WWF

CLIMATE & ENERGY

SCIENCE OF A 1.5 °C TEMPERATURE LIMIT

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Executive Summary

In the Paris Agreement on climate change from December 2015, countries agreed to holding "…the increase in the global average temperature to well below 2°C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5°C above pre-industrial levels." The IPCC has been commissioned to prepare a special report on 1.5°C to be published in 2018. The IPCC report will cover mitigation pathways, impacts and link with sustainable development and poverty. With the increased focus in the political and scientific community on 1.5°C pathways following the Paris Agreement, more literature is becoming available that details the impacts of, and mitigation pathways for, limiting the global temperature rise to such temperature levels. However, there are still significant gaps in the information.

Generally, impacts on natural and human systems from climate change become more severe as temperatures increase, which is the basis for the ambition to limit temperature increases. Available mitigation pathways suggest very rapid reductions in greenhouse gas emissions and options which remove carbon from the atmosphere such as reforestation or bio-CCS (BECCS) will be needed to reach 1.5°C. There are still significant uncertainties regarding the potential, costs and impacts of these carbon dioxide removal (CDR) options. To help inform the WWF position on the 1.5°C target, this report assesses:

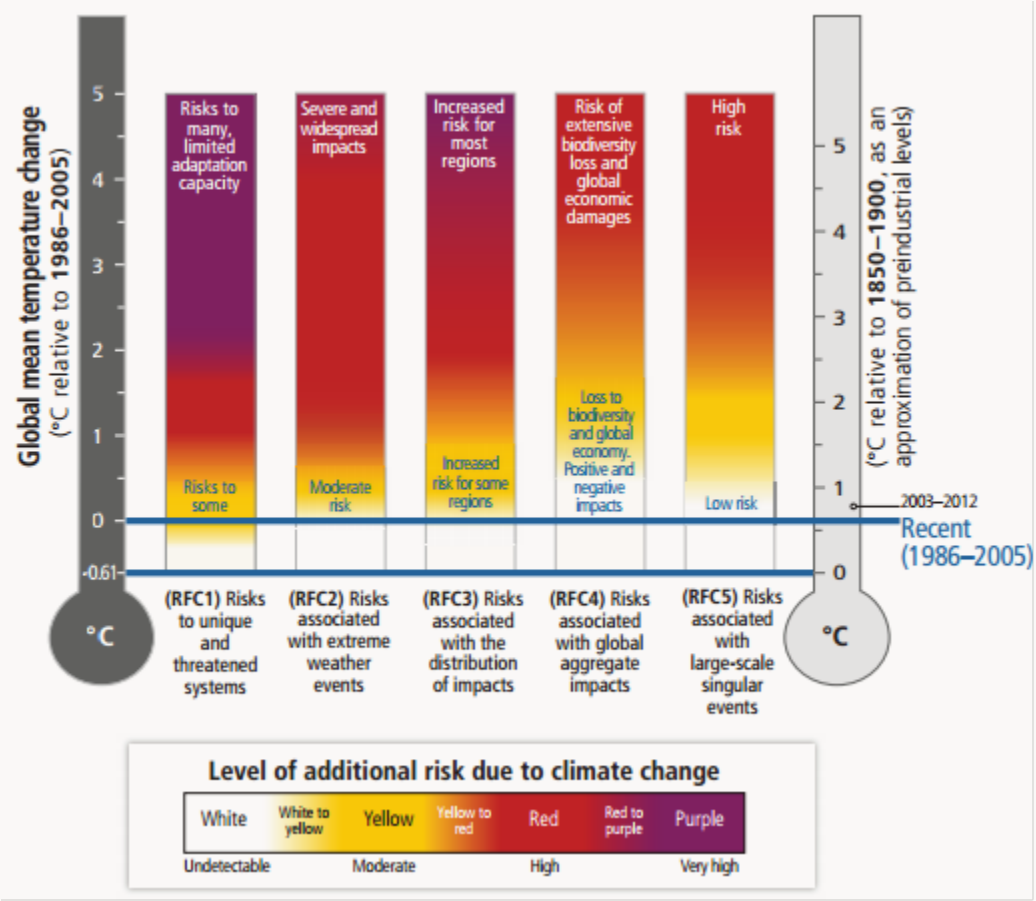
- the available evidence on the avoided impacts in going from a 2°C to 1.5°C global temperature limit
- the options for adaptation
- the mitigation and removal options needed, and the trade-offs that could be made between different options to limit the global temperature rise to 1.5°C.

Using the available evidence, we make recommendations for WWF's position on issues connected with the ambition to limit temperature rise to 1.5°C.

IMPACTS

There is substantial scientific research into the impact of a 2°C or higher global temperature rise on different sectors, which generally shows increasing impacts with increasing temperature. However, there is much more limited research on the incremental difference between impacts from a global average temperature rise of 1.5°C and 2°C. The figure below, which is from the 5th Assessment Report of the IPCC, shows there is an increase in risk due to climate change between 1.5°C and 2°C in several areas.

Figure 1 Levels of additional risk http://ipcc-wg2.gov/AR5/images/uploads/WGIIAR5-Chap19_FINAL.pdf



The table below provides a summary of findings from literature on the impacts of climate change on natural systems in a 2˚C and a 1.5˚C warming scenario for different sectors. In most cases, these specific conclusions are based on a single or a very limited number of studies, again illustrating the scarcity of literature. It is expected that by the time of the IPCC special report, there will be more studies available.

Table 1-1 Summary of findings on the impacts of climate change under 1.5˚C and 2˚C based on current literature.

Sector / systems	Overall level of impact	
	1.5°C	2°C
Agriculture		
Forest ecosystems		
Fresh water ecosystems		
Marine ecosystems		
Glaciers		
Permafrost		
Arctic/Antarctic ice sheets and sea ice		
Heat		
Precipitation		
Sea-level rise		
Floods	uncertain	uncertain
Droughts		

=Manageable and/or localised impact
=Regional impact
=Global or widespread impact

From the table above it is clear that the projected climate impacts at 1.5˚C in most sectors are less than at 2˚C, although in most cases there is impact even at 1.5˚C. The literature suggests that with 2˚C warming, there will be more pronounced weather and extreme events that can cause a global and widespread impact on humans and ecosystems. Two geographical regions in particular have higher risk: the tropics, due to the limited capacity of species to adapt to moderate global warming, as the species are already near their upper thermal limits, and high northern latitudes, where temperature increases are projected to be large.

From the details in the literature, the benefits identified of limiting warming to 1.5˚C (instead of 2°C) are:

- Limiting the reduction in global agricultural production loss to 10% or less.
- Reduction of the risk of coral reef bleaching from 99% to 70% by 2100.
- Reduction of glacier melting by up to 3cm of sea level rise equivalent before the end of the centuary.

- Reduction in heavy precipitation intensity by 2%.
- Limiting the sea level rise to 40 cm instead of 50cm.
- Reduction in warm spells (a period of abnormally hot weather) by up to one month.
- Limiting the widespread thawing of permafrost.
- Limiting the extent of loss of Artic and Antarctic ice sheets and Arctic sea ice.
- Limiting the impact of drought and forest fires on globally significant biomes; Amazon and Boreal forests.
- Decreased risk of extinction of many species.

In addition to the projected impact of the temperature rises, several tipping points in the climate system have been identified which could result in rapid and irreversible impacts. Some of these tipping points have ranges within the 2°C warming. They are primarily found in the cryosphere (Arctic sea-ice, Greenland and Antarctic ice sheets, some permafrost regions), biosphere (Amazon and Boreal Forests), and in natural processes (Atlantic Thermohaline Circulation (THC), El Niño–Southern Oscillation (ENSO), Indian Summer Monsoon, West African Monsoon, North Atlantic sub-polar gyre). Literature suggests that both Arctic sea-ice and the Greenland ice sheets have the nearest tipping points in the range of 0.5-2°C warming, although the transition time scale is greater than 300 years. There is thus a high risk that with a 2°C temperature rise we will pass an early tipping point and that it would be difficult to avoid large-scale ice sheet disintegration, which would cause sea level rise of several metres. There is still some risk this would occur at 1.5°C.

ADAPTATION

The current body of literature on the link between adaptation requirements and different levels of global temperature rise is sparse: a few resources outline the implications of different degrees of global warming on adaptation, however, none explicitly address adaptation in the context of 1.5°C in particular. Given this scarcity of adaptation literature relating directly to the difference between 1.5 and 2°C, in this paper we assess various aspects of adaptation for temperatures above and below 2°C. While it is clear from literature that adaptation has the potential to reduce damages from the impacts of climate change, in nearly all cases, the residual risk (the risk after adaptive action has been taken) still increases with global temperature rise. This means that even with adaptation, the risk increases of having to deal with more severe impacts at 2°C than at 1.5°C. Furthermore, with a greater the temperature rise, the more limited the type of adaptation actions that are available.

Adaptation actions required for 1.5°C compared to 2°C

The effectiveness of adaptation actions depends on the timescale, investment and technical possibilities available. The types of adaptation actions that could be taken may differ for 1.5°C compared with adaptation actions to be taken with 2°C temperature rise in highly temperature-sensitive systems, for many terrestrial and marine species, for regional food security and in response to sea-level rise. Adaptation is more effective at supporting existing species and ecosystems (e.g. natural corridors) at the lower end of warming. The higher above 1.5°C, the more likely it is that adaptation will be about accepting irreversible change.

The role of transformational adaptation

Transformational adaptation[1] is complex and ambiguous in all scenarios: there is medium evidence for and medium agreement on the need for transformative changes to improve climate resilience. It is not generally required for 1.5°C but transformational adaptation would be required in some circumstances as the global temperature rise approaches

[1] Transformational adaptation is also addressed in section 3.4. Transformational, or transformative change in terms of adaptation implies fundamental changes in the objectives of decision-makers (Horrocks and Harvey, 2009 as cited in Smith et al., 2011). The IPCC describes transformational adaptation as "adaptations at a greater scale or intensity than previously experienced, adaptations that are new to a region or system, or adaptations that transform places or lead to a shift in the types or locations of activities" (IPCC, 2014a, p.89). An example of which would be relocating an entire industry or swapping farming for another land use (Smith et al., 2011).

and exceeds 2°C. For ecosystems, it is likely that 2°C would result in climate change too rapid for some species to migrate fast enough to remain in their preferred temperature zone.[2]

Trade-offs between mitigation and adaptation

There is no literature to distinguish the trade-offs at 1.5. For temperatures over 2°C there are several trade-offs:

- Land-use change for biomass production and more incremental adaptation measures intended for a 2°C would increase vulnerability to a 4°C world, increasing potential for biodiversity loss
- Afforestation as a carbon sequestration measure can have a negative impact on biodiversity when planting non-native tree species or planting in areas not supportive of high forest biodiversity
- Irrigation as a response to crop failure at high impact level will negatively impact water availability
- Moving agricultural land to wooded areas could reduce biodiversity and potentially also human health in the surrounding area with global temperature rise of 4°C

Limits and costs of adaptation

The IPCC defines the limits to adaptation as a situation in which the "adaptive actions to avoid intolerable risks for an actor's objectives or for the needs of a system are not possible or are not currently available" (p.28).

In terms of adaptation limits, the IPCC points out that 2°C is not a global adaptation limit, however, it can be for specific geographic areas, ecosystems, and species. It is possible though that the limit for some species is even lower, as they have already exhausted their adaptation capacities (i.e. forest species in the tundra). Warming of 4°C presents an adaptation limit for human and natural systems in general but also specifically for urban water supply systems, heat-sensitive peoples, food security, and agricultural productivity.

Evidence on the costs of adaptation tends to be related to scenarios, but not specifically related to a warming limit of 1.5°C. Costs of adaptation differ under different warming scenarios but estimated costs vary considerably and are often incomparable as they are calculated in different ways. The evidence does suggest that more aggressive emissions reductions will result in lower adaptation costs as early as the 2030s.

UNEP puts forth a general estimate for the cost of adaptation totalling USD 140 and 300 billion per year by 2030 and between USD 280 and 500 billion by 2050. Other estimates also exist for adaptation measures in coastal areas to combat sea level rise and storm surge: The UNEP estimates global, annual adaptation costs of "between USD 12-31 billion to USD 27-71 billion for low-and high-warming scenarios respectively" up to 2100. For a 4°C world, Nicholls et al. estimates adaptation costs of between USD 25 and USD 270 billion (1995 values) per annum for 0.5 and 2.0 metres sea-level rise by 2100 respectively (based on SRES scenarios).

MITIGATION

[2] "In a world 1.5 °C warmer than in pre-industrial times: climate change velocity would be slow enough for most terrestrial and freshwater organisms to follow; up to half of coral reefs may remain intact; sea level rise may remain below 1 m; some Arctic summer sea ice may remain; ocean acidification impacts would stay at moderate levels; the capacity to increase food production would be reduced, but some scope would exist for adaptation; some unique systems would be at high risk; and the risks of combined ocean acidification and warming would become more prominent…With respect to the projected impacts of future climate change and the importance of the rate of change, Mr. Field described a graph showing the maximum speed at which terrestrial species can move across landscapes depending on the rate of climate change, which illustrates that RCP6, the impacts of climate change on many habitats are occurring faster than the estimated maximum speed at which most groups of organisms can move. The impacts of climate change are therefore outrunning the speed at which ecosystems can be expected to possibly shift in order to adapt to these changes" (UNFCCC-SED, 2015, p.118-19).

It is estimated that a global carbon budget of 590—1240 $GtCO_2$ can be emitted between 2015—2100 in order to retain a 66% chance of not exceeding a 2°C temperature increase (IPCC, 2014c; Rogelj, 2016). This equates to 15—30 years of current emission levels (40 $GtCO_2\,yr^{-1}$). The budget for limiting warming to below 1.5°C will be even tighter.

Integrated assessment models are used by the scientific community to investigate which mitigation actions are needed to meet different temperature limits at a cost-optimal level. There is a wide body of literature on scenarios that meet a 2°C temperature limit but only one paper that reports specifically on scenarios for 1.5°C (Rogelj, 2015). The key similarities and differences between characteristics and trends of the scenarios for the two temperature limits are:

- Both groups of pathways require significant emission reductions and employ a wide range of mitigation options.
- Both pathways stipulate that net total global emissions need to go to at least to zero, although the timing differs: 2˚C pathways tend to see zero emissions near the middle of the 2nd half of the century, whereas 1.5˚C pathways require zero emissions to be achieved by the middle of the century, i.e. up to two decades earlier.
- The emissions of greenhouse gases other than CO_2 are similar in both groups of pathways as no additional mitigation options are assumed to be available to achieve a 1.5˚C target compared to 2˚C.
- Of the 116 2°C scenarios assessed by IPCC AR5 that reach their target with a likelihood of 66%, 107 include CDR. The few scenarios that do not include negative emissions show that carbon emissions must fall to zero before 2050 (Peters, 2015). All 1.5°C scenarios deploy CDR (Rogelj, 2016).
- Of the 2°C scenarios assessed by IPCC AR5, most scenarios exceed the 2°C consistent carbon budget and emissions are net negative in the second half of the century to stabilise at the 'required' carbon budget for 2°C. In contrast, all existing 1.5°C scenarios take this 'overshoot' pathway, with net negative emissions soon after 2050 to reach 1.5°C-consistent carbon emissions (Van Vuuren et al., 2015).

To illustrate the differences in more detail, the table below summarises the main differences between scenarios limiting temperature to 1.5°C and 2°C within defined mitigation areas:

Table 1-2 Details of the difference in trends for defined mitigation areas

Mitigation area	Description of difference in trends between 1.5°C scenarios and 2°C
Decarbonisation of electricity supply	Similar end point reached in 2050 (95—98% of low carbon electricity[3]) but reached earlier in 1.5°C (73% of low carbon electricity in 2030 compared to 63% for 2°C). In 2050, 1.5°C pathways project 0 $GtCO_2\,yr^{-1}$ emissions compared to 1 $GtCO_2\,yr^{-1}$ for 2°C.
Decarbonisation of total energy supply	Faster decarbonisation in 1.5°C consistent scenarios than those for 2°C (2.1—2.8% yr^{-1} over the period 2010—2050 compared to 1.75—2.0% yr^{-1})
Decarbonisation in end use sectors	Overall large difference in carbon emission reduction rates. Slightly faster rate of carbon intensity improvements (2.6% yr^{-1} compared to 2.4% yr^{-1} in 2°C) over the period 2010-2050.
Decarbonisation in industry	Emissions from industry reach 4 $GtCO_2\,yr^{-1}$ for 1.5°C, compared to 5 $GtCO_2\,yr^{-1}$ for 2°C in 2050.
Decarbonisation in transport	Increase in rate of electrification needed in both 2°C and 1.5°C compared to scenarios above 2°C (details not given in the literature for 1.5°C). Similar percentage reached in 2050 in both 2°C and 1.5°C. 15% higher share of biofuels in liquid energy carriers in the 1.5°C-consistent scenarios by 2050. Median estimates for emissions in the transport sector in 2°C pathways

[3] Low carbon electricity—renewables, nuclear and power generation with CCS.

Mitigation area	Description of difference in trends between 1.5°C scenarios and 2°C
	assume almost twice the carbon emissions in 2050 compared to 1.5°C.
Decarbonisation in buildings	Half the emissions in 2050 in 1.5°C pathways (0.5 $GtCO_2$ yr^{-1}) compared to 2°C pathways (1 $GtCO_2$ yr^{-1}).
Carbon dioxide removal	Cumulative amount of carbon removed by 2100 is higher (800 Gt compared to 500 Gt in 2°C). In 1.5°C scenarios, CDR ramps up much faster and earlier, already reaching 1–8 Gt yr^{-1} negative emissions in 2040, compared to 0–2.5 Gt yr^{-1} for 2°C. After 2050, this difference slightly levels out to 2—15 Gt yr^{-1} for 1.5°C and 1—8 Gt yr^{-1} for 2°C. There is a delay of ~10 years in negative emissions scale-up.
Time to reach net zero CO_2 emissions (median)	15 years earlier (i.e. net zero in 2050 for 1.5°C).
Time to reach net zero non-CO_2 emissions (median)	15 years earlier (i.e. net zero in 2075 for 1.5°C).
Mitigation costs	Aggregated long term mitigation costs are up to two times higher in the 1.5°C scenarios than 2°C

The models used to calculate the scenarios are complex and the choices made on which technologies to deploy are heavily influenced by certain assumptions. In particular, on the costs and cost reductions of certain technologies or endogenous limits on the potential or rate of implementation of a technology. For some technologies, particularly renewables, the costs have been falling much more quickly than anticipated in many of the models, driven by deployment in response to government policies. For others such as CCS, implementation and therefore cost reductions, have been slower than anticipated. It is therefore possible that models could project trends that may not be seen in reality. An example is the high share of CCS and BECCS in the power sector in the models. In reality, the currently very expensive option of CCS is not being deployed whereas renewable power sources are being deployed at scale. Nuclear is also an option that is deployed to scale in many of the mitigation pathways for both 1.5°C and 2°C. However, with falling renewable prices it is also less cost competitive and in many countries there is a lengthy approval process which slows the rate at which it can be implemented. There are no specific scenarios from integrated assessment models in the literature that exclude CCS and nuclear and still meet 1.5°C, but scenarios such as The Energy Report and the Greenpeace Energy Revolution 2015 have 100% renewable energy scenarios by 2050.

To assess the real feasibility of meeting the 1.5°C global temperature limit with the latest cost information and thinking on constraints of the different options, new scenarios are needed.

DETAILED REPORT

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1 Introduction

In the Paris Agreement on climate change from December 2015, countries agreed to holding "…the increase in the global average temperature to well below 2°C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5°C above pre-industrial levels." The IPCC has been commissioned to prepare a special report on 1.5°C to be published in 2018[4]. The IPCC report will cover mitigation pathways, impacts and link with sustainable development and poverty. With the increased focus in the political and scientific community on 1.5°C pathways following the Paris Agreement, more literature is becoming available that details the impacts of, and mitigation pathways for, limiting the global temperature rise to such temperature levels. However, there are still significant gaps in the information.

WWF's overall mission is to stop the degradation of the planet's natural environment and to secure a future in which humans thrive in harmony with nature. The threat posed by climate change is an important consideration in this mission and WWF has long advocated for the 1.5°C limit. Even 1.5°C of warming will still result in in some large and disruptive climate impacts, particularly for poor and vulnerable communities and fragile ecosystems. However, 1.5°C is a more manageable threshold for temperature than 2°C. Available mitigation pathways suggest very rapid reductions in greenhouse gas emissions and options which remove carbon from the atmosphere such as reforestation or bio-CCS (BECCS) will be needed to reach 1.5°C. There are still significant uncertainties regarding the potential, costs and impacts of these carbon dioxide removal (CDR) options. To help inform WWF's position on a 1.5°C target, this report summarises:

- the available evidence on the avoided impacts in going from 2°C to 1.5°C as a global temperature limit (Section 2)
- the implications for adaptation options (Section 3)
- the mitigation and removal options are needed, and the trade-offs that could be made between different options, to limit global temperature rise to 1.5°C (Section 4).

Using this evidence, we make recommendations regarding the position of WWF in several areas including energy demand, resource efficiency, bioenergy and carbon removal options.

[4] www.ippc.ch/reports/r15/

2 Expected impacts of climate change

2.1 Introduction

There is substantial scientific research into the impact of a 2°C or higher global temperature rise on different sectors, which generally shows increasing impacts with increasing temperature. However, there is much more limited research on the difference between impacts at 1.5°C and those at 2°C. We have surveyed existing literature on the impacts of climate change in a 2°C and a 1.5°C warming scenario and summarise these in Section 2.2. Table 2-1 summarises the impacts in different sectors or systems. In most cases, the detailed conclusions are based on a single or a very limited number of studies, due to the scarcity of literature. It is expected that by the time of the IPCC special report on 1.5°C, there will be more studies available.

Table 2-1 Summary of the findings on the impacts of climate change under 1.5˚C and 2˚C based on current literature.

Sector / system	Overall level of impact			Expected impact on (global/regional) ecosystems		Affected ecosystems/regions
	Current	1.5°C	2°C	1.5°C	2°C	
Ecosystems and biodiversity						
Agriculture						Global (but mainly Africa and tropical regions)
Forest ecosystems						Global (but mainly in tropical forests, parts of Russia, Southern Europe)
Fresh water ecosystems						Mainly tropical and sub-tropical regions
Marine ecosystems						Coral reefs
Physical systems (cryosphere)						
Glaciers						Andes and Central Asia, Himalayas
Permafrost						Boreal forests, tundra
Arctic/Antarctic ice sheets and sea ice						
Weather and extreme events						
Heat						Mostly ecosystems in tropical and sub-tropical regions
Precipitation						
Sea-level rise						Coastal ecosystems
Floods	uncertain	uncertain	uncertain			Mainly South East Asia
Droughts						

=Manageable and/or localised impact
=Regional impact
=Global or widespread impact

2.2 Impacts in different sectors

The IPCC has warned repeatedly that a world warmer than 2ºC above pre-industrial levels will have harmful impacts on human society and economy and wider ecosystems. There is growing evidence that warming close to 1.5ºC above pre-industrial levels is already locked-in and many of the impacts may now be unavoidable and will be seen, even at lower levels of warming, especially in Sub-Saharan Africa, South Asia and South East Asia (World Bank, 2014). Significant differences in impacts are forecast for warming between 1.5°C and 2°C in temperature-sensitive systems like polar regions, high mountains and the tropics and low-lying coastal regions (UNFCCC-SED, 2015).

Although there is substantial scientific research into the consequences of a 2°C temperature increase, the evidence base is sparse for a 1.5°C temperature increase. The lack of research to inform a comparison between a 1.5°C and 2°C limit was also highlighted in the two-year review of adequacy in the UNFCCC expert dialogue (Tschakert, 2015). Where literature is not available on particular impacts at 1.5°C and 2°C, we summarise the evidence on above and below 2°C.

We summarise the available literature on impacts of climate change under the two temperature limits in the following sections. Each section starts with a summary of the impacts in the system being discussed, before providing more detail on specific impacts.

2.2.1 Ecosystems and biodiversity

Ecosystems and their biodiversity, which are already stressed through factors like land use change, environmental pollution and natural resources extraction, are exposed to additional risks due to climate change. The level of impact on biodiversity and ecosystems will vary with both, temperature and region. In most cases, the level of impact at 2°C projected in the models is higher than at 1.5°C. The IPCC reports that two geographical regions in particular have a higher risk: the tropics, due to limited capacity of species to adapt to moderate global warming, as the species are already near their upper thermal limits, and high northern latitude systems, where temperature increases are projected to be large (IPCC, 2014a).

Agriculture

Agriculture is highly dependent on specific climatic conditions. The effect of increased temperature will depend on the crop's optimal temperature for growth and development: while warming might allow cultivation of some crops in cooler regions, yields will be reduced in regions where crops are already at the warm end of their productive temperature ranges and there are no substitute crops available. However, there are large uncertainties with regard to temperature sensitivity in agricultural crops (Rosenzweig et al., 2014) with the region and the type of crop being additional differentiators. In most cases, higher crop yield losses are expected in countries that are near the equator where temperatures are already higher. In many parts of the world, significant crop yield impacts are already felt at the current 0.8°C warming and any further warming will add to the pressure on agricultural systems (IPCC, 2014a; World Bank, 2014).

For those countries near the equator, the reduction in the crop yields are projected to be higher than the global average (UNFCCC-SED, 2015). In Africa, for example, regional food security risks will be significantly higher at 2°C versus 1.5°C of warming. A recent study shows that, while the temperature increase might benefit high latitudes, large parts of the tropical region are negatively affected even at 1.5°C and local yields are projected to drop further when going from 1.5°C to 2°C for all type of crops (without CO_2 fertilisation) (Schleussner et al., 2016). The study projects that for all crop types there will be global reduction by up to 10% at 1.5°C and more at 2°C. If not mitigated by other productivity measures, crop yield losses could lead to decreases in food production and could increase pressure on land availability. A rising human population and the consequent increase in demand of food will drive the expansion of agriculture into forestlands causing land use changes[5]. This land use change has been projected to be a more dominant driver for species extinction in this century (Pereira et al., 2010 as cited in IPCC, 2014).

Forest ecosystems

Climate change directly and indirectly affects forest ecosystems. The direct changes are caused by the changes in temperature and atmospheric CO_2 concentrations and indirectly through complex interactions and disturbances within the forest ecosystems. Increasing temperatures has been found to cause physiological damage to the trees, increase the length of the growing season, shift geographic ranges, and expose forests to the risk of extreme events like droughts and forest fires.

An earlier study showed that higher temperatures and increased atmospheric CO_2 concentration accelerates the growth rate of species in temperate forest ecosystems (Medlyn et al 2000). Similarly, Boisvenue et al., (2006) has also reported that globally, when water is not limiting, the climatic changes generally have a positive impact on forest productivity. A recent study (Zhu et al., 2016) using long-term satellite leaf area index (LAI) has also shown that the earth is greening due to the effect of CO_2 fertilization (largest contribution) among other biogeochemical drivers (temperature, precipitation, radiation and nitrogen deposition) in southeast North America, the northern Amazon, Europe, Central Africa and South East Asia. It also suggests that the increasing gross primary productivity[6] is responsible for the increased LAI.

At the same time, studies have shown that forests in some regions have instead experienced productivity declines. (Allen et al., 2010; William et al., 2013). Extensive tree mortality and widespread forest dieback have been associated with temperature stress in some regions, however, it is currently unclear how these may change in the future (IPCC, 2014).

In response to the warming climate, many plant and animal species (including trees) have already moved their ranges in recent decades and will continue to do so in the future. An increased rate of warming limits the ability for species to move range fast enough and reduces their chances of survival (IPCC, 2014). Hence, there is an increased risk of extinction of many species if temperatures increase beyond 1.5°C to 2°C, but there are uncertainties on how this will happen (Convention on Biological Diversity in UNFCCC – SED, 2015).

The increase in forest fires is associated with the warming temperature but the level of this association remains elusive (Harvey, 2016). The complication in this attribution is because the incidence of forest fire also depends upon other factors like forest management practices, natural climate variability and human activities in forests (National Academies of Sciences et al., 2016).

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[5] IPCC: https://www.ipcc.ch/publications_and_data/ar4/wg3/en/ch3s3-2-1-6.html

[6] The amount of organic matter synthesized by the plants

Fire is already considered as the main driver of tree cover losses in boreal forests (Ma et al. 2016) and additional warming is likely to increase this risk. A study of forest conditions in Russia reports that a temperature rise of 2°C will increase the area affected by forest fire by a factor of 1.5–2 (Mollicone et al., 2006). There is expected to be a lower increase in area affected at lower temperature rises [7].

Freshwater ecosystems

Between temperature increases of 1.5 and 2°C, Schleussner et al (2015) assessed the changes to water availability by analysing the incremental differences in the annual mean surface and sub-surface runoff. It reports that the largest difference would be observed in the Mediterranean region where the median runoff reduction of 9% at 1.5°C doubles to 17% in 2°C.

The wetlands of the drier environments of the tropics and sub-tropics, which are the hotspots for biological diversity, are exposed to a higher risk of drying at more elevated temperature levels (Barros et al., 2014). Studies have also shown that the warming has already impacted global lake ecosystems (Cohen et al., 2016).

The reduction in water availability will affect both the human systems and natural ecosystems. Freshwater ecosystems are among the most threatened ecosystems worldwide for reasons not directly connected to climate change such as pollution and water extraction. Global warming will alter the water temperature, stream flows, river water levels and extent and timing of inundation. As many species in freshwater ecosystems have limited abilities and space to disperse to adopt to the changes, these species will be severely affected. Lack of freshwater will also impact human systems and economies, through for example increased need for desalination and the consequent increase in energy demand.

Marine ecosystems

Similar to freshwater systems, there will be substantial effects on marine ecosystems when temperatures rise. Even without considering ocean acidification from rising ocean CO_2 concentration—which causes physiological changes in marine flora and fauna—further temperature rises are likely to cause the migration of fish to both higher latitudes and deeper ocean levels (Perry, et al., 2005). This affects, among others, local food security and livelihoods based on fishery, especially in tropical regions.

Coral reefs, which are the most diverse ecosystem of the world, are highly sensitive to climatic changes. They are susceptible to degradation through both temperature rises and increased ocean acidification (Baker et al., 2008; Carpenter et al., 2008; Hoegh-Guldberg et al., 2007; Spalding et al., 2015). There have been observations of mass coral bleaching and mortality events since the early 1980s (Frieler et al., 2013). The thermal tolerance of reef-building corals is lost even with the temperature increase of only 0.5°C (Ainsworth et al., 2016). Currently, only one study (Schuleussner et al. 2015) quantifies the impact on coral reefs of 1.5°C and 2°C temperature rises. The model projections considering only the increased CO_2 concentrations—not including other stressors like sea level rise, tropical cyclones, invasive species and anthropogenic stressors—show that by 2100, there is a 99% probability of coral reef bleaching at 2°C and 70% at 1.5°C. This implies that globally, coral reefs face a threat even at a global warming of 1.5°C and that the reefs will be almost completely lost at 2°C. The societies that depend on coral reefs for various ecosystem services will be greatly affected (Cinner et. al., 2016).

[7] [7] IPCC AR5 WG2- Part A (pg. 303) At RCP 2.6 forests are less susceptible to fires. Considering only the temperature at RCP 2.6; Mean and likely temperature increase range (0.4-1.6°C in 2046-2065 and 0.3-1.7°C in 2081-2100)

2.2.2 Physical Systems (cryosphere)

The cryosphere is highly sensitive to changes in temperature. Many of the changes in the cryosphere have already begun and even stabilisation of warming at current levels will cause a sea level rise of up to one metre from glaciers, ice sheets and the thermal expansion of warming waters within the coming two centuries (ICCI, 2015). Higher temperature levels will create permanent changes in the cryosphere such as the complete loss of most mountain glaciers, the complete loss of portions of west Antarctica's ice sheets and parts of the Greenland ice sheet, the complete annual loss of summer Arctic sea ice and permafrost thawing. (ICCI, 2015).

Glaciers

Glacier retreats in the Alps, Andes, Rockies, East Africa and the Himalayas are the early visible impacts of global warming. The melting rate of many glaciers is accelerating with global warming and is expected to reach its peak water yield during the end of this century (ICCI, 2015). An ensemble of global glacier models project that under a 1.5°C warming scenario, glaciers will lose ice mass corresponding to 13 cm sea-level equivalent (SLE) and 16 cm SLE at 2°C; only a temperature increase of 0.17°C above pre-industrial levels would have a high likelihood of stabilising glaciers at their current global mass (Marzeion et al., 2016).

Another projection shows that at 2°C warming, around 50% of the glaciers in Central Asia and up to 90% in the Andes will be lost (World Bank, 2014), with consequences on the people and ecosystems that depend on them. An example is the Himalayan glaciers, most of which have been losing mass (Bolch et al., 2012). Almost 800 million people live in the adjoining basins and rely on the water from these glaciers. The continuous melting of the glaciers risks drinking water shortages in the long-term, but also causes flooding in the short-term (Bolch et al., 2012). Similarly, taking into account that the Himalayas have a higher level of biodiversity than the global average (Körner, 2004), the drying of the glaciers in the future will have significant biodiversity impacts.

Permafrost

Wide-spread permafrost thawing is already happening at current temperatures (Brown et al., 2008) and is likely to increase with warming, even at 1.5°C (Vaks et al., 2013). The warming in the Arctic occurs at faster rate than other regions resulting in loss of summer sea ice that causes the decrease in the albedo effect. A global 2°C temperature rise may translate into a 4-6°C in the Arctic, which may lead to greater permafrost loss (ICCI, 2015). The Siberian permafrost known as Yedoma will undergo runaway decomposition once it starts to thaw, releasing methane into the atmosphere. Melting of permafrost is thus considered a potential tipping point (Lenton et al., 2012) as the associated release of methane could produce a dramatic change in the climate. At this point there are no clear indications of the temperature at which this tipping point will be reached.

The degradation of permafrost has also been associated with ecological changes. Jorgenson et al. (2001) reported widespread and rapid permafrost degradation in regions in central Alaska is causing large shifts in ecosystems from birch forests to fens and bogs. The study also projects that the remaining birch forests will be eliminated by the end of the next century. Similarly, permafrost degradation associated with warming is a major disturbance to boreal forests, second only to wildfires (Jorgenson et al, 2005). Boreal forests, with a globally significant level of biodiversity, account for approximately one-third of the world's forest area and large areas of these forests have permafrost.

Permafrost is a large carbon reservoir with global significance. Soils in high-latitude ecosystem stock twice the carbon compared to the atmosphere (Schädel et al., 2016). Permafrost thawing will release the stored CO_2 and methane, and further amplify global warming. A recent study reveals that only a small amount of carbon in the form

of methane and CO_2 (0.2—2.5 Gt) has been released in the past 60 years from pan-Arctic lakes. However, much more could be released when the wider Arctic region warms (Anthony et al., 2016). Although the response of permafrost to warming is uncertain and occurs on longer time scales (Vaks et al., 2013), a temperature increase of 1.5°C and 2°C will both likely have a significant impact on the ecosystems of the regions and on the global climate.

Arctic and Antarctic ice sheets and sea ice

The Arctic, parts of Antarctica and many mountain regions in the northern hemisphere have warmed two-to-three times faster than the rest of the planet and even the 2°C temperature will translate into a peak cryosphere temperature of between 4-7°C above pre-industrial level (ICCI, 2015).

Arctic and Antarctic ice sheets

The ice sheets of Greenland and Antarctica have been losing ice over the last two decades and the rate of the loss has increased in the second decade. The total ice loss from the ice sheets for the 20 years (1992–2011) has been equivalent to 1.2 cm of sea-level rise (IPCC, 2013). Some of the massive ice sheets covering Antarctica and Greenland hold over 60 m of sea level rise (ICCI, 2015).

Some of these ice sheets have thresholds where near-total loss becomes unstoppable even at temperatures close to the current level of warming due to feedback loops between subsurface ocean warming and ice shelf melting (Hansen et al., 2016). The is already a risk of irreversible melting at current temperature and this risk will increase if the temperature rise increases to 1.5–2.5°C above pre-industrial levels (ICCI, 2015). Greenland has a higher temperature threshold but most of the West Antarctic and Antarctic Peninsula may have already retreated beyond the point of no return. Melting of the ice sheets might result in sea level rise of up to 3 metres over the next centuries to millennia and temperatures much lower than the pre-industrial level would be required to halt such processes (ICCI, 2015). In addition, the topography of the ice sheets strongly influences atmospheric circulation at high latitudes and the changes in its size and shape will affect prevailing weather patterns.

Arctic sea ice

Arctic summer sea ice has undergone rapid decline since 2000: the amount of ice that survives the summer today is only around one-half of what existed in 1950. At an average warming level of 3°C, ice free summers are virtually certain. Conversely, the summer sea ice extent (the area of summer sea ice) will stabilise at a lower average summer minimum of around 2.5 million km^2 if the temperature stabilises at 2°C and may also recover to today's levels of around 4 million km^2 at 1.5°C (ICCI, 2015).

Arctic sea ice serves as an important regulator of temperature in the northern hemisphere as it reflects most of the sun's rays (80% is reflected back) (albedo effect) (National Snow and Ice Data Center, n.d). The absorption of heat by arctic waters will lead to higher temperatures in the region and will potentially affect weather patterns and increase the rate of Greenland and other arctic glaciers melting and permafrost thawing. This increases sea level rise and helps release greenhouse gases from the permafrost. Finally, loss of sea ice has significant local economic and ecological impacts: there will be loss of livelihood for people dependent on stable sea ice for hunting and fishing and ecosystem impacts due to loss of and changes in the habitats and alteration of marine food chains.

2.2.3 Weather and extreme events

In the last decades, the frequency and intensity of extreme weather events has increased. This effect has been linked with anthropogenic climate change and is projected to continue with continued warming (IPCC, 2014). The extent to which climate influences weather events is difficult to determine as it involves interactions between many natural and anthropogenic factors.

The science to address this influence is advancing through improvements in the understanding of climate and weather mechanisms and the models and methods used, but the challenge to estimate the frequency and intensity of extreme events still remains. (National Academies of Sciences et al., 2016).

Many studies have projected the impact of climate change on weather and extreme events based on observational records and simulation models. Warming will affect the weather and extreme events and even a 1.5°C world will result in pronounced extreme weather events; at 2°C the effects will be even more pronounced and will pose a higher risk for human systems and ecosystems (UNFCCC-SED, 2015).

Heat

There will be a difference in not only in the intensity[8] of hot temperature extremes under 1.5 and 2°C warming but also in the duration of these events. Schleussner et al., (2016) projected that under global warming of 2°C, many parts of the world[9] will experience a temperature rise of up to 3°C with a prolonged warm-spell[10] duration of up to 3 months or more (particularly in tropical coastal areas). This is lower for a 1.5°C world, with tropical regions expected to experience up to 2 months of continuous warm spells. These heat extremes will affect both human and ecosystem health. Scientific studies on the impact of heat extremes on human health are sparse.

Wernberg et al. (2013) showed that warming anomalies of 2–4°C which persisted for more than 10 weeks in the Australian coastline in 2011 caused significant biodiversity pattern changes in temperate seaweeds, sessile invertebrates and fish. Similarly, desert birds were found to be severely affected by heat waves; for example, in a two-day heat wave in South Africa, large scale bird mortality was recorded (Saunders et al., 2011).

Precipitation

Global warming will intensify the hydrological cycle (Allen et al., 2002). Temperature rises increase the rate of evaporation of water from land and sea into the atmosphere. The warm atmosphere thereby holds more water, which likely results in heavier precipitation when a storm passes. Globally there will be a 5% (at 1.5°C) and 7% (at 2°C) increase in heavy precipitation intensity with more impact felt in South Asia where the increase is expected to be 10 % at 2°C (Schleussner et al., 2016; World Bank, 2014).

These trends can significantly increase the risk of floods and landslides and affect people, biodiversity and ecosystems. Knapp et al. (2008) show that extreme precipitation events have differential impacts on a range of

[8] defined as the annual maximum value of daily maximum temperature

[9] Over large parts of Northern Hemisphere, central South America and South Africa.

[10] IPCC Glossary of Terms: Warm spell is a period of abnormally warm weather. Heat waves and warm spells have various and in some cases overlapping definitions.

terrestrial ecosystems and are expected to increase the duration and severity of soil water stresses in mesic[11] ecosystems but will benefit xeric[11] ecosystems due to reductions in evaporative losses.

Sea level rise

Sea level rise (SLR) is caused by the thermal expansion of the ocean (direct effect of temperature rise) and the contribution of water from the melting of land based ice. The distribution of SLR is not equal across the globe. While SLR in low latitudes is projected to exceed the global mean, near polar regions are projected to have SLR below the mean. This is due to the decreasing gravitational pull of the massive polar ice sheets as they melt (World Bank, 2014). Similarly, local factors such as land subsidence or uplift from natural processes and regional ocean currents affect the SLR. The current estimated sea-level rise is at 19.5 cm (increase between 1870 and 2004) and there are already visible impacts of this on the ecosystem and societies living in coastal regions (Church et al., 2006). There are various estimates of the association between warming and SLR. A study (on a millennial time scale) has shown that sea level sensitivity to global mean temperature increase is around 2.3 m per degree of warming and that there is a steep increase in long term SLR between 1.5 and 2°C (attributed to the crossing of the destabilisation threshold for the Greenland ice sheet (Levermann et al., 2013). Similarly, another study (on a centennial time scale) projected a median SLR 40 cm by 2100 for a 1.5 °C world, and 50 cm for 2°C, with a rate of rise of 0.6 cm/yr over the 2081–2100 period (Schleussner et al., 2016). Even at 50 cm rise in sea level, 32% of the total current beach area could be lost, causing damage to coastal habitats (Fish et al., 2005).

Coastal and low-lying areas have already experienced adverse impacts of submergence, coastal flooding and coastal erosion due to SLR. These impacts are projected to rise with warming and pose a great threat to the settlements situated along coastlines (World Bank, 2014) and the insular ecosystems, which are also global biodiversity hotspots (Bellard et al., 2014). Many small islands are particularly threatened with the complete or partial inundation, coastal erosion, saline intrusion and coastal flooding. Among them are the Marshall Islands, Kiribati, Tuvalu, Tonga, the Federated States of Micronesia and the Cook Islands, Antigua and Nevis and Maldives (IPCC, 2014). While there is no literature that shows the level of impact of 50 cm or 40 cm SLR on these islands, some older studies had suggested that 80 or 90 cm of SLR associated with higher temperature increase could inundate two thirds of the Marshall Islands and Kiribati and about 85% of Male (Maldives) (Gaffin, 1997 as cited in IPCC, 2001).

Floods

The magnitude and intensity of flood events at 2°C and 1.5°C is not yet conclusively established although trends in extreme precipitation and discharge of floodon regional scales show regional increases of risks (IPCC, 2014). Some studies have projected that there might be an increase in the frequency and severity of floods (Arnell, 2016; Schiermeir, 2011). However, literature that shows the differences in the flood magnitude and intensity for the 1.5°C and 2°C does not currently appear to be available.

Global warming is expected to have significant effects on hydrology and water resources. For example, some effects are projected in the river basins of the Ganges, Brahmaputra and Meghna. This would lead to more serious floods in the future in Bangladesh—one of the most flood prone areas in the world—with up to 70% of the land at risk of inundation (Mirza, 2002).

[11] Mesic is a type of habitat with well balanced supply of water; Xeric is a type of habitat with dry conditions

Drought

Climate models predict warmer and drier conditions in the coming years. Even at the current level of warming, the area under drought has increased by 8% (Dai, A.,2013). With warming at 1.5°C, severe and widespread drought is projected to occur in many parts of the world including southern Europe, Australia and large parts of Africa and North and South America (Schaeffer et. al, 2013). Increase in the frequency and intensity of drought events will affect most ecosystems and agroecosystem. For example, the projected drought stress under global warming increase the risk of large-scale forest degradation in the Amazon rainforest (World Bank, 2014). Drought causes reduction in root growth and standing biomass and may change the Amazon from net CO_2 sink to net CO_2 source (Olivares et al., 2015). Changes in the Amazon basin will also affect the global and regional precipitation (Cox et al., 2004

2.2.4 Tipping points

Several tipping points in the climate system have been identified in recent years. They are primarily found in the cryosphere (Arctic sea-ice, Greenland and Antarctic ice sheets, some permafrost regions), biosphere (Amazon and Boreal Forests), and in natural processes (Atlantic Thermohaline Circulation (THC), El Niño–Southern Oscillation (ENSO), Indian Summer Monsoon, West African Monsoon, North Atlantic sub-polar gyre) (Lenton et. al., 2013). Lenton et al. (2013) finds that the causes of tipping are different for different tipping points and that they are not always related to global warming or CO_2.

Lenton et al. (2013) suggests that both Arctic sea-ice and the Greenland ice sheets have the lowest temperature tipping points in the range of 0.5-2°C warming, although the transition time scale is greater than 300 years. There is high risk that with a 2°C temperature rise, an early tipping point will be exceeded and it would be impossible to avoid large-scale ice sheet disintegration which will cause sea level rise of several metres. There is still some risk this would occur at 1.5°C.

The two major biomes of the world are also tipping elements—the boreal forests of the northern hemisphere and the Amazon rainforest in the tropics. The boreal forests are stressed by physical factors (temperature stress and water stress), forest fires and permafrost thawing. Boreal Forest dieback is projected to occur at around 3°C global warming, but this is highly uncertain due to limitations in existing models and physiological understanding. Similarly, Amazon dieback is predicted due to widespread reductions in precipitation and lengthening of the dry season governed by ENSO forcing and forest fires under 3–4°C, and direct land-use change (Lenton et al., 2008).

3 Adaptation

3.1 Introduction

In this section, we present an overview of the evidence regarding adaptation in the context of 1.5˚C, 2˚C and 4˚C temperature rises. In general, there is limited literature on adaptation action according to varying degrees of global temperature rise and as such, very few publications explicitly address adaptation in the context of different degrees of global warming and 1.5°C in particular. In the report "Turn down the heat: why a 4°C warmer world must be avoided", the authors report that "no readily available quantitative modeling assessment can provide reliable answers" to questions similar to the themes addressed in this chapter in regards to 2 and 4°C, let alone 1.5°C (World Bank, 2012). Given this scarcity of adaptation literature relating directly to the difference between 1.5 and 2°C, in this section we assess various aspects of adaptation for temperatures above and below 2°C.

We address four themes:

- Adaptation actions required for 1.5°C compared to 2°C;
- Adaptation relating to transformational change, urbanisation, ecosystems;
- Trade-offs between mitigation and adaptation;
- The limits of adaptation in terms of loss and damage and the costs of adaptation.

As adaptation action is directly linked to the type and magnitude of climate impacts experienced, it is important to consider this chapter in the context of the previous chapter on impacts. While much of the literature[12] on impacts according to varying degrees of global temperature rise makes reference to adaptation, such references are fleeting – in fact many sources assume that no (additional) adaptation action is taken.

While climate impacts and many adaptation responses are taken at the local level, much of the literature which is relevant to this chapter discusses adaptation pathways at the global, regional or national level. Where literature does refer to differences in adaptation scales according to different degrees of warming, geographically-contained examples at the local are used to illustrate adaptation pathways or scales that includes a range of adaptation measures.

[12] E.g. World Bank, 2012, "Turn Down the Heat: Why a 4°C Warmer World Must be Avoided"; Wiltshire, 2016, "Implications for food security of large scale BECCS deployment"; Barrios and Rivas, 2013, "Tourism demand, climatic conditions and transport costs: An integrated analysis for EU regions"; Feyen and Watkiss, 2011, "The Impacts and Economic Costs of River Floods in Europe, and the Costs and Benefits of Adaptation".

The tables below summarises the information compiled in this chapter:

Table 3-1: Adaptation Summary Table

1. Adaptation scales		
Adaptation related to temperature rise	***Sector / systems***	***Explanation***
Adaptation efforts required may differ for 1.5°C and 2°C	• In highly temperature-sensitive systems (i.e. polar regions, high mountains, the tropics and low-lying coastal regions) (UNFCCC-SED, 2015) • Agriculture: regional food security • Many terrestrial and marine species • Marine, coastal areas: sea level rise (SLR); (note that rate of SLR according to global temperature rise is uncertain due to time lag as levels keep rising for many decades after the temperature has stabilised)	• Some adaptation actions are possible in a 1.5°C world which could have a direct impacts on the survival rates of some species compared to 2°C [13] Adaptation can be more focused supporting existing species and ecosystems (e.g. natural corridors) at the lower end of warming, but the more 1.5°C is exceeded, the more likely it is that adaptation will be about accepting irreversible change; • Greater scope for adaptation at 1.5°C in some sectors, such as agriculture. • Incremental adaptation ceases to be an option the greater the global temperature change: and the need for increased scales of alternative and subsequently transformative adaptation is required. • SLR: 2°C may require more drastic measures (i.e. retreat) while defense measures may be sufficient for 1.5°C
Adaptation efforts required are similar regardless of future temperature rise of 1.5°C or 2°C	• Species extinction: Climate change is not the main driver for extinction in the immediate term: projected land-use change will be a more dominant driver for extinction in this century (Pereira et al., 2010 as cited in IPCC, 2014a)	• Even today when warming has not reached 1.5°C, adaptation efforts are insufficient. The need to reduce vulnerability and risk does not depend on the difference between 1.5 and 2°C, therefore differentiating in terms of adaptation scales is unnecessary.[14] • The World Bank sees both 1.5°C and 2°C as a way to "create breathing space for

[13] Dr. Mike Morecroft (Natural England) presentation "Building resilience or managing change? Managing for biodiversity and ecosystems in a changing climate" at the *1.5 Degrees: Meeting the Challenges of the Paris Agreement Conference* in Oxford, UK, 21 September 2016.

[14] Stephane Hallegatte (World Bank) presentation „Implications of a 1.5°C target for adaptation" at the *1.5 Degrees: Meeting the Challenges of the Paris Agreement Conference* in Oxford, UK, 21 September 2016.

1. Adaptation scales		
Adaptation related to temperature rise	***Sector / systems***	***Explanation***
		adaptation measures to limit damage and for populations to learn to cope with the significant, inevitable damage that would occur even at this level of change" (World Bank, 2013).
Adaptation efforts required >2°C	• Coral reefs, water availability: difference between climate risks and impacts are non-linear, with close to double impacts in a world 4°C warmer compared with one 2 °C warmer (UNFCCC-SED, 2015) • All sectors and systems: Warren (2011) claims that a future with a 2°C temperature increase will see half of the impacts from climate change projected in a 4°C world, with concomitantly smaller challenges for adaptation.	• Adaptation potential for 4°C is "limited for many systems and sectors" as risks cannot be abated by simply doubling the adaptation efforts at 2°C (IPCC 2014c as cited in World Bank, 2014, p.2). • Even at 2°C, additional adaptation (beyond current levels) has a limited potential to reduce risks (IPCC 2014c as cited in World Bank, 2014, p.2).

2. Adaptation relating to transformational change, ecosystems, and urbanisation		
Topic	***Temperature***	***Implications for adaptation***
Transformational adaptation	**1.5°C**	• Transformational adaptation is complex and ambiguous in all scenarios: there is medium evidence for and medium agreement on the need for transformative changes to improve climate resilience • Already required in some (eco)systems and areas that have exhausted their adaptive capacity • Otherwise transformational change generally not required[15]

[15] "Adaptation responses of socioecological systems can be classed by the magnitude of climate change. Prevailing adaptation responses to date have involved resisting or coping with change, predicated on persistence of current ecosystems under assumptions of a projected rise in mean surface temperature of 2°C by 2100 followed by stabilization (Jones et al. 2012, Wise et al. 2014). But a 4–6°C rise is increasingly likely (Betts et al. 2011) requiring major shifts in perspectives, behavior, and institutional arrangements" (Colloff et al, 2016, p.1005).

2. Adaptation relating to transformational change, ecosystems, and urbanisation		
Topic	***Temperature***	***Implications for adaptation***
	2°C	• Required for some species (biodiversity) and peoples • Incremental and planned adaptation moving increasingly to transformational adaptation (i.e. migration) generally required
	4°C	• Generally, either requires transformational adaptation (e.g. Australia's floodplains and wetlands) or represents an adaptation limit for many human and natural systems as ecosystem services would not be preserved • Migration (human ecosystems) would be "a core element of the affected populations' adaptive capacity" as opposed to a symptom of adaptation failure • Requires shifts in perspectives, behaviour, and institutional arrangements
Ecosystems	**1.5°C**	• Migration, as a form of adaptation is limited for some species (for high latitude, high altitude, islands, and low-lying areas)
	2°C	• The need for transformational adaptation is most frequently cited when considering impacts on ecosystems in all emissions scenarios • 2°C would result in climate change rapid enough to prevent some species from migrating to another temperature zone so adaptation in the form of migration is limited for some species at 2°C
	4°C	• Adaptation options for ecosystems in a 4°C world are extremely limited - naturally or with human assistance • Migration, as a form of adaptation is extremely limited, as latitudinal biome shifts of up to 400 km are possible in a 4°C world
Urbanisation	**4°C**	• Coastal cities highly impacted by sea level rise (e.g. London and Rotterdam) and strains on the urban water supply at 4°C • Migration (human ecosystems) would be "a core element of the affected populations' adaptive capacity" as opposed to a

2. Adaptation relating to transformational change, ecosystems, and urbanisation		
Topic	***Temperature***	***Implications for adaptation***
		symptom of adaptation failure • Requires shifts in perspectives, behaviour, and institutional arrangements

3. Trade-offs between mitigation and adaptation	
≥2°C	• Mitigation increases the time available for adaptation to a particular level of climate change, potentially by several decades (IPCC, 2014a) • Land-use change towards biomass production and more incremental adaptation measures intended for a 2°C would increase vulnerability to a 4°C world, increasing potential for biodiversity loss (World Bank, 2012; IPCC, 2014a) • Afforestation as a carbon sequestration measure can have a negative impact when planting non-native tree species / planting in areas not supportive of high forest biodiversity • Irrigation as a response to crop failure at high impact level will negatively impact water availability (World Bank, 2012) • Moving agricultural land to wooded areas could reduce biodiversity and potentially also human health in the surrounding area at 4°C (Warren, 2011)

4. Limits of adaptation	
Temperature	***Implication for limits of adaptation***
1.5°C	• Exceeds adaptive capacity of certain species (e.g. Forest species in the tundra) that have already reached their limit
2°C	• Not a "global adaptation limit", as limit has already been reached for some species but not for others • But also cited as a general limit for natural ecosystems and human systems, especially as a result of the loss of ecosystem services • Limit of marine and terrestrial ecosystems (Arctic) • While adaptation has the potential to reduce damages of climate change, in nearly all cases the residual risk and increased damages to systems[16] still increases with global temperature change even with adaptation.

[16] Residual risk can be defined as "the risk that remains in unmanaged form, even when effective disaster risk reduction measures are in place, and for which emergency response and recovery capacities must be maintained. Comment: The presence of residual risk implies a continuing need to develop and support effective capacities for emergency services, preparedness, response and recovery together with socio-economic policies such as safety nets and risk transfer mechanisms." (UNISDR)

4°C	<u>Adaptation limit at 4°C reached for the following:</u> • Urban water supply systems, heat-sensitive people[17], agricultural productivity and food security (Africa & Asia), means of implementation, and the preservation of cultural identity • Land-driven conflicts, displacement • Malnutrition (Africa and Central and South Asia) • Flooding (Asia & Americas) • Mountaintop, island, and high-latitude species unable to migrate • Coral reef systems (i.e. Change in composition and structure) (Australasia) • Agriculture sector in general

[17] "Exposure to extreme heat can lead to heat stroke and dehydration, as well as cardiovascular, respiratory, and cerebrovascular disease. Excessive heat is more likely to affect populations in northern latitudes where people are less prepared to cope with excessive temperatures. Certain types of populations are more vulnerable than others: for example, outdoor workers, student athletes, and homeless people tend to be more exposed to extreme heat because they spend more time outdoors. Low-income households and older adults may lack access to air conditioning which also increases exposure to extreme heat. Additionally, young children, pregnant women, older adults, and people with certain medical conditions are less able to regulate their body temperature and can therefore be more vulnerable to extreme heat" (USGCRP, 2009, 2016; CCSP 2008; as cited in EPA)

5. Costs of adaptation

Global costs of adaptation:

- There is no evidence on costs of adaptation for 1.5°C.
- There is agreement that more aggressive emissions reductions will result in lower adaptation costs.
- Between 2030 and 2050, models anticipate considerable variation in adaptation costs between a 2°C and high levels of global temperature rise. UNEP states that "model estimates illustrate the emissions-dependency of adaptation costs, and highlight that adaptation cost levels for different warming scenarios could diverge as early as the 2030s" (UNEP, 2016, p.xiii)
- USD 140 and 300 billion per year by 2030 and between 280 and 500 billion by 2050 (UNEP, 2016)

Adaptation of coastal areas arising from sea level rise and storm surge:

- Between USD 12-31 billion to USD 27-71 billion annually for low-and high-warming scenarios respectively (UNEP, 2016)[18]
- Beach and shore nourishment for low, mid and high scenarios are estimated to be between USD 1.4-5.3 billion per year (UNEP, 2016)[19]
- Coastal defences (dikes) and nourishment of the beach/shore face and estimated to cost the EU roughly EUR 1 billion per year in the SRES A1B or BAU scenario in the 2020s and EUR 1.6 billion in the 2080s. For the (PESETA II) E1 scenario, (2°C) adaptation cost approximately EUR 1.2 billion per year in the 2020s and EUR 0.7 billion in the 2080s (Brown et al., 2011)
- USD 25 and 270 billion (1995 values) per annum for 0.5 and 2.0m in 2100, respectively in 4°C world, based on SRES scenarios (A1B, A2 and A1FI) (Nicholls et al., 2011)
- For 136 of the world's coastal cities in particular, annual adaptation costs are estimated at USD 50 billion annually (Hallegatte et al., 2013 as cited in UNEP, 2016)[20]

Adaptation costs due to river flooding:

- EU under the SRES-A1B scenario…might be of the order of EUR 1.7 billion annually by the 2020s, EUR 3.4 billion by the 2050s, and €7.9 billion by the 2080s (constant 2006 prices and undiscounted)" (Feyen and Watkiss, 2011)

Adaptation costs due to rising water demand:

- At non-climate change levels, total costs add up to USD 531 billion for 200 countries to the year 2030. Reservoir construction and unmet irrigation demands are likely to cost USD 225 billion or USD 11 billion per year of the aforementioned sum, based on the SRES A1B scenarios (Kirshen, 2007 as cited in IPCC, 2014a)

Adaptation costs in the fisheries sector:

- USD 7 to 30 billion per year between 2010 and 2050 globally(IPCC, 2014a)[21]

[18] Based on a source from 2013 so scenarios likely SRES but unclear.

[19] Based on a source from 2013 so scenarios likely SRES but unclear.

[20] Based on a source from 2013 so likely SRES but unclear, timeframe not specified.

[21] Scenarios likely RCP but unclear.

3.2 Background

The global goal on adaptation is described in Article 7 of the Paris Agreement as "Enhancing adaptive capacity, strengthening resilience and reducing vulnerability to climate change, with a view to contributing to sustainable development and ensuring an adequate adaptation response in the context of the temperature goal". The Agreement emphasises that the current need for adaptation is "significant" and that "Parties should strengthen their cooperation on enhancing action on adaptation" whilst avoiding additional burden for developing countries. A natural outcome of agreement to limit warming to 1.5°C is an analysis of how this relates to adaptation. The IPCC seeks to do this in the report that will be published in 2018.

3.3 Adaptation scales

Adaptation scales for 1.5°C warming

Warming of 1.5°C is a relatively new topic for the adaptation community. The existing literature base on this specific issue is limited albeit likely to expand in response to Paris and the request for the IPCC to publish a study on 1.5°C. This is confirmed by Patrick Pringle (UKCIP), who stated that the adaptation community is struggling with the concept of corresponding adaptation scales for 1.5°C because although climate impacts vary at 1.5, 2, 3, and +4°C, the 1.5°C target is an arbitrary figure. Whilst it will be useful to understand the adaptation implications to make the case for rapid decarbonisation, it is less critical as in terms of messages to decision-makers.[22]

At the 1.5 Degrees Conference in Oxford (September 2016), Stephane Hallegatte was to present on the implications of a 1.5°C target for adaptation. However, he stated that for the World Bank, studying the difference in adaptation needs between 1.5 and 2°C is largely irrelevant. A 1.5°C mitigation pathway does not mean that warming will actually be limited to 1.5°C but rather only increases the probability (66%) of low warming. Furthermore, developing an adaptation strategy and measuring the benefits requires consideration of warming that exceeds 2 and 3°C. The possibility of further warming is present for all mitigation pathways before stabilization occurs, therefore preparing to adapt to beyond 1.5°C coupled with ambitious mitigation goals would be a precautionary approach to limit the risks and associated costs with overshooting 1.5°C. Hallegatte claimed that although the impacts (and one can assume adaptation needs) are more severe in a 2°C than a 1.5°C world in some specific circumstances, in general, the need to reduce vulnerability and risk is not dependent on these different global temperature increases.

Specific reference to the difference between 1.5 vs. 2°C is made in the UNFCCC's (2015) "Report on the structured expert dialogue on the 2013-2015 review": "there is a high likelihood of meaningful differences between these temperature limits as regards the level of risk of extreme events or tipping points" (p.73). We can assume that there are variations in the adaptation needs, adaptive capacity and adaptation responses required.

It was also noted in the report that "most terrestrial and marine species would be able to follow the speed of climate change" up to 1.5°C as, for example, "up to half of coral reefs may remain; sea level rise may remain below 1 m; some Arctic sea ice may remain; and ocean acidification impacts would stay at moderate levels" (p.31). This implies that there are different adaptation needs and responses but also, as was explicitly stated, there would be more scope for adaptation would exist, in the agricultural sector for example (UNFCCC-SED, 2015).

Adaptation scales for 2°C and beyond

[22] Informal conversation in response to the 1.5 Degrees Conference in Oxford

The evidence that addresses warming levels of ≥2°C, attempts to illustrate the implications for adaptation choices and tipping points at different levels of temperature change.

The authors of "Rethinking adaptation for a 4◦C world" illustrate the implications for adaptation decision making (see Figure 2) without going into detail about scales of adaptation in a specific sector, location, or ecosystem. In this example, the three climate scenarios start to diverge rapidly from the 2030s depending on the average global temperature rise projected. The 'recovery' scenario broadly illustrates the implications for adaptation required for a 1.5°C future, 'stabilisation' scenario for 3.5°C, and 'runaway' scenario for 5°C (Smith et al., 2011). This graph shows that whilst incremental adaptation can be effective in the near term up to the 2030s, as time progresses into the 2070s, the greater the need to allow for transformative adaptation. As temperature rises, so does the need for transformative adaptation. The higher the mean global temperature rise, the greater the limitation on the range of adaptation actions that will be available, as the adaptation requirements move away from incremental adaptation towards transformative adaptation.

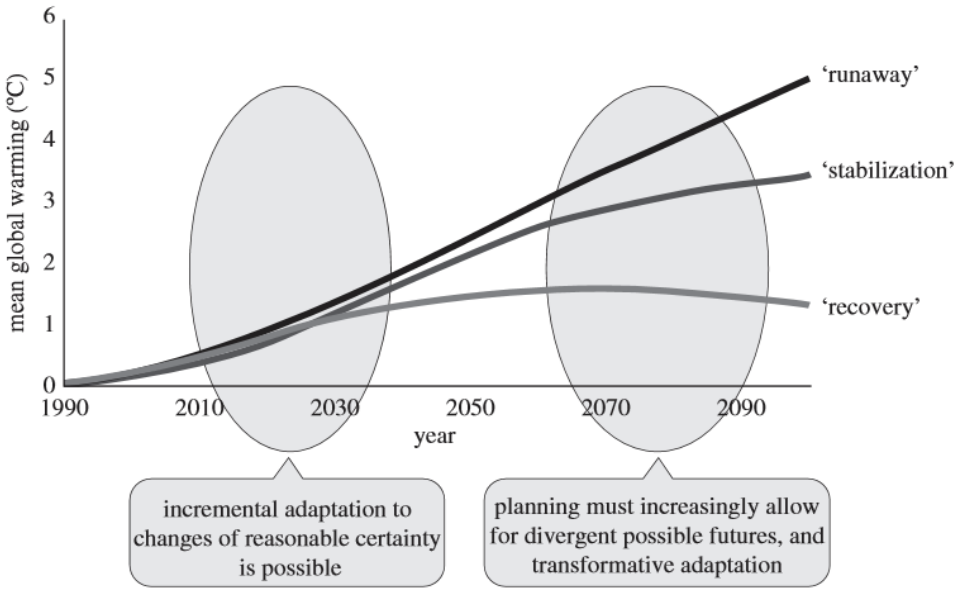

Figure 2. Future projections of climate change diverge over time as social uncertainty outstrips scientific uncertainty, with changing implications for adaptation. Adapted from stylized projections based on ('runaway') the A1FI+ scenario in Garnaut ([55], fig. 4.5), and ('stabilization') the MEP2030 reference and ('recovery') MEP2010-overshoot scenarios updated from Sheehan *et al.* ([56], fig. 8*c*; R. N. Jones (2010), personal communication).

Figure 2: General adaptation pathways against mean global warming (Smith et al., 2011)

Like adaptation pathways, limits, and transformational change, the concept of adaptation turning points can also be helpful when analysing adaptation needs at varying degrees of climate change. In fact, determining turning points can be seen as one step in the process of employing the adaptation pathways approach. A Briefing Note from the EU's MEDIATION project summarises this concept as "a moment in time at which a threshold of concern is likely to be exceeded" (Werners et al, 2013, p.2). In essence, adaptation turning points will be context and species-specific, requiring knowledge of critical thresholds and identifying a sequences of measures that can be employed depending on when those thresholds are met (Reeder and Ranger, 2011; Haasnoot et al., 2013 as cited in Werner et al., 2013).

Adaptation scales relating to sea level rise

Several authors (Nicholls et al., 2011; Stone, 2010; Rainbird, Speirs, 2016) present specific examples of adaptation scales or various degrees of adaptation depending on the severity of climate impacts. Many of them focus on the adaptation options and scales in relation to sea level rise - without making any link to the corresponding temperature rise. Linking sea level rise to global temperature change should be done with caution, as the relationship between climate impacts like sea level rise and temperature rise is complex and uncertain (Nicholls et al., 2011). Given the time lag, sea levels can continue to rise for many decades after temperatures have stabilised; also local conditions, impacts relative sea-level rise, for example where deltas are subsiding[22]. However, in the PESETA II climate scenarios (with a time horizon of 2071-2100), for example, sea level rise of 18 cm corresponds to maximum 2°C warming and 30cm rise with business as usual scenario in the 2080s. On the other hand, the IPCC projects a global mean sea level increase of 63 cm for the period from 2081-2100 for RCP 8.5 (mean temperature increase of 2.2°C) but between 40 and 47 cm for 1.5°C.

The example below (see Figure 3), illustrates how existing management strategies can be employed until the sea level rise reaches 0.2 metres, at which point current management can be incrementally continued (e.g. raise dikes) or alternative adaptation (e.g. broad, multi-functional dikes) can be pursued until 0.35 metres. Eventually, when sea levels rise reaches 0.7 metres, alternative strategies (e.g. retreat) are required to adapt. However, it should be noted that the cost of adapting to different levels of global temperature change vary dramatically: integrated assessment models estimates illustrate the emissions-dependency of adaptation costs, and highlight that adaptation cost levels for different warming scenarios could diverge as early as the 2030s ((World Bank, 2010 as cited in UNEP). For further information, see the section 3.6 on costs below.

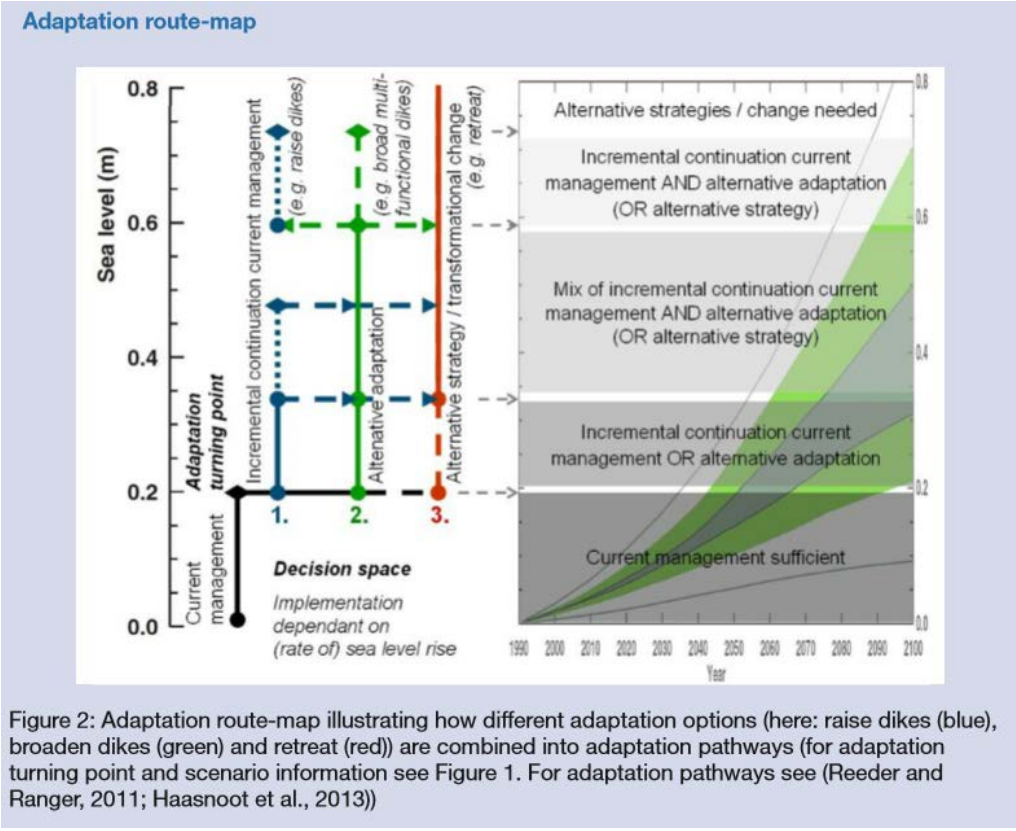

Figure 2: Adaptation route-map illustrating how different adaptation options (here: raise dikes (blue), broaden dikes (green) and retreat (red)) are combined into adaptation pathways (for adaptation turning point and scenario information see Figure 1. For adaptation pathways see (Reeder and Ranger, 2011; Haasnoot et al., 2013))

Figure 3: Adaptation route map (Werners et al., 2013)

One frequently cited example of adaptation pathways and sea level rise throughout the literature is that of the Thames Estuary 2100 project and different adaptation pathways that can be taken depending on sea level rise, however this example is not explicit about the link to global temperatures (see Annex 6.4).

The city of Rotterdam also applied the adaptation pathways approach when developing a flood risk management strategy; in the report "Exploring adaptation pathways" (Stone, 2010), the process of determining tipping points is outlined. On the basis of the assessment of tipping points, the effectiveness of various measures was tested and presented in the form of adaptation pathways (see Annex 6.5).

In "Adaptation Pathways: Plotting a course to an uncertain future" (Rainbird and Speirs, 2016) from the Adaptation Futures Conference in 2016, the authors present adaptation against sea level rise in the context of the Torres Strait in Australia (see Figure 4 below) without an explicit reference to temperature. The options presented include *do nothing*, *accommodate*, *defend*, and *retreat*. When the *do nothing* adaptation response is taken (i.e. only investments made in emergency response to flooding), *forced* retreat becomes likely when the sea level rises approximately 47 cm above the island benchmark. 'Accommodate' (i.e. restoration of coastal habitats, improved road construction standards) becomes ineffective at a sea level rise of 15 cm but at that point 'defense' measures and 'retreat' consultations begin. If hard infrastructure measures are undertaken in the '*defend*' scenario, a viability threshold is reached at 43 cm but defense systems can be prolonged to 55 cm in critical areas, albeit at escalating costs (unspecified). The measures under the 'retreat' scenario can begin at a sea level rise of 12 cm with 'commence community discussions' and continue gradually until a *voluntary* seasonal retreat of communities can be fully underway at 50 cm.

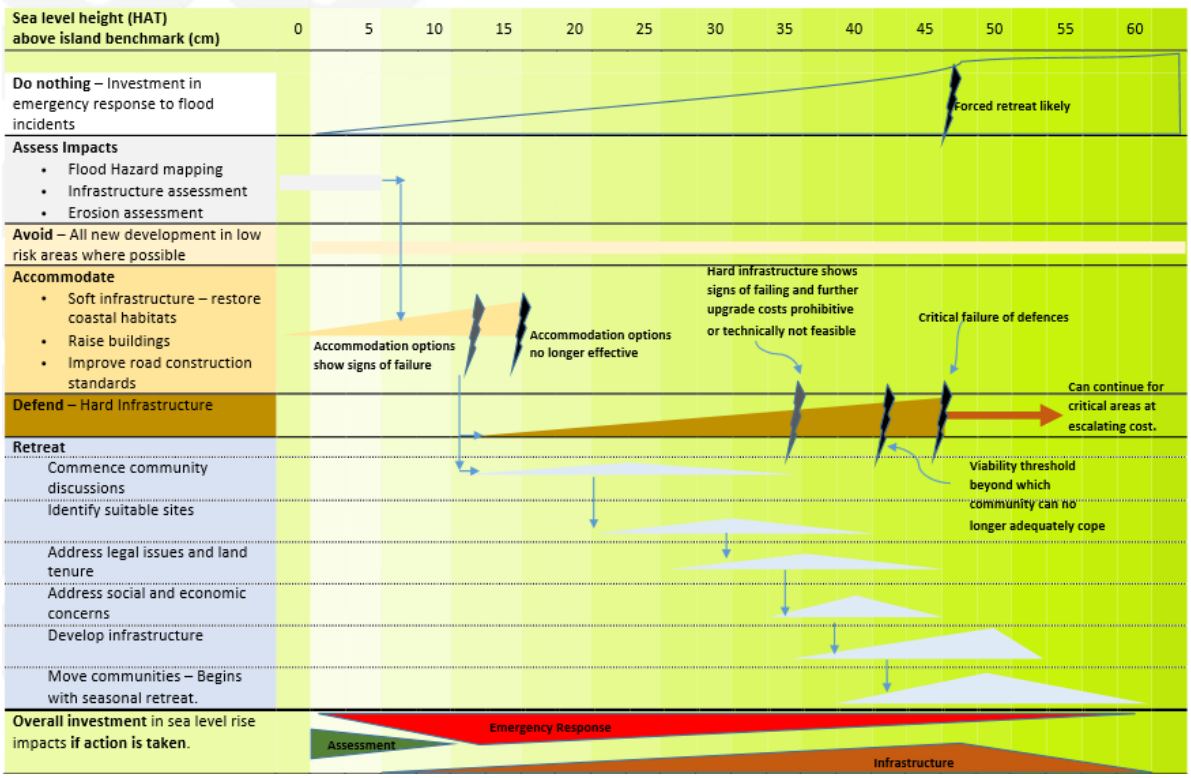

Figure 4: Adaptation pathways for Torres Strait (Rainbird, Speirs, 2016)

In the "Report on the structured expert dialogue on the 2013–2015 review," it is stated that the difference between climate risks and impacts in a 2 and 4°C future are non-linear, especially with regard to water availability, heat extremes or the bleaching of coral reefs, with close to double the climate impacts in a world 4°C warmer compared with one 2°C warmer than in pre-industrial times, implying very different adaptation needs (UNFCCC-SED. (2015). Warren, however, claims that a future with climate change at 2°C will see half of the impacts projected in a 4°C world and correspondingly smaller requirements for adaptation.

3.4 Adaptation relating to transformational change, ecosystems, and urbanisation

Transformational adaptation

Transformational (or transformative) change in terms of adaptation implies fundamental changes in the objectives of decision-makers (Horrocks and Harvey, 2009 as cited in Smith et al., 2011). The IPCC describes transformational adaptation as "adaptations at a greater scale or intensity than previously experienced, adaptations that are new to a region or system, or adaptations that transform places or lead to a shift in the types or locations of activities" (IPCC, 2014a, p.89). An example of transformational change includes the relocation of an entire industry or swapping farming for another land use (Smith et al., 2011).

The IPCC explains that there is medium evidence for, and medium agreement on, the need for transformative changes to improve climate resilience (2014a). Transformational adaptation, the IPCC asserts, remains complex and ambiguous, which may impact its effective operationalisation in practice and policy.

In general, much of the literature mentions the need for more widespread transformational adaptation in the context of a 4°C temperature rise. However, as some species and some areas are already nearing (or have exceeded) their adaptation limits, some degree of transformational adaptation is also required at 1.5 and 2°C. In the chapter "Climate Resilient Pathways: Adaptation, Mitigation, and Sustainable Development", the IPCC only goes as far as to say that with a 2°C average global temperature increase, "incremental adaptation may be needed to respond to changes in climate and climate variability" but that transformational adaptation *may be* required in the case of less ambitious mitigation efforts (IPCC, 2014a, p.1121). This sentiment is echoed by Colloff et al. who explain that adaptation responses predicated on projections of a mean surface temperature of 2°C by 2100 (and subsequent stabilization) involve resisting or coping with change, "but a 4–6°C rise is increasingly likely (Betts et al. 2011 as cited in Colloff et al., 2016, p.1005) requiring major shifts in perspectives, behavior, and institutional arrangements." Smith et al. (2011) use a simple timeline to display what transformative adaptation could look like on a scale of increasing global temperatures (see Figure 5). The left side of the chart represents lower global temperature change and autonomous and incremental adaptation measures (i.e. whole farm planning and plant breeding cycles), while the right side represents more planned and transformative measures under 4°C (i.e. forest succession, bridge design life, and suburb locations). The authors consider that adapting to a 4°C global temperature rise is a "more substantial, continuous and transformative process" as opposed to a simple "extrapolation of adaptation to 2°C" (Smith et al., 2011, p.196).

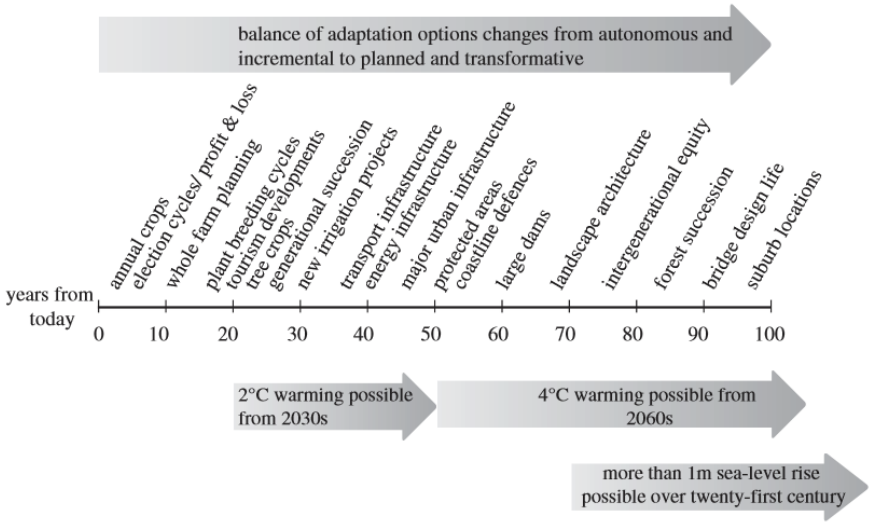

Figure 1. Timeline illustrating the lifetimes (sum of lead time and consequence time) of different types of decisions, compared with the time scales for some global environmental changes, and the changing implications for adaptation. Adapted from Jones & McInnes ([13], fig. 1.4), including items from Hallegatte ([8], table 1). Indicative global temperature rise since pre-industrial times from Betts *et al.* [1]. Indicative sea-level rise over the twenty-first century from Nicholls *et al.* [5].

Figure 5: Lifetime of adaptation decisions (Smith et al., 2011)

In regards to human ecosystems, "Climate-induced population displacements in a 4°C+ world" (Gemenne, 2011) addresses migration, which is often viewed as a form of transformative adaptation. The author asserted that in a 4°C+ world, migration would be "a core element of the affected populations' adaptive capacity" as opposed to a symptom of adaptation failure (p.190). For some populations, it may be the only viable adaptation option (Gemenne, 2011). As mentioned in the previous section on impacts, extinction and an inability to migrate is also a risk for some species at 1.5 and 2°C.

Additional information about ecosystems and transformational adaptation at varying global temperatures increases can be found in "Adaptation services of floodplains and wetlands under transformational climate change" (Colloff et al., 2016). Also referring to Australia, the authors claim that unlike current adaptation measures that assume a mean surface temperature of 2°C by 2100 (Jones et al. 2012, Wise et al. 2014 as cited in Colloff et al. 2016), future adaptation under the likely scenario of a 4–6°C temperature increase requires "shifts in perspectives, behaviour, and institutional arrangements" (Betts et al. 2011 as cited in Colloff et al., 2016, p.1005). With a temperature increase of greater than 4°C changes in the drivers of the socioecological system and the fact that livelihoods cannot be supported, make transformative adaptation necessary (Pelling et al., 2015; Feola, 2015 as cited in Colloff et al., 2016). The authors give an example of transformational change which could take the form of preventing the "over-grazing of drought-resistant chenopod shrubland to prevent erosion and its transformation to degraded grassland" (Lavorel et al. 2015 as cited in Colloff et al., p.1013). This might also include substituting inputs and crops as well as "opportunistic cropping and grazing following sporadic rainfall" (p.1013).

Ecosystems

The adaptation implications for ecosystems and the need for transformational adaptation are mentioned in several places in the literature. Either naturally or with human assistance, Warren claims that adaptation options for ecosystems in a 4°C world are "extremely limited" (Warren, 2011, p.228). It is anticipated that global warming will lead to global biome shifts (Barnosky et al. 2012 as cited in World Bank, 2012). While the "Turn Down the Heat" series does not focus on adaptation, the "Why a 4°C Warmer World Must be Avoided" report in the series claims that

"latitudinal biome shifts of up to 400 km are possible in a 4°C world" (Gonzalez et al., 2010 as cited in World Bank, 2012, p.50). Furthermore, even 2°C would result in climate change that is rapid enough to prevent some species from migrating to another temperature zone (UNFCCC-SED, 2015). Colloff et al. (2016) present the different transformational pathways of a specific ecosystem, using an example of temperate montane forests of Australia. While an interesting example of what transformational adaptation pathways could look like for a specific ecosystem, no clear link is made to a climate change scenario with the exception of a passing reference to a temperature increase exceeding 2°C by 2100 in the introduction of the article (Colloff et al., 2016).

Urbanisation

Urbanisation per se was not the focus of the literature reviewed but rather was mentioned or alluded to in the context of sea level rise for some coastal cities and river flooding. The *Report on the structured expert dialogue on the 2013–2015 review* briefly cites the limits of adaptation on the urban water supply system in a 4°C world in passing (UNFCCC, 2015). The issue of migration is also linked to urbanisation and urban areas. In "Climate-induced population displacements in a 4+°C world" (Gemenne, 2011) it is noted that in Vietnam, for example, rice farmers migrate to urban centres on a seasonal basis during the flooding season as a way to maintain their income and livelihood. However, as crops are destroyed by successive floods, many farmers have permanently migrated to these areas (Jäger et al., 2009; Dun, 2009 as cited in Gemenne, 2011). As evidenced by this example, in a 4+°C world, migration (often to existing urban areas, contributing to rapid urbanisation) is likely to become a "core element of the affected populations' adaptive capacity" (Gemenne, 2011, p.190).

3.5 Trade-offs between mitigation and adaptation

Trade-offs

The *IPCC AR5* report makes the link between mitigation and adaptation: by decreasing the rate and severity of warming global temperatures, mitigation "increases the time available for adaptation to a particular level of climate change, potentially by several decades" (IPCC, 2014a, p.28). In general, as global temperatures increase, the opportunities to exploit the positive linkages between adaptation and mitigation may decrease. Inadequate responses to climate impacts are already undermining opportunities for adaptation and sustainable development (IPCC, 2014a).

In "Turn Down the Heat" (World Bank, 2012), the authors suggest that land-use change for biomass production and more incremental adaptation measures intended for a 2°C would increase vulnerability to a 4°C world. This is because the value of land and resources would increase but not be guarded against extreme or sudden climate impacts. Some adaptation measures designed to protect against future high impacts could aggravate the impacts other sectors face. An example is that of irrigation as a response to crop failure negatively impacting water availability (Warren, 2011). The IPCC (2014a) also provides an example related to land use: they project that by 2100 in the RCP2.6 scenario (which roughly corresponds to 1°C), bioenergy crops will expand to occupy approximately 4 million km^2 of land, ultimately modifying the landscape, making adaptation more difficult, and increasing the potential for biodiversity loss. As many bioenergy crops also require irrigation, then this also puts additional strees on freshwater systems and other water use.

Poorly sited or designed storage dams, developed to reduce the impacts of droughts and floods, can in themselves increase vulnerability downstream by displacing settlements and degrading freshwater ecosystems (Pittock et al, 2015).

In “The role of interactions in a world implementing adaptation and mitigation solutions to climate change” (2011), Rachel Warren states that as the global temperature increase reaches 4°C, adaptation may encourage the move of agricultural activities from dry areas to those currently more wooded areas. This means that not only could the projected impacts on natural ecosystems be worse than expected but that human health could be impacted as a result of having vectors of disease in close proximity with human habitation (Molyneux et al., 2008 as cited in Warren, 2011). Another link that Warren makes between impacts, mitigation, and adaptation is that of afforestation: while afforestation contributes to mitigation (via carbon sequestration), it can have a negative impact when planting non-native tree species or planting in areas that are not supportive of high forest biodiversity. Spatial planning of land use is an area in which this mitigation-adaptation nexus is particularly relevant and taking both into account is “particularly important for mitigation planning when aiming for a 2°C world” (Warren, 2011, p.234).

3.6 Limits, costs of adaptation in terms of loss & damage

Literature about the limits of adaptation are often linked to broader discussions of adaptation scales and transformational adaptation. As these points have been addressed above, this section focuses on explicit references to the limits and costs of adaptation.

Limits to adaptation

The IPCC defines the limits to adaptation as a situation in which the “adaptive actions to avoid intolerable risks for an actor’s objectives or for the needs of a system are not possible or are not currently available” (IPCC, 2016b, p.80). They note that as actors’ objectives vary, so too can the limits of adaptation, which it makes it a subjective and situationally-dependent assessment. The IPCC explains “warming beyond 2°C is considered to give rise to “reasons for concern”, in part because adaptation to impacts associated with such warming would be constrained or limited (Smith et al., 2009a as cited in IPCC, 2014a, p.924). However, they note that literature on the degree (or level of mitigation) at which limits to adaptation become evident is scant and what is available mostly refers to natural systems (limited evidence, medium agreement). Given this, the claim that 2°C represents a “global adaptation limit” cannot be substantiated (IPCC, 2014a, p.925); however there is limited evidence that the current level of warming is already having a negative impact on some sytems, beyond their adaptive capacity (UNFCCC-SED, 2015).

The *Report on the structured expert dialogue on the 2013–2015 review* (UNFCCC-SED, 2015) makes a general reference to the limits of adaptation in the context of different global temperatures. Although the prospects for adaptation are significant at 2°C, the opportunities for reducing damage from climate impacts through adaptation are much more limited at 4°C. In a 4°C world, the adaptation limits would be met in the following areas: “urban water supply systems, heat-sensitive people, agricultural productivity and food security, means of implementation, and the preservation of cultural identity” (p.17). Furthermore, adaptation opportunities with regards to land-driven conflicts and displacement will substantially decrease and at the same time, the risks of malnutrition in Africa and Central and South Asia, food insecurity in Africa and Asia will reach very high and high levels respectively. Lastly, flooding risks may reach a turning point in Asia and the Americas, ultimately restricting the potential to take adaptation action (UNFCCC-SED, 2015).

Similarly, the report “Turn Down the Heat: Confronting the New Climate Normal” (World Bank, 2014) states that the adaptation potential for 4°C is “limited for many systems and sectors” as risks cannot be abated by simply doubling the adaptation efforts at 2°C, but they go on to state that even at 2°C, additional adaptation (beyond current levels) has a limited potential to reduce risks (IPCC 2014c as cited in World Bank, 2014, p.2).

The IPCC (2014b) attempts to show climate risks, risk reduction potential, but also the limits to adaptation in various scenarios and regions (see Figure 6 below). In four scenarios (present, near term (2030-2040), long term

2°C, and long term 4°C) the risk level with current adaptation, the risk level with high adaptation, and the potential for additional adaptation are depicted for key risks. Although the graph does not describe specific measures, one can glean useful information about the potential for adaptation to generally reduce those risks mentioned at different temperatures. For example, in the Arctic, additional adaptation will not reduce the climate-related risks posed to terrestrial and marine ecosystems and the risk level with high adaptation is the same as the risk level with current adaptation. On the other hand, for heat-related human mortality in North America, there is substantial potential for additional adaptation in all scenarios. From this chart, one can also obtain an idea of what the difference in temperature means for adaptation by referring to, for example, the near term and long term 2°C bars. For drought-related water and food shortage in Asia, increased water restrictions in Europe, heat-related mortality in the US, and reduced food production and quality in Central and South America, all risk categories (i.e. risk with current and high adaptation and the potential of additional adaptation) remains the same for both near term and 2°C regardless of additional adaptation. Whilst adaptation has the potential to reduce risk levels, in nearly all cases the residual risk still increases with global temperature change even with adaptation.

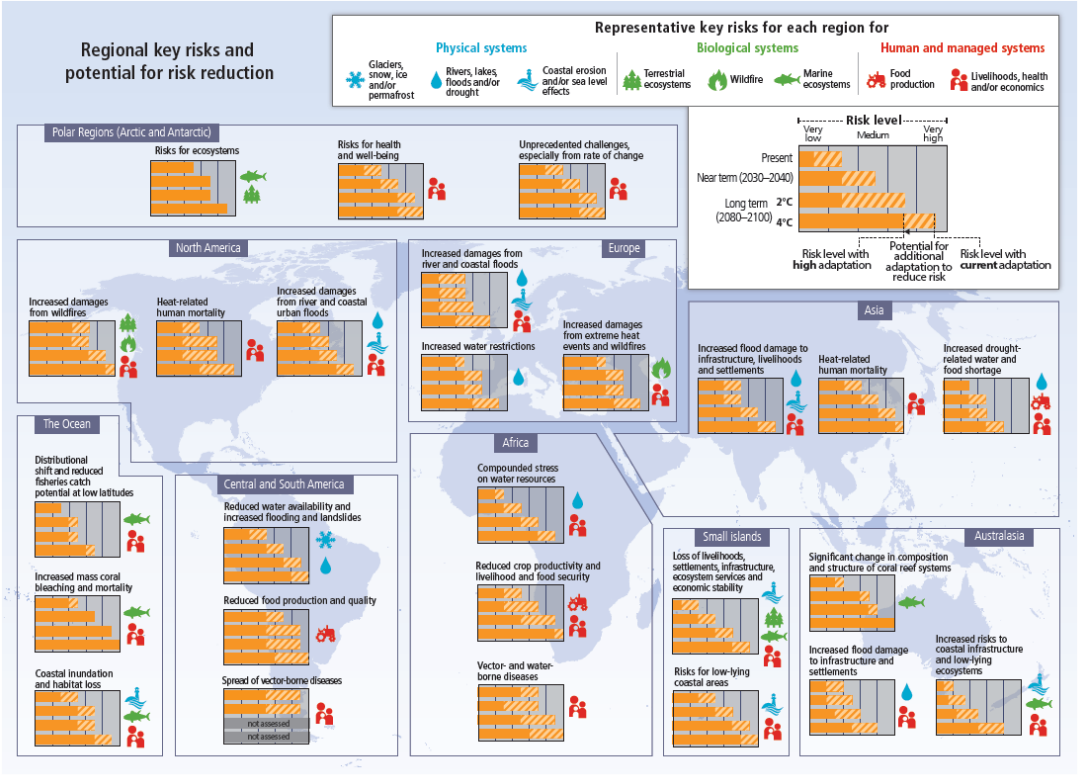

Figure SPM.8 | Representative key risks[14] for each region, including the potential for risk reduction through adaptation and mitigation, as well as limits to adaptation. Each key risk is assessed as very low, low, medium, high or very high. Risk levels are presented for three time frames: present, near term (here, for 2030–2040) and long term (here, for 2080–2100). In the near term, projected levels of global mean temperature increase do not diverge substantially across different emission scenarios. For the long term, risk levels are presented for two possible futures (2°C and 4°C global mean temperature increase above pre-industrial levels). For each timeframe, risk levels are indicated for a continuation of current adaptation and assuming high levels of current or future adaptation. Risk levels are not necessarily comparable, especially across regions. *(Figure 2.4)*

Figure 6: Representative key risk for region, including the potential for risk reduction through adaptation and mitigation, as well as limits to adaptation (IPCC, 2014b)

Warren claims that a temperature rise of 4°C would severely limit adaptation options for natural ecosystems and human systems as a result of the complete loss of ecosystem services (Warren, 2011). She claims that under such an increase in temperature change, the limits to adaptation would be reached and sustaining ecosystems would collapse, which is something that is not always taken into account in studies claiming that human systems could persist under such circumstances. This is supported by the authors of "Turn down the heat: Why a 4°C Warmer World Must be Avoided", as mentioned in section 3.3.2 above, they assert that biome shifts as large as 400km would

take place under a 4°C temperature increase (World Bank, 2012). Such a drastic shift signals an adaptation limit for mountain top, island, and high-latitude species that cannot migrate to ecosystems (World Bank, 2012).

Costs of adaptation

Overall, there are very few sources that link costs to global temperature rise but there is consensus that more aggressive emissions reductions will result in lower adaptation costs. The nexus between adaptation and mitigation pathways can be illustrated to some extent through the different costs of adaptation. Some of the works in the body of literature studied for this report touched on this topic, albeit indirectly. As the UNEP Adaptation Gap Report (AGR) (2016) points out, adaptation costs can vary based on the methodology, analytical principles, and assumption applied.

Given this, as well as the complex and subjective nature of such calculations, there is "no single estimate of the cost of adaptation" (UNEP, 2016, p.xii). The report goes on to describe some of the factors that explain why cost estimates differ but only mentions that adaptation costs will vary along with assumptions about future greenhouse gas emissions in passing. In the subsequent section on uncertainty, the report does not mention 1.5°C but rather focuses on 2°C and 4°C temperature rises. The chapter entitled "The costs of adaptation" depicts the adaptation costs in the present, in 2030s and in 2050s for three different pledge/investment scenarios to indicate how many times higher adaptation costs would be without public funding schemes for adaptation, but does not specify the emissions pathway used (UNEP, 2016, p.41).

Without specifying an emissions pathway or degree of global temperature increase, the authors of the Gap Report explain that the most recent estimates of global adaptation costs, based on an "in-depth review of national and sector cost estimates," range between USD 140 and 300 billion per year by 2030 and between 280 and 500 billion by 2050 (UNEP, 2016, p.xii).[23] For the current period from 2010 to 2019, the World Bank estimates adaptation costs at USD 56-73 billion per annum (World Bank, 2010 as cited in UNEP, 2016,p.40). They also explain that between 2030 and 2050, integrated assessment models anticipate considerable variation in adaptation costs between a 2°C and higher levels of global temperature rise (UNEP, 2016, p.xiii). Similarly, they explain that "model estimates illustrate the emissions-dependency of adaptation costs, and highlight that adaptation cost levels for different warming scenarios could diverge as early as the 2030s" (UNEP, 2016, p.xiv). While the aforementioned estimate and others are global and originate from a top-down approach, the authors explain that bottom-up national and sectoral studies form the basis for many estimates of adaptation costs (UNEP, 2016, p.12).

The Gap Report also provides some adaptation cost estimates for the coastal areas sector, as this sector has the most comprehensive estimates of risks related to sea level rise and storm surge (on flooding and erosion). These global estimates, the most recent of which is "between US$12-31 billion to US$27-71 billion for low-and high-warming scenarios respectively", are primarily based on the DIVA model,[24] which uses global annual investment and the maintenance costs of protecting costs up to 2100 (Hinkel et al. 2014 as cited in UNEP, 2016, p.13). Furthermore, the costs of beach and shore nourishment for low, mid and high warming (RCP) scenarios are estimated to be between

[23] Older studies from the IPCC and World Bank estimated the global cost of adaptation to be US$70 billion and US$100 billion per year for the period 2010-2050 (UNEP, 2016, p.10).

[24] "The DIVA model is an integrated research model of coastal systems that assesses biophysical and socio-economic consequences of sea-level rise and socio-economic development, taking into account coastal erosion, coastal flooding, wetland change, and salinity intrusion into deltas and estuaries, as well as adaptation in terms of raising dikes and nourishing shores and beaches. A complete description is available online at: http://www.diva-model.net/" (UNEP, 2016, p.13)

US$1.4-5.3 billion per year. The costs of adaptation for 136 of the world's coastal cities in particular, is estimated at US$50 billion annually or US$350 million per city[20] (Hallegatte et al., 2013 as cited in UNEP, 2016, p.13).

In "Sea-level rise and its possible impacts given a 'beyond 4 C world' in the twenty-first century", Nicholls et al. (2011) also cite dikes and beach/shore nourishment as responses to adaptation. They estimate that these responses cost approximately "US $25 and $270 billion (1995 values) per annum for 0.5 and 2.0m in 2100, respectively" (Nicholls et al., 2011, p.173). The results of their assessment are captured in Figure 7 below.

Additional information on the costs of adaptation in coastal areas at various global temperatures can

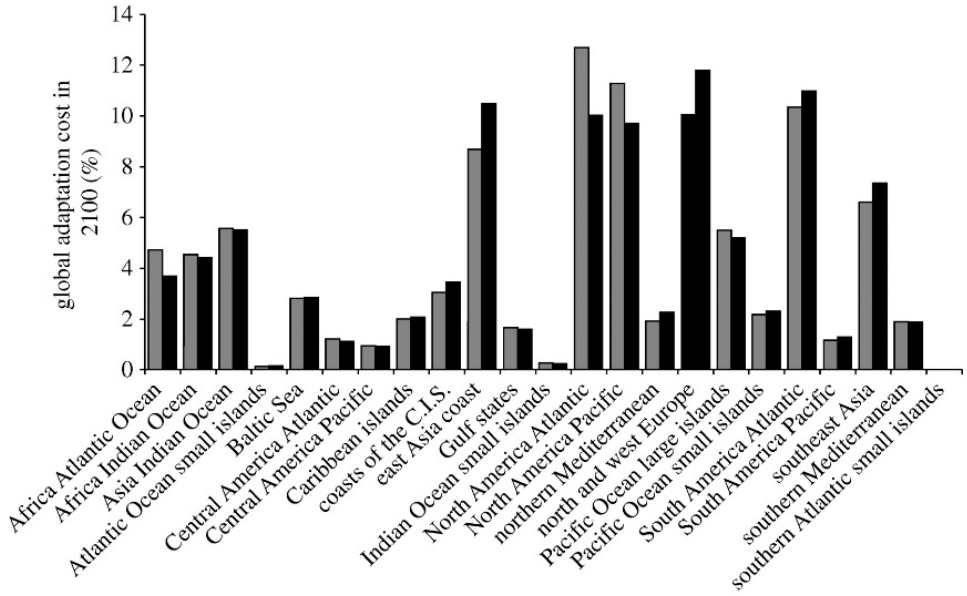

Figure 7 The annual protection cost by coastal region in 2100, as a percentage of global protection investment for a 0.5m (grey bars) and a 2.0m (black bars) rise in sea level by 2100 (Nicholls et al., 2011)

be found within the EU's ClimateCost program. In the programme, seven Technical Policy Briefing Notes were published on different topics. While (the costs of) adaptation is touched in each of them, Note 2 on sea level rise and Note 3 on river floods present the most concrete information on costs of adaptation in relation to the SRES scenarios. In the paper on sea level rise, adaptation is modeled in the form of dike building and nourishment of the beach/shore face and estimated to cost the EU roughly €1 billion per year in the A1B(1) or BAU scenario in the 2020s and €1.6 billion in the 2080s. For the E1 scenario, (2°C) adaptation cost approximately €1.2 billion per year in the 2020s and €0.7 billion in the 2080s (Brown et al, 2011). The report on river floods assessed that "ensemble-averaged adaptation costs (per year) for the EU under the SRES-A1B scenario…might be of the order of €1.7 billion by the 2020s, €3.4 billion by the 2050s, and €7.9 billion by the 2080s (constant 2006 prices and undiscounted)". Avoided damages on the other hand estimated at "€9.2 billion/year by the 2020s, €21.8 billion/year by the 2050s, and €53.1 billion/year by the 2080s (constant 2006 prices, undiscounted)" (Feyen and Watkiss, 2011, p.1747-8). These estimates, however, are less explicit about specific measures and do not incorporate what the authors refer to as socio-economic change. However, the authors point out that, the adaptation scenarios of course depend on the defined level of flood protection and risk, which in this case is that of a 1 in 100-year flood event in the future (Feyen and Watkiss, 2011).

Also more general in nature, the IPCC, assessed the cost of adaptation (in the form of additional infrastructure) in the water sector for 200 countries to the year 2030 as USD 531 billion for the SRES A1B scenario. With two additional adaptation measures, reservoir construction and unmet irrigation demands, adaptation costs are likely to be USD 225 billion or USD 11 billion per year (Kirschen, 2007 as cited in IPCC, 2014a). However, some more specific examples are cited. In the chapter on "Ocean Systems", for example, it is noted that a 2°C by 2050 will result in adaptation costs for fisheries to the tune of USD 7 to 30 billion per year between 2010 and 2050.

As indicated by the Gap Report, there is a lack of studies that focus on the cost of adaptation in other sectors such as ecosystems or industry and services.

4 Options for mitigating climate change

4.1 Mitigation effort increase when increasing ambition from 2°C to 1.5°C

It is estimated that a global carbon budget of 590—1240 $GtCO_2$ can be emitted between 2015—2100 in order to retain a 66% chance of not exceeding a 2°C temperature increase (IPCC, 2014c; Rogelj, 2016). This equates to 15—30 years of current emission levels (40 $GtCO_2\,yr^{-1}$). The budget for limiting warming to below 1.5°C will be even tighter.

There are several paths to achieving the transition in GHG emissions needed to keep within the carbon budget, employing varying degrees of mitigation measures. Future emission scenarios and the impact of various technological and policy choices in these scenarios are often based on integrated assessment models (IAMs). Hundreds of different scenarios were calculated using tens of different IAMs and various models for the 5th Assessment Report (AR5) of the IPCC, although none gave a 66% probability of meeting 1.5°C. Only a few of the models have been used since then to find possible transition scenarios for a 1.5˚C pathway. A dedicated IPCC Special Report scheduled for publication in 2018 will address this gap and efforts are currently underway to generate scientific evidence to include in the report.

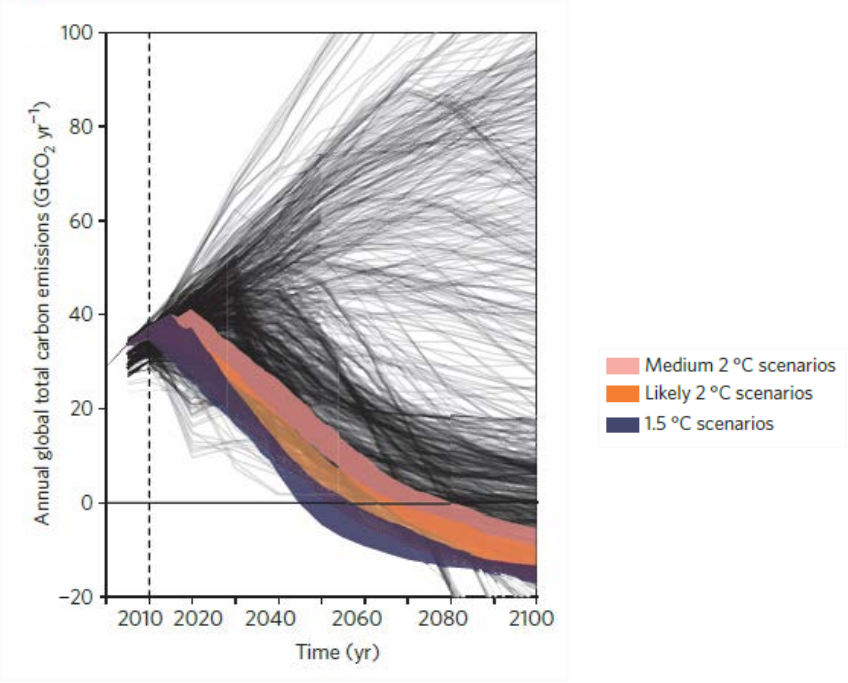

Figure 8 Emissions pathways of 1.5°C scenarios from Rogelj, 2015.

There is a wider body of literature on scenarios that meet a 2°C temperature limit but only one paper that reports specifically on scenarios for 1.5°C (Rogelj, 2015). Figure 8 is from that report and shows the emissions pathways for 1.5°C. The following are general conclusions illustrating the similarities and differences between the outcomes of scenarios for the two temperature limits:

- Both groups of pathways require significant emission reductions, but
    - 1.5°C compatible pathways require more ambition in most sectors.

    - Most of the increased ambition in emission reductions in 1.5˚C scenarios comes from the demand side, particularly transport and buildings. Energy efficiency starting immediately is a prerequisite to achieving 1.5°C by the end of the century.
    - The speed of decarbonisation required for 1.5˚C is almost twice as fast as for 2˚C, leading to significantly higher near-term costs (and long-term costs that are approximately double those for 2˚C)
    - The additional emissions reductions are primarily in CO_2 as potentials for other gases are already 'exhausted' in most 2˚C scenarios
        - Even in the 1.5˚C consistent scenarios, CH_4 and N_2O emissions will only stabilise (N_2O only after 2050). With CO_2 being actively removed from the atmosphere, residual non-CO_2 forcing will play an increasingly important role and can influence the remaining space for CO_2 emissions during this century in low stabilization scenarios (Rogelj et al., 2015).
- Both pathways stipulate that **net total global emissions** need to tend to **zero**, but
    - The timing differs: 2˚C pathways tend to see zero emissions near the middle of the 2nd half of the century, whereas 1.5˚C pathways require zero emissions to be achieved by the middle of the century, i.e. up to two decades earlier
    - The scale differs: 2˚C pathways typically see a stabilisation of the total long-term global emissions level near zero or at low negative emission levels while 1.5˚C pathways require several Gt of negative emissions
- Of the 116 2°C scenarios assessed by IPCC AR5 that reach their target with a likelihood of 66%, 107 include the use of CDR. The few scenarios that do not include negative emissions show that carbon emissions must fall to zero before 2050 (Peters, 2015). All 1.5°C scenarios deploy CDR (Rogelj, 2016).
- Of the 2°C scenarios assessed by IPCC AR5, CO_2 emissions in most scenarios exceed the 2°C-consistent carbon budget and typically are net negative in the second half of the century. In contrast, all existing 1.5°C scenarios overshoot 1.5°C and then use carbon dioxide removal to remove emissions and decrease temperature back down to 1.5°C (so-called 'overshoot'). In the 'overshoot' pathway, CO_2 emissions are net negative around 2050 (Van Vuuren et al., 2015).

To illustrate the differences in more detail, the table below summarises the main differences between scenarios limiting temperature to 1.5°C and 2°C within defined mitigation areas (Rogelj et al., 2015).

Table 4-1 Summary of main differences between 1.5°C and 2°C scenarios (Rogelj et al., 2015).

Mitigation area	Description of difference in trends between 1.5°C scenarios and 2°C
Decarbonisation of electricity supply	Similar end point reached in 2050 (95—98% of low carbon electricity[25]) but reached earlier in 1.5 (73% of low carbon electricity in 2030 compared to 63% for 2°C). In 2050, 1.5°C pathways assume 0 $GtCO_2\,yr^{-1}$ emissions compared to 1 $GtCO_2\,yr^{-1}$ for 2°C.
Decarbonisation of total energy supply	Faster decarbonisation in 1.5°C consistent scenarios than those for 2°C (2.1—2.8% yr^{-1} over the period 2010—2050 compared to 1.75—2.0% yr^{-1})
Decarbonisation in end	Overall large difference in carbon emission reduction rates. Slightly faster rate of carbon

[25] Low carbon electricity—renewables, nuclear and power generation with CCS.

Mitigation area	Description of difference in trends between 1.5°C scenarios and 2°C
use sectors	intensity improvements (2.6% yr^{-1} compared to 2.4% yr^{-1} in 2°C) over the period 2010-2050.
Decarbonisation in industry	Emissions from industry reach 4 $GtCO_2$ yr^{-1} for 1.5°C, compared to 5 $GtCO_2$ yr^{-1} for 2°C in 2050.
Decarbonisation in transport	Increase in rate of electrification needed in both 2°C and 1.5°C compared to scenarios above 2°C (details not given in the literature for 1.5°C). Similar percentage reached in 2050 in both 2°C and 1.5°C. 15% higher share of biofuels in liquid energy carriers in the 1.5°C-consistent scenarios by 2050. Median values for 2°C express almost twice the carbon emissions in 2050 compared to 1.5°C.
Decarbonisation in buildings	Half the emissions in 2050 in 1.5°C pathways (0.5 $GtCO_2$ yr^{-1}) compared to 2°C pathways (1 $GtCO_2$ yr^{-1}).
Carbon dioxide removal	Cumulative amount of carbon removed by 2100 is higher (800 Gt compared to 500 Gt in 2°C). In 1.5°C scenarios, CDR ramps up much faster and earlier, already reaching 1–8 Gt yr^{-1} negative emissions in 2040, compared to 0–2.5 Gt yr^{-1} for 2°C. After 2050, this difference slightly levels out to 2—15 Gt yr^{-1} for 1.5°C and 1—8 $Gtyr^{-1}$ for 2°C. So there is a delay of ~10 years in negative emissions scale-up.
Time to reach net zero CO_2 emissions (median)	15 years earlier (i.e. net zero in 2050 for 1.5°C).
Time to reach net zero non-CO_2 emissions (median)	15 years earlier (i.e. net zero in 2075 for 1.5°C).
Mitigation costs	Aggregated long term mitigation costs are up to two times higher in the 1.5°C scenarios than 2°C

Some caution is advised when interpreting global scenario models: the models used are complex and the choices made on which technologies to deploy are heavily influenced by certain assumptions. In particular, on the costs and cost reductions of certain technologies or endogenous limits on the potential or rate of implementation of a technology. For some technologies, particularly renewables, the costs have been reducing much more quickly than anticipated in many of the models, driven by deployment in response to government policies. As an example, several models used to evaluate scenarios for IPCC AR5, assumed that the cost of large-scale solar would drop to 1500 USD/kW between 2030 and 2060 (Gambhir et al., 2015), when in fact they are already below that level in some regions in 2014 (IRENA, 2016a5). Given expected trends in both renewable prices and average load factors, it is likely that on a levelised cost basis, renewables will be cheaper than coal and gas in the near future (Carbon Tracker, 2016). For other technologies such as CCS, implementation and therefore cost reductions, have been slower than anticipated. Nuclear is also an option that is deployed to scale in many of the mitigation pathways for both 1.5°C and 2°C. However, with falling renewable prices it is also less cost competitive and in many countries there is a lengthy approval process which slows the rate at which it can be implemented. It is therefore possible that models project trends that will not be seen in reality. An example is the high share of CCS and BECCS in the power sector in the

models. In reality, the currently very expensive option of CCS is not being deployed whereas renewable power sources are being deployed at scale. New scenarios are therefore needed with updated cost and constraint information, to assess the real feasibility of meeting the 1.5°C global temperature limit.

These issues notwithstanding, this section summarises the current state of research on comparisons between the different individual mitigation options used in scenarios which reach temperatures close to or just below 2°C below and give an overview and brief description of the major classes of mitigation options. Options for negative emissions are discussed in Section 4.5.

4.2 Trade-offs between mitigation options in climate models

As discussed, the IAMs used to calculate the scenarios that meet given temperature limits are complex and the choices made on which technologies to deploy are heavily influenced by certain assumptions. Useful insights into the impacts of the assumptions could be gained by comparing the same model with different variants in the assumptions. Unfortunately, this type of analysis does not yet exist for 1.5°C scenarios and is limited to choices in the energy supply sector for 2°C and higher scenarios. Table 4-2 summarises the available information on the effect of different assumptions in the subset of the scenarios for 2°C, which have been studied.

Table 4-2 Summary of the available literature on trade-offs in 2°C scenarios (Gambhir et al., 2015, Dessens et al., 2014, Jewell et al., 2014)

Difference in assumptions between a baseline and variant model for 2°C	Effect on mitigation choices in a 2°C scenario
No nuclear or CCS	Increase rates needed for decarbonisation of power, electrification of energy supply and energy efficiency
Delayed action on mitigation	CCS and nuclear are needed to meet temperature limit
CCS delayed to 2050	More nuclear needed
Lower rates of electrification of demand	More gas with CCS and BECCS needed
Limited renewable energy	More gas and coal with CCS and more BECCS

Further insight into the impact of different choices of mitigation options can be explored with different types of model. For example, a scenario from the Greenpeace Energy [R]evolution model reduces global carbon emissions to under 4 Gt CO_2 yr^{-1} in 2050 without the use of nuclear energy and CCS. In general, this scenario assumes a vast scale up of wind, solar (PV and CSP) and geothermal, and implicitly also an expansion of transmission grids and storage. This scenario also foresees a large shift from the heat sector towards the direct use of electricity. An even more ambitious scenario in this study manages to completely decarbonise the energy sector in 2050. This latter scenario assumes a stronger role for synthetic fuels from hydrogen, where this would replace 100% of the remaining gas consumption in 2050. To abate the remaining emissions on the supply side, the power sector relies on electrification and hydrogen technology. Energy intensity decreases by 3.5% yr^{-1} on average in both scenarios.

Large differences can be identified between the models used in studies such as Greenpeace Energy [R]evolution and the WWF Energy Report and the scenarios produced by integrated assessment models. IAMs tend to discount future impacts from climate change at relatively high rates, leading to relatively slow action in the short-term, which is then compensated in the long-term. IAMs use mitigation cost projections as an input which require assumptions on the pace and nature of technological change which have proven difficult to project (Ackerman et al., 2009). IAMs use

long-term economic optimisation as a response to stringent climate policy, whereas the Greenpeace and WWF models place a stronger focus on immediate decarbonisation with a horizon up to 2050.

4.3 Maturity and impact of mitigation options used in scenarios

Table 4-3 below summarises the technical maturity, cost and impact of the main supply-side mitigation options based on the discussions provided in this section. Demand side measures are not included in the table as the categories encompass a wide range of technologies with mainly positive impacts and very diverse costs and technical maturity.

Table 4-3 Maturity and impact of mitigation options

Mitigation Options	Current Technical Maturity	Cost	Impact of mitigation option		
	Current Level		Land use	Water	Ecosystems
Solar					
Wind					
Hydro					
Biomass					
CCS (with fossil fuel)					
Nuclear					
Biofuels for transport					

Low level of maturity medium to high level of maturity high level of maturity

low cost or impact medium cost or impact high cost or impact

4.3.1 Mitigation Options for Decarbonisation in the Electricity System

In this section, we provide a brief summary of the main mitigation options deployed in the scenarios. We describe the relative impacts and costs. We do not compare the impacts directly with fossil fuel generation, except with gas replacing coal, as these are not used as mitigation options in the model. The ranking of the costs for the supply side are based on levelised costs (Ecofys, 2014), which is the cost per unit of electricity produced.

Solar PV

The technical maturity of PV is high. The estimate of land use for utility-scale PV systems range from 1.4—4 ha per MW (UCS, n.d). Hence, in areas where there are land constraints, it might become economically feasible to install PV systems in agricultural, forested or other ecological sites. Fthenakis et al. (2009) report that among the renewables,

PV systems require the least amount of land. The demand of land could be reduced by using PV systems on unused lands and in case of small-scale PV on homes and commercial buildings.

Solar power also uses relatively low amounts of water; small amounts are used in the manufacturing process and the cleaning of panels.

Concentrated solar power (CSP)

The technological maturity of CSP is currently at a medium level. Estimated land-use ranges between 1.6—6.7 ha per MW. Water use in CSP plants is significant—around 3 m^3/MWh—as water-intensive wet recirculating technology is used to cool down the system (NAP. 2010). However, air-cooled systems exist as well that merely use a negligible amount of water. In comparison, fresh water consumption in coal power plants ranges from 0.16-2.8 m^3/MWh, with much larger quantities of withdrawal i.e. water used but recycled (Greenpeace 2016).

Wind

On-shore wind power has a high technological maturity, whereas there is still considerable potential for technological developments within off-shore wind (IRENA, 2016b). The installation of on-shore wind power systems requires large areas of land—about 0.3 ha MW^{-1} (permanently) and 0.7 ha MW^{-1} (temporary) of land are disturbed during the installation of wind turbines (Denholm et al. 2009). Nonetheless, there are reduced concerns for land-use changes due to the installation of the wind turbines as it can be used with other land-use purposes including agriculture and other commercial purposes. The direct impact of wind turbines is more pronounced on the avian fauna. Many studies have recorded the death of birds and bats due to collision with wind turbines. Collisions could be minimized by modifying operational times, stopping the turbines in times where bats show high level of activity. However, preliminary assessments of avian fauna mortality have shown that mortality from nuclear and wind facilities are considerably lower than from fossil fuel installations, with 0.3—0.4 and 5.2 fatalities per GWh, respectively (Sovacool, 2009).

Offshore wind is at an earlier stage of development and is higher cost because of the challenges of working offshore and the need for additional grid connection infrastructure. The advantages of developing offshore though are both a lower impact on land use and a more constant wind speed, leading to higher generation. The costs of offshore wind are also reducing rapidly[26].

With both solar and wind, there are wider impacts on the power system through for example the decentralised nature of PV in particular and the variable nature of the output from both. Decentralised power provides challenges for established power systems, which were largely built around large power stations, but also opportunities in providing energy access at lower cost. The variable nature of the output means that the grid needs to react with back-up capacity, demand response or storage. These tend to add costs to the power system.

[26] https://www.government.nl/latest/news/2016/07/05/netherlands-offshore-wind-farm-borssele-cheapest-world-wide. Under the Dutch system, interested market parties could bid in the subsidy and permit tender, with a maximum price cap set at 12.4 Euro cent per kilowatt hour. Dong Energy submitted the lowest bid with an average of 7.27 Euro cent per kilowatt hour.

Hydropower

Hydropower is a technologically mature renewable energy source. The different sizes and types of hydropower systems have different impacts on land-use, water and ecosystems. Hydroelectric plants that require flooding of land to create large reservoirs will have a higher impact on land-use, water and ecosystems than a mini-hydro run-off river plant. Average land-use was 120 m^2/MWh, slightly higher than wind power but with more impact on the land (NAP, 2010). In general, hydropower systems change the landscape/environment and create physical structures/barriers, which can have cultural impacts (NAP, 2010). Such practices also impact ecosystems as they alter water flow, habitat loss and restrictions in movement of aquatic flora and fauna. According to the UN, about 60% of the world largest rivers are already fragmented by dams (and diversions and canals) and this has led to degradation of ecosystems.

In addition to the ecosystem impacts, hydropower can have socio-economic impacts if not well sited and planned. These impacts are particularly felt in communities downstream that depend on freshwater ecosystems including fisheries and delta agriculture.

Nonetheless, use of innovative technologies, better planning, operation and management of the hydropower reservoirs have been successful in reducing the environmental impacts at some level. For example, the development of fish passage technologies has been successful in mitigating the impacts of dams. Similarly, measures like ensuring effective environmental flows, implementing compensatory measures and improving hydropower certification schemes could reduce the environmental impact (WWF, 2004).

Biomass

Energy from biomass generally has a high level of maturity, though it is significantly more complex than other renewable energy technologies. The biomass fuel cycle/system requires the most land of all RES options (Fthenakis et al., 2009). Without policies to manage land use and promote use of sustainable biomass, this could impact both food security and biodiversity (WRI, 2015). These negative side effects can be countered with policies that manage land-use change and ensure social and environmental sustainability. Water use is also significant and costs vary depending on the feedstock, conversion technology and end uses. NO_x emissions resulting from the combustion process also pose health threats for the local and regional population, together with other hazardous air pollutants, such as polycyclic aromatic hydrocarbons (NAP, 2010).

CCS in Electricity Production and Industries

Integration of CCS into electricity production has been seen as a way to enable the use of fossil fuels, particularly coal in a carbon constrained world. In industry, it is seen as a way of tackling emissions that cannot be easily avoided or substituted with renewable sources. When combined with bioenergy, CCS (BECCS) acts to not only mitigate but also remove carbon dioxide. Many mitigation scenarios include the assumption of wide-scale use of CCS to decarbonise the power supply and industry sector.

CCS technology is not mature and still expensive. Currently, CCS has not yet been applied at large scale in commercial fossil fuel plants but all components of integrated CCS systems exist and are in use by the fossil fuel extraction and refining industry (IPCC,2014). Given the level of technical maturity the estimates of costs are uncertain for CCS.

There are environmental risks with CCS associated with the long term storage of the captured CO_2 and short term operation. The environmental risks in operation are similar to any power plant, with some trade-offs for example

lower CO_2 emissions but more water use (Korneef, 2010). The risks from transport and storage are less well characterised so further monitoring of demonstration projects will be needed (Korneef, 2010).

Nuclear

Nuclear energy is a mature low-carbon technology and is still one of the largest sources of low-carbon electricity (IEA, 2016). However, there is opposition from the public in many countries to new nuclear power because of safety concerns both with operation and waste disposal. As discussed above, nuclear power is a part of the energy transition in many of the 2°C scenarios despite its relatively high cost compared to some renewables. Some newer reactor types are reported to be less expensive and take less time to build than the currently most widely adopted technologies.

There are still environmental and health concerns over the use of this technology. Nuclear power plants need to manage their heat, cooling down with towers or with water in the same way as any thermal power station. However, nuclear power plants use more water per MWh than other types of power plants[27]. If not managed properly, ejection of hot water into bodies of water can have negative impacts on the aquatic life and changing the flow rates of rivers. Another environmental concern related to nuclear power is the safe disposal of radioactive waste, with infrastructure for long term disposal not in place in all countries. Safety is another concern. The use of improved technologies, safety features and regulations have reduced the risk of nuclear accidents although the Fukushima disaster demonstrates that there remains a risk.

4.3.2 Biofuels for transport

There is a lot of experience worldwide with biofuels for transport and the potential is significant. The most successful use of biofuels in transportation comes from Brazil, which has been using ethanol in their vehicle fleet for decades and has set forward the legal framework to make sure that the associated sustainability impacts are minimized. However, the use of biofuels for long-haul transportation, aviation and shipping is more challenging. The global aviation and shipping sectors together produced about 5% of global CO_2 emissions and is expected to rise (level depends on the scenario). Currently there are several efforts to make the second generation of renewables to serve these modes of transportation but they are not yet market ready.

Concerning costs, the mere availability of sources for biofuels and innovations are pushing costs down. When oil prices were high, biofuels were affordable enough to compete with petrol. The current push for electric passenger and heavy duty vehicles will make biofuels harder to compete in areas where there is cheap electricity. In aviation, bio jet fuels will remain relatively expensive for the next decade.

As with biomass to power, there are concerns on the pressure the use of land for biofuels will have on agriculture and other competing demands. If land-use is not managed appropriately, the impact will be high on water, food security and biodiversity.

4.3.3 Demand sectors

As discussed in Section 4.1, scenarios for 1.5°C assume a much higher rate of energy demand reduction than those for 2°C. However, the options for demand reduction cover much broader technology categories than the supply side options that are discussed above and it is difficult to draw conclusions on relative costs and impacts. In this section therefore we describe only briefly the options related to each sector for reducing energy demand.

[27] http://www.world-nuclear.org/information-library/current-and-future-generation/cooling-power-plants.aspx

Industries

Many options for emission reductions in the industrial sector are cost-effective and profitable (IPCC, 2014d). Some of the options for emission reduction in the sector are: fuel switch (to low carbon electricity or biomass), reduction in process emissions, reduction, recycle, and reuse of waste (waste minimisation), efficiency enhancements (steam, furnace and boiler systems, electronic control systems, product designs), reduction of non-CO_2 emissions like HFCs and behavioural changes (reduction in demand for processed food, clothes and other materials). Deep decarbonisation may require implementation of different processes which are still in the development stage e.g ultra low lifecycle emissions steel. A switch from coal to natural gas with CCS deployment might be needed for a transitional decarbonisation option for industry through 2050 (Deep Decarbonization Pathways Project, 2015).

The industry sector has been subject to policy interventions on energy efficiency in many regions and as such has a more mature market/policy environment than households or transport.

Transport

Measures to reduce emissions from transport include increasing efficiency of engines and tyres, use of renewables as fuel, electrification of the vehicles, implementation of fuel economy standards, management of demand for travel through land-use planning, modal shift to low carbon transport modes (e.g. public transportation). Scenarios for 2°C and below require large scale electrification of transport.

Some of the measures require transformation of infrastructure, for example car charging points. There have been some policies aimed at reducing emissions from transport but at a lower level compared to the other demand sectors.

Buildings

Some of the mitigation measures in the building sector are integration of RE technology in buildings, enhancement of building efficiency (architectural and engineering designs, heating-cooling systems, ventilations, appliances and lightning systems), reduction in usage of cements and steels made from processes requiring high carbon emissions, energy metering and automation and behavioral changes (e.g. energy savings). In general, these options are technically mature however are often not taken up because of behavioural and economic factors.

Agriculture Forestry and Other Land-Use (AFOLU)

Mitigation potential from the AFOLU sector is derived from both the enhancement of carbon removals and reduction in emissions through management of land and livestock. Opportunities for mitigation includes both supply side (reduction of emissions from land-use change, land management and livestock management and increase in terrestrial carbon stocks by sequestration in soils and biomass) and demand side (reduction of food wastes, changes in diet and changes in wood consumption) (IPCC, 2014a). There have been actions to reduce emissions from agriculture and promote for example afforestation/reforestation and reduce deforestation but the policy and market maturity is relatively low.

4.4 Demand changes

All scenarios include underlying changes in the demand for services in the end use sectors (e.g. food, transport, housing) arising from for example population and economic growth. 1.5°C scenarios are reported to included limits to the demand growth but details are not given.

One of the main options to reduce emissions from agriculture is changes in demand, particularly for meat as emissions from livestock sectors are impossible to abate completely. Hence, a decrease in overall emissions is only feasible through demand-side reductions, i.e. adopting less meat-intensive diets (Bajzelj et al., 2014). As residual non-CO_2 forcing will play an increasingly important role in 1.5°C scenarios and can influence the remaining space for CO_2 emissions during this century (Rogelj et al., 2015), demand side reduction policies in the livestock industry through improved diets and reduced food waste become increasingly important. Even for 2˚C pathways this is a crucial aspect, as the cumulative BAU emissions from the agricultural sector already reach this centuries' budget in 2050 (Bajzelj et al., 2014).

Other demand changes include changing transport patterns for example promoting the use of public transport or restricting air transport. In addition, material efficiency including recycling and re-use of materials such as steel or glass reduces emissions in primary production of those materials.

4.5 Carbon dioxide removal

All 1.5°C scenarios and nearly all 2°C scenarios include a certain amount of negative emissions, meaning that these models incorporate mitigation options that sequester more carbon than they emit—a process called carbon dioxide removal. The IAMs predominantly use BECCS and afforestation and reforestation for CDR as these options are the best characterised and can be included easily into the current range of mitigation activities in the models.

In addition to the few CDR options that are being used for integrated assessment modelling, other options also exist, ranging from technologies that filter CO_2 directly from the air using chemical sorbents, to changing agricultural practices to increase the soil organic carbon content (see Annex 6.1 for description of options). Although all of the identified CDR methods would classify as mitigation options, the characteristics among them can vary greatly and also determine the social acceptability of a CDR option.

For instance, a low permanence of stored CO_2 is often perceived as less desirable as this implies a higher risk of the CO_2 flowing to the atmosphere and thus more stringent monitoring requirements and higher storage costs (Herzog et al., 2003; Kriegler et al., 2013). At the same time, in terms of technological readiness, the options with the lowest permanence are generally the most mature and could be implemented in the very short term. Such considerations and characteristics are discussed and displayed (Figure 9) in more detail in the sections below.

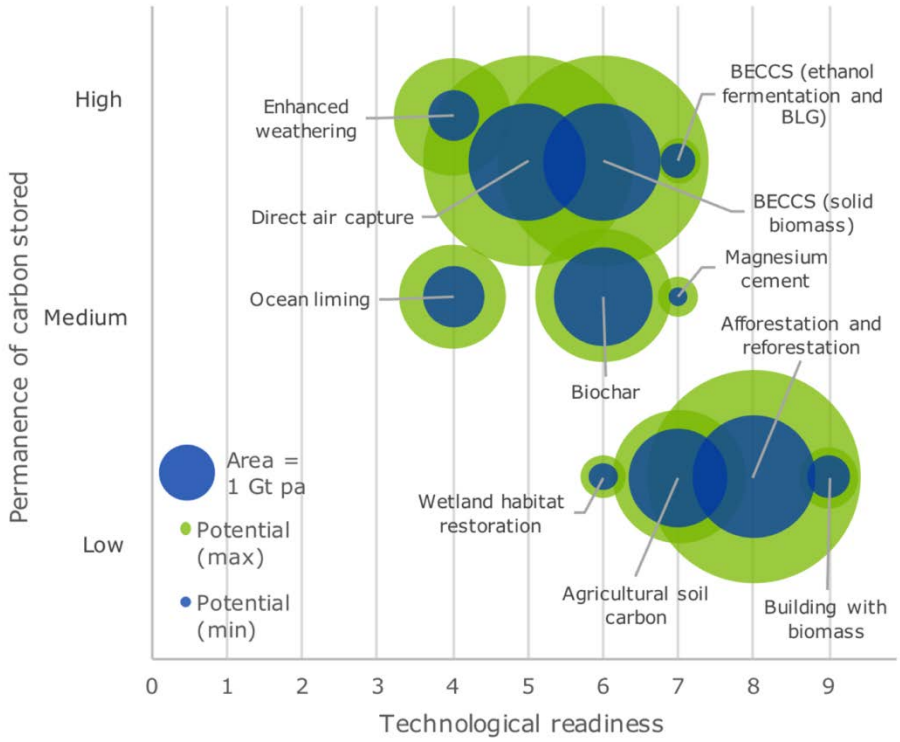

Figure 9: Identified CDR options, their min-max potential, technological readiness and the level of permanence of the carbon that is stored with the identified technologies. The surface area of the bubbles represents the annual CDR potential. Values for potential and cost estimates are provided in Annex 6.2.

Potential

The potential for CDR is typically expressed in the amount of atmospheric carbon that can be captured and stored per annum. The size of this figure is dependent on the sustainability criteria applied for the individual methods and the chosen portfolio of options. Estimates on the potential of a certain CDR method therefore vary enormously, especially for the bio-based options. It should be noted that the values that are represented in Figure 9 and Annex 6.2 are technical estimates and represent the full deployment potential in 2100 and would likely be smaller in reality due to economic or socio-political constraints.

Permanence

The carbon that is removed from the atmosphere can be stored in different reservoirs. Among the identified CDR options, four carbon reservoirs can be distinguished: biotic, pressurised, mineralised and oceanic. These reservoirs are inherently linked to the natural carbon cycle, which also determines the carbon fluxes between the reservoirs and the carbon residence time. In terms of carbon removal, the residence time is of particular importance, as this factor determines the permanence of the stored CO_2. Generally, high levels of permanence are favoured over low levels of permanence in the context of carbon sequestration (Kriegler et al., 2013). One argument for this is that storage mediums with a high proven level of permanence require less monitoring and safety measures to avoid leakage, which would reduce storage costs. Furthermore, Herzog et al. argue that there is little value to temporary storage of carbon if carbon prices increase quickly over time, as their release would become very costly later in the century (Herzog et al., 2003). A more ethical question also arises as to whether large non-permanent reservoirs should be used, which could impose a considerable economic burden on future generations. It is obvious that this risk is

significantly higher with the biological storage options as a result of their lower permanence (Canadell & Schulze, 2013).

Enhanced weathering, direct air capture, BECCS and biochar all store carbon as a part of the slow carbon cycle as the carbon is stored in a mineralised or pressurised form. The risk of reduced permanence increases slightly with pressurised storage compared to mineralised storage as a result of anthropogenic modifications to the geological reservoirs (i.e. holes in the subsurface from drilling). A more adequate level of monitoring is therefore required to evaluate long-term permanence and ensure this appropriately. Although also part of the slow carbon cycle, ocean liming (oceanic carbon) has a significantly lower residence time than mineralised carbon—about 400 years (Field, 2008). All the other CDR options store carbon in the form of biomass (biotic carbon), which is represented in the 'short carbon cycle'. Carbon stored in land biomass and soils have an average residence time of 10 and 40 years, respectively (Field, 2008). Exceptions exist, e.g. some species in tropical rainforests may live up to 500 years. However, it is still unclear how climate change will affect these biotic carbon pools.

Technology readiness

The individual CDR options are categorised in terms of technology readiness according to the definitions in the following text box.

Box 1 Definitions of different technology readiness levels (Source: European Commission, 2014)

TRL 0: Idea. Unproven concept, no testing has been performed.
TRL 1: Basic research. Principles postulated and observed but no experimental proof available.
TRL 2: Technology formulation. Concept and application have been formulated.
TRL 3: Applied research. First laboratory tests completed; proof of concept.
TRL 4: Small scale prototype built in a laboratory environment ("ugly" prototype).
TRL 5: Large scale prototype tested in intended environment.
TRL 6: Prototype system tested in intended environment close to expected performance.
TRL 7: Demonstration system operating in operational environment at pre-commercial scale.
TRL 8: First of a kind commercial system. Manufacturing issues solved.
TRL 9: Full commercial application, technology available for consumers.

4.5.1 CDR characteristics

A detailed overview of the characteristics categories of the identified CDR options is provided in Table 4-4. Furthermore, the categories will be described below to provide additional discussion and information to the table.

Costs. The economics of CDR options are typically assessed based on the costs per mitigated tonne of CO_2. In some cases, where there are additional benefits that are difficult to value, this can lead to higher costs for options with wider benefits. For example, the restoration of wetlands often also leads to increased flood protection and water quality. For the options with a lower level of technological readiness, the cost estimates are inevitably very uncertain.

Land-use. The amount of land-use that is needed for a CDR option is often expressed in hectares per tonne carbon (ha/tC) or ha/tCO_2. However, it should be noted that this simple measure of land use does not provide information on the usability of that land for other purposes at the same time. For example, *agricultural soil carbon* can be classified as having a 'very high' land-use, but as it is applied on agricultural land, it is likely to have less impact than *solid biomass BECCS*, which requires less ha/tC but where the land will be dedicated solely to the cultivation of energy crops.

Energy. Some CDR methods might have a negative energy usage, leading to an overall reduced energy consumption when implemented—with *soil carbon sequestration* practices for example. On the other hand, some options might require a significant share of the world's energy production, such as *direct air capture* or *ocean liming*. These technologies would make up roughly 160% and 13% of the world energy consumption[28], respectively—if they were deployed to remove 10 $GtCO_2/y$ (Nikulshina et al., 2009; Jenkins, 2010).

Water. As a result of climate change, more areas worldwide are facing the pressure of increased water stress (see Section 2). Future water availability will therefore be a likely limiting factor for the sustainable deployment of some CDR options. BECCS, for example, is estimated to have a substantial water footprint as a function of feedstock production and the use of carbon capture technologies such as amine-based wet scrubbing (IEEE, 2010; Smith, 2016). Biochar, on the other hand, might increase water availability due to its water retention properties (Smith, 2016).

Albedo. Some CDR methods have the potential to influence the albedo[29] of the area in which it is deployed. This could have a measurable global impact when engaging in large-scale deployment and this effect should be properly taken into account in future models. For example, *afforestation and reforestation* can significantly reduce albedo in higher latitudes, counteracting the intended purpose of deployment, whereas *enhanced weathering* could increase surface albedo and thus possesses a double benefit of removing carbon and cooling the surface (Dhingra et al., 2015).

Ecosystem impact. This factor encompasses a range of different effects and is affected by some of the other factors set out in this assessment, such as water use and land-use, but also impacts on soil nutrients and biodiversity are taken into account. Such impacts can be difficult to fully assess for some of the technologies at this stage of development. However, for the bio-based options, these effects are more well-known. For example, the use of bio-based options enhances nutrient retention in soils, which in the long term provides a net ecosystem benefit (Smith et al., 2013). Impacts for BECCS are generally dependent on the biomass regime the crop replaced and the indirect land-use change it causes. Ocean liming involves modifying the chemical composition of the oceans' surface waters. These implications are currently unknown and should be further investigated (McGlashan et al., 2012).

Measurability. This category gives an indication as to how well the carbon that is removed and stored can be measured and monitored. For example, for *BECCS* the carbon that is removed could be measured through a benchmark value at the point that the captured CO_2 enters the pipeline. Taking into account the multiple decades of experience in hydrocarbon exploration monitoring should be manageable as well (Eiken et al., 2011). In contrast, monitoring efforts might prove more difficult with *enhanced weathering* as dispersed silicate rocks respond differently to changing climate conditions and the composition of local ground water needs to be accuratelymonitored to prove the extent of CO_2 fixation (Schuiling & Krijgsman, 2006). Accounting for forestry stocks has also long been an issue as remote sensing is too inaccurate for carbon mitigation purposes (Gibbs et al., 2007).

[28] Based on 2008 world energy consumption, assuming 156,000 TWh/y for direct air capture and 12,000 TWh/y for ocean liming.

[29] Albedo expresses how much of the incoming electromagnetic radiation is reflected by the object in question.

Table 4-4: CDR characteristics in order of annual CDR potential. Colours represent the magnitude of the costs and the degree of impact. Measurability represents the certainty associated with the methods for measuring the carbon storage.

Negative emissions technology[30]	Costs[31]	Land-use	Energy	Water	Ecosystem impact	Albedo	Measurability
Afforestation and reforestation	Medium	High	Low	Yes	Positive	Negative	Low
BECCS (solid biomass)	Medium—High	High	Negative	Yes	Variable	Variable[32]	High
Direct air capture	Medium—Very High	Very Low[33]	Very High	Yes	No	No	High
Agricultural soil carbon	Negative—Low	Very High	Negative - Low	Negative	Positive	No	Low
Biochar	Medium—High	Very High	Negative - Low	Negative	Positive	Negative	High
Ocean liming	Medium—High	Low	Very High	n.a.	Unknown	No	Medium
Enhanced weathering	Low—Medium	Very Low	Very High	Negligible	Positive	Positive	Low
Building with biomass	Negative—Low	High[34]	n.a.	Yes	Variable	No[35]	High
BECCS (ethanol fermentation and BLG)	Low	Very Low[36]	Negative	Yes	Variable	No	High
Wetland habitat restoration	Low	Medium[37]	Low	No	Positive	Positive	Low
Magnesium cement[38]	Negative—Low	n.a.	n.a[39]	n.a.	No	No	Medium

[30] Ordinal values are defined as follows: **Costs** ($/tCO$_2$): Negative: < 0; Low: 0 - 50; Medium: 50 - 100; High: 100 - 200; Very High: > 200. **Land-use** (ha/tC): Very Low: <0.1; Low: 0.1 - 0.5; Medium: 0.5 - 1; High: 1 - 2; Very High: > 2. **Energy** (GJ/tC): Negative: < 0; Low: 0 - 1; Medium: 1 - 5; High: 5 - 10; Very High: > 10. **Water** (dimensionless): No: Does not need additional water input; Negative: Increases water availability. Yes: Requires additional water input; Negligible: Requires a negligible amount of additional water input. **Ecosystem impact**: Positive: Typically has a positive impact on ecosystem properties if sustainability criteria are taken into account; Variable: Even if sustainability criteria are taken into account, ecosystem impact can either be positive or negative (sometimes as a result of their complexity); No: No significant impact on ecosystem properties; Unknown: No data available. **Albedo**: No: Does not lead to decreased albedo (and thus surface warming); Positive: Leads to increased albedo (and thus decreased surface warming); Negative: Leads to decreased albedo (and thus increase surface warming). **Measurability**: Low: Difficult to measure removal and to monitor storage; Medium: Difficult to measure but relatively easy to monitor or vice versa; High: Both relatively easy to measure and to monitor.

[31] Some cost estimates may have a much wider range. However, these are often outliers. For comparison purposes such outliers were not taken into consideration (e.g. -$800 for biochar or $1000 for DAC).

[32] Albedo impact of crop BECCS is negligible if agricultural land is the reference; forest BECCS is more substantial and is comparable to afforestation and reforestation

[33] Depends on method of electricity generation. Solar energy would require a significant amount of land area.

[34] No land-use estimates were published for building with biomass. However, it can be argued that the land-use would be roughly similar to afforestation and reforestation.

[35] Estimated to have no significant effect on surface albedo when deployed at estimated maximum potential (0.4 Gt/y).

[36] Only holds when the land-use is attributed to its industrial purpose, otherwise roughly similar to *solid biomass BECCS*.

[37] No official estimates are known. However, wetlands are multiple times more carbon-dense than forests. A rough estimate would therefore categorise them as 'Medium'.

[38] No official cost estimates have been published for the application of magnesium cement techniques.

[39] Production process is less energy-intensive compared to regular Portland-cement.

4.6 Solar radiation management

In addition to carbon dioxide removal, there is another group of even less conventional mitigation options. Solar radiation management (SRM) is a collective term for methods that aim to increase the Earth's reflectivity or albedo, which can be done either at different points in the atmosphere or at the Earth's surface. Generally, SRM methods aim to balance the positive forcing GHGs cause by introducing sources of negative forcing to reduce the amount of forcing that is absorbed (The Royal Society, 2010). It should be noted that SRM methods do nothing to influence the GHG concentration in the atmosphere as they only help to mitigate a certain rise in global temperature. Other CO_2-related impacts are also not addressed, such as ocean acidification (Ricke et al., 2010). Most scientists therefore believe that SRM methods should only be deployed as an insurance against strong positive climate feedbacks, or to prevent reaching a certain climate 'tipping point' (Burns, 2011).

There are a number of specific SRM techniques, all varying in cost, impacts on ecosystems and presence of the 'termination effect', a term that is used to describe the risk of climate disruption in case the technique fails due to an unexpected event. A rapid transition would then likely take place to a climate state that corresponds with the present atmospheric GHG concentration (The Royal Society, 2010).

None of the technologies can currently be deployed at a significant scale due to uncertainties around their effectiveness, costs and climate impacts. However, the safest methods are generally considered to be the ones that alter the Earth's surface albedo by developing, for instance, reflecting roofs in human settlements or choosing certain high-albedo crops in agriculture. Such options are however relatively expensive and might take a significant period to roll out to be effective (The Royal Society, 2010). Theoretically, a more effective option in the short term would be the use of stratospheric aerosols, where different types of particles are released in the atmosphere with the purpose of scattering sunlight back into space. However, the wider impacts of this for example on ozone chemistry and cloud formation are very uncertain. Furthermore, researchers have found that there is a regional diversity among responses to this method of SRM, meaning that this method cannot be deployed to mitigate temperature impacts in all regions globally (Ricke et al., 2010). Other, even more effective methods exist, such as space-based reflectors, but carry with them even larger safety and cost implications.

5 Areas for future research

It is clear that there are significant gaps in the literature that can be used to inform discussions in on the implications of 1.5°C. It is expected that many more studies will be carried out to inform the IPCC special report in 2018.

- **Trade-offs between different mitigation options to meet 1.5°C.** The extended number of scenarios which will become available in the next two years could be a source of more insight. However, it is also probable that even at this stage, an extended analysis of the individual scenarios for 2°C aimed at identifying these trade-offs could be useful. These scenarios are available but such an analysis was beyond the scope of this project.
- **Implications of land use and biomaterial assumptions in scenarios on the potential for BECCS.** More insight could be gained on this from the 2°C scenarios and from previous analysis on land use (for example The Energy Report) but again was beyond the scope of this project.
- **Extent of impacts and adaptation options at 1.5°C.** Impacts will differ significantly between 1.5 and 2°C in certain areas such as **agriculture, forest ecosystems, and sea level rise** and while some research has been done on adaptation in the context of warming levels of 2°C and 4°C, 1.5°C should also be assessed and compared to 2°C. If the differences vary from a manageable and/or localised impact to a severe/global and/or irreversible impact, then it is highly likely that there are relevant, demonstrable differences in the adaptation requirements.
- **The adaptation needs of ecosystems and regions that have already been identified as highly vulnerable at 1.5°C.** From the existing, albeit limited literature on the issue of adaptation scales at different degrees of global temperature increase, it is evident that specific ecosystems and locations are particularly vulnerable (i.e. **high latitude, high altitude, low-lying, and tropical regions**). Studies on the different adaptation needs in these specific regions and ecosystems would illustrate the different adaptation options and the urgency of addressing them, where the evidence is not currently available.
- **Quantitative modelling of non-linear increases in impacts and costs as well as saturation of damages after 2°C.** While there is more literature on the scales of adaptation needed at 2 and 4°C, the point at which risks become non-linear could be studied in more detail. Furthermore, quantitative information on whether there are there likely to be nonlinear increases in impacts and costs, or conversely a saturation of damages after 2° or 3°C warming, is currently lacking.
- **Limits of human systems at different degrees of warming.** There are a few studies currently addressing the limits (in terms of global temperature increase) of adaptation in general and as much of this information pertains to natural systems, there is scope to expand the body of knowledge on the limits of human systems. This is one topic for which, as the IPCC admits, current evidence is scant (IPCC, 2014a). Similarly, more research could be done to find out if the "hard limits" of adaptation for species and human groups that have seemed to reach their adaptive can actually be improved.
- **The relationship between adaptation and migration (of specific species) and changing precipitation patterns at different levels of warming.** It is evident that the ability of certain species to migrate is impacted not only at 4°C but also 1.5 and 2°C. However, a more nuanced understanding of the exact species affected would provide a clearer picture of the necessary adaptation actions and the limits thereof. Also, it was found in the literature that heavy precipitation varies at 1.5 and 2°C but there is a lack of understanding of the adaptation needs under these circumstances. The relationship between changing precipitation patterns and adaptation needs at various degrees of global temperature increase could therefore be studied.
- **Costs of adaptation.** As suggested by UNEP and determined from the literature covered in this report, the adaptation community would benefit from additional empirical studies that address specific sectors or risks (in the context of varying degrees of global temperature change).

6 Annex

6.1 Detailed description carbon removal options

Negative emissions technology	Description	Benefits/opportunities	Challenges
Afforestation and reforestation[40]	Restoring cleared or damaged forests and planting new (carbon-dense) forests	Restoration of ecosystems potentially resulting in the increase of biodiversity and socioeconomic impacts	Carbon accounting methodology lacking; albedo effects on higher latitudes; vulnerability to future climate change (e.g. forest fires)
BECCS (others)[41]	Capturing CO_2 that is emitted from power generation or industrial processes with a biomass feedstock and storing it in geological reservoirs	Additional fuel or electricity production	Adapting CCS technologies to biomass combustion processes; quantification methods; public opposition; biomass pre-processing; matching biomass supply with storage
Direct air capture (DAC)[42]	Capturing carbon directly from the atmosphere using chemical sorbents in a scrubbing tower arrangement or 'passive' artificial trees	Use as feedstock for industrial processes or synthetic hydrocarbon fuels	Energy requirements; CO_2 sorbent improvement; water requirements and costs; development of full-scale systems
Agricultural soil carbon[43]	Adopting certain farming or grazing methods to increase the carbon content of soils and prevent them from entering the atmosphere	Improved SOC resulting in improved fertility and fertiliser efficiency; reduced (pollution from) runoff; flood and drought management	Unproven effectiveness of practices; effects on non-CO_2 GHGs not understood; soil carbon quantification
Biochar[44]	Converting biomass to charcoal with a long lifetime through pyrolisis or as a by-product of BECCS and storing it in soils for agricultural benefits	Increased soil health, fertility and retention of water and fertiliser; valuable co-products in production process (e.g. bio-oils)	Biochar stability in soils; Effects of biochar in different soils; effects of biochar on non-CO_2 GHGs in soils; slow pyrolysis process poorly understood

[40] Source: Canadell & Raupach (2008)
[41] Source: Koornneef et al. (2011); McGlashan et al. (2012)
[42] Source: Goeppert et al. (2012); McGlashan et al. (2012)
[43] Source: Stockmann et al. (2013); Powlson et al. (2011)
[44] Source: Stockmann et al. (2013); Powlson et al. (2011); Biederman & Harpole (2013); McGlashan et al. (2012)

Negative emissions technology	Description	Benefits/opportunities	Challenges
Ocean liming[45]	Adding lime or other metal/hydroxides to the ocean to convert dissolved CO_2 to bicarbonate and increase the uptake of carbon from the atmosphere	Local decrease of ocean acidification	Energy intensive rock grinding methods; ecological impacts not understood; calcination technologies should be improved; calcium transportation
Enhanced weathering[46]	Grinding up silicate rock and spreading the fine grains over land or ocean areas to accelerate the natural chemical reaction with atmospheric CO_2	Potentially increased soil pH and nutrients	Energy intensive rock grinding methods; ecological impacts not understood; ecological and geochemical feedbacks; quantification
Building with biomass[47]	Increasing the amount of wood used in construction where the absorbed carbon can be stored in long-term structures	Increased biomass residue from wood products value chain; bioenergy can be obtained at the end of lifecycle	Quantifiation methods and monitoring; ILUC
BECCS (ethanol and black liquor gasification)[48]	Capturing and storing the relatively pure stream of carbon that results from the fermentation process of bioethanol production and the paper and pulp industry	Environmental benefits; efficiency improvements in industrial processes and the bioenergy system	Capturing efficiency from the sugar mill fermentation process is low; quantification methods regarding LUC; black liquor gasification not well developed
Wetland habitat restoration[49]	Restoring damaged or disappeared carbon-dense wetlands such as peatlands and mangrove forests that can store carbon	Improved water quality and flood protection	Missing 'blue carbon' framework; monitoring of non-CO_2 GHGs; questionable permanence due to sea level rise
Magnesium cement	Replacing the carbonate in cement with a magnesium oxide that binds more atmospheric CO_2 than traditional cement when it hardens	Use of carbon-negative cement in a hard-to-abate sector; natural affinity for cellulose materials; greater compressive and tension strength	The demand for cement might be a limiting factor

[45] Source: Renforth et al. (2013); McGlashan et al. (2012)
[46] Source: Hartmann et al. (2013)
[47] Source: Gustavsson et al. (2010)
[48] Source: Moreira et al. (2016); Möllersten et al. (2003)
[49] Source: Parish et al. (2008); McLeod et al. (2011)

6.2 CDR cost and potential estimates

Table 6-1: Cost and potential estimates of the identified CDR options in order of potential (high-low). Data sources are similar to those in Annex 6.1.

Negative emissions technology	Min cost estimate ($/tCO2)	Max cost estimate ($/tCO2)	Min CDR potential (Gt pa)	Max CDR potential (Gt pa)
Afforestation and reforestation	65	108	4	12.1
BECCS (others)	59	138	3.7	12.1
Direct air capture	40	600	3.7	12.1
Agricultural soil carbon	-165	40	2.6	4.8
Biochar	51	386	2.6	4.8
Ocean liming	70	160	1	3
Enhanced weathering	20	130	0.7	3.7
Building with biomass	0	0	0.5	1
BECCS (ethanol fermentation and BLG)	25	45	0.3	0.5
Wetland habitat restoration	10	20	0.2	0.5
Magnesium cement	n.a.	n.a.	0.1	0.4

6.3 Adaptation options and pathways from the Thames Estuary 2100 project

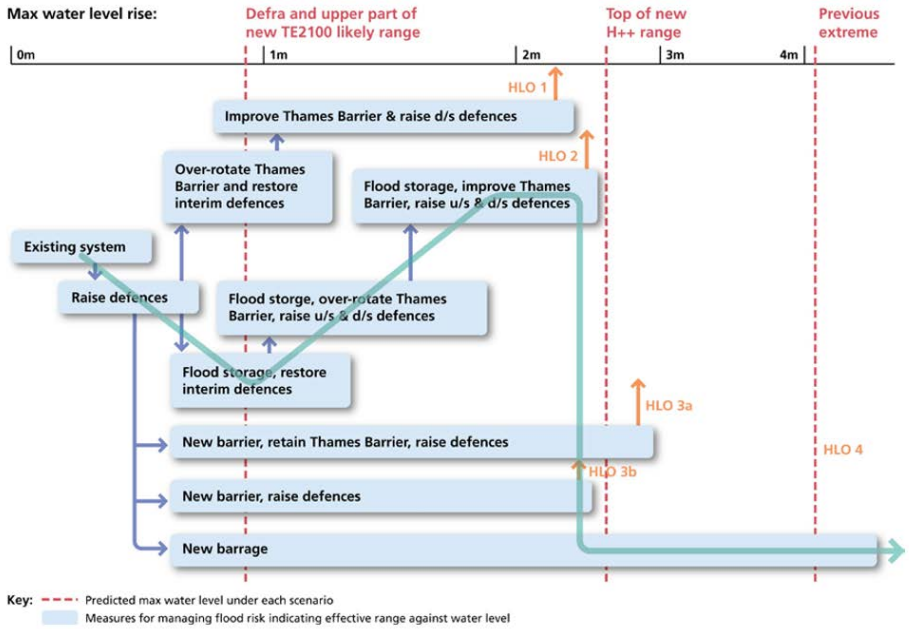

Figure 2. High-level adaptation options and pathways developed by TE2100 (on the y-axis) shown relative to threshold levels increase in extreme water level (on the x-axis). The blue line illustrates a possible 'route' where a decision maker would initially follow HLO 2 then switch to HLO4 if sea level was found to increase faster than predicted.

Figure 10: Adaptation options and pathways from the Thames Estuary 2100 project (Reeder and Ranger)

A illustration of the identified adaptation options and pathways for the Thames Estuary can be found in the Figure above. Along the scale of water level rise that ranges from 0 to 4m, scenarios, concrete measures, and a decision making route is depicted. From this, it is clear that the incremental adaptation option of raising defences would be sufficient for a less than 1m water level rise but that only a new barrage qualifies as a measure drastic enough to cope with a water level increase of 4m. Most of the other measures shown (e.g. restore interim defences, over-rotate Thames Barrier) would suffice but only up until a 3m water level rise at most.

6.4 Effectiveness of adaptation measures against sea level rise in Rotterdam's flood risk management approach

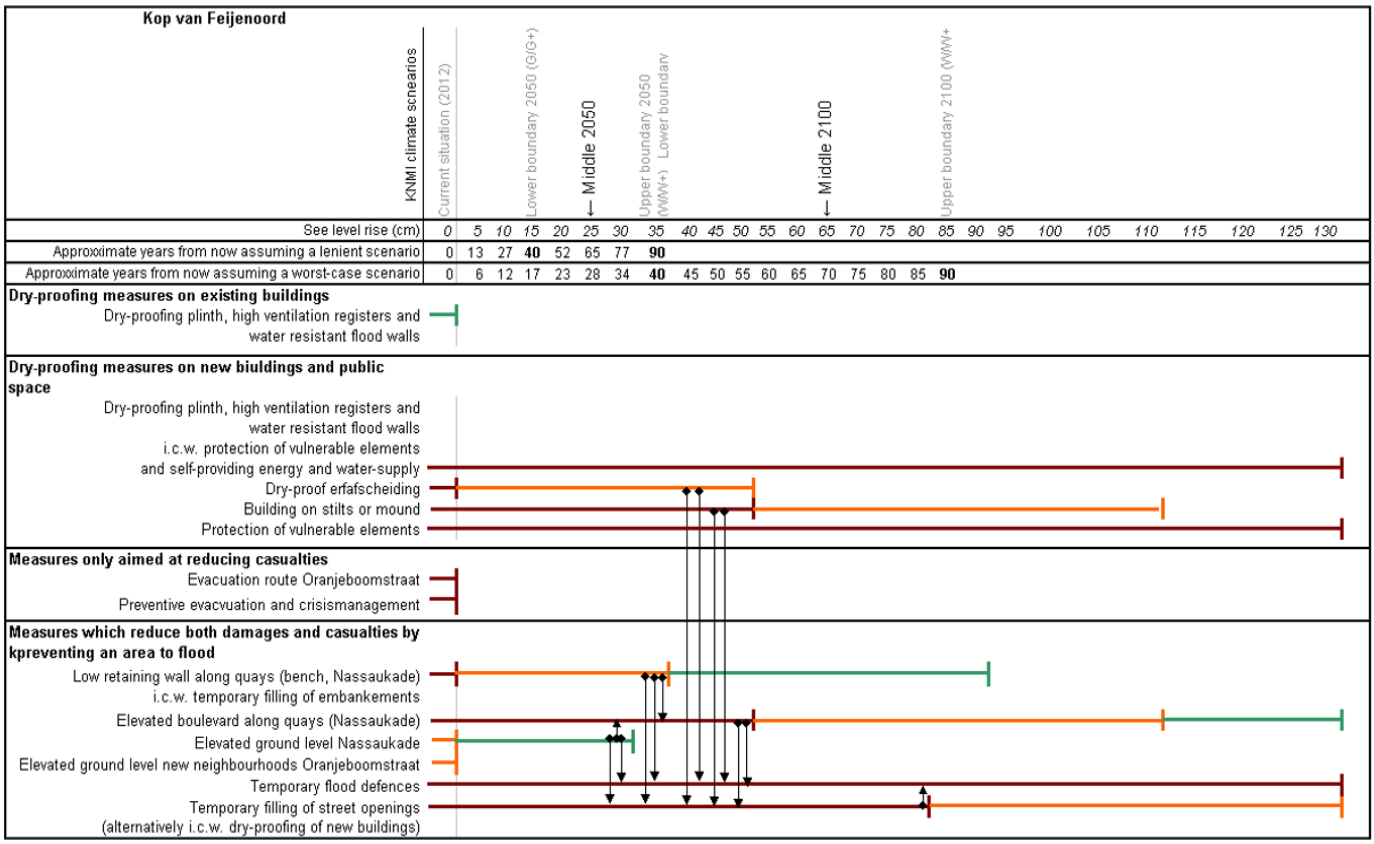

Figure 11: Effectiveness of adaptation measures (Stone, 2010)

The figure above provides an overview of the measures assessed in one of the districts studied in "Exploring adaptation pathways" (Stone, 2010) according to their ability to improve social disruption (red lines), reduce damage to new buildings (orange lines), and reduce damage to existing buildings and public spaces (green lines). For one of the districts studied, the strategies can be summarised as 1) focus on citizen safety, 2) prevention of flooding for the long term, 3) reactive prevention of flooding, 4) allow partial flooding of are, share responsibility, and 5) allow partial flooding of area, prevention of flooding in initial stage. In general, this particular resource presents a thorough overview of the key turning or tipping points for a specific case but also the possible adaptation pathways given the uncertainty about the increase in global temperature and sea level rise.

7 References

7.1 References for climate change impacts

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Why we are here

To stop the degradation of the planet's natural environment and to build a future in which humans live in harmony with nature.

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