal *et al.*, 2012). The observed dependence of disasters upon underlying patterns of development is indicative of the opportunities for increasing societal resilience through sustainable development. In addition, incorporating adaptation into multi-hazard risk management may be an effective strategy for the efficient integrated management of natural hazards and future climate risk (O'Brien *et al.*, 2012).

The SREX report also discussed the constraints associated with enhancing disaster risk reduction and climate adaptation. In particular, ongoing development deficits as well as inequality in coping and adaptive capacities pose fundamental constraints (Cardona *et al.*, 2012). The SREX noted that national systems and institutions are critical for generating the capacity needed to manage the risks associated with climate variability and change (Lal *et al.*, 2012). Yet capacity at one level of governance does not necessarily convey capacity to other levels (Burton *et al.*, 2012). Even in the presence of robust institutions, rates of socioeconomic and climate change can interact to constrain adaptation. For example, O'Brien *et al.* (2012) note that rapid socioeconomic development in vulnerable urban areas can increase societal exposure to natural hazards while simultaneously constraining the capacity of actors to implement policies and measures to reduce vulnerability. Overcoming these constraints to achieve development objectives is constrained by a paucity of disaster data at the local level as well as persistent uncertainties regarding the manifestation of extreme events in future decades (Cutter *et al.*, 2012; Seneviratne *et al.*, 2012).

The SREX report cautioned that natural hazards, climate change and societal vulnerability can pose fundamental limits to sustainable development. Such limits can arise from the exceedance of natural and/or societal thresholds or tipping points (Lal *et al.*, 2012; O'Brien *et al.*, 2012; Seneviratne *et al.*, 2012). Accordingly, the SREX concludes that adaptation options should include not only incremental adjustments to climate variability and climate change, but also transformational changes that alter the fundamental attributes of systems. Though challenging to implement, such transformation may be aided by actors questioning prevailing assumptions, paradigms, and management objectives toward the development of new ways of managing risk and identifying opportunities (O'Brien *et al.*, 2012).

16.2. A Risk-Based Framework for Assessing Adaptation Opportunities, Constraints, and Limits

Risk is an intrinsic element of any understanding of "*dangerous anthropogenic interference with the climate system*" (UNFCCC, 1992) and associated assumptions about the capacity of human and natural systems to adapt to climatic change. The United Nations Framework Convention on Climate Change (UNFCCC) refers specifically to adaptation of ecosystems, threats to food production, and sustainable economic development. While there is evidence of opportunities in natural and human systems to adapt to climate changes, there is also evidence that the potential to adapt is constrained, or more difficult, in some situations, and faces limits in others (e.g. Adger *et al.*, 2009; Dow *et al.*, 2013a, b; 16.3; 16.4; 16.5) (*very high confidence*).

This chapter applies a risk-based framework and a set of linked definitions to the assessment of adaptation opportunities, constraints and limits. This approach is consistent with other risk management approaches to guiding adaptation responses to climate change (IPCC, 2012; 1.3.4; 2.1.2; 14.5; 15.2.3.2). The adaptation literature ascribes a number of different meanings to the terms opportunities, constraints and limits, which may have added confusion to an important scientific and policy debate. The AR4, for example, provided a specific definition of adaptation limits, but used the terms barriers and constraints interchangeably to describe general impediments to adaptation (Adger *et al.*, 2007). Similar ambiguities are apparent within the rapidly expanding literature focused on adaptation constraints (Biesbroek *et al.*, 2013a). The framework and definitions employed here draw on a number of literatures (Dow *et al.*, 2013a, b), in particular vulnerability assessment (Füssel, 2006; Füssel and Klein, 2006) and risk assessment (Jones, 2001; Klinke and Renn, 2002; Renn, 2008; NRC, 2010) as well as climate adaptation (Hulme *et* *al.*, 2007; Adger *et al.*, 2009; Hall *et al.*, 2012). Moving from such general definitions to applications requires specifying who or what is adapting, what they are adapting to, and the process of adaptation (Smit *et al.* 1999). Hence, this chapter explores adaptation opportunities, constraints, and limits from the context of social actors, which includes individuals, businesses, government agencies, or informal social groups.

An explicit focus on risk is particularly useful to understanding climate adaptation (Jones and Preston, 2011; Dow *et al.*, 2012b). Adaptation is intended to reduce the risk to assets or systems of value (Adger *et al.*, 2012b). The concept of risk integrates the dimensions of probability and uncertainty with the material and normative dimensions that shape societal responses to threats (Renn, 2008). Figure 16-1 relates judgements about risk and the ability to maintain risks at a tolerable level to the concept of adaptation and adaptation opportunities, constraints, and limits (Box 16-1). Drawing on the work of Klinke and Renn (2002), actors evaluate risks based on one of three categories – acceptable, tolerable, and intolerable. Acceptable risks are those deemed so low that additional efforts at risk reduction, in this case climate adaptation efforts, are not justified. Tolerable risks relate to situations where adaptive, risk management efforts are required and effective for risks to be kept within reasonable levels. The scope of risks that fall within the tolerable area is influenced by adaptation opportunities and constraints. Therefore, the categorization of risks varies across spatial, jurisdictional, and temporal. As discussed further later in this chapter, opportunities and constraints may be physical, technological, economic, institutional, legal, cultural, or environmental in nature [16.3; 16.5; 16.5; 16.6; 16.7]. Constraints may limit the range of available adaptation options creating the potential for residual damages for actors, species or ecosystems associated with specific regions or sectors. Under some circumstances, the risk of residual damage may be viewed as an acceptable or tolerable trade-off (Stern *et al.*, 2006; de Bruin *et al.*, 2009a).

[INSERT FIGURE 16-1 HERE
Figure 16-1: Conceptual model of the determinants of acceptable, tolerable, and intolerable risks and their implications for limits to adaptation (Dow *et al.*, 2013b, based on Klinke and Renn, 2002; also see Renn and Klinke 2013). In this conceptual diagram, adaptation efforts are seen as keeping risks to objectives within the tolerable risk space. Opportunities and constraints influence the capacity of actors to maintain risks within a tolerable range. The dotted lines indicate that individual or collective views on risk tolerance with respect to the frequency and intensity of climate-related risks are not fixed, but may vary and change over time. In addition, the shape or angle of the lines and the relative area in each section of the diagram are illustrative and may themselves change as capacities and attitudes change. The shaded areas represent the potential differences in perspective among actors.]

Intolerable risks may be related to threats to core social objectives associated with health, welfare, security or sustainability (Klinke and Renn 2002; Renn 2008; Dow *et al.*, 2013a, b). Risks become intolerable when practicable or affordable adaptation options to avoid escalating risks to such valued objectives or biophysical needs become unavailable. Therefore, a limit is a point when an intolerable risk must be accepted; the objective itself must be relinquished; or some adaptive transformation must take place to avoid intolerable risk. Such a discontinuity may take several forms such as individual's decision to relocate, an insurance company's decision to withdraw coverage, or a species' extinction. The alternative to such discontinuities is an escalating and unmediated risk of losses (Moser and Ekstrom 2010; 16.4.2). While individuals have their own perspectives about what are acceptable, tolerable or intolerable risks, collective judgements about risk are also codified through mechanisms such as engineering design standards, air and water quality standards, and legislation that establishes goals for regulatory action. There are also international agreements that establish norms and rights relevant to climate change risks (Knox, 2009; OHCHR, 2009; Crowley, 2011), such as the Universal Declaration of Human Rights, the International Covenant on Civil and Political Rights, and the International Covenant on Economic, Social and Cultural Rights. Further, these high level responses often shape the constraints and opportunities to adaptation and responses to risk at lower levels through the distribution of resources, institutional design, and support of capacity development (16.2; 16.3; 16.4.1). If these risks and discontinuities have global-scale consequences, they can be linked to 'key vulnerabilities' to climate change (19.6). Consistent with our framing of adaptation limits, such key vulnerabilities would need to be assessed in terms of the limits they imply for specific social actors, species and ecosystems.

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Box 16-1. Definitions of Adaptation Opportunities, Constraints, and Limits

Adaptation Opportunities: *Factors that make it easier to plan and implement adaptation actions, that expand adaptation options, or that provide ancillary co-benefits.* These factors enhance the ability of an actor(s) to secure their existing objectives, or for a natural system to retain productivity or functioning. For instance, increased public awareness and support for adaptation, availability of additional resources from actors at other levels of governance to overcome constraints and soft limits, and interest in acquiring co-benefits arising from adaptation strategies can all facilitate adaptation planning and implementation. Private sector efforts in research and development that can improve affordability, flexibility, or ease of implementation could also create opportunities (14.4.8). Such adaptation opportunities, sometimes also referred to as adaptation enablers, are distinct from opportunities arising from climate change (e.g., longer growing seasons), which are commonly referred to as potential benefits of climate change or adaptation options.

Adaptation Constraints: *factors that make it harder to plan and implement adaptation actions.* Adaptation constraints restrict the variety and effectiveness of options for an actor to secure their existing objectives, or for a natural system to change in ways that maintain productivity or functioning. These constraints commonly include lack of resources (e.g., funding, technology or knowledge) (16.3.2), institutional characteristics that impede action (16.3.2.8), or lack of connectivity and environmental quality for ecosystems (4.4). The terms ‘barriers’ and ‘obstacles’ are frequently used as synonyms. Constraints, alone or in combination, can drive an actor or natural system to an adaptation limit.

Adaptation Limit: *The point at which an actor’s objectives or system’s needs cannot be secured from intolerable risks through adaptive actions* (Adger *et al., 2*009; Moser and Ekstrom 2010; Dow *et al.*, 2013a, b; Islam *et al.*, 2014).

> *Hard Adaptation Limit: No adaptive actions are possible to avoid intolerable risks.*
> *Soft Adaptation Limit: Options are currently not available to avoid intolerable risks through adaptive action*

A limit to adaptation means that, for a particular actor, system, and planning horizon of interest, no adaptation options exist, or an unacceptable measure of adaptive effort is required, to maintain societal objectives or the sustainability of a natural system. Objectives include, for example, maintaining safety standards such as those codified in laws, regulations, or engineering design standards (*e.g.*, 1 in 500 year levees); security of air or water quality; as well as equity, cultural cohesion, and preservation of livelihoods. Requirements for sustaining natural systems might include temperature ranges or moisture availability. In the case of hard limits, no adaptation options are foreseeable, even when looking beyond the current planning horizon. For soft limits, however, adaptation options could become available in the future due to changing attitudes or values or as a result of innovation or other resources becoming available to an actor. For example, 31 Native Alaskan villages are facing “imminent threats” due to coastal erosion and at least 12 of the 31 have begun to explore relocation or have decided to partially or totally relocate (US GAO, 2009). In the case of these communities with minimum local revenue, the ability to relocate depends on the political and financial support of the U.S. federal government (Huntingon *et al.,* 2012). Therefore, limits are strongly influenced by relationships among public and private actors and institutions across different spatial, temporal, and jurisdictional scales (Cash *et al.*, 2006; 16.4.1).

_____ END BOX 16-1 HERE _____

It is essential to evaluate opportunities, constraints, and limits with respect to both the rate and magnitude of climate change and the relevant time horizon for an actor, a species, or an ecosystem. Opportunities, constraints and limits to adaptation develop along a dynamic continuum (i.e., the dotted lines in Figure 16-1 can shift), together conditioning the capacity of natural and human systems to adapt to climate change. New opportunities for adaptation may emerge through time, constraints may be loosened, and some, although not all, limits that arise in the present may eventually be shifted or removed altogether. For a given social actor, the time horizon for adaptation decisions usefully bounds an analysis of opportunities, constraints and limits. For natural systems, the rate of species responses relative to changes in environmental conditions is a limit to the capacity to adapt (4.3.2.5; 4.4; 16.3.2.3; 16.4.1). The observed rate of evolutionary and other species responses ranges from rapid to inadequate to allow persistence (Hoffmann and Sgro, 2011).

Because adaptation limits relate to adaptation resources and attitudes to risk that may change over time, some limits may be viewed as 'soft' or time sensitive (16.4.1). While a given adaptation option may not be available today or require impracticable levels of effort, it may become available through innovation or changes in attitudes in time. Soft limits may be shifted by investments in research and development, changes in regulatory rules or funding arrangements, or by changing social or political attitudes (Park *et al., 2*012; Adger *et al., 2*013). Other limits are 'hard' or time insensitive in that there is no known process to change them (16.4.1). Examples of hard limits include water supply in fossil aquifers, limits to retreat on islands, and loss of genetic diversity.

16.3. Adaptation Opportunities and Constraints

Different actors, sectors, and geographic regions have differential capacities to adapt to climate variability and change (Adger *et al.*, 2007; IPCC, 2012) (*very high confidence*), although those capacities can be difficult to measure (Tol *et al.*, 2008; Hinkel, 2011). Since the AR4 (Adger *et al.*, 2007), the literature on the factors that contribute to adaptive capacity has deepened (Adger *et al.*, 2009; Moser and Ekstrom, 2010). This literature has evolved along two different pathways. One focuses on the range of opportunities that exist to facilitate adaptation planning and implementation. The other, which is also more extensive, focuses on describing the constraints that inhibit adaptation. Although they are sometimes treated in the literature as distinct, opportunities and constraints are complementary in that adaptive capacity is influenced jointly by the extent to which actors take advantage of available opportunities to pursue adaptation responses and the extent to which those actors or natural, unmanaged systems experience constraints. In addition, factors that are identified as constraints may also reveal valuable opportunities for adaptation interventions to build adaptive capacity.

While some level of generalization regarding opportunities and constraints that are common to different regions, sectors, communities, and actors is possible, the manner in which they manifest is context-dependent (Adger *et al.*, 2007; Orlove, 2009; Kasperson and Berberian, 2011; Weichselgartner and Breviere, 2011; IPCC, 2012) (*very high confidence*). For example, actors that frame adaptation as a process of capacity building or sustainable development may pursue different adaptation options with different opportunities and constraints compared with those that frame adaptation as largely addressing climate change impacts (McGray *et al.*, 2007; Fünfgeld and McEvoy, 2011). Adaptation researchers apply their own frameworks and heuristics that influence understanding of adaptation processes (Biesbroek *et al.*, 2013b; Preston *et al.*, 2013b). Therefore, one must be cautious in applying generic assumptions regarding adaptation opportunities and constraints in assessments of vulnerability and adaptive capacity or in the identification of appropriate adaptation responses (Adger and Barnett, 2009; Barnett and Campbell, 2009; Mortreux and Barnett, 2009). The recent adaptation literature suggests significant work remains in understanding such context-specific determinants of vulnerability and adaptive capacity and in effectively using the knowledge gained from available case studies to facilitate adaptation more broadly (Tol and Yohe, 2007; Klein, 2009; Smith *et al.*, 2010; Hinkel, 2011; Preston *et al.*, 2011b; Biesbroek *et al.*, 2013a). Therefore, the discussion of opportunities and constraints here should be considered in the context of the sectoral and regional synthesis (16.5) as well as the sector- and region-specific material on constraints and opportunities in other WGII chapters.

16.3.1. Adaptation Opportunities

16.3.1.1. Enabling Conditions for Adaptation

Adaptation opportunities represent enabling factors that enhance the potential for an actor to plan and implement actions to achieve their adaptation objective(s) or facilitate adaptive responses by natural systems to climate risk (Box 16-1). Therefore, an opportunity is distinct from an adaptation option, which is a specific means of achieving an adaptation objective (such as an early warning system as a means of reducing vulnerability to tropical cyclones) or a strategy for the conservation of an ecological system (14.3; Table 14-2). Adaptation opportunities described here also do not consider the potential beneficial consequences of climate change (Box 16-1), an issue addressed to varying degrees among the various sectoral and regional chapters.

[INSERT TABLE 16-1 HERE]
Table 16-1: Identification of key adaptation opportunities considered in this chapter. Each general type of opportunities is represented by multiple illustrative examples as well as supporting key references.*]*

Opportunities for adaptation range from increasing awareness of climate change, its consequences, and the potential costs and benefits of adaptation options to the implementation of specific policies that create conditions that are conducive to adaptation implementation. For example, rice is a key food crop, particularly in Asia in which 90% of rice is produced and subsequently consumed (Timmer, 2010). Multiple studies have identified rice as being particularly vulnerable to the effects of climate change including both temperature and water availability impacts (Papademetriou *et al.*, 2000). Therefore, planning and implementation of adaptive responses will be an important component of managing the risk of climate change to rice production (Howden *et al.*, 2007; Lobell *et al.*, 2008; Tilman *et al.*, 2011; Anwar *et al.*, 2013). A range of opportunities are available to support adaptation (Table 16-1; Table 16-3) (*very high confidence*). Hypothetically, these could include the use of analysis tools to better understand vulnerabilities and thresholds in rice and develop scenarios of future consequences. That information could then be communicated to farmers, national governments, and international agencies to increase awareness of potential risks. Policies can be used to incentivize adaptation including investments in biotechnology research to breed more resistant strains as well as field studies to identify potential new regions that might be appropriate for rice cultivation in the future.

Such opportunities exist for other agricultural commodities as well as other sectors and regions at risk from climate change (Box 16-2). For example, there is growing recognition of the potential for using disaster response and recovery processes as a means of increasing resilience to future extreme events (Lavell *et al.*, 2012). Meanwhile, case studies of Australian local governments as well as Inuit communities in the Arctic have identified a range of opportunities for building adaptive capacity and overcoming constraints (Smith *et al.*, 2008; Ford, 2009; Ford *et al.*, 2010). These include risk assessment, partnerships, establishment of monitoring and evaluation frameworks, developing finance mechanisms, and formal adaptation policy development.

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Box 16-2. A Case Study of Opportunities for Adaptation and Disaster Risk Reduction

Bangladesh has been identified as a region of South Asia that is particularly vulnerable to tropical cyclones (Ali, 1999; Mallick and Rahman, 2013), and this vulnerability is projected to increase due to climate change (Karim and Mimura, 2008; Dasgupta *et al.*, 2010). The nation’s response to this vulnerability illustrates the manner in which multiple opportunities can converge to facilitate adaptation and disaster risk reduction. The Cyclone Preparedness Program (CPP) was launched in the 1960s to establish a warning system in coastal regions (Habib *et al.*, 2012). The CPP has been continually improved in subsequent years with assistance from the International Federation of Red Cross and Red Crescent Societies and the International Foundation (Mallick and Rahman, 2013). A coastal reforestation program was also established in the 1960s to enhance natural buffers to storm surge (Mallick and Rahman, 2013; Box CC-EA). The Bangladesh Government initiated construction of cyclone shelters in the late 1980s, yet a cyclone in 1991 revealed that too few shelters were available (Bern *et al.*, 1991; Chowdhury *et al.*, 1993). This prompted collaboration between the government of Bangladesh, the United Nations Development Programme, and the World Bank to launch the Multipurpose Cyclone Shelter Program. That program characterized shelter needs along the coast and provided resources for their construction. In addition, shelter construction, which was concentrated around primary and secondary schools, coincided with national legislation requiring compulsory attendance in primary school, which required the construction of new schools. This created the opportunity for multi-purpose construction of buildings, reflecting the potential ancillary benefits that can arise from integrated planning (16.3.1.2).

More recently, Bangladesh has begun to focus on increasing the resilience of the built environment. This effort has focused on the development of disaster resilient habitat (Mallick and Rahman, 2007), where communities participate in the design and construction of resilient housing with support from international donors (Mallick *et al.*, 2008; Mallick and Rahman, 2013). This may be a more cost-effective strategy for both reducing mortality and property damage (Mallick *et al.*, 2008). The observed progress in reducing vulnerability to tropical cyclones is a function of various opportunities (awareness, assessment, policies, innovation, and capacity building) that have emerged over the past several decades that created conditions that enabled the implementation of specific policies, projects, and programs. Nevertheless, the additional risk posed by future climate change may necessitate further future investments (Dasgupta *et al.*, 2010).

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Sustainable economic development is a critical foundation for the creation of adaptation opportunities (20.2; 20.6), because it has the potential to build the capacity of individuals and organizations to adapt (*very high confidence*). Sustainable development is associated with increasing opportunities for research, training and education as well as for enhancing access to expertise and tools for assessment activities and decision-support. It also increases access to technologies that can enhance efficiencies. For example, water use in the United States has remained relatively constant since the mid-1980s, despite population growth, increases in agricultural yields, and expansion of electricity generation (Kenny *et al.*, 2009). Improvements in technology and management practice stimulated by innovation, education and learning have increased water use efficiency. This phenomenon may increase the resilience of U.S. water resources to climate change. Yet, these advances are a function of broader national and regional economic development trends. Therefore, future development pathways may have a significant influence on the opportunities for adaptation and therefore the adaptive capacity of adaptation actors (16.3.2.10; 20.6; Box 16-3).

16.3.1.2. Ancillary Benefits of Adaptation

Some adaptation options may offer ancillary benefits (or co-benefits) independent of their direct benefits with respect to reducing vulnerability to climate change (17.4) (*very high confidence*). The potential for ancillary benefits has two important implications for adaptation planning and implementation. First, their consideration may result in a more favorable assessment of the cost-effectiveness of a specific adaptation option (Hallegatte, 2009). Second, consideration of the ancillary benefits of adaptation may help in efficiently integrating adaptation into existing management and decision-making processes (Ahmed and Fajber, 2009; Dovers, 2010).

Such ancillary benefits may arise from adaptation responses in three ways:

- *Stimulating adaptation to current climate variability*: While it is generally assumed that physical, ecological and social systems are well-adapted to current climatic conditions; this is frequently not the case (Heyd and Brooks, 2009; Dugmore *et al.*, 2009). Increased awareness of the potential impacts of future climate change may, in some instances, lead to the implementation of adaptation options in order to reduce vulnerability or capitalize on opportunities (16.3.2.1) (*high agreement, medium evidence*). These options may have near-term ancillary benefits with respect to reducing vulnerability to current climate variability and extreme weather events (Füssel, 2008; Hallegatte, 2009; Ford *et al.*, 2010). On the other hand, future reductions in vulnerability to climate change can be perceived as ancillary benefits of near-term responses to current climate variability and natural disasters (Ziervogel *et al.*, 2010a, b). Hence, there may be some ambiguity with respect to what actors perceive as the primary versus ancillary benefit of a particular policy or measure.
- *Generation of climate adaptation goods and services*: Adaptation planning and implementation often may require additional knowledge and investment of resources. Adaptation therefore represents a potential economic opportunity for producers of goods and services used to satisfy adaptation needs (EBI, 2013) (*medium agreement, limited evidence*). Such services range from vulnerability assessment and risk analysis to the implementation of technology and engineering solutions. The Stern Review indicated that the market opportunities for new infrastructure and buildings resilient to climate change in OECD countries could be quite significant (Stern *et al.*, 2006). For example, the market for snow machines will be influenced by growing concerns about snow cover in more marginal ski resorts (Scott *et al.*, 2006). Higher elevation regions may see new opportunities as a result of snow resort shifts (Bark *et al.*, 2010). Likewise, increased risks associated with track buckling caused by higher summer temperatures may trigger innovation and

investment in new railway track and drainage systems (Bark *et al.*, 2010). Rising damage caused by climate change could provide new markets for innovative insurance products and other risk-based financial services (Botzen *et al.*, 2009; Botzen *et al.*, 2010) (*medium agreement, limited evidence*). However, these ancillary benefits must be weighed against the adverse impacts that create the market for such services.

- *Advancement of sustainable development*: As part of a larger portfolio of policies and measures, adaptation can assist in addressing existing development deficits while also meeting long-term sustainable development objectives (20.2, 20.6) (*very high confidence*). For example, policy options related to management of water and natural resources under a changing climate; the development of water, transportation, and communication infrastructure; and the promotion of credit and insurance services can promote economic development, increase adaptive capacity and reduce the impacts of climate change on the poor (Hertel and Rosch, 2010). Therefore, effective adaptation and climate risk management may be important enablers of sustainable economic development.

16.3.2. Adaptation Constraints

As discussed in the AR4 (Adger *et al.*, 2007), a number of factors constrain planning and implementation of adaptation options (*very high confidence*). More recent studies have documented an expanded range of constraints in a diverse array of contexts, but Biesbroek *et al.* (2013a) note that there is no consensus definition of constraints or a consistent framework for their assessment. Although constraints are often discussed in the literature as discrete determinants of adaptive capacity, they rarely act in isolation (Dryden-Cripton *et al.*, 2007; Smith *et al.*, 2008; Moser and Ekstrom, 2010; Shen *et al.*, 2011). Rather actors are challenged to navigate multiple, interacting constraints in order to achieve a given adaptation objective (Adger *et al.*, 2007; Dryden-Cripton *et al.*, 2007; Smith *et al.*, 2008; Shen *et al.*, 2008; Adger *et al.*, 2009; Jantarasami *et al.*, 2010; Moser and Ekstrom, 2010; Shen *et al.*, 2011; 16.3.2.10) (*very high confidence*). Multiple constraints can significantly reduce the range of adaptation options and opportunities available to actors and therefore may pose fundamental limits to adaptation (16.4) (*very high confidence*), and/or drive actors toward responses that may be maladaptive (Barnett and O'Neill, 2010; Eriksen *et al.*, 2011) (*medium agreement, limited evidence*).

16.3.2.1. Knowledge, Awareness, and Technology Constraints

The AR4 concluded that there are significant knowledge gaps and impediments to flows of information that can constrain adaptation, but knowledge in itself is not sufficient to drive adaptive responses (Adger *et al.*, 2007). These conclusions are echoed by more recent literature. Adaptation practitioners and stakeholders in both developed (Tribbia and Moser, 2008; Jantarasami *et al.*, 2010; Gardner *et al.*, 2010; Ford *et al.*, 2011; Milfont, 2012) and developing nations (Bryan *et al.*, 2009; Deressa *et al.*, 2009; Begum and Pereira, 2013; Pasquini *et al.*, 2013) continue to identify knowledge deficits as an adaptation constraint (*very high confidence*). Often this demand for more information is linked to concerns regarding decision-making under uncertainty about the future (Tribbia and Moser, 2008; Moser, 2010a; Whitmarsh, 2011; Stoutenborough and Vedlitz, 2013) (*medium agreement, medium evidence*). A broad range of guidance on adaptation planning and implementation continues to emerge as a means of empowering actors to pursue adaptation efforts (Clar *et al.*, 2013; EU, 2013; FAO, 2013; USCTI, 2013; Webb and Beh, 2013), and the World Meteorological Organization have emphasized the importance of climate services for vulnerability and disaster risk reduction (WMO, 2011).

A number of recent studies have investigated the extent to which education and knowledge about climate change influences perceptions of risk (Hamilton, 2011; McCright and Dunlap, 2011; Milfont, 2012). For example, studies suggest over-confidence in the ability of actors to manage risk (Wolf *et al.*, 2010; Kuruppu and Liverman, 2011) or differences in the perception of climate risk between actors and governing institutions (Patt and Schröter, 2008a) can constrain adaptation (*medium agreement, medium evidence*). Therefore, capacity building through education, training, and information access represents a valuable opportunity for adaptation (16.3.1.1).

Nevertheless, numerous recent studies caution that addressing knowledge deficits may not necessarily lead to adaptive responses (Tribbia and Moser, 2008; Kellstedt *et al.*, 2008; Adger *et al.*, 2009; Malka and Krosnick, 2009;

Moser, 2010b; Preston *et al.*, 2011b; Kahan *et al.*, 2012; Lemos *et al.*, 2012) (*very high confidence*). Research from the United States indicates that those most informed about science and climate change are not necessarily the most concerned about its potential consequences (Kellstedt *et al.*, 2008; Kahan *et al.*, 2012), although these findings run counter to research from New Zealand where increased knowledge translated into increased public concern and efficacy (Milfont, 2012). Recent research also indicates that multiple factors influence how knowledge is perceived including political affiliation (Hamilton, 2011; McCright and Dunlap, 2011), educational attainment (McCright and Dunlap, 2011), and the confidence placed on different information sources (Sundblad *et al.*, 2009). Various studies have questioned a common assumption in the climate change literature that improvements in climate information are needed to facilitate adaptation (Dessai *et al.*, 2009; Hulme *et al.*, 2009; Wilby and Dessai, 2010; Verdon-Kidd *et al.*, 2012; 2.3). Similarly, multiple authors have questioned the utility and robustness of vulnerability metrics and indices for informing adaptation decision-making (Barnett *et al.*, 2009; Klein, 2009; Hinkel, 2011; Preston *et al.*, 2011b).

Similar tensions arise with respect to the role of traditional knowledge in adaptation. For example, cultural preferences regarding the value of traditional versus more formal scientific forms of knowledge influence what types of knowledge, and therefore adaptation options, are considered legitimate (Jones and Boyd, 2011). In the Arctic, Inuit traditional knowledge (*Inuit Qaujimajatuqangit*, IQ) encompasses all aspects of traditional Inuit culture including values, world-view, language, life skills, perceptions and expectations (Nunavut Social Development Council, 1999; Wenzel, 2004). Inuit IQ includes, for example, weather forecasting, sea ice safety, navigation, hunting and animal preparation skills that are may have value for managing climate risk. Yet, as noted in the AR4 and more recent studies, these skills are declining among youth (Adger *et al.*, 2007; Pearce *et al.*, 2011) (*medium agreement, medium evidence*). Increasing reliance on non-traditional forecasting (national weather office forecasts) and other technologies (GPS) in Arctic communities is in part responsible for increased risk taking when travelling on the land and sea ice (Aporta and Higgs, 2005; Ford *et al.*, 2006; Pearce *et al.*, 2011) (*medium agreement, medium evidence*). Collectively, the recent literature suggests the extent to which knowledge acts to constrain or enable adaptation is dependent upon how that knowledge is generated, shared, and used to achieve desired adaptation objectives (Patt *et al.*, 2007; Nelson *et al.*, 2008; Tribbia and Moser, 2008; Moser, 2010a, b) (*very high confidence*).

Individual, institutional, and societal knowledge influences the capacity to develop and use technologies to achieve adaptation objectives (*very high confidence*) (UNFCCC, 2006; Adger *et al.*, 2007). The AR4 noted the role of technology in contributing to spatial and temporal heterogeneity in adaptive capacity and the potential for technology to constrain adaptation or create opportunities (Adger *et al.*, 2007). Key considerations with respect to technology as an adaptation constraint include a) availability; b) access (including the capacity to finance, operate and maintain); c) acceptability to users and affected stakeholders; and d) effectiveness in managing climate risk (Adger *et al.*, 2007; Dryden-Cripton *et al.*, 2007; van Aalst *et al.* 2008; 9.4.4; 11.7; 14.2.4; 15.3.2). Although technology has implications for regional adaptive capacity (e.g., 22.4.5.7; 27.3.6.2; 29.6.2), in-depth exploration of technology in the adaptation literature is often associated with specific sectors (Howden *et al.*, 2007; Bates *et al.*, 2008; van Koningsveld *et al.*, 2008; Parry *et al.*, 2009; US EPA, 2009; Zhu *et al.*, 2010). For example, Howden *et al.* (2007) note the importance of technology options for facilitating adaptation including applications of existing management strategies as well as introduction of innovative solutions such as bio- and nanotechnology (see also Hillie and Hlophe, 2007; Bates *et al.*, 2008; Fleischer *et al.*, 2011). Several studies from Africa have explored how different factors drive awareness, uptake and use of adaptation technologies for agriculture (Nhemachena and Hassan, 2007; Hassan and Nhemachena, 2008; Deressa *et al.*, 2009, 2011). While such literature identifies specific adaptation technology options, and in some cases the costs associated with their implementation, quantitative understanding of the extent to which improving technology will enhance adaptive capacity or reduce climate change impacts remains limited (Piao *et al.*, 2010).

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Box 16-3. Rates of Change as a Cross-Cutting Constraint

Future rates of global change will have a significant influence on the demand for, and costs of, adaptation (*very high confidence*). Since, the AR4, new research has confirmed the commitment of the Earth system to future warming (Lowe *et al.*, 2009; Armour and Roe, 2011; AR5 WGI 12.5) and elucidated a broad range of tipping points or 'key vulnerabilities' that would result in significant adverse consequences should they be exceeded (Lenton *et al.*, 2008;

Rockstrom *et al.*, 2009; Chapter 19). While the specific rate of climate change to which different ecological communities or individual species can adapt remains uncertain (16.3.2.3; 16.4.1), more rapid rates of change can constrain adaptation of natural systems (Hoegh-Guldberg, 2008; Gilman *et al.*, 2008; Maynard *et al.*, 2008; Allen *et al.*, 2009; Hallegatte, 2009; Malhi *et al.*, 2009a; Malhi *et al.*, 2009b; Thackeray *et al.*, 2010; Lemieux *et al.*, 2011; Fankhauser and Soare, 2013; 4.3.2.5; 5.5.5), particularly in the presence of other environmental pressures (Brook *et al.*, 2008) (*very high confidence*). Literature suggests that the near-term economic costs of societal adaptation may be substantial, and those costs increase incrementally over time as the climate changes (17.6.3). Therefore, higher rates or magnitudes of climate change may reduce the effectiveness of some adaptation options, and higher costs for adaptation may be incurred (New *et al.*, 2011; Stafford Smith *et al.*, 2011; Peters *et al.*, 2013; 16.6). However, more rapid rates of change may also create greater incentives for adaptation resulting in a faster pace of implementation (Travis and Huisenga, 2013).

Although rapid socioeconomic change, including economic development and technological innovation and diffusion, can enhance adaptive capacity (16.3.1), it can also pose constraints (20.3.2) (*very high confidence*). Globally, economic losses from climate extremes are doubling approximately every one to two decades due to increasing economic exposure (Pielke Jr. *et al.*, 2008; Baldassarre *et al.*, 2010; Bouwer, 2011; Gall *et al.*, 2011; Munich Re, 2011; IPCC, 2012; Preston, 2013). Such losses are associated with high interannual variability (Preston, 2013), but current trends are projected to continue in future decades (Pielke Jr., 2007; Montgomery, 2008; O'Neill *et al.*, 2010; UN, 2011; Preston, 2013; 10.7.3), although losses may decline relative to growth in GDP (IPCC, 2012). In addition, population growth and economic development can lead to greater resource consumption and ecological degradation (Alberti, 2010; Chen *et al.*, 2010; Raudsepp-Hearne *et al.*, 2010; Liu *et al.*, 2012), which can constrain adaptation in regions that where livelihoods are closely linked to ecosystem goods and services (Badjeck *et al.*, 2010; Marshall, 2010; Warner *et al.*, 2010; 16.3.2.3; CC-EA) (*very high confidence*). The adaptation literature also suggests that successful adaptation will be dependent in part upon the rate at which institutions can learn to adjust to the challenges and risks posed by climate change and implement effective responses (Adger *et al.*, 2009; Moser and Ekstrom, 2010; Stafford Smith *et al.*, 2011) (*very high confidence*).

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16.3.2.2. Physical Constraints

The capacity of human and natural systems to adapt to a changing climate is linked to characteristics of the physical environment including the climate itself. Recent studies have suggested that the effort required to adapt to an increase in global mean temperature of 4°C by 2100 may be significantly greater than adapting to lower magnitudes of change (Fung *et al.*, 2011; Gemenne, 2011; New *et al.*, 2011; Nicholls *et al.*, 2011; Stafford Smith *et al.*, 2011; Thornton *et al.*, 2011; Zelazowski *et al.*, 2011; 19.5.1) (*very high confidence*). This challenge arises from the magnitude of climate change, as well as the rate (Box 16-3).

A variety of non-climatic physical factors also can constrain adaptation efforts of natural systems (*very high confidence*). For example, migration can be constrained by geographical features such as lack of sufficient altitude to migrate vertically or barriers posed by coastlines or rivers (Clark *et al.*, 2011). Alternatively, Lafleur *et al.* (2010) identify soil conditions as a factor that may influence the migration of North American forests in response to climate change. Such physical barriers to migration can also arise from human activities. Feeley and Silman (2010) note that anthropogenic land use change can constrain the migration of Andean plant species to higher altitudes. Meanwhile, Titus *et al.* (2009) analyze state and local land use plans along the U.S. Atlantic coast and conclude that approximately 60% of coastal land below 1 meter in elevation is anticipated to be developed in the future, posing a physical barrier to inland migration of wetlands (see also Bulleri and Chapman, 2010; Jackson and McIlvenny, 2011). Collectively, such physical constraints can reduce available migration corridors and the distances over which migration is a feasible adaptive response.

Physical constraints have important implications for human adaptation as well (*high agreement, medium evidence*). For example, the distribution and abundance of water is a feature of the physical environment that is influenced by climate. Human consumption of freshwater increasingly is approaching the sustainable yield of surface and groundwater systems in a number of global regions (Shah, 2009; Pfister *et al.*, 2009, 2011a, b; 3.3.2; 3.5). Water-dependent enterprises in such regions may therefore have reduced flexibility to cope with transient or long-term reductions in water supply. This in turn influences the portfolio of adaptation actions that can be implemented effectively to manage risk to water security and, subsequently, agriculture and food security (Hanjra and Qureshi, 2010) as well as energy security (Voinov and Cardwell, 2009; Dale *et al.*, 2011). Similarly, water quality and soil quality can constrain agricultural activities and therefore the capacity of agricultural systems to adapt to a changing climate (Delgado *et al.*, 2011; Kato *et al.*, 2011; Lobell *et al.*, 2011; Olesen *et al.*, 2011).

It is important to note, however, that these physical characteristics of the environment are often amenable to management (*very high confidence*). The AR4 presented case studies where adaptive capacity was linked to the ability of human populations or communities to access physical capital (Adger *et al.*, 2007), such as machinery or infrastructure, to manage the environment and associated risks. Similar findings have appeared in more recent studies (Paavola, 2008; Thornton *et al.*, 2008; Iwasaki *et al.*, 2009; Badjeck *et al.*, 2010; Nelson *et al.*, 2010a, b). Human modification of the physical environment is particularly apparent in urban areas, where the location and design of buildings and infrastructure influence vulnerability to climate variability and change (8.2.2.2). However, past decisions regarding the built environment and its need for continual maintenance can constrain future adaptation options and/or their costs of implementation (16.3.2.10).

16.3.2.3. Biological Constraints

Since the AR4, the literature on biological (including behavioural, physiological, and genetic) tolerances of individuals, populations, and communities to climate change and extremes has continued to expand (4.4; 5.5.5; 6.2). This has resulted in a significant increase in the number of studies describing mechanisms by which biological factors can constrain the adaptation options for humans, non-human species, and ecological systems more broadly. In particular, biological characteristics influence the capacity of organisms to cope with increasing climate stress in situ through acclimation, adaptation, or behavior (Jensen *et al.*, 2008; Somero, 2010; Tomanek, 2010; Aitken *et al.*, 2011; Gale *et al.*, 2011; Sorte *et al.*, 2011; Donelson *et al.*, 2011) as well as the rate at which organisms can migrate to occupy suitable bioclimatic regions (Hill *et al.*, 2011; Morin and Thuiller, 2009; Feeley *et al.*, 2012) (*very high confidence*). Studies of humans also find age and geographic variation among populations with respect to perceptions of thermal comfort in indoor and outdoor space, which in turn influences the use of technologies (e.g., air conditioning, vegetation) and behaviour to adjust to the thermal environment (Indraganti, 2010; Chen and Chang, 2012;Yang *et al.*, 2012; Fuller and Bulkeley, 2013; Müller *et al.*, 2013).

The biological capacity for migration among non-human species is linked to characteristics such as fecundity, phenotypic and genotypic variation, dispersal rates, and interspecific interactions (Aitken *et al.*, 2008; Engler *et al.*, 2009; Hellmann *et al.*, 2012). For example, Aitken *et al.* (2008) argue that migration rates of tree species necessary to track a changing climate are higher than what has been observed since the last glaciation. However, Kremer *et al.* (2012) note that long-distance gene flow of tree species can span distances in one generation that are greater than habitat shifts predicted under climate change. Additional research is needed to clarify the capacity of species and communities to migrate in response to a changing climate.

The degradation of environmental quality is another source of constraints (Côté and Darling, 2010) (*very high confidence*), with multiple studies including natural capital as a foundation for sustainable livelihoods (Paavola, 2008; Thornton *et al.*, 2008; Iwasaki *et al.*, 2009; Badjeck *et al.*, 2010; Nelson *et al.*, 2010a, b). Non-climatic stresses to ecological systems can reduce their resilience to climate change as evidenced by studies on coral reefs and marine ecosystems, tropical forests, and coastal wetlands (Malhi *et al.*, 2009a, b; Diaz and Rosenberg, 2008; Kapos and Miles, 2008; Afreen *et al.*, 2011) (*very high confidence;* 4.2.4; CC-CR). For example, several studies have noted interactions between anthropogenic land use change and species migration rates on the risk of extirpation (Feeley *et al.*, 2010; Yates *et al.*, 2010; Cabral *et al.*, 2013; Svenning and Sandel, 2013).

Ecological degradation also reduces the availability of ecosystem goods and services for human populations (Nkem *et al*, 2010; Tobey *et al.*, 2010; 4.4.3; 6.4.1; (*very high confidence*). For example, degradation of coastal wetlands and coral reef systems may reduce their capacity to buffer coastal systems from the effects of tropical cyclones (Das and Vincent, 2009; Tobey *et al.*, 2010; Gedan *et al.*, 2011; Keryn *et al.*, 2011; Box CC-EA). Similarly, soil degradation and desertification can reduce crop yields and the resilience of agricultural and pastoral livelihoods to climate stress (Iglesias *et al.*, 2011; Lal, 2011).

Ecosystem constraints can also arise from non-native species, including pests and disease, that compete with endemic species (Hellman *et al.*, 2008; Dukes, *et al.*, 2009; Moser *et al.*, 2011; Ziska *et al.*, 2011; Pautasso *et al.*, 2012; Svobodová *et al.*, 2013) (4.2.4.6). Climate change could reduce the effectiveness of current control mechanisms for invasive species (Hellmann *et al.*, 2008) (*very low confidence*). However, studies also indicate that uncertainty associated with predictions of future pests, disease, and invasive species remains high (Dukes *et al.*, 2009).

16.3.2.4. Economic Constraints

The AR4 concluded that adaptive capacity is influenced by the entitlements of actors to economic resources and by larger macro-level driving forces such as economic development and trends in globalization (Adger *et al.*, 2007). More recent literature continues to identify economic constraints associated with adaptation. However, such constraints are often associated with the financing of discrete adaptation options (e.g., Matasci *et al.*, 2013; Islam *et al.*, 2014). This chapter draws a distinction between such financial constraints (16.3.2.5) and economic constraints, which are associated with broader macroeconomic considerations.

Long-term trends in economic development as well as short-term dynamics in economic systems can have a significant influence on the capacity of actors to adapt to climate change (*very high confidence*) (16.3.1.1). Multiple authors, for example, discuss the concept of ‘double exposure’ where actors are subjected to stresses associated with climate change as well as those associated with economic disruptions such as the recent global financial crisis or other stresses (Leichenko *et al.*, 2010; Silva *et al.*, 2010; Leichenko, 2012; Jeffers, 2013; McKune and Silva, 2013). Similarly, Kiem and Austin (2013) argue that prevailing economic conditions have an important influence on the capacity of Australian farmers to cope with drought.

The implications of economic constraints vary among different sectors that have differential vulnerability to climate change. Economies that are disproportionately comprised of climate-sensitive sectors such as agriculture, forestry and fisheries, may be particularly vulnerable to the effects of climate change and may encounter greater constraints on their capacity to adapt (*very high confidence*). Such economies occur disproportionately in the developing world (Thornton *et al.*, 2008; Allison *et al.*, 2009; Feng *et al.*, 2010; Füssel, 2010), although multiple studies have explored climate-sensitive regional economies in developed nations as well (Edwards *et al.*, 2009; Aaheim *et al.*, 2012; Leichenko *et al.*, 2010; Kiem and Austin, 2013). Poverty and development deficits that are linked to economic conditions also exist in urban areas (8.1.3; 8.3.2.1).

While economic development and diversification are generally seen as factors that can ameliorate resource deficits (20.2.1.2; 20.3.2), certain economic enterprises can constrain adaptation. For example, the AR4 noted that activities such as shrimp farming and conversion of coastal mangroves, while profitable in an economic sense, can exacerbate vulnerability to sea-level rise (Agrawala *et al.*, 2005 in Adger *et al.*, 2007). More recent studies have demonstrated that economic development and urbanization of hazardous landscapes may increase human exposure to extreme weather events and climate change resulting in greater economic losses and risks to public health and safety (Baldassare *et al.*, 2010; IPCC, 2012; Preston, 2013). Economic development also can put pressure on natural resources and ecosystems that can constrain their capacity to adapt (Titus *et al.*, 2009; Sydneysmith *et al.*, 2010; 16.3.2.3; 20.3.2). The extent to which economic development creates opportunities or constrains adaptation is dependent on the development pathway (17.4.3; 20.6). Low resource-intensive economic growth can enhance adaptive capacity while minimizing externalities of development that can increase vulnerability of human and natural systems (20.6).

16.3.2.5. Financial Constraints

In addition to broader macroeconomic constraints on adaptation (16.3.2.4), the implementation of specific adaptation strategies and options can be constrained by access to financial capital (*very high confidence*). Financial capital can manifest in a variety of forms including credit, insurance, tax revenues, as well as earnings of individual households or private entities. The AR4 concluded that the global costs of adaptation could be quite substantial over the next several decades (Adger *et al.*, 2007). More recent studies suggest costs on the order of $75 to $100 billion per year by 2050 (17.6; Table 17-2). In the context of the UNFCCC, mechanisms have been established to help meet these costs. The Least Developed Country Fund was established to assist developing nations in developing National Adaptation Plans of Action (14.5.4; 15.2.2.1; 15.2.2.2). The Adaptation Fund was established within the context of the UNFCCC to finance adaptation in developing nations through the sale of certified emissions reductions credits (CERs) under the Clean Development Mechanism (14.3.2; 15.2.2.1). Nevertheless, declines in CER prices since early 2011 have reduced the flow of revenue to the Adaptation Fund (Adaptation Fund Board, 2013), and the demand for adaptation finance in general is larger than the current availability of resources represented through these funds (Bouwer and Aerts, 2006; Flåm and Skjærseth, 2009; Hof *et al.*, 2009). Furthermore, developing a framework for the equitable and effective allocation of adaptation funds to developing nations is a non-trivial challenge (Barr *et al.*, 2010; Smith *et al.*, 2009a).

Overseas development assistance (ODA) represents another mechanism for channeling financial capital into adaptation programs and projects. However, multiple authors have identified potential constraints associated with the use of ODA for financing adaptation including concerns among donors for the effectiveness of ODA (Kalirajan *et al.*, 2011), lack of incentives among donors to allocate ODA to adaptation (Buob and Stephan, 2013), and potential for allocation of ODA to adaptation to reduce the availability of funds for achieving development goals (Ayers and Huq, 2009).

The potential for finance to constrain adaptation also emerges from a broad range of recent case studies exploring adaptive capacity in different sector and regional contexts, although finance is often identified as just one of a broad range of resource constraints (Paavola, 2008; Jantarasami *et al.*, 2010; Moser and Ekstrom, 2010; Osbahr *et al.*, 2010; Biesbroek *et al.*, 2013a). Investigations of farming communities in Africa have identified finance as a key determinant of vulnerability and adaptive capacity of farmers to climate variability and change (Nhemachena and Hassan, 2007; Hassan and Nhemachena, 2008; Deressa *et al.*, 2009, 2011). Islam *et al.* (2014) cite access to credit as a key constraint on adaptation among fishing communities in Bangladesh, and financial constraints have also been documented in municipal governments in South Africa (Pasquini *et al.*, 2013). Huntington *et al.* (2012) question whether relocating the 184 Alaskan Native villages threatened by coastal erosion and inundation is politically feasible given the high costs, estimated at up to $1 million per person or $100 million per village on average.

Institutions in developed nations face constraints in funding adaptation options despite their comparatively high adaptive capacity. For example, Jantarasami *et al.* (2010) report that staff from U.S. federal land management agencies identified resource constraints as a key barrier to adaptation. Similarly, surveys and interviews with state and local government representatives in Australia indicate that the costs of investigating and responding to climate change are perceived to be significant constraints on adaptation at these levels of governance (Smith *et al.*, 2008b; Gardner *et al.*, 2010; Measham *et al.*, 2011). However, Burch (2010) argues that financial constraints on adaptation reported by local governments in Canada are secondary to other institutional practices and cultures (16.3.2.8).

Insurance represents a cross-cutting financial instrument that is relevant to a range of public and private institutions in both developing and developed nations. While insurance can represent an opportunity to influence decision-making regarding climate risk management (Næss *et al.*, 2005; Herweijer *et al.*, 2009; 10.7), reduced accessibility and/or increased costs of insurance can constrain the utility of insurance as an adaptation option (Herwijer *et al.*, 2009; Islam *et al.*, 2014; 10.7).

16.3.2.6. Human Resource Constraints

The effectiveness of societal efforts to adapt to climate change is dependent upon humans who are the primary agents of change (*very high confidence*). Human resources provide the foundation for intelligence gathering, the uptake and use of technology, as well as leadership regarding the prioritization of adaptation policies and measures and their implementation. Although the AR4 and subsequent adaptation literature identify human resources as one of the factors influencing adaptive capacity (Adger *et al.*, 2007), there has been little attention given specifically to human resources as a constraint on adaptation by adaptation researchers. Rather the literature mentions human resources in two principle contexts. First, it highlights the linkages between the development of human resources and adaptive capacity more broadly. For example, Ebi and Semenza (2008) treat human resources as part of the portfolio of resources that can be harnessed to facilitate adaptation in the public health arena. Similarly, Nelson *et al.* (2010a, b) use human capital as one indicator of the capacity of rural communities to cope with climate impacts. In addition, a number of recent studies call attention to the role of leadership in enabling or constraining organisational adaptation (Gupta *et al.*, 2010; Tompkins *et al.*, 2010; Termeer *et al.*, 2012; van der Berg *et al.*, 2010). Murphy *et al.* (2009) discuss the emergence of institutions to build human resources in the climate change arena, including expanded higher education opportunities to build climate expertise as well as professional societies. Second, the literature highlights the finite nature of human resources as a need to prioritize adaptation efforts including the extent of engagement in participatory processes (van Aalst *et al.*, 2008) as well as the selection of adaptation actions for implementation (Millar *et al.*, 2007).

16.3.2.7. Social and Cultural Constraints

Adaptation can be constrained by social and cultural factors that are linked to societal values, world views, and cultural norms and behaviors (O'Brien, 2009; Moser and Ekstrom, 2010; O'Brien and Wolf, 2010; Hartzell-Nichols, 2011) (*very high confidence*). These social and cultural factors can influence perceptions of risk, what adaptation options are considered useful and by whom, as well as the distribution of vulnerability and adaptive capacity among different elements of society (Grothmann and Patt, 2005; Weber, 2006; Patt and Schröter, 2008; Kuruppu, 2009; Adger *et al.*, 2009; O'Brien, 2009; Nielsen and Reenberg, 2010; Wolf and Moser, 2011; Wolf *et al.*, 2013). Although the AR4 noted that social and cultural constraints on adaptation have not been well researched, more recent literature has significantly expanded their understanding. As a case-in-point, the erosion of traditional knowledge among the Arctic Inuit is the consequence of a long-term process of changing livelihoods, technology, and sources of knowledge (Pearce *et al.*, 2011; 16.3.2.1). Studies from the United States indicate that increasing demand for amenity lifestyles is resulting in the settlement of individuals in locations where there is little experience or oral history regarding natural hazards – a phenomenon that subsequently influences risk perception and engagement in risk management (Heyd and Brooks, 2009; Gordon *et al.*, 2013).

Different actors within and among societies experience different constraints, which result in differential adaptive capacities and preferences for adaptation options (Wolf *et al.*, 2013). As discussed in the AR4, for example, gender can be a factor that constrains adaptation. Recent studies from Nepal and India report that adaptation decisions among women, in particular, can be constrained by cultural and institutional pressures that favor male land ownership (Jones and Boyd, 2011) and constrain access to hazard information (Ahmed and Fajber, 2009), respectively. Studies of evacuation during hurricane Katrina suggest that females were more likely to evacuate New Orleans than males (Brunsma *et al., 2*010), as were individuals without sufficient resources and access to transportation (Cutter and Emrich, 2006). Studies from both the United States and United Kingdom find that the elderly do not necessarily perceive themselves as vulnerable to extreme heat events (Sheridan, 2007; Wolf *et al.*, 2009), which may create disincentives to react to such events (Chapter 11).

Barriers to taking action have also been attributed to sense of place, which shapes individual identity (Adger *et al.* 2011; 2012; Fresque-Baxter and Armitage, 2012). Foresight (2011) notes that processes that constrain migration could be maladaptive, resulting in the abandonment of livelihoods or geographic locations. For example, Park *et al.* (2012) find that sense of place attachment among some wine grape growers in Australia precludes consideration for migration to other growing areas in response to a changing climate.

Case studies from multiple developing countries report that some actors view natural phenomena as being controlled by God, supernatural forces, or ancestral spirits which are not amenable to human management (Sehring, 2007; Schipper, 2008; Byg and Salick, 2009; Mustelin *et al.*, 2010; Kuruppu and Liverman, 2011; Artur and Hilhorst, 2012). Such perspectives are not confined to the developing world. Surveys conducted after Hurricane Katrina also indicated that religious beliefs were a factor influencing the decision to remain rather than evacuate (Brunsma *et al.*, 2010).Yet, religion was also identified as a factor that enabled affected individuals to cope with the stress of the event.

16.3.2.8. Governance and Institutional Constraints

Research conducted since the AR4 has expanded understanding of adaptation constraints associated with governance, institutional arrangements, and legal and regulatory issues. Adaptation to climate change will necessitate the mobilization of resources, decision-making, and the implementation of specific policies by societal institutions (Huang *et al.*, 2011). Yet, these processes may be most effective when they are aligned to the given context and group of actors (Berkhout, 2012; Garschagen, 2013). The adaptation literature provides extensive evidence that institutional capacity is a key factor that can potentially constrain the adaptation process (Berkhout, 2012) (*very high confidence*). Lesnikowski *et al.* (2013), for example, find that planned adaptation by the public health sector among different nations is significantly associated with national GDP. Similarly, it’s been argued that U.S. institutions across different levels of governance lack the mandate, information, and/or professional capacity to select and implement adaptation options (NRC, 2009). Institutional capacity may be linked to the level of priority assigned to adaptation (Keskitalo *et al.*, 2010; Westerhoff *et al.*, 2010; Measham *et al.*, 2011; Sowers *et al.*, 2011; Maibach *et al.*, 2011). For example, Ebi *et al.* (2009) argue that U.S. public health agencies allocate less than US$3 million per year to address climate change, yet a budget greater than US$200 million is needed to adequately address the problem. Keskitalo (2010) and Lesnikowski *et al.* (2013) find that adaptation efforts are associated with the extent to which institutions prioritize environmental management more broadly. Corruption within institutions may also undermine adaptation efforts, as evidenced by empirical studies among multiple nations (Lesnikowski *et al.*, 2013), as well as case studies within nations (Schilling *et al.*, 2012)

A key role that institutions play in facilitating adaptation is through legal and regulatory responsibilities and authorities (*very high confidence*). Multiple studies have documented the adaptation constraints affecting institutions in Australia engaged in the development of local and regional planning policy (Pini *et al.*, 2007; Measham *et al.*, 2011; Matthews, 2013). Similar capacity constraints have been observed within institutions governing Canada’s Inuit population (Ford *et al.*, 2010). Li and Huntsinger (2011) observe how increasing land privatization and the institutionalization of rigid land tenure in the Inner Mongolia region of China have reduced the resilience of pastoralists to cope with drought, although the lack of secure land tenure has been found to constrain adaptation in other contexts (Almansi, 2009; Ebi *et al.*, 2011; Hisali *et al.*, 2011; Larson, 2011; 8.4.2.2; 9.3.5.2.3). In addition to such capacity issues, multiple studies from both developed and developing nations suggest that the current structure of institutions and regulatory policies may be poorly aligned to achieve adaptation objectives (Craig, 2010; Spies, 2010; Stillwell *et al.*, 2010; Stuart-Hill and Schulze, 2011; Eisenack and Stecker; 2012; Huntjens *et al.*, 2012; Herrfahrdt-Pähle, 2013), Changing legal principles to accommodate more forward-looking adaptation responses as opposed to basing them on historical precedent and practice may be a difficult process (Craig, 2010; McDonald, 2011).

Adaptation can also be constrained due to the complexities of governance networks that often comprise multiple actors and institutions such as government agencies, market actors, non-governmental organizations, as well as informal community organizations and social networks (Rosenau, 2005; Adger *et al.*, 2009; Juhola and Westerhoff, 2011; Carlsson-Kanyama *et al.*, 2013; Sosa-Rodriguez, 2013) (*very high confidence*). Coordination among these different actors is important for facilitating adaptation decision-making and implementation (Young, 2006; van Nieuwaal *et al.*, 2009; Grothmann, 2011). Yet, different actors may have different objectives, jurisdictional authority, as well as levels of power or resources. Adaptation efforts may recognize these constraints, but don’t necessarily articulate institutional arrangements that facilitate their coordination and reconciliation to achieve common adaptation objectives (Zinn, 2007; Preston, 2009; Birkmann *et al.*, 2010; 15.3.1). This may arise, in part, from the dominant focus of the adaptation discourse on formal, public institutions of governance (Eisenack *et al.*, 2012), although work examining the role of private institutions has emerged recently (Tompkins *et al.*, 2010; CDP, 2012; Mees *et al.*, 2012; Taylor *et al.*, 2012; Tompkins and Eakin, 2012; EBI, 2013; 14.4.8).

Actors and institutions associated with different scales may have different perceptions of the need for adaptation as well as the factors that constrain or enable adaptation (Biesbroek *et al.*, 2011) (*very high confidence*). In this context, scale refers to analytical dimensions used to study adaptation (including spatial, temporal, institutional or jurisdictional), and each scale can be comprised of multiple levels (e.g., local to global in the context of spatial scales or household to central government in the context of jurisdictions of governance) (Cash *et al.*, 2006; Adger *et al.*, 2009). A large number of studies have emerged since the AR4 that focus on how local adaptation efforts are constrained by higher levels of governance, such as state or federal governments or private companies (Urwin and Jordan, 2008; Huntjens *et al.*, 2010; Abel *et al.*, 2011; Measham *et al.*, 2011; Pittock, 2011; Westerhoff *et al.*, 2011; Amaru and Chhetri, 2013; Carlsson-Kanyama *et al.*, 2013; Mukheibir *et al.*, 2013; Sosa-Rodriguez, 2013). This has led some to question whether it is appropriate to consider adaptation as an exclusively local process (Burton *et al.*, 2008; Preston *et al.*, 2013b). For example, a study of adaptation policy initiatives in EU member countries concluded that central governments can play a significant role in supporting local adaptation policies. However, in cases where there is weak top down leadership on adaptation, it may be useful to have less centralized mechanisms for supporting local adaptation efforts (Keskitalo, 2010). In addition, EU funding has enabled local adaptation even in the absence of funding from the relevant EU member state (Keskitalo, 2010), suggesting opportunities exist for trans-national governance to overcome adaptation constraints. Other authors have also noted that informal social institutions may help to extend the reach of formal government actors (Wolf *et al.*, 2010; Juhola and Westerhoff, 2011) or drive adaptation processes when formal actors are unable to do so (Measham and Preston, 2012). Adaptation planning and implementation thus creates new governance challenges, and new institutions and bridging organizations may be needed to facilitate integration of complex planning processes across scales (Preston, 2009; NRC, 2010; UKCIP, 2011) (*high agreement, medium evidence*).

16.3.2.9. Constraints and Competing Values

A number of the aforementioned types of adaptation constraints arise from a common cause – the differential values of societal actors and the trade-offs associated with prioritizing and implementing adaptation options (Haddad, 2005; UNEP, 2011; 2.3.3; Table 16-2) (*very high confidence*). At the international level, for example, agreements such as the Bali Action Plan (UNFCCC, 2007a) and Cancun Adaptation Framework (UNFCCC, 2011) indicate that deliberation over how the adaptation needs of least developed countries will be financed has become central to the UNFCCC policy agenda (see also UNFCCC, 2007b; Ayers and Huq, 2009; Dellink *et al.*, 2009; Flåm and Skjærseth, 2009; Denton, 2010; Patt *et al.*, 2010a). Yet the extent to which the developed world bears responsibility for compensating the developing world for climate impacts has been a contentious issue (Hartzell-Nichols, 2011). Rayner and Jordan (2010) and Brouwer *et al.* (2013) report concern among EU water policy-makers that adaptation may undermine efforts to maintain water quality. For example, technological solutions to enhance water supply in a changing climate may occur at the expense of water quality. Alternatively, placing adaptation on the policy agenda may create the perception that climate change will eventually necessitate the acceptance of reduced water quality. At the local level, Measham *et al.* (2011) report that some local governments in Australia find it difficult to pursue adaptation efforts due to perceived conflicts between potential adaptation options and the values and preferences of individuals and stakeholder groups within the community.

Such potential differences among stakeholders regarding adaptation options may result in some actions being simultaneously perceived as adaptive and maladaptive (Bardsley and Hugo, 2010) (*medium agreement, limited evidence*). Maladaptation arises from the implementation of adaptation options that increase the vulnerability of individuals, institutions, sectors, or regions (Barnett and O'Neill, 2010). Individuals or institutions may have specific management objectives or values that they seek to achieve or maintain through adaptation (16.2, Table 16-2). For every objective, however, there may be multiple adaptation options, each of which is associated with a particular set of costs, benefits, and externalities. For example, biotechnology may contribute to the development of drought and pest resistant cultivars that can maintain or enhance yields despite more challenging climate conditions. Yet, ecological and public health concerns over the use of biotechnology and genetically modified crops, in particular, can constrain the use of such technologies (Table 16-2). Agricultural producers may view biotechnology as an adaptive response, while some consumers may view it as a maladaptation that increases risks to ecosystems and food security. Similar types of trade-offs can be identified across different sectors (Table 16-2), and thus a challenge in adaptation planning and implementation is determining who decides what options are adaptive or maladaptive and successful or unsuccessful. The potential for maladaptation or for some adaptation options to undermine sustainability (Eriksen *et al.*, 2011), suggests that actors may choose to regulate adaptation and deliberately constrain possible options to avoid adverse externalities (*very low confidence*).

Recognizing the potential for values conflicts to constrain adaptation, researchers and practitioners have advocated for so-called ‘no regrets’ or ‘low regrets’ adaptation strategies that create net benefits under the current climate as well as a range of future potential climates (Hallegatte, 2009; Heltberg *et al.*, 2009). Such strategies can focus adaptation efforts on options where there are fewer perceived trade-offs (Preston *et al.*, 2013b). However, identifying options that are perceived as having no regrets across all potential stakeholders may be quite difficult (Merz *et al.*, 2010; Preston *et al.*, 2013b), and it has been suggested such strategies may reduce the perceived need for more substantive adaptations necessary to protect highly vulnerable systems or avoid irreversible consequences (Preston *et al.*, 2013b). Reconciling such trade-offs may necessitate deliberation among decision-makers and other stakeholders regarding adaptation objectives and the manner in which competing or conflicting values can be reconciled to achieve outcomes (McNamara and Gibson, 2009; de Bruin *et al.*, 2009b; McNamara *et al.*, 2011; UNEP, 2011).

[INSERT TABLE 16-2 HERE
Table 16-2: Examples of potential trade-offs associated with an illustrative set of adaptation options that could be implemented by actors to achieve specific management objectives.]

16.3.2.10. Consideration of Cross-Scale Dynamics

The AR4 noted that adaptation processes can be constrained by interactions and dynamics within or among different scales (Adger *et al.*, 2007). Recent literature since the AR4 has expanded understanding of vulnerability and adaptive capacity as a cross-scale and multi-level process (16.3.2.8). The vulnerability of different communities, regions, and sectors are linked through processes and feedbacks that span multiple scales and levels (*high agreement, medium evidence*). Adger *et al.* (2008) and Eakin *et al.* (2009) refer to this phenomenon as “nested and teleconnected vulnerability.”

A number of recent studies focused on agriculture and global commodities provide evidence of this phenomenon, (see also 16.3.2.8). Adger *et al.* (2008) and Eakin *et al.* (2009) illustrate such teleconnected vulnerability with case studies of coffee production. Although coffee is a global commodity, the majority of production occurs in developing nations among small-scale farmers. As such, household vulnerability and adaptive capacity among coffee farmers is linked to global markets and coffee prices as well as local environmental conditions and policies. Such interactions were also apparent in 2006–2008 and again in 2010–2011 when global food commodity prices increased sharply in part due to the impacts of extreme weather events on food producing regions (FAO, 2011). The resulting increase in food prices benefited producers that were unaffected by the drought who were able to capitalize on higher prices, but higher prices adversely affected consumer welfare and food security (Abbott and de Battisti, 2009; Woden and Zaman, 2009; FAO, 2011). Similar constraints on adaptation arise in the context of transboundary water resources where river management is influenced by processes occurring at different jurisdictional levels (i.e., local, regional, national, and international water policies and management practice) as well as different spatial levels (e.g., linkages between global climate change and climate trends at more regional or local levels) (Iglesias *et al.*, 2007; Goulden *et al.*, 2009; Krysanova *et al.*, 2010; Huntjens *et al.*, 2010; Timmerman *et al.*, 2011; Wilby and Keenan, 2012; Milman *et al.*, 2013).

Constraints on adaptation are also associated with temporal scaling. A key factor constraining future adaptation options and costs is path dependence (*very high confidence*), which Preston (2013, pg. 719) defines as “*the dependence of future societal decision processes and/or socio-ecological outcomes on those that have occurred in the past*.” Libecap (2010) suggests that water infrastructure developed in the U.S. West in the late-19th and early 20th centuries has constrained management choice regarding water allocation in the present. Chhetri *et al.* (2010) suggest similar constraints may exist for the U.S. agricultural industry in the future due to constraints on farmers' capacity to alter management practices and technology in response to a changing climate. Major development of water management and allocation systems in watersheds of Australia and the U.S. Southeast over the latter half of the 20th century occurred during periods of favorable rainfall relative to long-term instrumental and paleo records (Jones and Pittock, 2002; Jones, 2010; Chiew *et al.*, 2011; Pederson *et al.*, 2012), and thus those systems were adapted to conditions that were not representative of the long-term risk of extensive drought (Jones and Pittock, 2002; Jones, 2010; Connell and Grafton, 2011; Pederson *et al.*, 2012).

Adjusting large-scale, complex systems and institutional behavior established by past decision-making can be costly. The Australian Government, for example, has engaged in a water management reform process since the 1980s (Connell and Grafton, 2011), and in recent years has committed more than AUS$12.9 billion for a number of initiatives to address historical resource over-allocation and support sustainable water management practices in the Murray-Darling Basin (Commonwealth of Australia, 2010). In order to avoid adverse outcomes associated with path dependence, the literature on flexible adaptation pathways emphasizes the implementation of reversible and flexible options that allow for ongoing adjustment (Stafford Smith *et al.*, 2011; Haasnoot *et al.*, 2013). In addition, the literature on 'real options' suggests that, under certain circumstances, there may be value in such flexible adaptation strategies or in delaying investments in certain adaptation options until new information or management options are available (Hertzler, 2007; Dobes, 2008; Jeuland and Whittington, 2013).

16.4. Limits to Adaptation

The various constraints discussed previously (16.3.2) can, if sufficiently severe, pose limits to the ability of actors to adapt to climate change (Meze-Hausken, 2008; O'Brien, 2009; Adger *et al.*, 2009; Moser and Ekstrom, 2010; Dow *et al.*, 2013a, b) (*high agreement, medium evidence*). A 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 (Box 16-1). For example, one of the key messages from the WGII chapter on Africa (Chapter 22) is, "*Progress is being achieved on managing risks to food production from current climate variability but these will likely not be sufficient to address long-term risks from climate change (high confidence)*."

There are a variety of circumstances and terminology in the literature that imply adaptation limits including 'thresholds' (Meze-Hausken, 2008; Briske *et al.*, 2010; Washington-Allen *et al.*, 2010); 'regime shifts' (Washington-Allen *et al.*, 2010); 'tipping points' (Lenton *et al.*, 2008; Kriegler *et al.*, 2009); 'dangerous climate change' (Mastrandrea and Schneider, 2004; Ford, 2009a); 'reasons for concern' (Smith *et al.*, 2009a); 'planetary boundaries' (Rockström *et al.*, 2009); or 'key vulnerabilities' (Schneider *et al.*, 2007; Johannessen and Miles, 2011; Hare *et al.*, 2011; 19.6). In addition, terms such as barriers, constraints, and limits are sometimes used interchangeably. Due to this diversity in language, this discussion builds on recent efforts to develop a common lexicon to facilitate research and practice (Hulme *et al.*, 2007; Adger *et al.*, 2009; Dow *et al.*, 2013a, b; 16.2; Box 16-1).

_____ START BOX 16-4 HERE _____

Box 16-4. Historical Perspectives on Limits to Adaptation

Does human history provide insights into societal resilience and vulnerability under conditions of environmental change? Archeological and environmental reconstruction provides useful perspectives on the role of environmental change in cases of significant societal change – sometimes termed 'collapse' (Diamond, 2005). These may help to illuminate how adaptation limits were either exceeded, or where collapse was avoided to a greater or lesser degree. Great care is necessary to avoid over-simplifying cause and effect, or over-emphasizing the role of environmental change, in triggering significant societal change, and the societal response itself. Coincidence does not demonstrate causality, such as in the instance of matching climatic events with social crises through the use of simple statistical tests (Zhang *et al.*, 2011), or through derivative compilations of historical data (deMenocal, 2001; Thompson *et al.*, 2002; Drysdale *et al.*, 2006; Butzer, 2012). Application of social theories may not explain specific cases of human behavior and community decision-making, especially because of the singular importance of the roles of leaders, elites and ideology (Hunt, 2007; McAnany and Yoffee, 2010; Butzer and Endfield, 2012; Butzer, 2012).

There are now roughly a dozen case studies of historical societies under stress, from different time ranges and several parts of the world, that are sufficiently detailed (based on field, archival, or other primary sources) for relevant analysis (Butzer and Endfield, 2012). These include Medieval Greenland and Iceland (Dugmore *et al.*, 2012; Streeter *et al.*, 2012); Ancient Egypt (Butzer, 2012); Colonial Cyprus (Harris, 2012); the prehistoric Levant (Rosen and Rivera-Collazo, 2012); Islamic Mesopotamia and Ethiopia (Butzer, 2012); the Classic Maya (Dunning *et al.*, 2012; Luzzadder-Beach *et al.*, 2012); and Colonial Mexico (Endfield, 2012). Seven such civilizations underwent drastic transformation in the wake of multiple inputs, triggers, and feedbacks, with unpredictable outcomes. These can be seen to have exceeded adaptation limits. Five other examples showed successful adaptation through the interplay of environmental, political and socio-cultural resilience, which responded to multiple stressors (e.g., insecurity, environmental or economic crises, epidemics, famine). In these cases, climatic perturbations are identified as only one of many 'triggers' of potential crisis, with preconditions necessary for such triggers to stimulate transformational change. These preconditions include human-induced environmental decline mainly through over-exploitation.

Avoidance of limits to adaptation requires buffering feedbacks that encompass social and environmental resilience. Exceedance of limits occurred through cascading feedbacks that were characterized by social polarization and conflict that ultimately result in societal disruption. Political simplification undermined traditional structures of authority to favor militarism, while breakdown was accompanied or followed by demographic decline. Although climatic perturbations and environmental degradation did contribute to triggering many cases of breakdown, the most prominent driver at an early stage was institutional failure, which refers to the inability of societal institutions to address collective-action problems (Acheson, 2006). In these cases, collapse was neither abrupt nor inevitable, often playing out over centuries. Lessons from the implementation of adaptation responses over historical time periods in Mexico City suggest that some responses may create new and even more significant risks (Sosa-Rodriguez, 2010).

Recent work on resilience and adaptation synthesizes lessons from extreme event impacts and responses in Australia (Kiem *et al.*, 2010). This further emphasizes an institutional basis for resilience, finding that government intervention through the provision of frameworks to enable adaptation is beneficial. Furthermore, it was found that a strong government role may be necessary to absorb a portion of the costs associated with natural disasters. On the other hand, community awareness and recognition of novel conditions were also found to be critical elements of effective responses. It would be useful to consider how lessons learned from historical experience may relate to the perceived multiple environmental changes characterized by the "Anthropocene" era (Crutzen, 2002).

16.4.1. Hard and Soft Limits

Although limits to adaptation are at times described in the literature as fixed thresholds (Adger *et al.*, 2009), recent studies have emphasized the need to consider the perspective of actors in defining adaptation limits (Adger *et al.*, 2009; Dow *et al.*, 2013 a, b; 16.1; 16.2) as well as the dynamic nature of both biophysical and socioeconomic processes that influence adaptation decision-making and implementation (Park *et al.*, 2012; Preston *et al.*, 2013a; Islam *et al.*, 2014). Informed by the distinctions drawn in the work of Meze-Hausken (2008), Adger *et al.* (2009), and Moser and Ekstrom (2010), one can distinguish between 'hard' limits, those that will not change, and 'soft' limits, which could change over time. For human actors, whether a limit is hard or soft is usefully evaluated at a given point in time by asking whether an adaptation response to manage an intolerable risk could emerge in the future. For example, projected climate change impacts in Europe indicate that increasing irrigation needs will be constrained by reduced runoff, demand from other sectors, and economic costs. As a consequence, by the 2050s farmers will be limited by their inability to use irrigation to prevent damage from heat waves to crops (23.4.1; 23.4.3). For natural systems, whether a limit is hard or soft is defined by the rate and capacity of species and ecosystem responses relative to environmental changes (Shaw and Etterson, 2012).

Discussions of hard limits in the literature are often associated with thresholds in physical systems that, if exceeded, would lead to irreversible changes or the loss of critical structure or function (Lenton *et al.*, 2008; Adger *et al.*, 2009; IPCC, 2012). Such limits arise from the magnitude and/or rate of climate change (Box 16-3). For example, a number of physical thresholds in the Earth system have been proposed as posing potential limits to adaptation, particularly large-scale events such as irreversible melting of the Greenland or Antarctic Ice Sheets (Schneider and Lane, 2006a; Sheehan *et al.*, 2008; Travis, 2010). Such physical thresholds, however, though relevant to understanding adaptation limits, are not necessarily limits in themselves as they neglect consideration for the adaptive capacity of natural and human systems (Leary *et al.*, 2009; Adger *et al.*, 2009; Dow *et al.*, 2013a, b; Klein and Juhola, 2013; Preston *et al.*, 2013a).

For species and ecosystems, hard limits to adaptation are often associated with exceedance of the physiological capacity of individual organisms or communities to adapt to changes in the climate (i.e., temperature, rainfall, and/or disturbance regimes (Peck *et al.*, 2009); or to climate-induced changes in the abiotic environment (e.g., ocean circulation and stratification, (Harley *et al.*, 2006; Doney *et al.*, 2012) (16.3.2.2; 16.3.2.3). Such systems tend to be those that persist at the upper limit of their climate tolerances (Sheehan *et al.*, 2008; Dirnböck *et al.*, 2011; Benito *et al.*, 2011); those for which sustainability is closely tied to vulnerable physical systems (Johannessen and Miles, 2011); or those that are under significant pressure from non-climatic forces (Jenkins *et al.*, 2011). For example, many species, including humans (11.8.1) and key food crops (e.g., wheat, maize, and rice; 7.3.2; 11.8.2) are known to have thermal limits to survival. Similarly, increased ocean acidity is expected to reduce the ability of some marine organisms such as corals to grow, posing threats of significant ecosystem damage (CC-OA; CC-CR). Nevertheless, defining those limits remains challenging due to system complexity and lack of information regarding responses across different levels of biological organization (Steffen *et al.*, 2009; Wookey *et al.*, 2009; Lavergne *et al.*, 2010; Preston *et al.*, 2013a). Furthermore, species have mechanisms for coping with climate change including phenotypic plasticity (Charmantier *et al.*, 2008; Matesanz *et al.*, 2010) genetic (evolutionary) responses (Gienapp *et al.*, 2008; Bradshaw and Holzapfel, 2006; Visser, 2008; Wang *et al.*, 2013), and range shifts (Colwell *et al.*, 2008; Thomas, 2010; Chen *et al.*, 2011; 16.3.2.3). Such mechanisms influence adaptation limits by extending the range of climate conditions with which individual organisms can cope in situ and/or enabling species to migrate over time to more suitable climates. Yet, more comprehensive assessments of such adaptive mechanisms are needed to develop robust understanding of ecological limits.

While human systems may also experience hard limits, such systems are influenced by exogenous climate change as well as endogenous processes such as societal choices and preferences (Adger *et al.*, 2009). This creates the potential for limits encountered by actors to be soft. Although they may limit adaptation for the current planning horizon, they may be ameliorated in the future by changing circumstances. Various authors have noted that adaptation limits are socially-constructed by human agency in that economics, technology, infrastructure, laws and regulations, or broader social and cultural considerations can limit adaptation (Flåm and Skjærseth, 2009; O'Brien, 2009; Adger *et al.*, 2009; de Bruin *et al.*, 2009b; Wilbanks and Kates, 2010; McNamara *et al.*, 2011; Morrison and Pickering, 2012; 16.3) (*high agreement*, *medium evidence*). Cost-benefit analyses and associated discount rates, for example, reflect a social value on investment returns (17.3.7.2). Yet, Morgan (2011) notes that adaptation planning based on cost-benefit analysis can pose limits to adaptation by discounting the future economic benefits of adaptation actions and excluding non-market benefits. Meanwhile, increasing loss and damage from societal exposure and climate change may pose financial limits to the insurability of disaster risks (10.7.3), which ultimately influences what activities can occur in certain locations. All of these factors are dynamic and can change over time. The Shared Socioeconomic Pathways, which have been designed to facilitate comparison of findings across modeling teams, reflect different perspectives on future changes in the capacity of actors to adapt (Kriegler *et al.*, 2012; Ebi *et al.*, 2013; Schweizer and O'Neill, 2013; van Ruijven *et al.*, 2013). Given rising incomes and advances in knowledge and technology, a greater number of adaptation options may become available to a greater number of actors over time. In contrast, impediments to development, constraints on investments in adaptation, or rapid escalations in risk may increase the likelihood of experiencing a limit.

Societal assessments of risk and willingness to invest in risk management are subject to many influences (Renn, 2008; IPCC, 2012; 14.3.1.1), such as experience of a recent disaster, some of which can result in rapid changes (Ho *et al.*, 2008; Breakwell, 2010; Renn, 2011). Adger *et al.* (2009; pg. 338), argue that many limits to adaptation are dependent on the changing goals, values, risk tolerances and social choices of society which make them "*mutable,* *subjective, and socially constructed*." Similarly, Meze- Hausken (2008) views adaptation as being triggered in part by subjective thresholds including perceptions of change; choices, needs, and values; and expectations about the future (see also O'Brien, 2009). For instance, the distribution of grape suitability will change in response to climate change, but the potential for relocation as an adaptation is limited by the concept of 'terroir', which reflects biophysical traits and local knowledge and wine making traditions to a cultural landscape (Box 23-1). However, terroir could become a soft limit if the rigid, regionally defined regulatory frameworks and concepts of regional identity that prescribe what grapes can be grown where were to become more geographically flexible and tied to the culture and history of the winemakers rather than regional climate and grape suitability (Box 23-1).

Limits also have scale-dependent properties (see also 16.3.2.10) (*high agreement, limited evidence*). Adaptation finance and capacity building activities more broadly, for example, enable resources for adaptation to be transferred from a variety of governmental and non-governmental entities to developing nations in order to overcome soft limits to adaptation (16.3.2.5). For example, a local community may not have the necessary resources to adapt, but these constraints may be overcome by drawing in resources, such as technical expertise, from regional, national, or international authorities as well as from NGOs, other civil society organizations, or the private sector (16.3.2.5). Scale-dependence also manifests among different actors within sectoral supply chains. For example, climate change that poses limits to the sustainability of an individual farm enterprise may have less impact on a national or international agribusiness (Park *et al.*, 2012).

16.4.2. Limits and Transformational Adaptation

Adaptation has traditionally been viewed as a process of incremental adjustments to climate variability and change to maintain existing objectives and values despite changes in climate conditions (Smit *et al.*, 2001). As evidenced by the examples in 16.4.1, however, future changes in climate could exceed the capacity of human actors and/or natural systems to successfully adapt using incremental adjustments (*high agreement, medium evidence*). Since the AR4, the adaptation and resilience literature has suggested that climate change or other factors may drive actors toward the deliberate pursuit of transformational adaptation as a mechanism for managing the discontinuities associated with experiencing an adaptation limit (Pelling, 2010; Kates *et al.*, 2012; O'Brien, 2012; O'Brien *et al.*, 2012; O'Neill and Handmer, 2012; Dow *et al.*, 2013a, b; 20.3). In addition, some studies have discussed the interactions between incremental and transformational adaptation and the pathways by which actors can transition from one to the other (Pelling, 2010; Park *et al.*, 2012).

As a relatively new concept in the adaptation literature, clear operational definitions of what constitutes transformational adaptation remain elusive. Several authors have offered criteria that include a significant increase in the magnitude of a management effort; introduction of new technologies or practices; formation of new structures or systems of governance; or geographic shifts in the location of activities (Pelling, 2010; Stafford Smith *et al.*, 2011; Kates *et al.*, 2012; O'Neill and Handmer, 2012; Park *et al.*, 2012; 20.2.3). However, the concept has also been identified as having normative elements involving changes in desired values, objectives, and perceptions of problems (Pelling, 2010; O'Neill and Handmer, 2012; Park *et al.*, 2012; O'Brien *et al.*, 2012). The current complexity and ambiguity in the definition of transformational adaptation may constrain its effective operationalization in policy environments (*very low confidence*). However, this matter has not been investigated.

In the context of limits to adaptation, transformational adaptation represents options and strategies that human actors can exploit to reorganize systems when incremental adaptation has reached its limits. As with incremental adaptation, these changes can be reactions to what has been experienced in the past or decisions made in anticipation of the future (Kates *et al.*, 2012). As a fundamental change in a system, transformation may involve changes in actors' objectives and associated values. Therefore, transformational adaptation isn't without risks or costs (Orlove, 2009; Kates *et al.*, 2012; O'Brien, 2012). For example, the level of investment needed to relocate a community or economic enterprise to reduce the risk of system failure (Kates *et al.*, 2012; O'Neill *et al.*, 2012) and/or to take advantage of changing climatic conditions (Park *et al.*, 2012) may be quite substantial.

Furthermore, transformational adaptation may be associated with various externalities. Strategies such as migration, for example, may involve the loss of sense of place and cultural identity, particularly if migration is involuntary

(Adger *et al.*, 2009). The feasibility of transformational adaptation may therefore be dependent in part upon whether it results in outcomes that are perceived to be positive versus negative (Preston and Stafford Smith, 2009). This suggests that the factors that constrain incremental adaptation (e.g., 16.3.2) also can constrain transformation, but the greater level of investment and/or shift in fundamental values and expectations required for transformational change may create greater resistance (Pelling, 2010; O'Brien, 2012; O'Neill and Handmer, 2012; Park *et al.*, 2012) (*medium agreement, limited evidence*).

16.5. Sectoral and Regional Synthesis

The adaptation literature since the AR4 indicates that despite a range of opportunities to enable adaptation, multiple factors will constrain adaptation planning and implementation (16.3) (*very high confidence*), and, in some cases, such constraints may limit adaptation (16.4) (*high agreement*, *medium evidence*). However, adaptation opportunities, constraints, and limits for adaptation vary significantly among different sectors and regional contexts (Adger *et al.*, 2007; 16.3; 16.4; Table 16-3) (*very high confidence*). This heterogeneity arises from a range of sources including regional differences with respect to the rate and magnitude of climate change that is experienced, differential exposure and sensitivity of sectors or ecological systems, and differential capacity to adapt. Given this diversity, it is important that opportunities, constraints and limits are evaluated in the specific context in which they arise. Therefore, this section draws on the various assessments of adaptation presented in the sectoral (Chapters 3–13) and regional (Chapters 22–30) chapters of the AR5 Working Group II report to synthesize knowledge regarding opportunities, constraints, and limits across these contexts.

16.5.1. Sectoral Synthesis

Each of the sectoral chapters in the Working Group II report addresses the opportunities for, and constraints associated with, the pursuit of adaptation (Table 16-3). Collectively, this represents a rich body of knowledge regarding how adaptation processes are evolving among different human and natural systems. Although each sectoral chapter assesses the relevant literature on adaptation independently, common themes emerge in opportunities, constraints and limits to adaptation (Table 16-3). Opportunities most often cited include building awareness, strengthening adaptive capacity, developing tools for improving vulnerability and risk assessments, and adopting favorable policies to improve governance. Likewise, common constraints arise among different sectors, but the bulk of the evidence for adaptation constraints is focused on inadequate governance and institutional structures at the scale of the challenge, lack of access to financial resources or relevant information for adaptation, and social and cultural norms that prevent adoption of viable adaptation options.

There are a number of emerging, integrated approaches to adaptation planning, governance and implementation identified by many sectoral and regional chapters. For example, Integrated Water Resource Management (IWRM), Integrated Coastal Zone Management (ICZM), Community-Based Adaptation, and Ecosystem-Based Adaptation (EBA) are identified as cross-sectoral adaptation options, which are viewed as more effective than standalone efforts to reduce climate-related risks (Bijlsma *et al.*, 1996; 5.5.1.4; 14.4.5; CC-EA). Such integration is important as many sectors experience threats not from by climate change, but also from a range of existing or emerging threats. The sectoral chapters also reflect on the distinction between autonomous adaptation, which is particularly important for natural systems such as freshwater, coastal, terrestrial, and ocean ecosystems (e.g., WGII Chapters 3–6), and planned adaptation, which features strongly in the literature associated with human-managed systems (WGII Chapters 5, 7–13).

While the sectoral chapters offer few explicit definitions of adaptation limits, they reflect the potential for hard limits to be reached and the potential for them to be persistent due to interactions among multiple constraints (16.3.5). For example, the sustainability of individual species or ecosystems may experience hard limits in a changing climate, as may ecosystem services for humans such as food crop and fisheries production. While significantly more attention is given to sectoral adaptation opportunities, constraints, and limits than in the AR4, the AR5 chapters suggest that literature relevant to the coastal (Chapter 5), food systems (Chapter 7), and urban sectors

(Chapter 8) has expanded more rapidly, perhaps because of the experience within these sectors with risk reduction planning associated with extreme weather events.

[INSERT TABLE 16-3 HERE
Table 16-3: Sectoral and regional synthesis of adaptation opportunities, constraints, and limits. Each icon represents types of opportunities, constraints and limits (described below). The size of the icon represents when there is relatively little (small icon) or relatively ample (large icon) information in the sectoral and regional chapters to describe each type of opportunity, constraint, or limit. If no information was presented, the table cell is blank.

Opportunities are defined *as factors that make it easier to plan and implement adaptation actions, that expand adaptation options, or that provide ancillary co-benefits.* Types of opportunities include (1) **Awareness -** communication, education and awareness raising; (2) **Capacity -** human and institutional capacity building including preparedness, resource provision, and development of human and social capital; (3) **Tools -** decision-making, vulnerability and risk analysis, decision support and early warning tools; (4) **Policy -** integration and mainstreaming of policy, governance and planning processes including sustainable development, resource and infrastructure planning, and design standards; (5) **Learning -** mutual experiential learning and knowledge management of climate vulnerability, adaptation options, disaster risk response, monitoring and evaluation; and (6) **Innovation -** development and dissemination of new information, technology development, and technology application.

Constraints *are defined as factors that make it harder to plan and implement adaptation actions*. Types of constraints include (1) **Economic -** existing livelihoods, economic structures and economic mobility; (2) **Social** and cultural **-** social norms, identity, place attachment, beliefs, worldviews, values, awareness, education, social justice, and social support; (3) **Human capacity -** individual, organizational, and societal capabilities to set and achieve adaptation objectives over time including training, education, skill development; (4) **Governance,** Institutions & Policy - existing laws, regulations, procedural requirements, governance scope, effectiveness, institutional arrangements, adaptive capacity, and absorption capacity; (5) **Financial -** lack of financial resources; (6) **Information**/ Awareness/ Technology - lack of awareness or access to information or technology; (7) **Physical -** presence of physical barriers; and (8) **Biological -** temperature, precipitation, salinity, acidity, intensity and frequency of extreme events including storms, drought and wind**.**

A ***Limit*** *is defined* as the *point at which actor's objectives or natural system's needs cannot be secured from intolerable risks through adaptive actions*. Types of limits include (1) **Biophysical -** temperature, precipitation, salinity, acidity, intensity and frequency of extreme events including storms, drought and wind, (2) **Economic -** existing livelihoods, economic structures and economic mobility; and (3) **Social/cultural -** social norms, identity, place attachment, beliefs, worldviews, values, awareness, education, social justice, and social support.]

16.5.2. Regional Synthesis

While the regional chapters assess the relevant literature on key sectors affected by climate change, those discussions are specific to the various regional contexts (Table 16-3). Mainstreaming adaptation to climate change into national development policies, regional and local planning, and economic development has emerged as an opportunity across all regions for addressing multiple, interacting, stresses (Dovers and Hezri, 2010; Tompkins *et al.*, 2010; Table 16-3). Most regional chapters reveal there are significant spatial and temporal mismatches between national adaptation planning on adaptation and local implementation to achieve substantive reductions in vulnerability. Adaptation interventions largely emphasize short-term risk management over long-term transformative strategic planning to reduce long-term risk, which potentially increases vulnerability and therefore the costs associated with future adaption efforts. Such short-sighted decision-making can also create the potential for maladaptation (Barnett and O'Neill, 2010; Berrang-Ford *et al.*, 2011; Preston *et al.*, 2013b).

Effective governance and institutions for facilitating adaptation planning and implementation across multiple sectors within regions was by far the dominant opportunity and constraint. Both a shift to risk-based approaches to adaptation and to the multi-sector planning for adaptation mentioned above (EBA, IRWM and ICZM) offer opportunities for the development of approaches, tools and guidelines for the construction of adaptation plans at a regional scale with a long-term focus. Developing and developed nations alike identified opportunities for building adaptive capacity and access to better information at the scale of decision-making as important to making this happen. Compared with sectoral chapters, the regional chapters identified limits to adaptation less frequently (Figure 16-3). This reflects the tendency for the literature to focus on limits for specific sectors, species, or ecosystems (16.5).

16.6. Effects of Mitigation on Adaptation Opportunities, Constraints, and Limits

The AR4 identified four ways in which adaptation and mitigation can inter-relate, one of which is mitigation actions that have consequences for adaptation (Klein *et al.*, 2007). It follows that mitigation actions could have consequences for adaptation constraints and limits. Klein *et al.* (2007) concluded that without mitigation, a magnitude of climate change could be reached that makes adaptation impossible for some natural systems, while for most human systems such high magnitudes of change would involve very high social and economic costs. Adaptation constraints and limits therefore have implications for the definition of dangerous anthropogenic interference under Article II of the UNFCCC (UNFCCC, 1992; see also Travis, 2010; Hoegh-Guldberg, 2011; Tao *et al.*, 2011; Preston *et al.*, 2013a). A number of studies published since the AR4, for example, demonstrate that constraining future greenhouse gas emissions would lower the magnitude of climate change experienced over the 20^{th} century and constrain the magnitude of future adverse impacts or the likelihood of exceeding system thresholds (Stern *et al.*, 2006; Meinshausen *et al.*, 2009; Preston and Jones, 2008; Sheehan *et al.*, 2008; O'Neill *et al.*, 2010; Garnaut, 2011; Arnell *et al.*, 2011; Rogelj *et al.*, 2011; Webster *et al.*; 2011; see also discussion of mitigation in the AR5 WGII sectoral and regional chapters) (*very high confidence*). Therefore, mitigation can potentially reduce the magnitude of climate change to which human and natural systems must adapt.

Understanding the relationship between damages avoided by mitigation and adaptation limits requires information regarding what magnitude of climate change and associated damages would constitute an intolerable risk. The WGI contribution to AR5 quantifies the cumulative CO_2 emissions below which – with probabilities of >33%, >50%, and >66% – global mean warming would be limited to less than 2°C since the period 1861–1880 (see WGI AR5 12.5.4). Warming beyond 2°C is considered to give rise to 'reasons for concern' (Smith *et al.*, 2009a; see also 19.6), in part because adaptation to impacts associated with such warming would be constrained or limited (16.3.2.2; 16.4.1; Box 16-3). Uncertainty about the location of both hard and soft limits is due to the fact that these limits are determined not only by the degree and rate of climate change (as a function of mitigation pathways), but also by the degree and rate of non-climatic stresses affecting the resilience or adaptive capacity of natural and human systems (16.4). Little empirical information is available on the functional relationships between climate change, non-climatic stresses and the emergence of limits to adaptation. The literature aiming to establish at which degree and rate of climate change, or at which levels of mitigation, such adaptation constraints and limits emerge is sparse and refers primarily to natural systems (16.4) (*medium agreement, limited evidence*).

Nevertheless, studies indicating that limits to adaptation have already been reached for some systems suggest the climate change observed to date has been sufficient to threaten the sustainability of human communities, ecosystem services, or ecological systems (16.4) (*medium agreement, limited evidence*). Nevertheless, for many valued human and natural systems, the complex spatial and temporal dynamics of impacts, adaptive capacity, and adaptation make it difficult to quantitatively project with any degree of accuracy and confidence when and where limits to adaptation will be encountered. Furthermore, although constraints and limits have been demonstrated to have cross-scale and cross-level interactions (16.3.2.10; 16.4.1), there is little evidence that indicates how limits to adaptation experienced by actors, species, or ecosystems in individual regions or sectors scale to a global aggregate limit. Therefore, there is little evidence to either substantiate or refute the idea that global mean warming beyond 2°C represents a global adaptation limit.

Analysis by Christensen *et al.* (2011) (see also WGI AR5 12.4.1) shows that all emission scenarios – whether aggressive mitigation scenarios consistent with a 2°C stabilization pathway or medium-high emission scenarios such as SRES A1B and A1Fi, or RCP6.0 and RCP8.5 – are very similar in terms of projected climate up to 2040 (i.e. the 'era of climate responsibility'). The effects of mitigation on overall adaptation potential will therefore arise in the medium to long term, during the 'era of climate options'. Integrated assessment models (IAMs) can assess the relative damage-reducing effect of mitigation and adaptation, based on the assumption that the two strategies are substitutes. In reality, however, mitigation and adaptation are hardly substitutable: they create benefits on different spatial, institutional and temporal scales and involve different actors with different interests. Substitutability of mitigation and adaptation in IAMs requires the reconciliation of welfare impacts on people living in different places and at different points in time into an aggregate measure of well-being (Klein *et al.*, 2007). Moreover, defining the costs and benefits of adaptation is particularly difficult, limited by data, and depends on value judgments (chapter 17).

Since AR4 the literature on tipping elements (Lenton *et al.*, 2008; Kriegler *et al.*, 2009; Levermann *et al.*, 2012) has provided a greater separation of mitigation and adaptation, because only mitigation can avoid these discontinuities. While there could be potential for mitigation and adaptation substitutability under scenarios where catastrophic climate change is avoided, the thresholds for the onset of any tipping elements (anticipated to drive some systems to the limits of adaptation) are not known. These concerns have been picked up in the economic literature, in relation to the plausible, if unknown, probability of catastrophic climate change as well as ‘fat tails’, where uncertainty is so large that the tails of the probability distribution tend to dominate (Weitzman, 2009). Against this background, mitigation can prevent or delay catastrophic climate change and the reaching of adaptation limits.

Several studies using IAMs have investigated tradeoffs between mitigation and adaptation (de Bruin *et al.*, 2009a; Bosello *et al.*, 2010), treating the two strategies as substitutes in order to find a balance or even an optimal mix. De Bruin *et al.* (2009a) report that short-term optimal policies need to consist of a mixture of substantial investments in adaptation measures, coupled with investments in mitigation, even though the latter will only decrease damages in the longer term. They also find that the relative mix of the two depends critically on the assumptions, notably in relation to the discount rate and the parameterization of damages. Felgenhauer and de Bruin (2009) examine the role that uncertainty over climate sensitivity has on optimal mitigation and adaptation policy levels over time. They find that optimal levels of both mitigation and adaptation are lower under uncertainty than under certainty, and that the optimal mitigation level is more dependent on adaptation costs than vice versa.

Such findings are all preliminary, because the current representation of adaptation in IAMs is generally very simple (Ackerman *et al.*, 2009; Patt *et al.*, 2010b). The models adopt a highly aggregated and theoretical approach without considering any real-world constraints on adaptation (Ackerman *et al.*, 2009; Patt *et al.*, 2010b). They also often assume perfect foresight, no uncertainty and no maladaptation (see also Watkiss, 2011; Berkhout, 2012). More recent models have attempted to address some of these issues. De Bruin and Dellink (2011), for example, model different types of constraints of adaptation over time. Also the PAGE09 model assumes adaptation to be about half as effective as it was inPAGE02 (Hope, 2011). Along with other factors, the reduced effectiveness of adaptation in the model leads to a strong increase in the economic costs of climate change (Hope, 2011).

16.7. Ethical Dimensions of Adaptation Opportunities, Constraints, and Limits

Hartzell-Nichols (2011, pg. 690) argues that, in general terms, “*Adaptation is fundamentally an ethical issue because the aim of adaptation is to protect that which we value.*” More specifically, ethical issues concern the distribution of costs and benefits of prevention measures and adaptation activities, compensation for residual damages, and participation in the related decision processes (Grasso, 2009). These distributive and procedural justice-related issues can be diverse and contextually specific (Paavola, 2011). Brisley *et al.* (2012) argue that ensuring social justice in adaptation requires both an understanding of which groups are most vulnerable to climate change impacts, as well as social choice processes about adaptation responses that are seen to meet the needs of the vulnerable fairly. The key ethical issues raised by adaptation opportunities, constraints and limits as they are discussed here are summarized in Table 16-4, together with the public policy questions they raise.

[INSERT TABLE 16-4 HERE
Table 16-4. Ethical dimensions of adaptation opportunities, constraints and limits and their policy implications.]

Defining general moral principles to clarify how to handle risks to objectives, values and needs, including where they are unavoidable and catastrophic, is difficult. According to Gardiner (2006, pg. 407),

> "*Even our best theories face basic and often severe difficulties addressing basic issues … such as scientific uncertainty, intergenerational equity, contingent persons, nonhuman animals, and nature. But climate change involves all of these matters and more*".

Complicating this picture further is the observation that social and personal values are not universal or static (O'Brien, 2009; O'Brien and Wolf, 2010). There may be different, but equally legitimate, values that are fostered or put at risk by climate change (Adger *et al.*, 2012). These are not limited to instrumental or economic values, but include cultural values as well. Berkes (2008, pg. 163), for instance, documents that in Inuit culture, the loss of sea ice in summer months leaves some people "*lonely for the ice*." Whether the risk of irreversible cultural losses would be seen as intolerable remains a complicated question, but has been noted to manifest in a psychological response termed "solastalgia" (Albrecht *et al.*, 2007). The loss of traditional ways of experiencing and seeing the world is a common occurrence throughout human history. The ethical question is whether such losses should be acknowledged in considering adaptation opportunities, constraints and limits (as well as in human responses to climate change more generally).

One ethical principle that is widely applied in ethical discussions of climate is 'equity' (Gardiner, 2010). It is now well-established that nations, peoples and ecosystems are differentially vulnerable to current and future projected climate change impacts, which themselves are unequally distributed across world regions (IPCC, 2007b; Füssel, 2009; Füssel, 2010) (*very high confidence*). This inequity is exacerbated by the fact that exposure to adverse impacts is involuntary for many societies (Paavola and Adger, 2006; Patz *et al.*, 2007; Dellink *et al.*, 2009; Füssel, 2010). Therefore, adaptation constraints have the potential to create or exacerbate inequitable consequences due to climate change (*very high confidence*). Where limits to adaptation lead to catastrophic losses there is often a need for humanitarian responses, as well as more structural adaptations at the societal level (Bardsley and Hugo, 2010) (*high agreement, medium evidence*). Linked to this is the complex question of the attribution of risks to anthropogenic forcing of climate change and whether there could be grounds for redress or compensation (Verheyen, 2005). In this regard, different ethical positions taken by countries such as through 'equity weighting' would result in very different compensation outcomes (Anthoff and Tol, 2010)

Inequity resulting from adaptation constraints and limits emerge across several dimensions; namely inter-country equity, inter-generational equity, inter-species equity (Schneider and Lane, 2006b), and intra-country or sub-national equity (Thomas and Twyman, 2005). Climate change, and the need for adaptation, unfairly shifts burdens onto future generations, contradicting the principle of intergenerational equity. This raises ethical and justice questions since benefits are extracted from the global environment by those who do not bear the burden of that extraction (UNEP, 2007). Policy debates about inter-generational equity considerations have been dominated by the need to treat the time discount rate consistently across cases (Nordhaus, 2001; Stern *et al.*, 2006; Beckerman and Hepburn, 2007). But this debate largely ignores the challenge of irreversible damages associated with limits to adaptation, especially those that may result from non-linear damage functions (Hanemann, 2008). Inter-species equity is the subject of an evolving ethics debate (e.g., Jolibert *et al.*, 2011), but adaptation interventions involving ecosystems and wild species increasingly invoke human and societal benefits as a primary motivation (CBD, 2009; CC-EA).

Law codifies the social values and objectives influenced by opportunities, constraints and limits to adaptation, and sets norms and procedures for dealing with problems of risk and loss, including the intolerable losses experienced at adaptation limits (16.3.2.8). Changing such values and objectives, including the shifting and sharing of risks this may involve, will often involve complex and time-consuming governance effort. National and international law will play a role in managing and sharing climate-related risks. The Cancun Adaptation Framework (UNFCCC, 2011) adopted at COP16 of the UNFCCC sets out principles for international cooperation on adaptation "*…to enable and support the implementation of adaptation actions*" (UNFCCC, 2010, p. 4). Nevertheless, the complexity of international law comprises a significant constraint to making the case for addressing the breaching of adaptation limits (Koivurova, 2007). At national and sub-national levels, cultural attitudes can contribute to stakeholder marginalization from adaptation processes (16.3.2.7), thus preventing some constraints and limits from being identified (such as gender issues and patriarchal conventions).

16.8. Seizing Opportunities, Overcoming Constraints, and Avoiding Limits

As discussed in this chapter, researchers and practitioners now have a richer understanding of how constraints and limits influence adaptation (16.3; 16.4; 16.5; 16.6; 16.7). Based on the available literature, however, less attention has been paid to understanding the range of opportunities that exist and how they create enabling conditions for adaptation (16.3.1; Table 16-1). Focused research on facilitating such enabling conditions and how these lead to the minimization or avoidance of adaptation constraints would support capacity building of individuals and institutions (Smith *et al.*, 2008; Ford, 2009; Burch, 2010; Ford *et al.*, 2010; Eisenack, 2012; Biesbroek *et al.*, 2013a) (*very high confidence*). Translating knowledge of potential opportunities into adaptation responses requires that they be recognized and then exploited by actors. Such opportunities are being created through policies, tools and guidelines that are emerging throughout the developed and developing world (15.2; 16.3.2.1). It is not yet clear if these efforts are translating into effective adaptation actions for the benefit of human and natural systems including the avoidance of limits. As adaptation practice has focused on what adaptation efforts can achieve in terms of avoided damages rather than on the residual damages that adaptation cannot avoid (Jenkins *et al.*, 2011; McNamara *et al.*, 2011), this question remains largely unexplored.

Adaptation constraints have contributed to uneven adaptation planning and implementation with some sectoral and regional actors progressing more rapidly than others (Urwin *et al.*, 2008; Biesbroek *et al.*, 2010; Tompkins *et al.*, 2010; Bichard and Kazmierczak, 2012; Bierbaum *et al.*, 2012; Carmin *et al.*, 2012; (*very high confidence*). Multiple studies have concluded that adaptation is largely proceeding autonomously and incrementally, often in response to perceived climate change trends and impacts that have been experienced (Ford, 2009; Ford *et al.*, 2010; Berrang-Ford *et al.*, 2011; Ford *et al.*, 2011; Preston *et al.*, 2011a; Lesnikowski *et al.*, 2013) (*high agreement, medium evidence*). In so doing, however, actors may not adequately invest in adaptation responses that will address future long-term risks associated with higher levels of climate change (Preston *et al.*, 2013b; 16.3.2.2) (*medium agreement, limited evidence*). The suggestion that incremental approaches to mitigation and adaptation may be inadequate to avoid intolerable risks has led to a growing discourse regarding transformational adaptation (Pelling, 2010; Kates *et al.*, 2012; O'Brien, 2012; O'Neill and Handmer, 2012; Park *et al.*, 2012). While various practical examples of transformational adaptation appear in the literature (Kates *et al.*, 2012; O'Neill and Handmer, 2012; Park *et al.*, 2012; 16.4.2), the extent to which transformational adaptation can be operationalized within adaptation policy remains unclear. Unresolved issues including which actors, sectors, and regions should be considering transformational adaptations, when, and what constitutes appropriate adaptation actions under such circumstances would benefit from focused investigation.

Better understanding and quantification of how future greenhouse gas emissions trajectories and climate change translates into impacts would improve understanding of limits to adaptation. Fundamental understanding of the vulnerability of different regions and sectors to climate change suggest that adaptive capacity is finite and thus, in general, limits to adaptation can be anticipated to arise as a consequence of future global change (16.3.2; 16.4; 16.5; 16.6) (*high agreement, medium evidence*). Yet, at present, understanding of limits to adaptation is largely qualitative, and it is unclear whether current approaches to assessing climate change impacts and adaptation sufficiently explore the range of potential future climates and adaptive capacities of human and natural systems in a manner that is sufficient to identify limits. The parallel process for scenario development may provide a coherent framework for internally consistent analyses of climate change impacts that address uncertainty among climate models, emissions scenarios, and socioeconomic scenarios (Moss *et al.*, 2010; van Vuuren *et al.*, 2012; Ebi *et al.*, 2013). Such knowledge could subsequently provide early warning of systems at risk of experiencing intolerable risks (Dow *et al.*, 2013a, b) while also providing guidance regarding greenhouse gas mitigation targets.

Finally, recent literature questions whether existing institutions and systems of governance are adequate to effectively manage climate change risk. This includes not only institutions engaging in adaptation planning and implementation (Berkes and Armitage, 2010; Chapin *et al.*, 2010; NRC, 2010; UKCIP, 2011; Kates *et al.*, 2012; Biesbroek *et al.*, 2013a), but also those associated with adaptation research (Meyer, 2011; Kates *et al.*, 2012). New institutions and institutional arrangements have in fact emerged including adaptation research institutions with boundary spanning functions (Preston *et al.*, 2013c; 14.2.4), as well as those designed to facilitate adaptation and improve environmental and risk management (NRC, 2009; Biesbroek *et al.*, 2011; Jäger and Moll, 2011; Lemos *et al.*, 2013) (*high agreement, medium evidence*). However, others have cautioned that the complexity of modern governance systems poses significant constraints on institutional change (Adger *et al.*, 2009; 16.3.2.8), and new institutions do not necessarily resolve complex governance challenges (Lebel *et al.*, 2013). Additional research is therefore needed regarding the extent to which new institutions will be required to effectively govern adaptation.

Frequently Asked Questions

FAQ 16.1: What is the difference between an adaptation barrier, constraint, obstacle, and limit?
[to be insert in Section 16.2]
An adaptation constraint represents a factor or process that makes adaptation planning and implementation more difficult. This could include reductions in the range of adaptation options that can be implemented, increases in the costs of implementation, or reduced efficacy of selected options with respect to achieving adaptation objectives. In this context, a constraint is synonymous with the terms adaptation barrier or obstacle that also appear in the adaptation literature. However, the existence of a constraint alone doesn't mean that adaptation is not possible or that one's objectives can't be achieved. In contrast, an adaptation limit is more restrictive in that it means there are no adaptation options that can be implemented over a given time horizon to achieve one or more management objectives, maintain values, or sustain natural systems. This implies that certain objectives, practices, or livelihoods as well as natural systems may not be sustainable in a changing climate, resulting in deliberate or involuntary system transformations.

FAQ 16.2: What opportunities are available to facilitate adaptation? *[to be inserted in Section 16.3.1.1]*
Although an extensive literature now exists regarding factors that can constrain adaptation, there is *very high confidence* that a broad range of opportunities exist for actors in different regions and sectors that can ease adaptation planning and implementation. Generally, sustainable economic development is an over-arching process that can facilitate adaptation, and therefore represents a key opportunity to reduce adaptation constraints and limits. More specifically, those actions or processes that enhance the awareness of adaptation actors and relevant stakeholders and/or enhance their entitlements to resources can expand the range of adaptation options that can be implemented and help overcome constraints. The development and application of tools to support assessment, planning, and implementation can aid actors in weighing different options and their costs and benefits. Policies, whether formal policies of government institutions, initiatives of informal actors, or corporate policies and standards, can direct resources to adaptation and/or reduce vulnerability to current and future climate. Finally, the ability for humans to learn from experience and to develop new practices and technologies through innovation can significantly expand adaptive capacity in the future.

FAQ 16.3: How does greenhouse gas mitigation influence the risk of exceeding adaptation limits?
[to be insert in Section 16.6]
There is *very high confidence* that higher rates and/or magnitudes of climate change contribute to higher adaptation costs and/or the reduced effectiveness of certain adaptation options. For example, increases in global mean temperature of 4°C or more would necessitate greater investment in adaptation than a temperature increase of 2°C or less. As future climate change is dependent upon emissions of greenhouse gases, efforts to mitigate those emissions can reduce the likelihood that human or natural systems will experience a limit to adaptation. However, uncertainties regarding how future emissions translate into climate change at global and regional levels remain significant, and therefore it is difficult to draw robust conclusions regarding whether a particular greenhouse gas stabilization pathway would or would not allow residual risk to be successfully managed through adaptation. For example, evidence regarding limits to adaptation does not substantiate or refute the idea that an increase in global mean temperature beyond 2°C represents an adaptation limit or, subsequently "dangerous anthropogenic interference" as defined by the UNFCCC's Article II.

Cross-Chapter Boxes

Box CC-CR. Coral Reefs

[Jean-Pierre Gattuso (France), Ove Hoegh-Guldberg (Australia), Hans-Otto Pörtner (Germany)]

Coral reefs are shallow-water ecosystems that consist of reefs made of calcium carbonate which is mostly secreted by reef-building corals and encrusting macroalgae. They occupy less than 0.1% of the ocean floor yet play multiple important roles throughout the tropics, housing high levels of biological diversity as well as providing key ecosystem goods and services such as habitat for fisheries, coastal protection and appealing environments for tourism (Wild *et al*., 2011). About 275 million people live within 30 km of a coral reef (Burke *et al*., 2011) and derive some benefits from the ecosystem services that coral reefs provide (Hoegh-Guldberg, 2011) including provisioning (food, livelihoods, construction material, medicine), regulating (shoreline protection, water quality), supporting (primary production, nutrient cycling) and cultural (religion, tourism) services. This is especially true for the many coastal and small island nations in the world's tropical regions (29.3.3.1).

Coral reefs are one of the most vulnerable marine ecosystems (*high confidence*; 5.4.2.4, 6.3.1, 6.3.2, 6.3.5, 25.6.2, and 30.5) and more than half of the world's reefs are under medium or high risk of degradation (Burke *et al*., 2011). Most human-induced disturbances to coral reefs were local until the early 1980s (e.g., unsustainable coastal development, pollution, nutrient enrichment and overfishing) when disturbances from ocean warming (principally mass coral bleaching and mortality) began to become widespread (Glynn, 1984). Concern about the impact of ocean acidification on coral reefs developed over the same period, primarily over the implications of ocean acidification for the building and maintenance of the calcium carbonate reef framework (Box CC-OA).

[INSERT FIGURE CR-1 HERE
Figure CR-1: A and B: the same coral community before and after a bleaching event in February 2002 at 5 m depth, Halfway Island, Great Barrier Reef. Coral cover at the time of bleaching was 95% bleached almost all of it severely bleached, resulting in mortality of 20.9% (Elvidge *et al*., 2004). Mortality was comparatively low due in part because these coral communities were able to shuffle their symbiont to more thermo-tolerant types (Berkelmans and van Oppen, 2006; Jones *et al*., 2008). C and D: three CO_2 seeps in Milne Bay Province, Papua New Guinea show that prolonged exposure to high CO_2 is related to fundamental changes in the ecology of coral reefs (Fabricius *et al*., 2011), including reduced coral diversity (-39%), severely reduced structural complexity (-67%), lower density of young corals (-66%) and fewer crustose coralline algae (-85%). At high CO_2 sites (panel D; median pH_T ~7.8), reefs are dominated by massive corals while corals with high morphological complexity are underrepresented compared with control sites (D; median pH ~8.0). Reef development ceases at pH_T values below 7.7. pH_T: pH on the total scale. E: temporal trend in coral cover for the whole Great Barrier Reef over the period 1985–2012 (N, number of reefs, mean ± 2 standard errors; De'ath et al., 2012). F: composite bars indicate the estimated mean coral mortality for each year, and the sub-bars indicate the relative mortality due to crown-of-thorns starfish, cyclones, and bleaching for the whole Great Barrier Reef (De'ath et al., 2012). Photo credit: R. Berkelmans (A and B) and K. Fabricius (C and D).]

A wide range of climatic and non-climatic drivers affect corals and coral reefs and negative impacts have already been observed (5.4.2.4, 6.3.1, 6.3.2, 25.6.2.1, 30.5.3, 30.5.6). Bleaching involves the breakdown and loss of endosymbiotic algae, which live in the coral tissues and play a key role in supplying the coral host with energy (see 6.3.1. for physiological details and 30.5 for a regional analysis). Mass coral bleaching and mortality, triggered by positive temperature anomalies (*high confidence*), is the most widespread and conspicuous impact of climate change (Figure CR-1A and B, Figure 5-3; 5.4.2.4, 6.3.1, 6.3.5, 25.6.2.1, 30.5 and 30.8.2). For example, the level of thermal stress at most of the 47 reef sites where bleaching occurred during 1997-98 was unmatched in the period 1903 to 1999 (Lough, 2000). Ocean acidification reduces biodiversity (Figure CR-1C and D) and the calcification rate of corals (*high confidence*; 5.4.2.4, 6.3.2, 6.3.5) while at the same time increasing the rate of dissolution of the reef framework (*medium confidence*; 5.2.2.4) through stimulation of biological erosion and chemical dissolution. Taken together, these changes will tip the calcium carbonate balance of coral reefs towards net dissolution (*medium confidence*; 5.4.2.4). Ocean warming and acidification have synergistic effects in several reef-builders (5.2.4.2, 6.3.5). Taken together, these changes will erode habitats for reef-based fisheries, increase the exposure of coastlines to waves and storms, as well as degrading environmental features important to industries such as tourism (*high confidence*; 6.4.1.3, 25.6.2, 30.5).

A growing number of studies have reported regional scale changes in coral calcification and mortality that are consistent with the scale and impact of ocean warming and acidification when compared to local factors such as declining water quality and overfishing (Hoegh-Guldberg *et al*., 2007). The abundance of reef building corals is in rapid decline in many Pacific and SE Asian regions (*very high confidence*, 1-2% per year for 1968-2004; Bruno and Selig, 2007). Similarly, the abundance of reef-building corals has decreased by over 80% on many Caribbean reefs (1977 to 2001; Gardner *et al*., 2003), with a dramatic phase shift from corals to seaweeds occurring on Jamaican reefs (Hughes, 1994). Tropical cyclones, coral predators and thermal stress-related coral bleaching and mortality have led to a decline in coral cover on the Great Barrier Reef by about 51% between 1985 and 2012 (Figure CR-1E and F). Although less well documented, benthic invertebrates other than corals are also at risk (Przeslawski *et al*., 2008). Fish biodiversity is threatened by the permanent degradation of coral reefs, including in a marine reserve (Jones *et al*., 2004).

Future impacts of climate-related drivers (ocean warming, acidification, sea level rise as well as more intense tropical cyclones and rainfall events) will exacerbate the impacts of non-climate related drivers (*high confidence*). Even under optimistic assumptions regarding corals being able to rapidly adapt to thermal stress, one-third (9 to 60%, 68% uncertainty range) of the world's coral reefs are projected to be subject to long-term degradation (next few decades) under the RCP3-PD scenario (Frieler *et al*., 2013). Under the RCP4.5 scenario, this fraction increases to two-thirds (30 to 88%, 68% uncertainty range). If present day corals have residual capacity to acclimate and/or adapt, half of the coral reefs may avoid high frequency bleaching through 2100 (*limited evidence, limited agreement*; Logan *et al*., 2013). Evidence of corals adapting rapidly, however, to climate change is missing or equivocal (Hoegh-Guldberg, 2012).

Damage to coral reefs has implications for several key regional services:

- *Resources*: Coral reefs account for 10 to 12% of the fish caught in tropical countries, and 20 to 25% of the fish caught by developing nations (Garcia and Moreno, 2003). Over half (55%) of the 49 island countries considered by Newton *et al*. (2007) are already exploiting their coral reef fisheries in an unsustainable way and the production of coral reef fish in the Pacific is projected to decrease 20% by 2050 under the SRES A2 emissions scenario (Bell *et al*., 2013).
- *Coastal* protection: Coral reefs contribute to protecting the shoreline from the destructive action of storm surges and cyclones (Sheppard *et al*., 2005), sheltering the only habitable land for several island nations, habitats suitable for the establishment and maintenance of mangroves and wetlands, as well as areas for recreational activities. This role is threatened by future sea level rise, the decrease in coral cover, reduced rates of calcification and higher rates of dissolution and bioerosion due to ocean warming and acidification (5.4.2.4, 6.4.1, 30.5).
- *Tourism*: More than 100 countries benefit from the recreational value provided by their coral reefs (Burke *et al*., 2011). For example, the Great Barrier Reef Marine Park attracts about 1.9 million visits each year and generates A$ 5.4 billion to the Australian economy and 54,000 jobs (90% in the tourism sector; Biggs, 2011).

Coral reefs make a modest contribution to the Global Domestic Product but their economic importance can be high at the country and regional scales (Pratchett *et al*., 2008). For example, tourism and fisheries represent 5% of the GDP of South Pacific islands (average for 2001-2011; Laurans *et al*., 2013). At the local scale, these two services provided in 2009-2011 at least 25% of the annual income of villages in Vanuatu and Fiji (Pascal, 2011; Laurans *et al*., 2013).

Isolated reefs can recover from major disturbance, and the benefits of their isolation from chronic anthropogenic pressures can outweigh the costs of limited connectivity (Gilmour *et al*., 2013). Marine protected areas (MPAs) and fisheries management have the potential to increase ecosystem resilience and increase the recovery of coral reefs after climate change impacts such as mass coral bleaching (McLeod *et al*., 2009). Although they are key conservation and management tools, they are unable to protect corals directly from thermal stress (Selig *et al*., 2012) suggesting that they need to be complemented with additional and alternative strategies (Rau *et al*., 2012; Billé *et* *al*., 2013). While MPA networks are a critical management tool, they should be established considering other forms of resource management (e.g., fishery catch limits and gear restrictions) and integrated ocean and coastal management to control land-based threats such as pollution and sedimentation. There is *medium confidence* that networks of highly protected areas nested within a broader management framework can contribute to preserving coral reefs under increasing human pressure at local and global scales (Salm *et al*. 2006). Locally, controlling the input of nutrients and sediment from land is an important complementary management strategy (Mcleod *et al*., 2009) because nutrient enrichment can increase the susceptibility of corals to bleaching (Wiedenmann *et al*., 2012) and coastal pollutants enriched with fertilizers can increase acidification (Kelly *et al.*, 2011). In the long term, limiting the amount of ocean warming and acidification is central to ensuring the viability of coral reefs and dependent communities (*high confidence*; 5.2.4.4, 30.5).

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Box CC-EA. Ecosystem Based Approaches to Adaptation - Emerging Opportunities

[Rebecca Shaw (USA), Jonathan Overpeck (USA), Guy Midgley (South Africa)]

Ecosystem-based adaptation (EBA) integrates the use of biodiversity and ecosystem services into climate change adaptation strategies (e.g., CBD, 2009; Munroe et al., 2011; see Chapters 3, 4, 5, 8, 9, 13, 14, 15, 16, 19, 22, 24, 25, and 27). EBA is implemented through the sustainable management of natural resources and conservation and restoration of ecosystems, to provide and sustain services that facilitate adaptation both to climate variability and change (Colls et al., 2009). It also sets out to take into account the multiple social, economic, and cultural co-benefits for local communities (CBD COP 10 Decision X/33).

EBA can be combined with, or even a substitute for, the use of engineered infrastructure or other technological approaches. Engineered defenses such as dams, sea walls and levees adversely affect biodiversity, potentially resulting in maladaptation due to damage to ecosystem regulating services (Campbell et al., 2009; Munroe et al., 2011). There is some evidence that the restoration and use of ecosystem services may reduce or delay the need for these engineering solutions (CBD, 2009). EBA offers lower risk of maladaptation than engineering solutions in that their application is more flexible and responsive to unanticipated environmental changes. Well-integrated EBA can be more cost effective and sustainable than non-integrated physical engineering approaches (Jones et al., 2012), and may contribute to achieving sustainable development goals (e.g., poverty reduction, sustainable environmental management, and even mitigation objectives), especially when they are integrated with sound ecosystem management approaches. In addition, EBA yields economic, social, and environmental co-benefits in the form of ecosystem goods and services (World Bank, 2009).

EBA is applicable in both developed and developing countries. In developing countries where economies depend more directly on the provision of ecosystem services (Vignola et al., 2009), EBA may be a highly useful approach to reduce risks to climate change impacts and ensure that development proceeds on a pathways that are resilient to climate change (Munang et al., 2013). EBA projects may be developed by enhancing existing initiatives, such as community-based adaptation and natural resource management approaches (e.g., Khan et al., 2012; Midgley et al., 2012; Roberts et al., 2012).

Examples of ecosystem based approaches to adaptation include:

- Sustainable water management, where river basins, aquifers, flood plains, and their associated vegetation are managed or restored to provide resilient water storage and enhanced baseflows, flood regulation services, reduction of erosion/siltation rates, and more ecosystem goods (e.g., Day et al., 2007; Midgley et al., 2012; Opperman et al., 2009)
- Disaster risk reduction through the restoration of coastal habitats (e.g., mangroves, wetlands, and deltas) to provide effective measure against storm-surges, saline intrusion, and coastal erosion (Jonkman et al., 2013)
- Sustainable management of grasslands and rangelands to enhance pastoral livelihoods and increase resilience to drought and flooding
- Establishment of diverse and resilient agricultural systems, and adapting crop and livestock variety mixes to secure food provision; traditional knowledge may contribute in this area through, for example, identifying indigenous crop and livestock genetic diversity, and water conservation techniques
- Management of fire-prone ecosystems to achieve safer fire regimes while ensuring the maintenance of natural processes.

Application of EBA, like other approaches, is not without risk, and risk/benefit assessments will allow better assessment of opportunities offered by the approach. The examples of EBA are too few and too recent to assess either the risks or the benefits comprehensively at this stage. EBA is still a developing concept but is should be considered alongside adaptation options based more on engineering works or social change, and existing and new cases used to build understanding of when and where its use is appropriate.

[INSERT FIGURE EA-1 HERE
Figure EA-1: Adapted from Munang et al. (2013). Ecosystem based adaptation (EBA) uses the capacity of nature to buffer human systems from the adverse impacts of climate change. Without EBA, climate change may cause degradation of ecological processes (central white panel) leading to losses in human well-being. Implementing EBA (outer blue panel) may reduce or offset these adverse impacts resulting in a virtuous cycle that reduces climate-related risks to human communities, and may provide mitigation benefits.]

Box CC-EA References

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Box CC-OA. Ocean Acidification

[Jean-Pierre Gattuso (France), Peter Brewer (USA), Ove Hoegh-Guldberg (Australia), Joan A. Kleypas (USA), Hans-Otto Pörtner (Germany), Daniela Schmidt (UK)]

Anthropogenic ocean acidification and global warming share the same primary cause, which is the increase of atmospheric CO_2 (Figure OA-1A; WGI, 2.2.1). Eutrophication, loss of sea ice, upwelling and deposition of atmospheric nitrogen and sulphur all exacerbate ocean acidification locally (5.3.3.6, 6.1.1, 30.3.2.2).

[INSERT FIGURE OA-1 HERE
Figure OA-1: A: Overview of the chemical, biological, socio-economic impacts of ocean acidification and of policy options (adapted from Turley and Gattuso, 2012). B: Multi-model simulated time series of global mean ocean surface pH (on the total scale) from CMIP5 climate model simulations from 1850 to 2100. Projections are shown for emission scenarios RCP2.6 (blue) and RCP8.5 (red) for the multi-model mean (solid lines) and range across the distribution of individual model simulations (shading). Black (grey shading) is the modelled historical evolution using historical reconstructed forcings. The models that are included are those from CMIP5 that simulate the global carbon cycle while being driven by prescribed atmospheric CO_2 concentrations. The number of CMIP5 models to calculate the multi-model mean is indicated for each time period/scenario (WGI AR5 Figure 6.28). C: Effect of near future acidification (seawater pH reduction of 0.5 unit or less) on major response variables estimated using weighted random effects meta-analyses, with the exception of survival which is not weighted (Kroeker et al., 2013). The log-transformed response ratio (LnRR) is the ratio of the mean effect in the acidification treatment to the mean effect in a control group. It indicates which process is most uniformly affected by ocean acidification but large variability exists between species. Significance is determined when the 95% bootstrapped confidence interval does not cross zero. The number of experiments used in the analyses is shown in parentheses. * denotes a statistically significant effect.]

Chemistry and Projections

The fundamental chemistry of ocean acidification is well understood (*robust evidence*, *high agreement*). Increasing atmospheric concentrations of CO_2 result in an increased flux of CO_2 into a mildly alkaline ocean, resulting in a reduction in pH, carbonate ion concentration, and the capacity of seawater to buffer changes in its chemistry (*very high confidence*). The changing chemistry of the surface layers of the open ocean can be projected at the global scale with high accuracy using projections of atmospheric CO_2 levels (Fig. CC-OA-1B). Observations of changing upper ocean CO_2 chemistry over time support this linkage (WGI Table 3.2 and Figure 3.18; Figures 30.8, 30.9). Projected changes in open ocean, surface water chemistry for year 2100 based on representative concentration pathways (WGI, Figure 6.28) compared to preindustrial values range from a pH change of -0.14 unit with RCP 2.6 (421 ppm CO_2, +1 ºC, 22% reduction of carbonate ion concentration) to a pH change of -0.43 unit with RCP 8.5 (936 ppm CO_2, +3.7 ºC, 56% reduction of carbonate ion concentration). Projections of regional changes, especially in the highly complex coastal systems (5.3.3.6, 30.3.2.2), in polar regions (WGI 6.4.4), and at depth are more difficult but generally follow similar trends.

Biological, Ecological, and Biogeochemical Impacts

Investigations of the effect of ocean acidification on marine organisms and ecosystems have a relatively short history, recently analyzed in several metaanalyses (6.3.2.1, 6.3.5.1). A wide range of sensitivities to projected rates of ocean acidification exists within and across diverse groups of organisms, with a trend for greater sensitivity in early life stages (*high confidence*; 5.4.2.2, 5.4.2.4, 6.3.2). A pattern of positive and negative impacts emerges (*high confidence*; Fig. OA-1C) but key uncertainties remain in our understanding of the impacts on organisms, life histories and ecosystems. Responses can be influenced, often exacerbated by other drivers, such as warming, hypoxia, nutrient concentration, and light availability (*high confidence*; 5.4.2.4, 6.3.5).

Growth and primary production are stimulated in seagrass and some phytoplankton (*high confidence*; 5.4.2.3, 6.3.2.2-3, 30.5.6). Harmful algal blooms could become more frequent (*limited evidence, medium agreement*). Ocean acidification may stimulate nitrogen fixation (*limited evidence, low agreement*; 6.3.2.2). It decreases the rate of calcification of most, but not all, sea-floor calcifiers (*medium agreement, robust evidence*) such as reef-building corals (Box CC-CR), coralline algae, bivalves and gastropods reducing the competitiveness with non-calcifiers (5.4.2.2, 5.4.2.4, 6.3.2.5). Ocean warming and acidification promote higher rates of calcium carbonate dissolution resulting in the net dissolution of carbonate sediments and frameworks and loss of associated habitat (*medium confidence*; 5.4.2.4, 6.3.2.5, 6.3.5.4-5). Some corals and temperate fishes experience disturbances to behavior, navigation and their ability to tell conspecifics from predators (6.3.2.4). However, there is no evidence for these effects to persist on evolutionary timescales in the few groups analyzed (6.3.2).

Some phytoplankton and mollusks displayed adaptation to ocean acidification in long-term experiments (*limited evidence, medium agreement*; 6.3.2.1), indicating that the long-term responses could be less than responses obtained in short-term experiments. However, mass extinctions in Earth history occurred during much slower rates of ocean acidification, combined with other drivers changing, suggesting that evolutionary rates are not fast enough for sensitive animals and plants to adapt to the projected rate of future change (*medium confidence*; 6.1.2).

Projections of ocean acidification effects at ecosystem level are made difficult by the diversity of species-level responses. Differential sensitivities and associated shifts in performance and distribution will change predator-prey relationships and competitive interactions (6.3.2.5, 6.3.5-6), which could impact food webs and higher trophic levels (*limited evidence, high agreement*). Natural analogues at CO_2 vents indicate decreased species diversity, biomass and trophic complexity of communities (Box CC-CR; 5.4.2.3, 6.3.2.5, 30.3.2.2, 30.5). Shifts in community structure have also been documented in regions with rapidly declining pH (5.4.2.2).

Due to an incomplete understanding of species-specific responses and trophic interactions the effect of ocean acidification on global biogeochemical cycles is not well understood (*limited evidence, low agreement*) and represents an important knowledge gap. The additive, synergistic or antagonistic interactions of factors such as temperature, concentrations of oxygen and nutrients, and light are not sufficiently investigated yet.

Risks, Socioeconomic Impacts and Costs

The risks of ocean acidification to marine organisms, ecosystems, and ultimately to human societies, include both the probability that ocean acidification will affect fundamental physiological and ecological processes of organisms (6.3.2.1), and the magnitude of the resulting impacts on ecosystems and the ecosystem services they provide to society (Box 19-2). For example, ocean acidification under RCP4.5 to RCP8.5 will impact formation and maintenance of coral reefs (*high confidence*; Box CC-CR, 5.4.2.4) and the goods and services that they provide such as fisheries, tourism and coastal protection (*limited evidence, high agreement*; Box CC-CR, 6.4.1.1,19.5.2, 27.3.3, 30.5, 30.6). Ocean acidification poses many other potential risks, but these cannot yet be quantitatively assessed due to the small number of studies available, particularly on the magnitude of the ecological and socioeconomic impacts (19.5.2).

Global estimates of observed or projected economic costs of ocean acidification do not exist. The largest uncertainty is how the impacts on lower trophic levels will propagate through the food webs and to top predators. However, there are a number of instructive examples that illustrate the magnitude of potential impacts of ocean acidification. A decrease of the production of commercially-exploited shelled mollusks (6.4.1.1) would result in a reduction of US production of 3 to 13% according to the SRES A1FI emission scenario (*low confidence*). The global cost of production loss of mollusks could be over 100 billion USD by 2100 (*limited evidence, medium agreement*). Models suggest that ocean acidification will generally reduce fish biomass and catch (*low confidence*) and that complex additive, antagonistic and/or synergistic interactions will occur with other environmental (warming) and human (fisheries management) factors (6.4.1.1). The annual economic damage of ocean-acidification-induced coral reef loss by 2100 has been estimated, in 2009, to be 870 and 528 billion USD, respectively for the A1 and B2 SRES emission scenarios (*low confidence*; 6.4.1). Although this number is small compared to global GDP, it can represent a very large GDP loss for the economies of many coastal regions or small islands that rely on the ecological goods and services of coral reefs (25.7.5, 29.3.1.2).

Mitigation and Adaptation

Successful management of the impacts of ocean acidification includes two approaches: mitigation of the source of the problem (i.e. reduce anthropogenic emissions of CO_2), and/or adaptation by reducing the consequences of past and future ocean acidification (6.4.2.1). Mitigation of ocean acidification through reduction of atmospheric CO_2 is the most effective and the least risky method to limit ocean acidification and its impacts (6.4.2.1). Climate geoengineering techniques based on solar radiation management will not abate ocean acidification and could increase it under some circumstances (6.4.2.2). Geoengineering techniques to remove carbon dioxide from the atmosphere could directly address the problem but are very costly and may be limited by the lack of CO_2 storage capacity (6.4.2.2). Additionally, some ocean-based approaches, such as iron fertilization, would only re-locate ocean acidification from the upper ocean to the ocean interior, with potential ramifications on deep-water oxygen levels (6.4.2.2; 30.3.2.3 and 30.5.7). A low-regret approach, with relatively limited effectiveness, is to limit the number and the magnitude of drivers other than CO_2, such as nutrient pollution (6.4.2.1). Mitigation of ocean acidification at the local level could involve the reduction of anthropogenic inputs of nutrients and organic matter in the coastal ocean (5.3.4.2). Some adaptation strategies include drawing water for aquaculture from local watersheds only when pH is in the right range, selecting for less sensitive species or strains, or relocating industries elsewhere (6.4.2.1).

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Table 16-1: Identification of key adaptation opportunities. Each type of opportunity is represented by multiple illustrative examples as well as supporting references.

Opportunity	**Examples**	**References**
Awareness raising	Positive stakeholder engagement	Kahan (2010); O'Neill and Chicholson-Cole (2009)
	Communication of risk and uncertainty	Berry *et al.* (2011); Pidgeon and FIschhoff (2011); Pidgeon (2012); Lieske *et al.* (2013)
	Participatory research	Pearce *et al.* (2009) ; McNamara and McNamara (2011); Sheppard *et al.* (2011); Duru *et al.* (2012); Faysse *et al.* (2012)
Capacity building	Research, data, education, and training	PCAST (2011); WMO (2011); Bangay and Blum (2012); Lemos *et al.* (2013)
	Extensions services for agriculture	Deressa *et al.* (2009); Fosu-Mensah *et al.* (2012)
	Resource provision	Ayers (2009); Ayers and Huq (2009); Grasso (2010); Klein (2010); Rübbelke (2011)
	Development of human capital	Bowen *et al.* (2012); Lemos *et al.* (2013)
	Development of social capital	Deressa *et al.* (2009); Adger *et al.* (2010); Engle and Lemos (2010); Huang *et al.* (2011)
Tools	Risk analysis	van Aalst *et al.* (2008); Pidgeon and Butler (2009); Chin *et al.* (2010); Zhou *et al.* (2012); Wade *et al.* (2013)
	Vulnerability assessment	Allison *et al.* (2009); Moreno and Becken (2009); Nelson *et al.* (2010b); Romieu *et al.* (2010); Koh (2011); Preston *et al.* (2011b)
	Multi-criteria analysis	de Bruin *et al.* (2009b); Garfi *et al.* (2011); Yang *et al.* (2012); Kyung-Soo *et al.* (2013)
	Cost/benefit analysis	Hallegatte (2009); Mechler and Islam (2013); Tol *et al.* (2008);Weitzman (2009)
	Decision support systems	Norman *et al.* (2010); Wenkel *et al.* (2013)
	Early warning systems	Lowe *et al.* (2011); Marvin *et al.* (2013); Lenton (2013)
Policy	Integrated resource and infrastructure planning	Rosenberg *et al.* (2010); Becker *et al.* (2012); Heeres *et al.* (2012)
	Spatial planning	Brown (2011); Wheeler (2012); Pinto *et al.* (2013)
	Design/planning standards	Hamin and Gurran (2009); Mailhot and Duchesn (2009); Kwok and Rajkovich (2010); Ren *et al.* (2011); Nassopoulos *et al.* (2012)
Learning	Experience with climate vulnerability and disaster risk	Fiksel (2006) ; Crespo Cuaresma *et al.* (2008); Cuttter *et al.* (2012)
	Learning-by-doing	Berkhout *et al.* (2006); Roberts *et al.* (2012); Bulkeley and Castán Broto (2012)
	Monitoring and evaluation	GIZ, 2011a,b; Preston *et al.* (2011a), Adaptation Sub-Committee (2012)
Innovation	Technological change	Hanjra and Qureshi (2010); Chhetri *et al.* (2012); Lybbert and Sumner (2012); Rodima-Taylor *et al.* (2012); Vermeulen *et al.* (2012)
	Infrastructure efficiencies	Beard *et al.* (2009); Newton (2013)
	Digital/mobile telecommunications	Ospina and Heeks (2010a, b); Meera *et al.* (2012)

Table 16-2: Examples of potential trade-offs associated with an illustrative set of adaptation options that could be implemented by actors to achieve specific management objectives.

Sector	Actor's Adaptation Objective	Adaptation Option	Real or Perceived Trade-Off	References
Agriculture	Enhance drought and pest resistance; enhance yields	Biotechnology and genetically modified crops	Perceived risk to public health and safety; ecological risks associated with introduction of new genetic variants to natural environments	Howden *et al.* (2007); Nisbet and Scheufele (2009); Fedoroff *et al.* (2010)
	Provide financial safety net for farmers to ensure continuation of farming enterprises	Subsidized drought assistance; crop insurance	Creates moral hazard and distributional inequalities if not appropriately administered	Productivity Commission (2009); Pray *et al.* (2011); Trærup (2011); O'Hara (2012); Vermeulen *et al.* (2012)
	Maintain or enhance crop yields; suppress opportunistic agricultural pests and invasive species	Increased use of chemical fertilizer and pesticides	Increased discharge of nutrients and chemical pollution to the environment; adverse impacts of pesticide use on non-target species; increased emissions of greenhouse gases; increased human exposure to pollutants	Gregory *et al.* (2005); Howden *et al.* (2007); Boxall *et al.* (2009)
Biodiversity	Enhance capacity for natural adaptation and migration to changing climatic conditions	Migration corridors; expansion of conservation areas	Unknown efficacy; concerns over property rights regarding land acquisition; governance challenges	Hodgson *et al.* (2009); West *et al.* (2009); Krosby *et al.* (2010); Levin and Petersen (2011)
	Enhance regulatory protections for species potentially at-risk due to climate and non-climatic changes	Protection of critical habitat for vulnerable species	Addresses secondary rather than primary pressures on species; concerns over property rights; regulatory barriers to regional economic development	Clark *et al.* (2008); Ragen *et al.* (2008); Bernanzzani *et al.* (2012)
	Facilitate conservation of valued species by shifting populations to alternative areas as the climate changes	Assisted migration	Ultimate success of assisted migration is difficult to predict; introduction of species into new ecological regions could have adverse impacts on indigenous flora and fauna	Lovejoy (2005, 2006); McLachlan *et al.* (2007); Dunlop and Brown (2008)
Coasts	Provide near-term protection to financial assets from inundation and/or erosion	Sea walls	High direct and opportunity costs; equity concerns; ecological impacts to coastal wetlands	Nicholls (2007); Hayward (2008); Hallegatte (2009); Zhu *et al.*, (2010)
	Allow natural coastal and ecological processes to proceed; reduce long-term risk to property and assets	Managed retreat	Undermines private property rights; significant governance challenges associated with implementation	Rupp-Armstrong and Nicholls (2007); Hayward (2008); Abel *et al.* (2011); Titus (2011)
	Preserve public health and safety; minimize property damage and risk of stranded assets	Migration out of low-lying areas	Loss of sense of place and cultural identify; erosion of kinship and familial ties; impacts to receiving communities	Hess *et al.* (2008); Heltberg *et al.* (2009); McNamara and Gibson (2009); Adger *et al.* (2011)

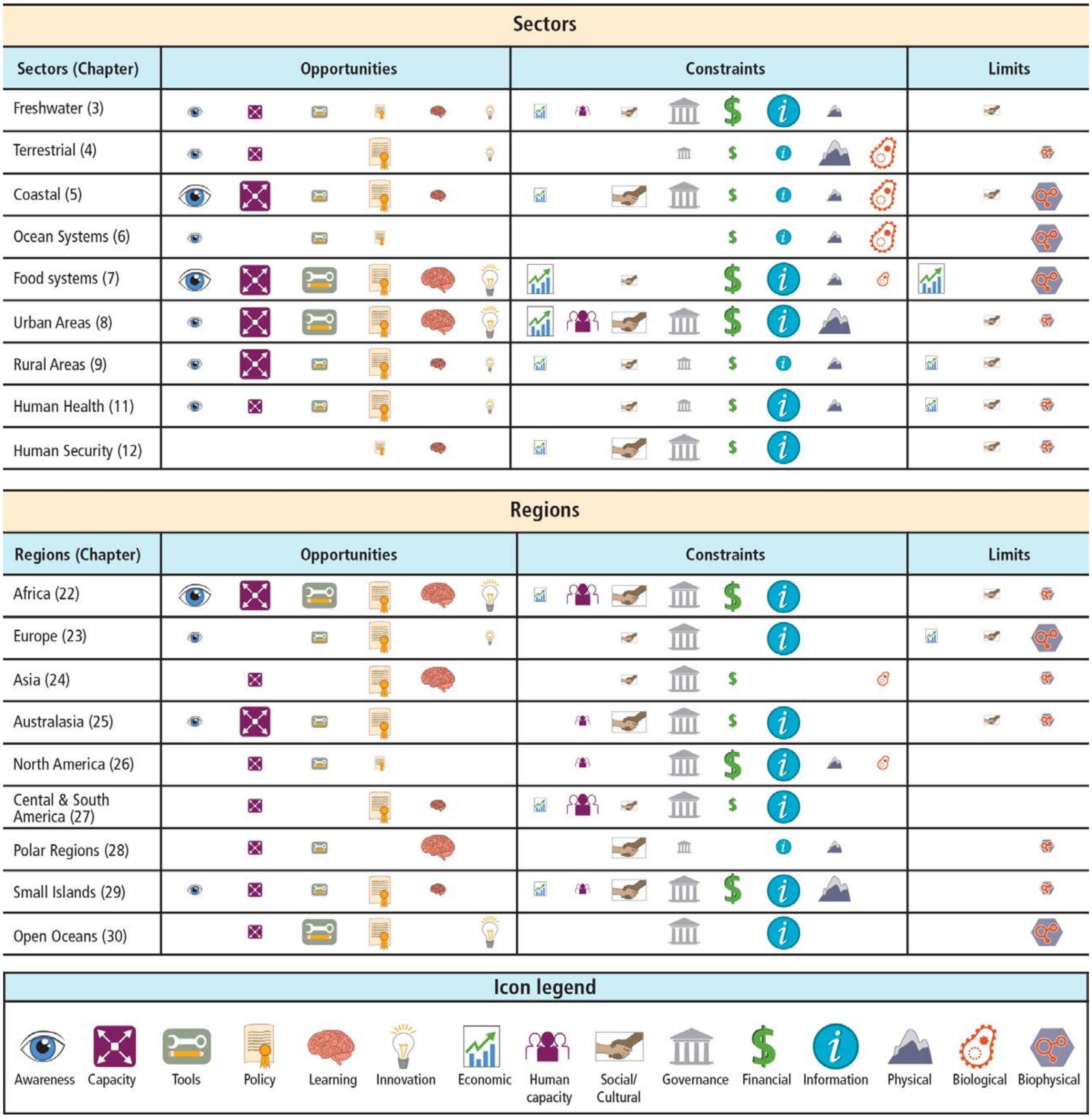
Water resources management	Increase water resource reliability and drought resilience	Desalination	Ecological risk of saline discharge; high energy demand and associated carbon emissions; creates disincentives for conservation	Adger and Barnett (2009); Barnett and O'Neill (2010); Becker *et al.* (2010, 2012); Rygaard *et al.* (2011); Tal *et al.* (2011)
	Maximize efficiency of water management and use; increases flexibility	Water trading	Undermines public good/social aspects of water	Alston and Mason (2008); Bourgeon *et al.* (2008); Donohew (2008); Mooney and Tan (2012); Tan *et al.* (2012)
	Enhance efficiency of available water resources	Water recycling/reuse	Perceived risk to public health and safety	Hartley (2006); Dolcinar *et al.* (2011)

Table 16-3. Sectoral and regional synthesis of adaptation opportunities, constraints, and limits. Each icon represents types of opportunities, constraints and limits (described below). The size of the icon represents when there is relatively little (small icon) or relatively ample (large icon) information in the sectoral and regional chapters to describe each type of opportunity, constraint, or limit. If no information was presented, the table cell is blank.

Opportunities are defined *as factors that make it easier to plan and implement adaptation actions, that expand adaptation options, or that provide ancillary co-benefits.* Types of opportunities include (1) **Awareness -** communication, education and awareness raising; (2) **Capacity -** human and institutional capacity building including preparedness, resource provision, and development of human and social capital; (3) **Tools -** decision-making, vulnerability and risk analysis, decision support and early warning tools; (4) **Policy -** integration and mainstreaming of policy, governance and planning processes including sustainable development, resource and infrastructure planning, and design standards; (5) **Learning -** mutual experiential learning and knowledge management of climate vulnerability, adaptation options, disaster risk response, monitoring and evaluation; and (6) **Innovation -** development and dissemination of new information, technology development, and technology application.

Constraints *are defined as factors that make it harder to plan and implement adaptation actions*. Types of constraints include (1) **Economic -** existing livelihoods, economic structures and economic mobility; (2) **Social** and cultural **-** social norms, identity, place attachment, beliefs, worldviews, values, awareness, education, social justice, and social support; (3) **Human capacity -** individual, organizational, and societal capabilities to set and achieve adaptation objectives over time including training, education, skill development; (4) **Governance,** Institutions & Policy - existing laws, regulations, procedural requirements, governance scope, effectiveness, institutional arrangements, adaptive capacity, and absorption capacity; (5) **Financial -** lack of financial resources; (6) **Information**/ Awareness/ Technology - lack of awareness or access to information or technology; (7) **Physical -** presence of physical barriers; and (8) **Biological -** temperature, precipitation, salinity, acidity, intensity and frequency of extreme events including storms, drought and wind**.**

*A **Limit** is defined* as the *point at which an actor's objectives or system's needs cannot be secured from intolerable risks through adaptive actions*. Types of limits include (1) **Biophysical -** temperature, precipitation, salinity, acidity, intensity and frequency of extreme events including storms, drought and wind, (2) **Economic -** existing livelihoods, economic structures and economic mobility; and (3) **Social/cultural -** social norms, identity, place attachment, beliefs, worldviews, values, awareness, education, social justice, and social support.


Sectors
Sectors (Chapter)
Opportunities
Constraints
Limits
Freshwater (3)
Terrestrial (4)
Coastal (5)
Ocean Systems (6)
Food systems (7)
Urban Areas (8)
Rural Areas (9)
Human Health (11)
Human Security (12)
Regions
Regions (Chapter)
Opportunities
Constraints
Limits
Africa (22)
Europe (23)
Asia (24)
Australasia (25)
North America (26)
Cental & South America (27)
Polar Regions (28)
Small Islands (29)
Open Oceans (30)
Icon legend
Awareness
Capacity
Tools
Policy
Learning
Innovation
Economic
Human capacity
Social/ Cultural
Governance
Financial
Information
Physical
Biological
Biophysical

16-4: Ethical dimensions of adaptation opportunities, constraints, and limits and their policy implications.

Ethical dimensions	Commentary	Public policy issues	References
Adaptation opportunities			
Access to opportunities	Inequitable access to the factors making it easier to adapt and achieve adaptation objectives	Whether national or international policy should support more equitable access to adaptation opportunities	Thomas and Twyman (2005); Paavola and Adger (2006); Paavola, (2008); Füssel (2010); Rübbelke (2011); Klinsky *et al.* (2012)
Adaptation constraints			
Distribution of constraints	Inequitable distribution of factors that make it harder to plan and implement adaptation actions	Whether national or international policy should reduce or remove constraints to adaptation	Paavola and Adger, (2006); Klein and Möhner (2009); Grasso (2010)
Adaptation limits			
Differing attitudes to risk	What is deemed an acceptable, tolerable and intolerable risk will vary across cultures, social groups and individuals	Risk governance is concerned with balancing differentiated and dynamic attitudes to risk in allocating resources to managing risks	Bisaro *et al.* (2010); Juhola *et al.* (2011); Lata and Nunn (2012); Sovacool (2012); Fatti and Patel (2013); Ward *et al.* (2013)
Rights and potentials of people to secure particular valued objectives	Limits are related to given valued objectives, but such objectives vary between individuals and collectives	Risk governance related to adaptation limits is concerned with setting priorities between different (and conflicting) valued objectives	Foale (2008); Devine-Wright (2009); Gorman-Murray (2010); Jacob *et al.* (2010); Brown *et al.* (2011); Adger *et al.* (2012)
Differing rates at which limits are reached	Limits will be reached earlier by some groups and regions (Arctic, unprotected coastal zones) than others	Risk governance at different scales will be confronted with choices about adaptation limits emerging through time	Baum and Easterling (2010); Edvardsson-Bjornberg and Hansson (2011); Dow *et al.* (2013a)
Trade-offs in securing valued objectives	Adaptive responses will involve choices between valued objectives at adaptation limits (i.e. between river water quality and water demand from irrigation)	As adaptation limits affecting multiple valued objectives are reached, private and public choices will be made about which values have priority over others	Steenberg *et al.* (2011); Towler *et al.* (2012); Seidl and Lexer (2013); Pittock (2013)
Intergenerational and interspecies equity and adaptation limits	Valued objectives may be irrecoverably lost at adaptation limits, denying them to future generations	Species extinctions, and loss cultural heritage, place or identity may call for extraordinary public policy interventions	Albrecht *et al.* (2013)

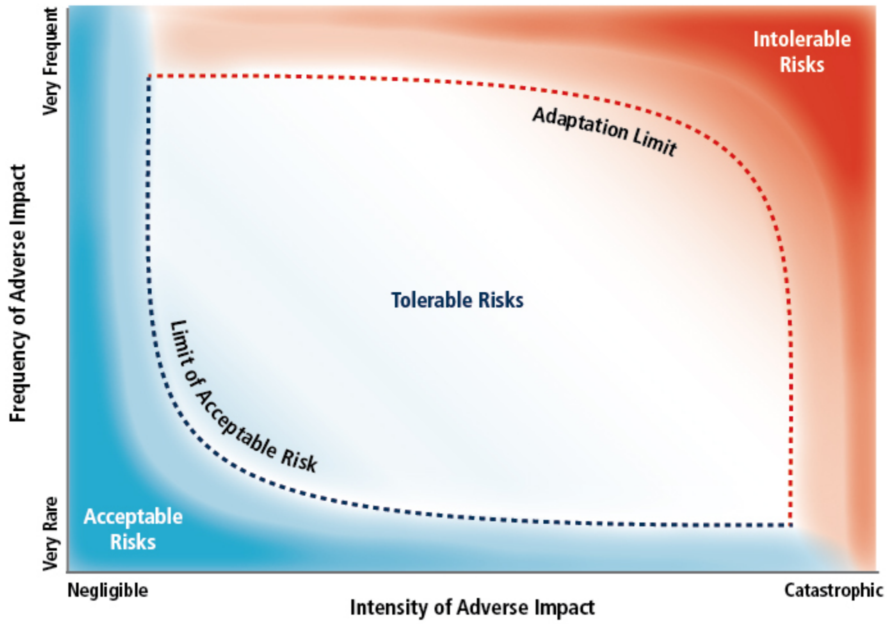


Figure 16-1: Conceptual model of the determinants of acceptable, tolerable and intolerable risks and their implications for limits to adaptation (Dow *et al.*, 2013b; based on Klinke and Renn, 2002; also see Renn and Klinke 2013). In this conceptual diagram, adaptation efforts are seen as keeping risks to objectives within the tolerable risk space. Opportunities and constraints influence the capacity of actors to maintain risks within a tolerable range. The lines are dotted to indicate that individual or collective views on risk tolerability with respect to the frequency and intensity of climate-related risks are not fixed, but may vary and change over time. In addition, the shape or angle of the lines and the relative area in each section of the diagram are illustrative and may themselves change as capacities and attitudes change. The shaded areas represent the potential differences in perspective among actors.

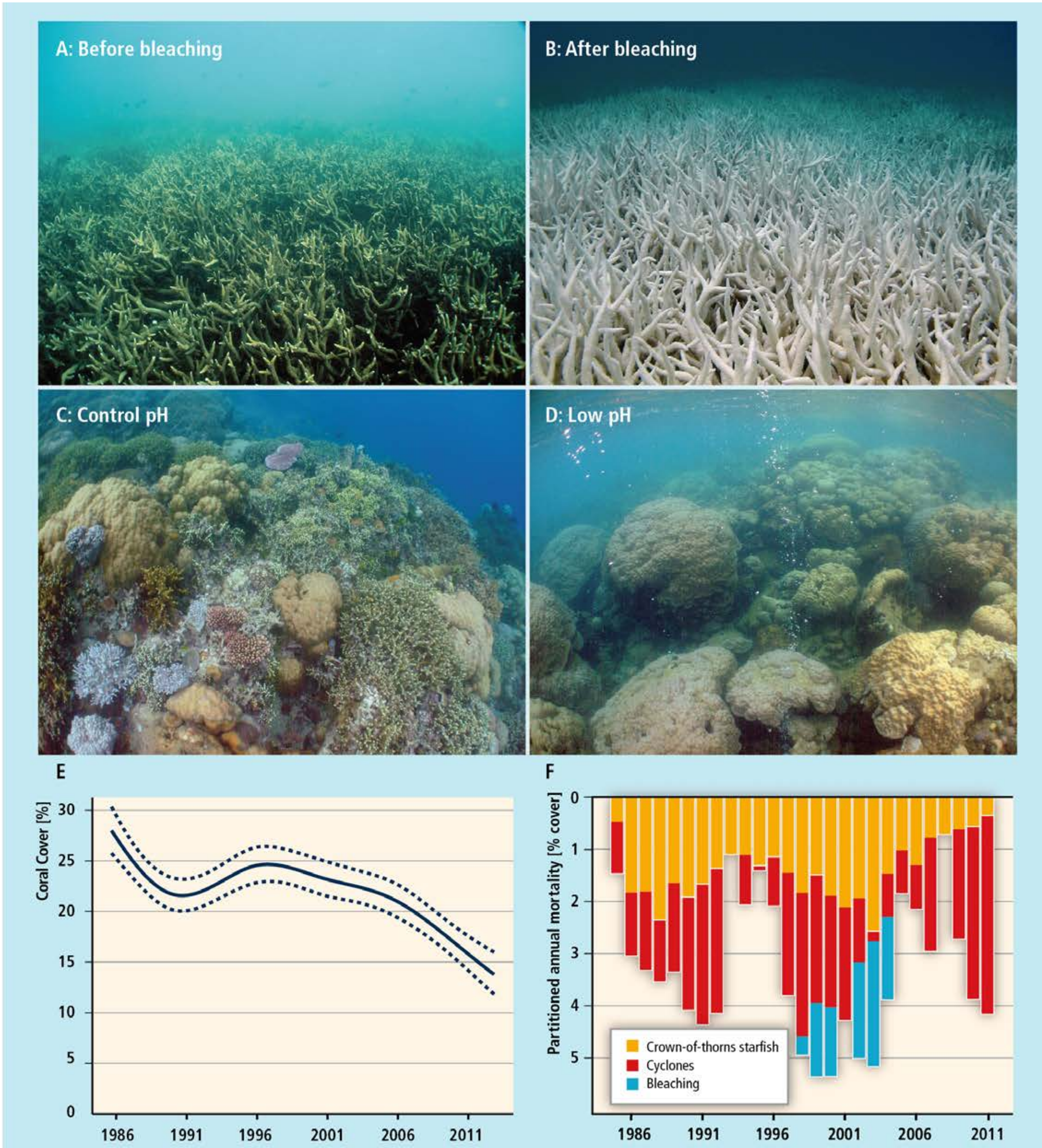


Figure CR-1: A and B: the same coral community before and after a bleaching event in February 2002 at 5 m depth, Halfway Island, Great Barrier Reef. Coral cover at the time of bleaching was 95% bleached almost all of it severely bleached, resulting in mortality of 20.9% (Elvidge *et al*., 2004). Mortality was comparatively low due in part because these coral communities were able to shuffle their symbiont to more thermo-tolerant types (Berkelmans and van Oppen, 2006; Jones *et al*., 2008). C and D: three CO_2 seeps in Milne Bay Province, Papua New Guinea show that prolonged exposure to high CO_2 is related to fundamental changes in the ecology of coral reefs (Fabricius *et al*., 2011), including reduced coral diversity (-39%), severely reduced structural complexity (-67%), lower density of young corals (-66%) and fewer crustose coralline algae (-85%). At high CO_2 sites (panel D; median pH_T ~7.8), reefs are dominated by massive corals while corals with high morphological complexity are underrepresented compared with control sites (D; median pH ~8.0). Reef development ceases at pH_T values below 7.7. pH_T: pH on the total scale. E: temporal trend in coral cover for the whole Great Barrier Reef over the period 1985–2012 (N, number of reefs, mean ± 2 standard errors; De'ath et al., 2012). F: composite bars indicate the estimated mean coral mortality for each year, and the sub-bars indicate the relative mortality due to crown-of-thorns starfish, cyclones, and bleaching for the whole Great Barrier Reef (De'ath et al., 2012). Photo credit: R. Berkelmans (A and B) and K. Fabricius (C and D).

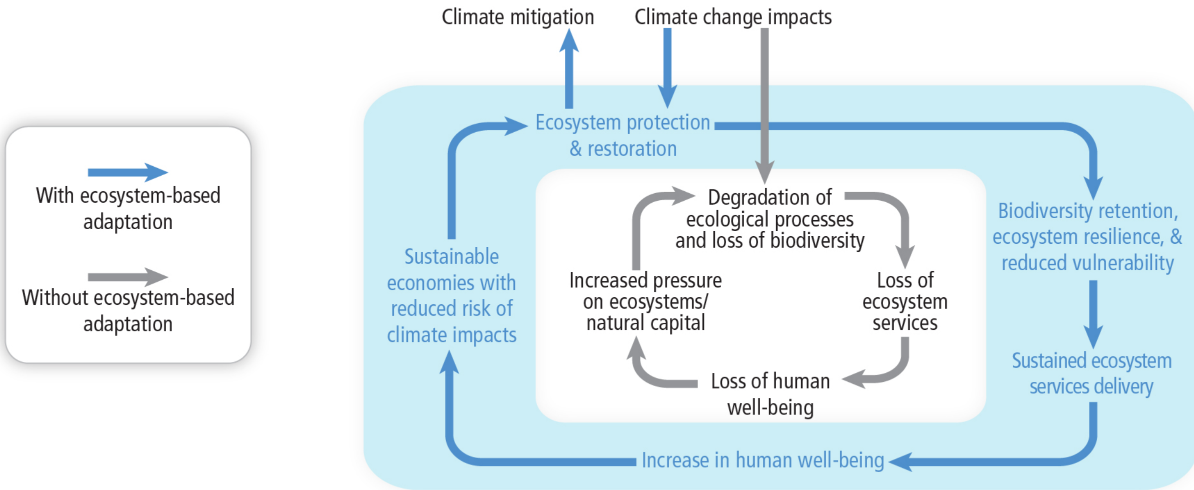


Figure EA-1: Adapted from Munang et al. (2013). Ecosystem based adaptation (EBA) uses the capacity of nature to buffer human systems from the adverse impacts of climate change. Without EBA, climate change may cause degradation of ecological processes (central white panel) leading to losses in human well-being. Implementing EBA (outer blue panel) may reduce or offset these adverse impacts resulting in a virtuous cycle that reduces climate-related risks to human communities, and may provide mitigation benefits.

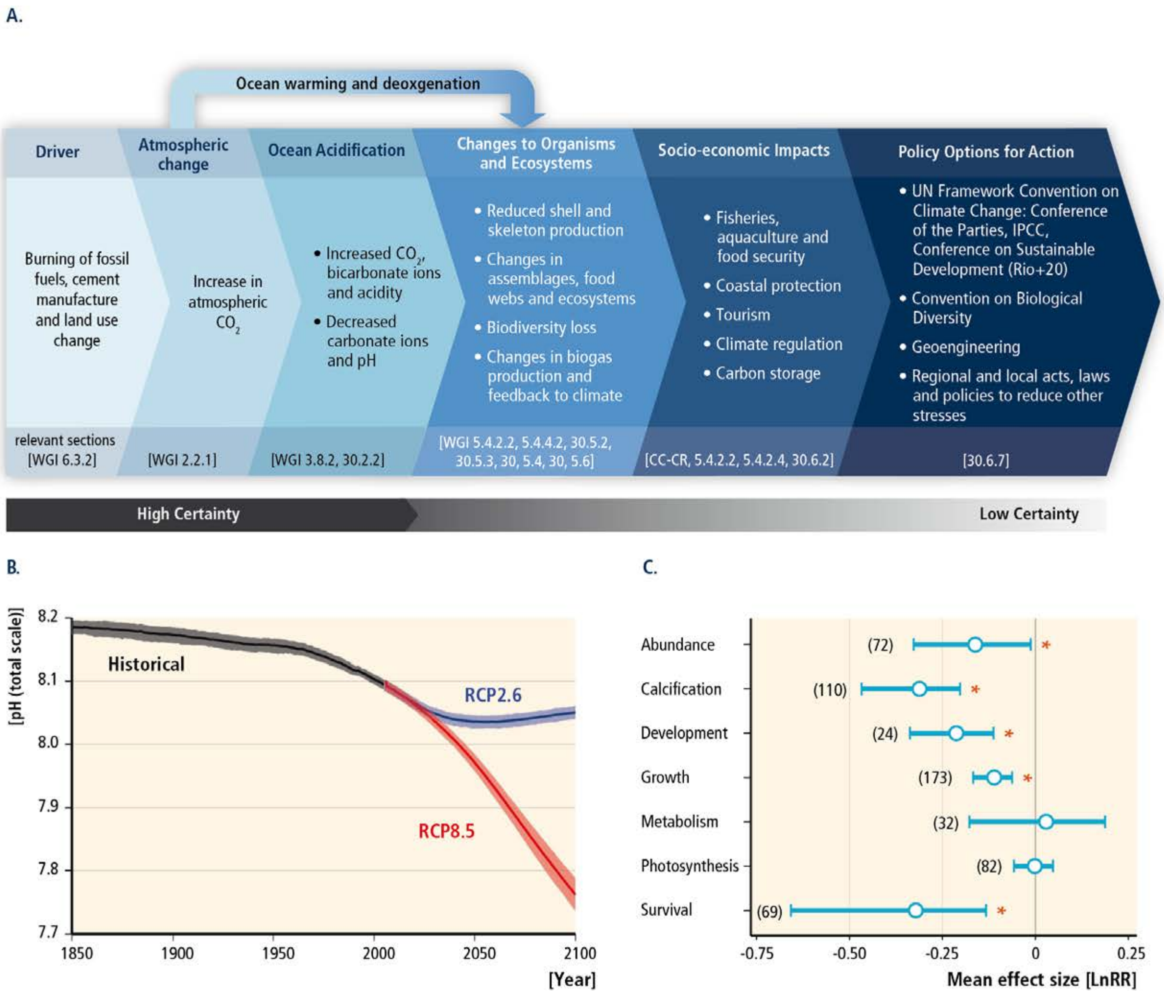


Figure OA-1: A: Overview of the chemical, biological, socio-economic impacts of ocean acidification and of policy options (adapted from Turley and Gattuso, 2012). B: Multi-model simulated time series of global mean ocean surface pH (on the total scale) from CMIP5 climate model simulations from 1850 to 2100. Projections are shown for emission scenarios RCP2.6 (blue) and RCP8.5 (red) for the multi-model mean (solid lines) and range across the distribution of individual model simulations (shading). Black (grey shading) is the modelled historical evolution using historical reconstructed forcings. The models that are included are those from CMIP5 that simulate the global carbon cycle while being driven by prescribed atmospheric CO_2 concentrations. The number of CMIP5 models to calculate the multi-model mean is indicated for each time period/scenario (WGI AR5 Figure 6.28). C: Effect of near future acidification (seawater pH reduction of 0.5 unit or less) on major response variables estimated using weighted random effects meta-analyses, with the exception of survival which is not weighted (Kroeker et al., 2013). The log-transformed response ratio (LnRR) is the ratio of the mean effect in the acidification treatment to the mean effect in a control group. It indicates which process is most uniformly affected by ocean acidification but large variability exists between species. Significance is determined when the 95% bootstrapped confidence interval does not cross zero. The number of experiments used in the analyses is shown in parentheses. * denotes a statistically significant effect.