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IPCC Reasons for Concern regarding climate change risks

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The Reasons for Concern (RFC) framework communicates scientific understanding about risks in relation to varying levels of climate change. The framework, now a cornerstone of the IPCC assessments, aggregates global risks into five categories as a function of global mean temperature change (GMT). We review the RFC's conceptual basis and the risk judgments made in the most recent IPCC report, confirming those judgments in most cases in the light of more recent literature and identifying their limitations. We point to extensions of the framework that offer complementary climate change metrics to GMT and better account for possible changes in social and ecological system vulnerability. Further research should systematically evaluate risks under alternative scenarios of future climatic and societal conditions.

The RFC framework was developed in the IPCC Third Assessment Report (TAR) to inform discussions relevant to implementation of Article 2 of the UN Framework Convention on Climate Change (UNFCCC). Article 2 presents the Convention's long-term objective of avoiding "dangerous anthropogenic interference with the climate system." The RFC framework and the associated "Burning Embers" diagram illustrating authors' risk judgments have since been widely discussed and used to inform policy decisions. For example, they informed a recent dialog between Parties to the UNFCCC and experts[1, 2] on the adequacy of the long-term goal of avoiding a warming of 2°C relative to pre-industrial, contributing to a strengthening of that goal in the recent Paris Agreement[3]. Elaborations of the Burning Embers have been used to represent climate impacts and risks at the regional level[4] and for specific systems (e.g., ocean systems[5]).

This article reviews the conceptual basis for the RFCs (Box 1) and offers an explanation of the reasoning behind associated risk judgments that is complementary to, but goes beyond, the treatment in the IPCC Fifth Assessment Report[6]. We focus explicitly on the evidence base for transitions from one risk level to the next, incorporate post-AR5 literature in those discussions, and offer thoughts about limitations of the subjective judgments behind each RFC. We also improved the synthesis of RFC-related material across AR5, and in turn provide both a clearer connection to evidence from AR5 that supports the RFC judgments, as well as a comparison of the RFCs to similar approaches employing metrics other than GMT for characterizing risk. Perhaps most importantly, we consider improvements in the framework, particularly emphasizing the dynamic nature of exposure and vulnerability, two key components of risk not sufficiently covered in the current approach.

TEXT BOX 1: Conceptual Basis

The Reasons for Concern (RFCs) reported in AR5 are:

1. *risks to unique and threatened systems (indicated by RFC1 below);*
2. *risks associated with extreme weather events (RFC2);*
3. *risks associated with the distribution of impacts (RFC3);*
4. *risks associated with global aggregate impacts (RFC4); and*
5. *risks associated with large-scale singular events (RFC5).*

Types of risk included in each category are discussed in the next section. The categories share an emphasis on going beyond changes in biophysical systems to possible consequences for society and ecosystems, including their interdependencies (henceforth "socio-ecological systems"). *Risk* is the potential for negative consequences, whereas *impacts* are the manifestation of that potential[7, 8]. Climate-related risk depends on the probability of hazardous events or trends and on the consequences manifested when a physical, climate-related hazard interacts with the exposure and vulnerability of society and ecosystems. *Hazards* related to climate change include altered occurrence of extreme events, trends in precipitation or temperature, sea level rise, ocean acidification, deoxygenation or ocean circulation changes. *Exposure* is the presence of people, ecosystems, or assets in places and settings that could be adversely affected, and *vulnerability* is their susceptibility and predisposition to harm[9, 10]. These definitions follow the choices laid out in AR5, although alternatives can be found in the literature[11].

The process of making judgments about levels of risk for each RFC (Supplementary Text 1) was underpinned by the identification of “key risks”. Key risks reflect potentially severe adverse consequences for socio-ecological systems that could be used to inform the interpretation of “dangerous” in the UNFCCC Article 2 objective. Criteria for identifying key risks include[6, 12, 13].

(1) high probability of significant risk materializing, taking into account its timing;
(2) large magnitude of associated consequences, taking into account the importance of affected systems;
(3) persistent vulnerability or exposure contributing to risks, or the irreversibility, at least on human timescales, of associated impacts; and
(4) limited potential to reduce risks through adaptation or mitigation.

AR5 authors drew on these criteria to characterize climate-related risk for each RFC as a function of GMT as Undetectable, Moderate, High, or Very High. The transition from Undetectable to Moderate is defined by the GMT at which there is at least *medium confidence* that impacts associated with a given RFC are both detectable and attributable to climate change (based on the analysis in ref. 14, 18.6.4[*]), while also accounting for the magnitude of the risk and the other criteria noted above. The transition from Moderate to High risk is assigned to the GMT at which associated impacts become severe and widespread. The transition from High to Very High is set at the GMT at which risk is high according to all criteria and in particular the ability to adapt is limited. In each case, variations in regional climate outcomes for a given GMT are accounted for and the likelihood of the associated hazardous event or trend is judged.

Defining the risk levels this way enables integration within each RFC across different but related risks and many different types of evidence. The scale is inherently nonlinear and qualitative, even if quantified evidence enters the judgments.

REASONS FOR CONCERN

Risk judgments for each RFC are based on the key risk criteria (Box 1) but the relative importance of each varies across RFCs depending on the quality and quantity of information available in the literature.

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[*] To be more explicit about the source of information in chapters of IPCC reports, we provide specific sub-sections or figure/table numbers following the citation number.

It is also not possible to rely on a single quantitative metric of risk for a given RFC since each one aggregates over a number of different risks. An enhanced Burning Embers diagram (Fig. 1) summarizes the evidence, indicating both individual risks that played important roles in identifying particular risk transitions, as well as overarching key risks relevant in broader terms to each RFC (Table 1). These overarching key risk categories were developed in AR5[6] from risks identified as being of high concern by chapter authors from across IPCC Working Group (WG) II (Supplementary Text 1). Unless otherwise specified, we refer to GMT relative to pre-industrial (1850-1900). Note that conversions from units used in AR5 can give the appearance of overly precise temperature levels (Supplementary Text 2).

RFC1: Risks to unique and threatened systems

Unique and threatened systems encompass ecological and human systems that (1) have restricted geographic ranges that are constrained by climate-related conditions, and (2) have high endemism or other distinctive properties. Many of these systems also face exceptional human-driven threats. Examples include tropical glacier systems, coral reefs, mangrove ecosystems, biodiversity hotspots[15], and unique indigenous communities[16].

AR5 located the transition from Undetectable to Moderate risk below recent temperatures based on the detection and attribution (with at least *medium confidence*) of impacts on Arctic, mountain, and warm-water coral reef systems (ref. 14, 18.6.4), with indirect support from impacts on other systems (Supplementary Text 3.1). In the Arctic, impacts include the observed decline in sea ice extent[17], warming and thawing of permafrost in Alaska and associated land-sliding[14, 18, 19], substantial changes in ecosystems and ecological dynamics, including signs of broad-scale boreal forest encroachment into tundra[20, 21, 22], and livelihood impacts on indigenous Arctic peoples[14]. In mountain systems, there is evidence of shrinking or receding glaciers from all continents[14]. There is also *high confidence* that climate change has contributed to widespread and frequent coral bleaching and mortality due to high temperatures[23, 24, 25, 26].

A transition from Moderate to High risk occurs over the range ~1.1-1.6 °C above pre-industrial. In broad terms, this transition is placed halfway between the Undetectable-to-Moderate transition and High-to-Very High transition (discussed next) to reflect the generally increasing risks over this range. However, specific projected impacts for Arctic and coral reef systems also informed the judgment (Supplementary Text 3.2).

A transition to Very High risk is located around 2.6°C to reflect very high risks and limited ability to adapt for a wide range of unique and threatened ecosystems[27, 28] (Supplementary Text 3.3.1). Substantial impacts to unique and threatened systems are projected at or even below this level of warming[29, 30]. These systems include both major ecoregions and biodiversity hotspots containing unique (including endemic) and threatened systems. They include the Cerrado in South America, the Fynbos and Succulent Karoo ecoregions in South Africa, Australian rainforest ecoregions, the Caribbean, Indo-Burma, Mediterranean Basin, Southwest Australia, and the Tropical Andes[30, 31, 32]. Risks to Arctic, coral reef, and mountain systems also escalate above this level of warming (Supplementary Text 3.3.2). For example, large-scale coral reef dissolution may occur if CO_2 concentrations reach approximately 560 ppm due to the combined effects of warming and ocean acidification (ref. 33, 5.4.2.4; ref. 25), consistent with a warming of approximately 2.5°C (ref. 34, Fig. 3 and Table 2).

More comprehensive impact assessments are needed that consider more fully the human dimensions of impacts on unique and threatened systems. Most projections of impacts on species and ecosystems fail to consider how adaptation may ameliorate or exacerbate existing pressures and threats and introduce new ones[35] (Supplementary Text 3.3.3; see Box 2 for general description of adaptation level assumed in RFCs). Also, whether species will be able adapt or move fast enough to keep up with their changing environments will be crucial to the resilience of ecological systems[36] but remains poorly studied[37].

RFC2: Risks associated with extreme weather events

RFC2 encompasses risk to human health, livelihoods, assets, and ecosystems from extremes such as heat waves, heavy rain, drought and associated wildfires, and coastal flooding.

The transition from Undetectable to Moderate risk is located at recent temperatures based primarily on evidence for the detection and attribution of impacts of extreme events on coral reefs and human health (Supplementary Text 4.1). Bleaching of warm-water corals has resulted from periods of elevated near-surface ocean temperature to levels attributed to climate change (ref. 38; ref. 14, 18.6.4, Table 18-10; ref. 6, 19.6.3.2). For human health impacts, there has been detection and attribution of mortality impacts of temperature extremes in some regions (ref. 39, 11.4.1). Additional support for this transition comes from the detection and attribution of extreme heat and precipitation events, including post-AR5 analyses at the global scale[40], along with the widespread occurrence of high vulnerability and exposure and abnormal levels of mortality in some events[41].

The transition to High risk is located at ~1.6°C, relying primarily on projections of large, near-term changes in the magnitude and likelihood of extremes of temperature and precipitation. The choice is somewhat subjective due to the paucity of literature projecting the impacts of changes in heat extremes. By about 2035 (during which time the increase in model- and scenario- averaged GMT remains below ~1.6°C), 25-30% of daily maximum temperatures are projected to exceed the historical (1961-1990) 90th percentile value (ref. 42, Fig. 11-17). Duration, intensity and spatial extent of heat waves and warm spells also increase in the near term. We chose 2035 as a benchmark for the transition to high risk because the potential impacts from changes in temperature extremes are large and AR5 indicates such changes are likely[42]. Furthermore, there is high confidence in projected mean changes through 2035 because they are not strongly dependent on future emissions. In addition, on average, the frequency and intensity of heavy precipitation events over land will likely increase over much of the world (Supplementary Text 4.2). A reduction in return period for historical once-in-20-yr precipitation events globally (land only) to about once-in-14-yr or less by 2046-65 is also expected[43].

A key limitation is that changing exposure has been quantified for very few types of events, e.g., exposure to tropical cyclones[44, 45] or heat waves[46, 47], and quantification of future vulnerability is also rare[4, 48, 49]. Lower mean age, greater wealth, and increased penetration of air conditioning could ameliorate risk. Recent experience in France[50] and Bangladesh (ref. 43, 9.2.5) provides evidence for the potential for reductions in vulnerability in both developed and developing countries. In contrast, risks could increase in the future even if the temperature change remains moderate, since exposure to climate-influenced hazards is increasing significantly in various world regions[48], particularly in Asia and Africa due to population-growth, urbanization[51, 52], and migration.

RFC3: Risks associated with the uneven distribution of impacts

This category of risk reflects climate change impacts that disproportionately affect particular groups due to uneven distribution of physical climate change hazards, exposure or vulnerability. Unevenness can be with respect to geographic location, income and wealth, gender, age, or other physical and socioeconomic characteristics.

The transition from Undetectable to Moderate risk is located at recent temperatures based primarily on the detection and attribution with at least medium confidence of negative impacts on wheat yields in Europe and South Asia (ref. 14, Table 18.9) and evidence of negative agricultural impacts in other regions as well (ref. 53, Figs. 7.2, 7.7; ref. 54; Supplementary Text 5.1). Some positive impacts on crop yield have also been detected, for example in Northern Europe and South America (ref. 14, Table 18.9). AR5 authors took yield impacts as an early warning sign of attributable risk to food security[6].

The transition to High risk occurs between ~1.6 and ~2.6°C based on risks of increased water stress and reductions in crop production in some regions (Supplementary Text 5.2). Without adaptation, losses in production of wheat, rice and maize are expected by 2.6 °C of local warming (and therefore typically a lower level of global warming) although individual locations may benefit[53, 55]. Projections of yield loss are greatest in low latitudes and tropical regions such as Africa, S. Asia and Central and S. America[53, 55, 56, 57]. Substantial decreases in water resources are projected for warming of 2.3°C[58, 59].

A transition to Very High risk occurs around 4.6°C based primarily on projected large impacts on crop yields and water resources in many regions combined with limited scope for agricultural adaptation[53, 55, 57, 58, 59], although other risks contribute (Supplementary Text 5.3). Poorer populations in less developed countries would be at highest risk of malnutrition, for example in sub-Saharan Africa[60] where food security is projected to be at risk even under high adaptation levels (ref. 61, 22.5). .

A principal limitation to the judgments for this RFC is the sparseness of literature on impacts that can be linked to levels of GMT in sectors beyond food and water (such as health, energy, civil conflict, urban areas, and migration[62, 63]) that also have distributional consequences, especially for the poor[64] (Supplemental Text 5.4). In addition, the food and water literature focuses primarily on biophysical impacts (such as crop yields or water supply) as opposed to societal impacts (such as food and water security). The agronomic limits to adaptation considered in the judgment of Very High Risk do not account for additional means of offsetting yield changes[65] such as changes in cropland and pasture area, reductions in food waste[66, 67], and changes in diet[68] or international trade. Biophysical impact studies are also subject to substantial uncertainties, including the strength of the CO_2 fertilization effect on crop yields[53], and the yield effects of extreme events, neither well accounted for (Supplementary Text 5.4).

RFC4: Risks associated with global aggregate impacts

This category of risk reflects impacts to socio-ecological systems that can be aggregated globally according to a single metric such as lives affected, monetary damage, number of species at risk of extinction, or degradation and loss of a number of ecosystems at a global scale. Ecosystem degradation may be caused by wholescale transformation of biomes, by large scale extirpation of species induced by climatic range loss, and by the disruption of ecosystem functioning as interacting species respond differently to climate change[29].

AR5 concluded that global aggregate impacts on socio-ecological systems by any of the metrics listed above have not yet been detected and attributed to climate change with sufficient confidence to locate the transition from Undetectable to Moderate risk at recent temperatures[14] (Supplementary Text 6.1).

A Moderate risk level occurs at warming of ~1.6-2.6°C based on projected impacts to biodiversity and the global economy (and therefore a transition from Undetectable to Moderate risk between current temperatures and ~1.6°C). A global assessment of 16,857 species of all birds, amphibians and corals found that with approximately 2°C of warming above preindustrial (A1B, 2050s), 24-50% of birds, 22-44% of amphibians and 15-32% of corals were at increased risk of extinction (Supplementary Text 6.2.1) due to their vulnerability to climate change[27]. Other studies found increasing extinction risks with warming and project range losses exceeding 50%[69] for large fractions of species globally at 2°C warming (Supplementary Text 6.2.2). Estimates of global economic damages transition from generally small, negative projected impacts around 1°C warming[70] to central estimates of impacts ranging from 0 to 3% of global Gross Domestic Product for levels of warming between 1.9 and 3.0°C (Supplementary Text 6.2.3).

The transition to High risk around 3.6°C reflects an increase in the magnitude and likelihood of extensive loss of biodiversity (including losses in range, equating to local extirpations) and concomitant loss of ecosystem services (Supplementary Text 6.3). There are too few studies of aggregate economic damages to provide support for the judgment of risks above 3°C.

Limitations of the judgments for this RFC include the limited number of studies that assess global aggregate economic impacts that can be associated with specific levels of warming. In addition, global estimates of economic damages are incomplete, generally inadequately represent the possibility of abrupt and irreversible changes, ignore some impacts that are difficult to monetize, and depend in part on value-based judgments that can mask differential impacts through space and time[71] (Supplementary Text 6.4). Finally, assessments of impacts on ecosystems insufficiently consider how biotic interactions between species may be disrupted by climatic change[72].

RFC 5: Risks associated with large-scale singular events

Large-scale singular events (sometimes called “tipping points”, or critical thresholds) are relatively large, abrupt and sometimes irreversible changes in physical, ecological, or social systems in response to smooth variations in driving forces (accompanied by natural variability)[73, 74]. AR5 focused on two types of such events in assessing this risk: disintegration of the Greenland and West Antarctic ice sheets (GIS and WAIS, respectively) leading to a large and rapid sea level rise and major regime shifts in ecosystems such as degradation of coral reef and Arctic systems. In each case, there is *low confidence* in the precise temperature changes at which thresholds might exist for these phenomena (ref. 6, 19.6.3.6; ref. 75, 12.4.5, 12.5.5; ref. 76, 13.4). For coral reefs, the distinction between the “regime shift” criterion here and the systematic degradation indicated under RFC1 resides in the likelihood of abrupt change. While the long term outcome for coral reefs under each of the two categories of risk may be similar, RFC5 is concerned with a rapid undermining of system function (where “rapid” and “abrupt” are relative terms; see discussion below and Supplementary Text 7.2).

The transition from Undetectable to Moderate risk between ~0.6 and ~1.6°C warming is based on potential regime shifts in the Arctic and in coral reef systems. Impacts on the Arctic and on warm water coral reef systems are already observed (see RFC1), but for RFC5, the detection and attribution criterion applies to a large and sudden change. There is robust evidence of early warning signals that a biophysical regime shift already may be underway in Arctic ecosystems, including impacts on human livelihoods (ref. 14, 18.6.4), and observed increases in mass coral bleaching are considered to be a strong warning signal for the irreversible loss of an entire biome (ref. 14, 18.6.4).

The transition to High risk over the ~1.6-4.0^{o}C warming range (slightly revised from AR5) is based on ice sheet responses and the resulting sea level rise. The warming level associated with eventual, near-complete loss of the Greenland ice sheet is greater than about 1°C (*low confidence*) but less than about 4°C (*medium confidence*) (ref. 77, based on ref. 78, 5.8, and ref. 76, 13.4, 13.5). The difference between the risk range and the ice sheet loss range arises because the risk range implicitly incorporates a quantification of the implications of the qualitative confidence levels presented by IPCC WGI[77]. Within this range, a more rapid increase in risk is judged to occur as temperature rises between ~1.6°C and ~2.6°C, reflecting additional risk of a very large sea level rise due to ice loss from both ice sheets as occurred during the Last Interglacial (Supplementary Text 7.1), when GMT was no more than 2°C warmer than preindustrial levels[79].

Due to the large uncertainty in *timing* of ice sheet loss (which affects the probability of it occurring sufficiently slowly to allow effective adaptation, e.g. over a millennium, as well as the probability that action during the next centuries may reduce the warming sufficiently early to limit the melting), RFC5 is not judged to attain Very High risk in the temperature range below ~5.6°C, the maximum warming considered in Figure 1.

Improved prognostic modeling of continental ice sheets is a necessity for significantly sharpening this risk assessment. Post-AR5 literature on such models[80, 81, 82, 83], observations[84], and additional lines of evidence[85] indicate the possibility of large, very fast (decade-to-century scale) responses providing further support for a tipping point (Supplementary Text 7.2).

ADDITIONAL METRICS

The RFCs and associated Burning Embers diagram use GMT rise as the proxy indicator for climate-related hazards. This approach has the benefit of simplifying the communication of risk. However, there are important climate-related hazards that are inadequately captured by the temperature indicator alone. We discuss three metrics that were incorporated in complementary ember diagrams in the AR5 Synthesis Report[81] as illustrations of ways in which the analysis of key risks could be extended (Fig. 2) and informed a recent UNFCCC policy dialog on long-term targets[1].

Rate of climate change

For many socio-ecological systems the *rate* of climate change determines the success or failure to adapt. Theory as well as paleo-ecological and paleo-climatic data indicate that adaptation of organisms to climate change through geographic movement has limits (Supplementary Text 8.1). The 'rate of climate change' ember assigns risk levels as a function of the rate of climate change during the 21st century, translated into a velocity at which climate zones move across the landscape. A range of species movement rates was estimated for a number of groups of species by authors of ref. 86, using data from fossil records, dispersal studies, and models of species movement (see listing of the primary sources in the caption of fig 4.5 in ref. 86).

The relationship between 'climate velocity' (the rate of movement of climate zones) and the rate of GMT change depends on topography (Supplementary Text 8.2). Thus, at a given rate of GMT change, risks to species vary depending on location. In addition, there are geographical barriers to species-range shifts, such as coasts, mountaintops, or habitat fragmentation breaking connections to cooler areas[87]. Rate of change considerations supplement amount of change rather than replacing it; for instance there are situations (such as mountaintops) where potentially fast-moving species have nowhere to go.

Authors of the IPCC Synthesis Report compared the estimated rates of species movement with estimates of the climate velocity during past[88, 89, 90] and projected future[91, 92, 93] climate change. Since trees and herbaceous plants form the productive basis of most terrestrial ecosystems, and flat landscapes occupy a large part of the land surface, moderate risk was assigned to commence when the climate velocity exceeded the lower end of the range of observed movement rates (trees in flat landscapes) and end at the median movement rate for rodents and primates. The risk was assessed as High beginning where the movement rate exceeded the upper end of the range for trees and ending at the upper limit for herbs and rodents, beyond the upper limit for primates, and at the median for freshwater molluscs. Substantial biotic community and ecosystem disruption over large areas could be anticipated in this range. Very High risks were assigned when the median movement rate was exceeded in all assessed groups (which included carnivores and split-hoofed animals in addition to the groups described above). The impact on species assemblages and thus ecosystem function would, with high likelihood, be large, persistent and difficult to adapt to for this rate of climate change.

Anthropogenic CO_2 causing ocean acidification

This ember diagram depicts the increasing risk for the well-being and survival of marine organisms due to accumulating CO_2 in seawater causing ocean acidification (OA). Since pre-industrial times, atmospheric CO_2 levels have risen from 280 to presently about 400 ppm, paralleled by a drop in ocean pH of approximately 0.1 units[94]. Anthropogenic OA occurs on a background of natural temporal and spatial variability of pH, CO_2, and aragonite and calcite saturation levels, for example in upwelling areas, where oxygen-deficient and CO_2-enriched deep water is brought to the surface.

Risks of harmful ecosystem effects of OA are considered Moderate around CO2 levels of 380 ppm. This judgment is based on observed declines in calcification of foraminifera and pteropods attributed to anthropogenic OA[95]. In addition, negative impacts on pteropods and oyster cultures along the west coast of North America have been attributed to upwelling of acidified water shifted closer to shore combined with anthropogenic acidification[96].

Under OA only, warming excluded, the transition to High risk occurs at a CO_2 level of about 500 ppm, beyond which studies reflect onset of significantly negative effects and High risk in 20 to 50 % of extant calcifying taxa (corals, echinoderms, molluscs). The negative effects comprise declines in physiological performance, indicated by changes in characteristics such as standard metabolic rate, aerobic scope, growth, morphology, calcification, acid-base regulation, immune response, fertilization, sperm motility, developmental time, changes in gene expression patterns, behavioral changes and abundance[81, 95, 97]. Risks are judged to be Very High with limited capability to adapt beyond about 700 ppm, based on a rising percentage of the calcifying taxa being negatively affected. For the calcifying invertebrate taxa, these conclusions are confirmed by observations at natural analogues (volcanic CO_2 seeps, upwelling systems) and by the similarity of sensitivity distributions among taxa during paleo-periods[97].

Current knowledge indicates that the combined pressures of ocean warming extremes and acidification lead to a shift in sensitivity thresholds to lower CO_2 concentrations, as seen in corals and crustaceans[95]. For corals this comes with the risk that OA will increasingly contribute to the reduction in areal extent of coral ecosystems, already underway as a result of interacting stressors (extreme events, increased predation, bleaching[98]). Knowledge on the long-term persistence of acidification impacts presently relies on findings in the paleo-records. Therefore, evidence that changes in extant ecosystems will persist is limited, especially for fishes. Additionally, knowledge is scarce on compensatory mechanisms and their capacity and associated limits to long-term evolutionary adaptation under ocean warming and acidification.

Sea-level rise

While sea level change is driven by temperature change, the relationship is uncertain and involves delays, so that coastal risks are not directly and linearly related to temperature. Accounting for variability in sea level is also important, because a change in average sea level can disproportionately increase the likelihood of water levels that exceed the coping capacity of socio-ecological systems.

For this ember, the detection and attribution of impacts on society or ecosystems was not used for judging risk levels due to the difficulty of attributing such impacts. Impact attribution is difficult because observed increases in impacts are overwhelmingly due to population and socio-economic changes (ref. 33, 5.4.4) or non-climatic, anthropogenic stress (ref. 33, 5.2), and also influenced by historical investments in coastal protection for which data are lacking. Therefore attribution of sea level rise itself was used.

The transition to Moderate risk starts before the recent period, given that global sea level rise over the past several decades is attributable to climate change (ref. 17, 10.4.3) and increases the risk of coastal flooding, soil salinization, and saltwater intrusion. The risk is estimated to reach the Moderate level at about 10 cm above the 1986-2005 level, which authors of the Synthesis Report estimated to be the level at which increased flood risks become significant and require changes in coastal management.

At this level, the transition to High risks starts and risks are expected to become High at around 100 cm above the same reference level. High risk is defined for this RFC as the risk of losses that, in the absence of adaptation, would reach levels that are at least an order of magnitude higher than today, and cause coastal ecosystem losses that are visible and widespread. High risks may occur before the 100 cm level is reached, since some evidence suggests the risk would increase rapidly even before this value (Supplementary Text 8.3). For example, for sea level rise of 40-130 cm, 1.3 to 2.9% of the world population could be flooded every year[99].

The transition to Very High risk is expected over the range of 100 – 200 cm above the 1986-2005 level. This transition starts where adaptation limits for ecosystems and human systems are reached in many places. Limited evidence suggests that only a small number of adaptation options are available for specific coastal areas if sea level exceeds 100 cm at the end of the century (ref. 33, 5.5.6). There are also biophysical limits to the adaptation of ecosystems and natural areas, which vary greatly depending on the rate of change, location and other stressors (ref. 33, 5.2).

TEXT BOX 2: RFCS AND THE VULNERABILITY OF SOCIO-ECOLOGICAL SYSTEMS

The Burning Embers diagram does not explicitly account for differences in the exposure and vulnerability of socio-ecological systems over time, including those changes arising from adaptation. In AR5, judgments about risks reflected in the Burning Embers diagram were based on the varied assumptions in the underlying literature about future societal conditions that would affect vulnerability and exposure, including income and poverty, technology, demography, institutions, and other factors. These assumptions range from complete disregard of future societal conditions, to central or middle-of-the-road expectations, to differing societal futures across studies which were then aggregated by IPCC authors. Only autonomous adaptation (i.e., adaptation that does not require coordinated planning) is reflected in the impacts used to make risk judgments.

At the same time, a growing number of examples in the impact literature demonstrate the dependence of impacts on societal conditions, especially the differential vulnerability of people and ecosystems exposed[100] (Supplementary Text 9). AR5 concluded with *high confidence* that risks vary substantially across plausible alternative development pathways, and that both climate change and societal development are important to understanding possible future risks (ref. 6, 19.6.2.2). AR5 also introduced an alternative version of a burning ember with an additional axis for exposure and vulnerability. However, the figure was conceptual, illustrating how risks for a particular RFC might vary by societal conditions as well as by the level of climate change.

Here we illustrate how a vulnerability-dependent version of a burning ember diagram could be developed, drawing on impact studies[101, 102, 103] that project the number of people at risk of hunger under alternative assumptions about future vulnerability and climate change. There is substantial uncertainty about estimates of hunger risk for any given societal and climate future, due to, for example, uncertainties in crop modeling, the effects of CO_2 fertilization, economic models of food consumption, and factors affecting access to food. This uncertainty precludes judgments about the *absolute* level of risk for any given climate and vulnerability outcome, and therefore the production of a burning-ember style diagram. However, judgments about changes in risk if climate or vulnerability varies from a given outcome in the future are possible. Fig. 3a shows changes in the number of people at risk of hunger due to climate change relative to the number at risk for a particular set of conditions used as a benchmark (medium vulnerability, and about 2.6 °C of GMT). The general pattern confirms that lower vulnerability development pathways minimize risk, while increases in level of future warming result in a larger risk. Exceptions occur in studies in which relatively large CO_2 concentration increases improve access to food in scenarios with a further warming of 3°C and high vulnerability (figure 3). As additional literature accumulates, it may be possible to use the type of approach illustrated here to produce a fuller assessment of vulnerability-dependent RFCs, including explicit treatment of adaptation (Supplementary Text 10.1).

A complementary view of future risks is provided by Figure 3b, which shows that the total number of people at risk of hunger is much more sensitive to the development pathway than to the level of climate change.

DISCUSSION AND FUTURE DIRECTIONS

The RFCs were designed to categorize and depict increasing risks from warming of the climate system and thereby inform (but not determine) judgments about danger from climate change. Within the current limits of the framework, the RFC assessment provides a number of insights relevant to Article 2. First, continued high emissions would lead to High or Very High risk of severe, widespread, and in some cases irreversible impacts globally within this century. Risks to unique and threatened systems, among the most sensitive natural and human systems, increase most quickly with additional warming. Risks associated with global aggregate impacts increase most slowly.

In addition, the RFCs can communicate the specific nature of current and future risks. For RFCs 1-3, risks from anthropogenic climate change are currently Moderate, based primarily on detection and attribution of associated impacts on Arctic ecosystems and coral reefs (RFC1); extreme heat and precipitation events and their impacts on human health and coral reefs (RFC2); and impacts on crop production in some regions (RFC3). In terms of future risk, at 2°C above preindustrial, High risks are based on increasing risks to Arctic systems and coral reefs, as well as increasing species extinction risks (RFC 1), and projected increasing magnitude and likelihood of extreme weather events (RFC 2). Moderate-to-High risks are based on projections of increasing risks to crop production and water resources (RFC 3), and to the risks associated with ice sheet disintegration and very large sea level rise (RFC5). Limiting warming to 1.5°C would reduce the risks for RFCs 1 and 2 from High to the Moderate-to-High transition.

At 3°C above pre-industrial, risks are at least High, or nearly so, for all RFCs. In addition to the basis for High risk judgments that apply to 2°C, additional factors include a higher risk of species extinction (RFCs 1 and 4), limited ability to adapt to impacts on coral reefs and Arctic systems (leading to Very High risk for RFC 1), and the higher risk of very large sea level rise associated with eventual ice sheet loss (RFC 5).

Judgments, choices, and decisions informed by the RFCs should take into account key challenges faced by this framework. First, the assessment of risk levels across the RFCs has been based primarily on impacts to physical and ecological systems, given a literature on consequences for society that is either thin or difficult to relate to specific levels of climate change and future societal conditions. Extensions to the framework to explicitly account for the vulnerability of socio-ecological systems (Fig. 3) offer a means of incorporating new knowledge of this type.

Second, aggregating risks across affected sectors and systems necessarily suppresses the detail and variation of associated risks. Communicating the specific key risks informing the RFC assessment is important to prevent misinterpretation of risk judgments and to better inform discussion of response options. It may also be possible to extend the burning embers diagram to better represent individual risks (Supplementary Fig. 2).

Third, the perceived seriousness of risks will vary by stakeholder and among authors carrying out the assessment. Some may value the existence of species and ecosystems – beyond their role in providing ecosystem services – more highly than others, and therefore perceive particular RFCs (such as RFC1) as more important. Others may prioritize aggregate damages or may consider equity and distributional impacts as paramount.

Finally, additional dimensions of climate change beyond GMT, such as the rate of climate change, ocean acidification, and sea-level rise, can be important metrics of hazard, sometimes more directly linked to impacts than global mean temperature.

These caveats, and the review of the RFCs as a whole, suggest a number of research needs. More systematic evaluation of key risks and impacts at varying levels of climate change is needed to inform a more complete, specific and quantitative understanding of the differential impacts across possible climate futures for a larger number of key risks. A deeper literature of this kind would avoid imbalances in the role of specific risks, such as the large role of agricultural risks in RFC3 and the role of risks to coral reefs across several RFCs. It would also improve understanding of the uncertainty in the level of GMT associated with risk transitions. There is an equally strong need for research on socioeconomic dimensions of risks, to improve on the current common use of physical climate system outcomes as a proxy for societal impacts. In particular, more work is needed on how alternative societal development pathways, implying different levels of vulnerability to climate change and possibilities for adaptation, affect the risks of any given level of warming.

Beyond improving the research base, modifications to or extensions of the RFC framework itself may be called for, especially as new evidence accumulates, while also recognizing the value of simplicity in communicating risk. Efforts should be continued to make the methods for producing the RFCs and the associated burning embers diagram more systematic, transparent and comparable across generations. Improvements in these aspects of the RFCs will also make them more effective tools for informing decisions related to avoiding dangerous climate change.

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Author Contributions

B.C.O. and M.O. led the design of the study. B.C.O. led, and M.O. contributed to, the coordination of the paper. M.O., R.W., S.H., R.E.K., B.C.O., H.O.P., and B.S. led the drafting of subsections of the paper. B.C.O., P.M., R.L., K.J.M., M.M., and K.T. led the development of figures. All authors contributed to writing and/or editing the paper.

TABLES

Table 1: Eight overarching key risks representative of the range of key risks identified by WG II authors as of highest concern to their chapters (ref. 6, 19.6.2.1, based on Table 19-4). These risks inform judgments regarding the indicated RFCs.

		Reason for Concern				
Overarching Key Risk	**Description**	**1**	**2**	**3**	**4**	**5**
i	Risk of death, injury, ill-health, or disrupted livelihoods in low-lying coastal zones and small island developing states and other small islands, due to storm surges, coastal flooding, and sea level rise.	✓	✓	✓	✓	✓
ii	Risk of severe ill-health and disrupted livelihoods for large urban populations due to inland flooding in some regions.		✓	✓		
iii	Systemic risks due to extreme weather events leading to breakdown of infrastructure networks and critical services such as electricity, water supply, and health and emergency services.		✓	✓	✓	
iv	Risk of mortality and morbidity during periods of extreme heat, particularly for vulnerable urban populations and those working outdoors in urban or rural areas.		✓	✓		
v	Risk of food insecurity and the breakdown of food systems linked to warming, drought, flooding, and precipitation variability and extremes, particularly for poorer populations in urban and rural settings.		✓	✓	✓	
vi	Risk of loss of rural livelihoods and income due to insufficient access to drinking and irrigation water and reduced agricultural productivity, particularly for farmers and pastoralists with minimal capital in semi-arid regions.		✓	✓		
vii	Risk of loss of marine and coastal ecosystems, biodiversity, and the ecosystem goods, functions, and services they provide for coastal livelihoods, especially for fishing communities in the tropics and the Arctic.	✓	✓		✓	
viii	Risk of loss of terrestrial and inland water ecosystems, biodiversity, and the ecosystem goods, functions, and services they provide for livelihoods.	✓		✓	✓	

FIGURES

Figure 1: The enhanced burning embers diagram, providing a global perspective on climate-related risks. Levels of risk associated with 5 different reasons for concern are illustrated for increasing global mean temperature and are the same as those presented in the IPCC Working Group II report. Icons indicate selected risks that played an important role in locating transitions between levels of risks. Colored dots indicate overarching key risk categories that were considered in the assessment for each RFC (see Table 1). Confidence in the judgments of risk transitions is indicated as provided in ref. 104. For example, RFC1 is underpinned by overarching key risks i, vii, and viii from Table 1; there is medium confidence in the location of the transition from Undetectable to Moderate risk, which is informed by impacts to coral reef, Arctic and mountain systems; and there is high confidence in the location of the transition from High to Very High risk, which is informed by impacts to coral reef and Arctic systems as well as to species associated with unique and threatened systems.

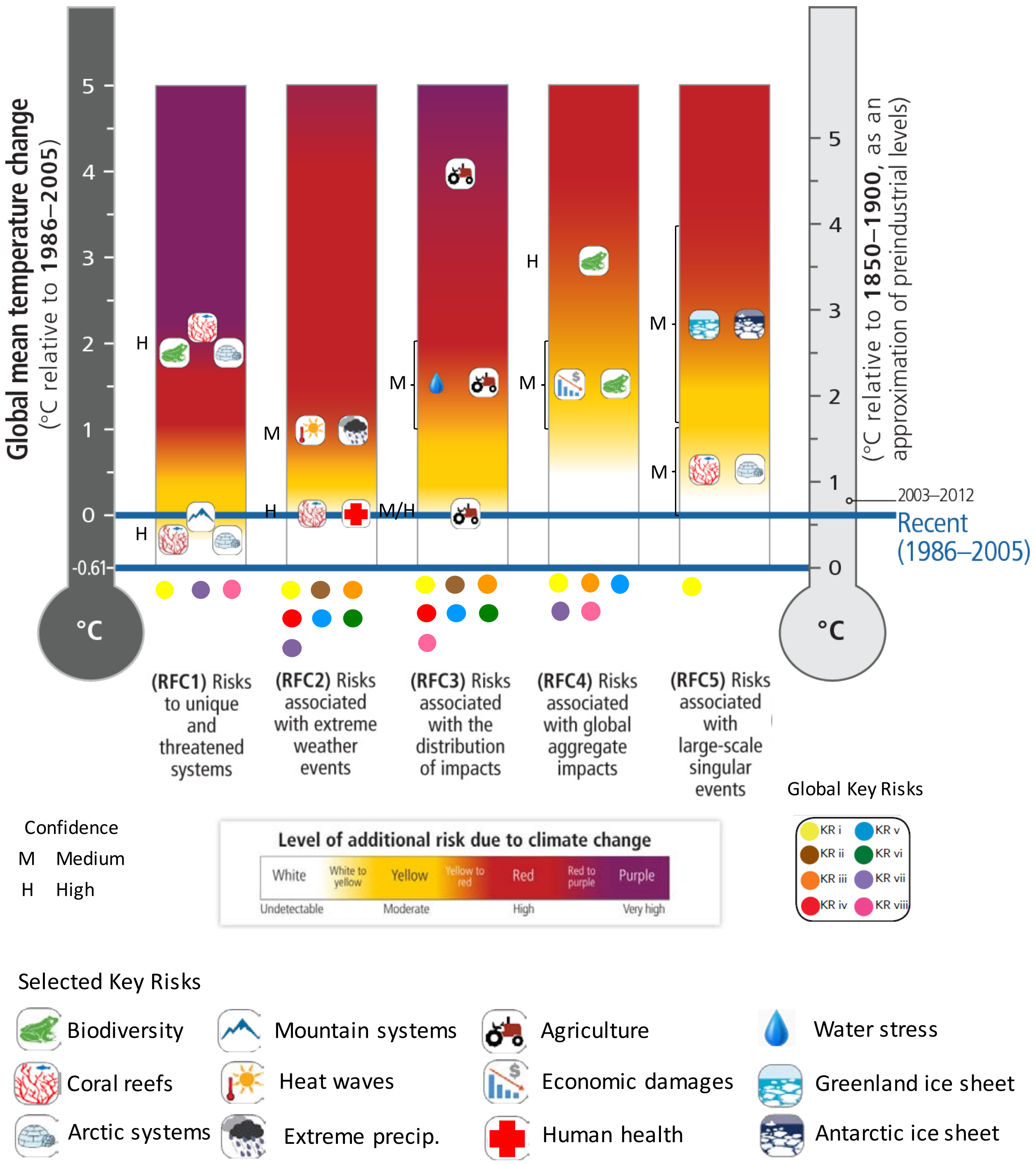
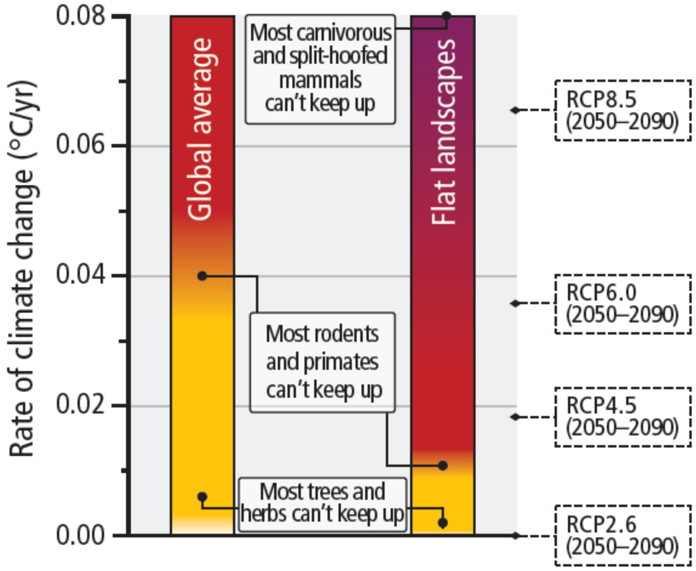
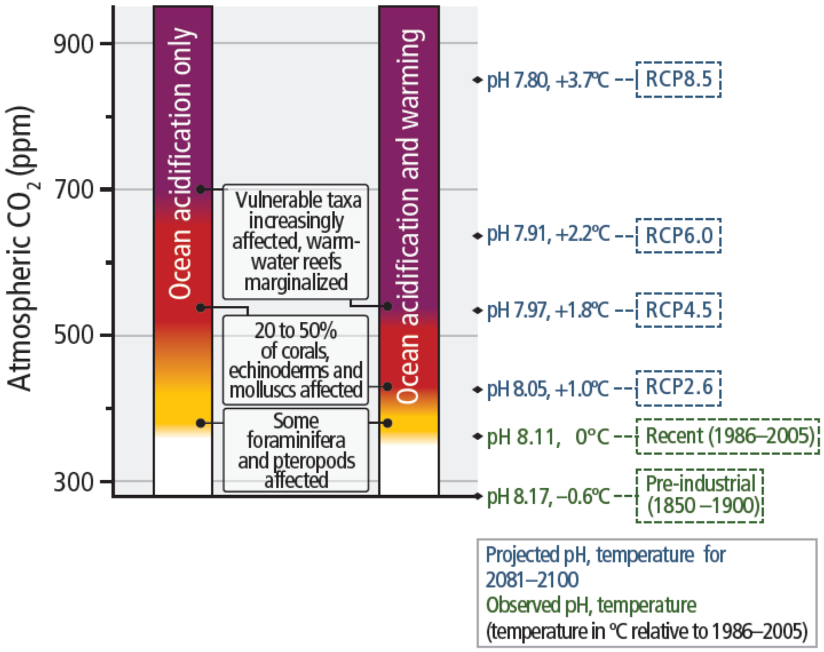

Global mean temperature change
(°C relative to 1986–2005)
5
4
3
2
1
0
-0.61
°C
H
H
M
H
M
M/H
H
M
M
M
M
(RFC1) Risks to unique and threatened systems
(RFC2) Risks associated with extreme weather events
(RFC3) Risks associated with the distribution of impacts
(RFC4) Risks associated with global aggregate impacts
(RFC5) Risks associated with large-scale singular events
(°C relative to 1850–1900, as an approximation of preindustrial levels)
5
4
3
2
1
0
°C
2003–2012
Recent (1986–2005)
Global Key Risks
KR i
KR v
KR ii
KR vi
KR iii
KR vii
KR iv
KR viii
Confidence
M Medium
H High
Level of additional risk due to climate change
White
White to yellow
Yellow
Yellow to red
Red
Red to purple
Purple
Undetectable
Moderate
High
Very high
Selected Key Risks
Biodiversity
Mountain systems
Agriculture
Water stress
Coral reefs
Heat waves
Economic damages
Greenland ice sheet
Arctic systems
Extreme precip.
Human health
Antarctic ice sheet

Figure 2: Additional burning embers diagrams from the AR5 Synthesis Report[81]. These figures use (a) rate of climate change, (b) atmospheric CO_2 and associated ocean acidification as well as (c) sea level rise as the metric of climate-related hazard, rather than global mean temperature (for further explanations see text).



(a) Risk for terrestrial and freshwater species impacted by the rate of warming



(b) Risk for marine species impacted by ocean acidification only, or additionally by warming extremes

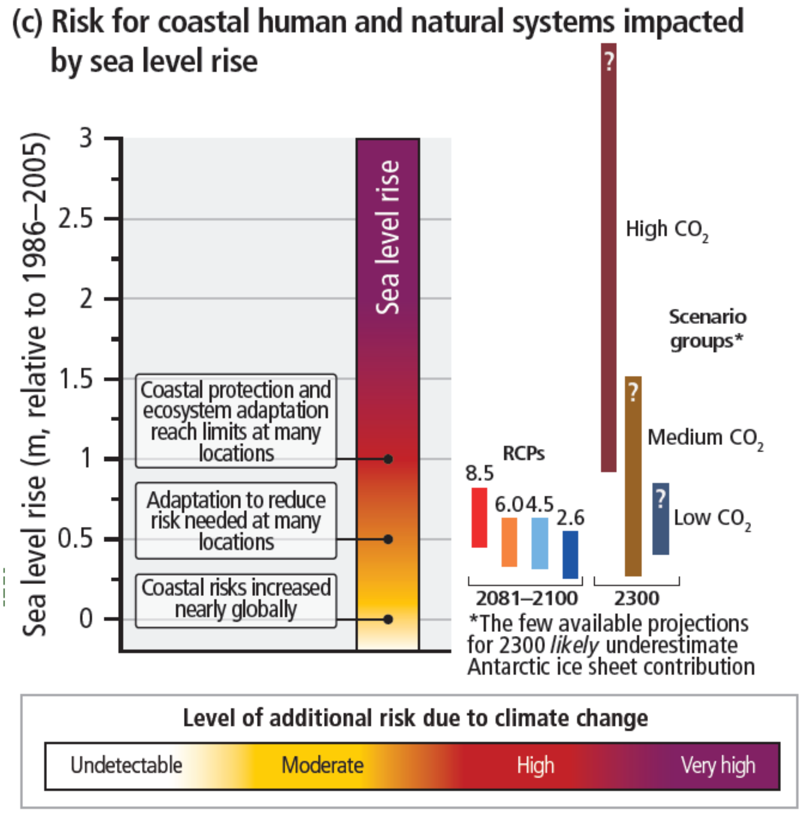

(c) Risk for coastal human and natural systems impacted by sea level rise
Sea level rise (m, relative to 1986–2005)
3
2.5
2
1.5
1
0.5
0
Sea level rise
Coastal protection and ecosystem adaptation reach limits at many locations
Adaptation to reduce risk needed at many locations
Coastal risks increased nearly globally
RCPs
8.5
6.0
4.5
2.6
2081–2100
2300
High CO₂
Scenario groups*
Medium CO₂
Low CO₂
?
*The few available projections for 2300 *likely* underestimate Antarctic ice sheet contribution
Level of additional risk due to climate change
Undetectable
Moderate
High
Very high

Figure 3, panel a: Illustrative version of a vulnerability-dependent burning embers diagram. The figure uses results for one type of climate change impact (additional population at risk of hunger due to climate change) based on three studies[101, 102, 103]. The x-axis categorizes scenarios of societal development by trends in exposure and vulnerability based on ref. 34. Each colored circle indicates the difference between the number of people at risk of hunger due to climate change according to one scenario and the number at risk as calculated under benchmark outcomes. Benchmark conditions are defined as those associated with a medium vulnerability scenario with about 2.6 °C warming relative to preindustrial (Box 2, and Supplementary Text 10 for further description). Results for this benchmark outcome are plotted as zero (a white square) in the figure. Green circles indicate lower risk than this benchmark outcome (values <0), and generally occur for lower levels of climate change and/or lower levels of societal vulnerability. Yellow, red and purple circles indicate greater risk (values >0), and generally occur for more climate change and/or higher societal vulnerability. The figure incorporates 40 scenarios with a range of economic, crop and climate models and assumptions about CO_2 fertilization and adaptation (Supplementary Table 1). The medium vulnerability, 2.6° C (benchmark) outcomes span a range of -12 to 151 million additional people at risk of hunger, illustrating the relatively large uncertainty in estimates of this risk. The Exposure and Vulnerability (E&V) axis indicates relative trends over time rather than absolute levels, with current conditions defined as “Medium” E&V. For example, a future development path in which E&V remains “Medium” is assumed to change over time (and therefore also with changes in GMT along the y-axis) at a moderate rate, driven by trends in socioeconomic conditions that are in the middle of the range of future scenarios. “Low” and “High” E&V indicate futures that are substantially more optimistic or pessimistic, respectively, regarding trends in exposure and vulnerability.

a

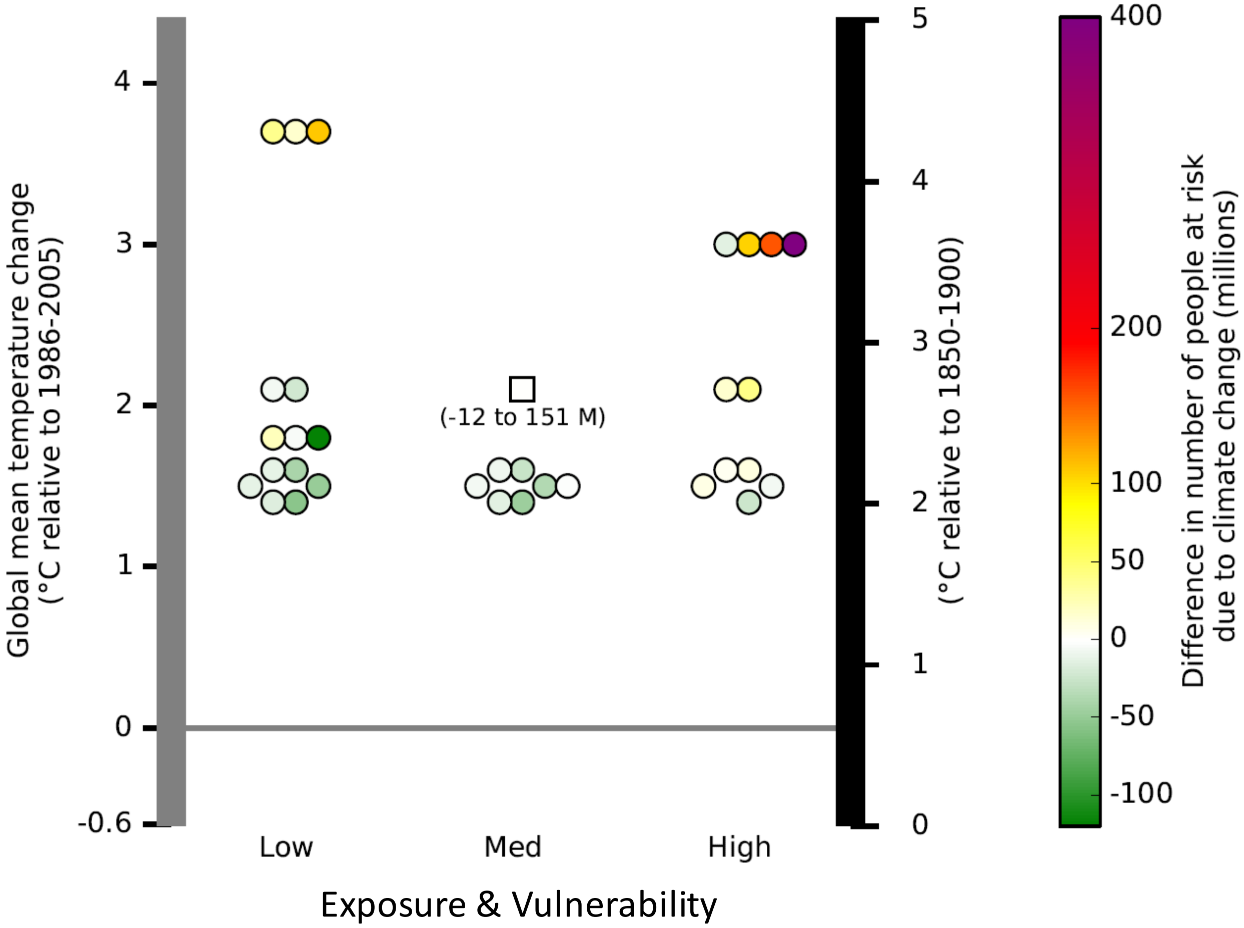
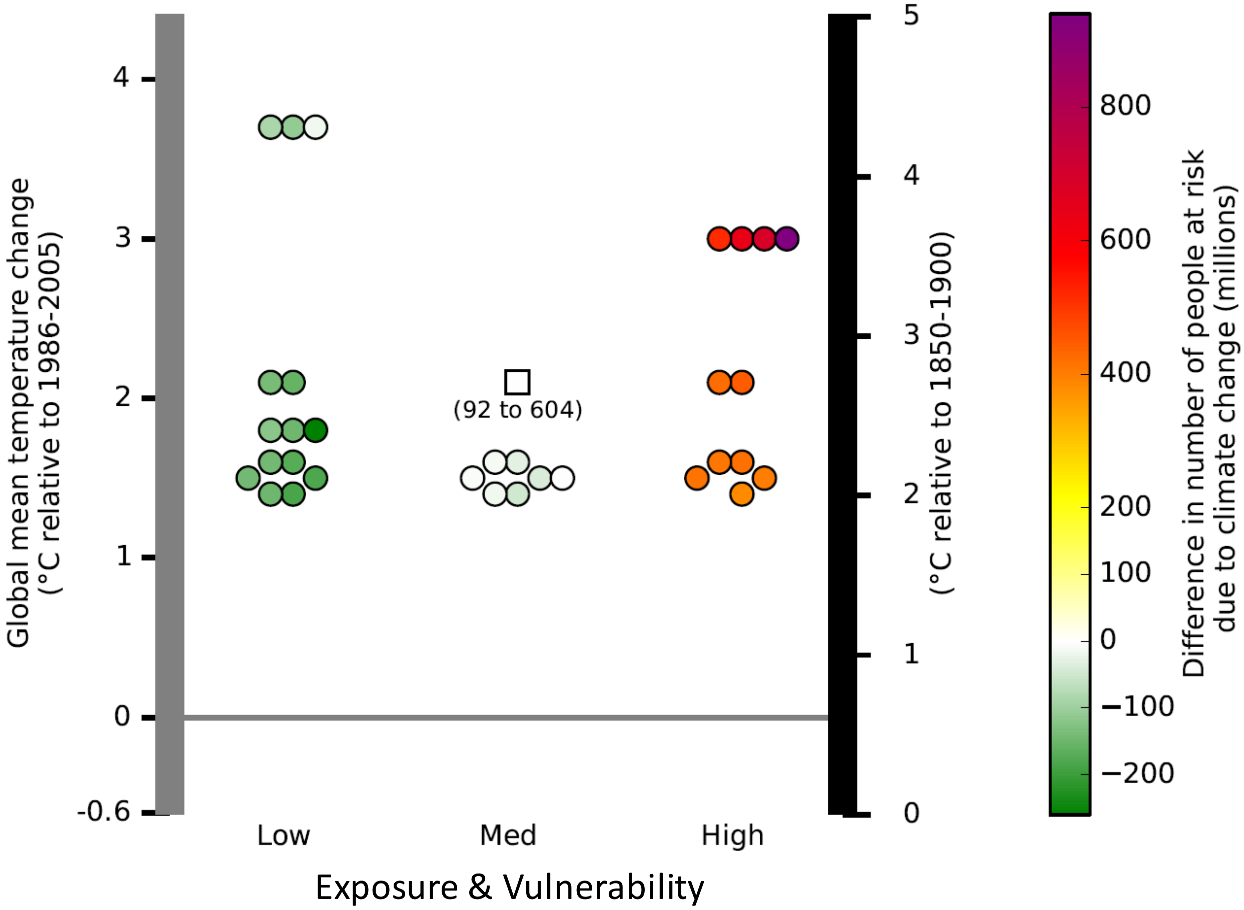

4
3
2
1
0
-0.6
Global mean temperature change
(°C relative to 1986-2005)
5
4
3
2
1
0
(°C relative to 1850-1900)
(-12 to 151 M)
Low
Med
High
Exposure & Vulnerability
400
200
100
50
0
-50
-100
Difference in number of people at risk
due to climate change (millions)

Figure 3, panel b: Same as panel a, but for the total population at risk of hunger rather than the additional population at risk due only to climate change. As for panel (a), the Exposure and Vulnerability (E&V) axis is relative rather than absolute.

b



Supplementary Information

IPCC Reasons for Concern regarding climate change risks

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This document contains Supplementary Discussion for the following topics appearing in the main paper:

1. **Process for making judgments about RFC risk levels**
2. **Units of global mean temperature change (GMT)**
3. **RFC1: Unique and Threatened Systems**
4. **RFC2: Extreme events**
5. **RFC3: Distributional Impacts**
6. **RFC4: Global Aggregate Impacts**
7. **RFC 5: Large-scale singular events**
8. **Additional Metrics: Rate of climate change**
9. **RFCs and the vulnerability of socio-ecological systems**
10. **Figure captions**

It also contains the following supplemental tables and figures:

Supplementary Table 1: Scenario results informing Figure 3.

Supplementary Figure 1: Process for assessing risks associated with Reasons for Concern in the IPCC Fifth Assessment Report.

Supplementary Figure 2: Decomposition of burning ember for RFC4 into two primary key risks.

Note that as in the main text, all undesignated temperatures are with respect to preindustrial.

1. Process for making judgments about RFC risk levels

The assessment based on the criteria for key risks listed in the main text proceeded in two streams, which eventually merged. In the first, AR5, Working Group II, Chapter 19 authors defined varying discrete levels of risk in terms of the key risk criteria, and made a preliminary assessment of risks as a function of GMT for each RFC based on relevant impact studies. At the same time, regional and sectoral chapters of the assessment used the criteria in combination with their own expert judgment to identify key risks in their domains (ref. 6, Table KR-1, Table 19.4). For example, risk of loss of rural livelihoods is a broader concern than loss of urban livelihoods, based on the observed large and pervasive rural-to-urban migration and the expected intensification of climate-related factors underlying this migration. Similarly, the risk from water stress is greater for rural than urban areas due to the limited potential to adapt for the former areas. The risk from heat-related morbidity and mortality is widespread and imminent, and increases in extreme heat are virtually certain by 2100. In contrast, the relationship of climate changes to incidence of vector-borne diseases is less direct and more difficult to quantify.

These regional and sectoral key risks were synthesized into 8 overarching risk categories, each of which was then associated with one or more of the RFCs and integrated with the preliminary assessment of risk levels for each RFC (Table 1, main text; ref. 6, 19.6.2.1). For example, the fourth key risk,

> **"risk of mortality and morbidity during periods of extreme heat, particularly for vulnerable urban populations and those working outdoors in urban or rural areas",**

is associated with RFC2 and RFC3 because it is directly connected with outcomes of extreme events and is unevenly distributed given geographic differences in hazards and variations in the vulnerability and exposure of populations.

Levels of risk were associated with GMT for each RFC by Chapter 19 authors based on an aggregation of the relevant key risks and on individual key risks for which the underlying scientific literature allowed clear association with particular levels of climate change. Although this assessment expressed additional risk due to climate change as a function of GMT, it required direct or indirect consideration of exposure and vulnerability since these dimensions of risk are part of the key risk criteria.

Due to the limits of current information, the assignment of risk levels for each RFC comes down to an assessment of risk of only some of the impacts pertinent to each RFC. Ideally, the approach described here would provide a systemization that may allow consistency and transparency, at least in the basis of judgment used by the same or different groups of experts in future assessments.

2. Units of global mean temperature change (GMT)

In AR5[6], risk transitions were located using GMT relative to recent temperatures (defined as the 1986-2005 average), and the approximate nature of these transitions was signaled in part by using round numbers (1 C, 2 C, etc.). To convert to warming relative to pre-industrial (defined as the 1850-1900 average), we subtracted 0.6 C from these values, following ref. 105 which evaluates it as 0.61±0.06 °C cooler than the recent period. This can lead to the appearance of overly precise locations. We indicate the approximate nature of these transitions either by explicitly stating that locations are “around” or “approximately” a certain value, or using the “~” symbol (e.g., ~1.6 C).

3. RFC1: Unique and Threatened Systems

3.1. *Transition from Undetected to Moderate risk at below recent temperatures.*

Climate change impacts have also been detected and attributed in numerous ecosystems around the world, including those usually considered unique and threatened (see RFC4). Regarding mountain systems, a range of climate change-induced ecosystem impacts such as increased mountain forest mortality and wildfire, and tree line shifts have been observed in Europe, Asia, Africa and elsewhere[89, 106, 107, 108, 109]. Socioecological systems dependent on glacier melt are unique, and there is high confidence that glaciers have continued to shrink almost worldwide[77].

3.2. *Transition to High risk at 1.1 – 1.6 °C above preindustrial.*

As indicated in the main text, this judgment was supported by projected impacts on Arctic and coral reef systems. The mean projected loss of Arctic sea ice at around 1.6 °C of warming above preindustrial is more than 2 million km^2 (30%) relative to recent extent (ref. 75, Figure 12.28b and Table 12.2, based on RCP2.6 for the period 2046-2065 when global temperatures have reached 1.6°C ± 0. 3°C). Reductions in sea ice affect the Inuit culture, which subsists on sea ice-dependent ecosystems, as well as species dependent on sea ice, such as polar bears[110], which have recently been listed as Vulnerable on the IUCN Red List due to climate change driven habitat loss[111]. Recent work shows polar bears have exhibited little adaptive capacity to the loss of sea ice (e.g., they are generally not changing their behavior by feeding in terrestrial areas[28]).

Most warm-water coral reefs are projected to be in rapid and terminal decline from warming and acidification at atmospheric CO_2 levels of 450 ppm[112] and a corresponding global temperature rise of around 1.6°C (as in RCP2.6 in the 2050s). Similarly, if there is no change in corals’ thermal tolerance, a median of 95% of coral reefs is projected to be subject to long-term degradation for a global mean temperature rise of 1.5-2°C above pre-industrial, and protection of >10% of the world’s reefs is considered to require constraining warming to 1.5°C above pre-industrial[113]. This assessment is conservative as it does not consider the combined impacts of warming and acidification.

3.3. *Transition to Very High risk at 2.6 °C above preindustrial.*

3.3.1. *Impacts on unique and threatened species and ecosystems around or above 2° C warming*

Ref. 29 found that 15-37% of the thousands of species studied, which included a large proportion of species found in unique and threatened systems, would be at an increasing risk of extinction for a global temperature rise of 2.1-2.3°C above pre-industrial. There are a number of important examples of risks to specific unique and threatened species and ecosystems. A large fraction (48-57%) of the plants of the Cerrado are projected to be at increased risk of extinction[114]. In South Africa, 51-65% of the area of the Fynbos and 80% of the area of the unique Succulent Karoo floral kingdom[115], both of which are unique and threatened biodiversity hotspots and of global significance, are projected to be lost[15]. A 24% loss of freshwater fish habitat in N America is also projected for this level of temperature rise[116]. In the

Queensland World Heritage rainforest, another unique ecosystem, which comprises the oldest rainforest in the world, a local warming of 1°C above recent (equivalent to a global warming of approximately 2°C above pre-industrial; ref. 75, Table 12.2; ref. 117, Figure A1.69) is projected to cause a loss of approximately 40% of the rainforest habitat of endemic rainforest vertebrates, with the regionally iconic Golden Bowerbird losing 40-60% of its range, one other species losing its entire range[106, 118] and 5% of western Australian Banksia plant species projected to become extinct[119]. A meta-analysis of projections of increased extinction risk found that the global extinction risk nearly doubled from current rates with an increase of 2°C, and then trebled again between 2°C and 4°C[32]. While the proportions at risk in ref. 32 for endemics were lower than those originally calculated in ref. 29, the differences come from a more restricted definition of increased extinction risk. This most recent meta-analysis supported the other findings in that it found that endemic species were more at risk than widespread ones, and that species in South America, Australia/New Zealand and Africa were at higher risk than those in North America or Europe.

3.3.2. *Risks to Arctic, coral reef, and mountain systems*

For example, a large proportion of CMIP5 climate models project a nearly ice-free Arctic Ocean in the summer between 1.6°C and around 2.6°C of warming (ref. 75, Fig. 12-30), while a much smaller proportion project that this occurs between 2.6°C and 3.6°C. Regarding coral reefs, ref. 113 find that even under optimistic assumptions about ability to adapt to warming, only 6% of reefs would avoid long-term degradation with 2.0°C warming above pre-industrial. Loss or degradation of corals would endanger the livelihoods of resource dependent human communities and cause substantial economic damage in East Africa, Asia, Australia, and parts of N. and S. America. For example, revenue loss of between US$95-140 million annually is expected in the Caribbean basin in the next decade, while in Fiji, impacts of between US$0.1 million to 2 million in subsistence fisheries, and US$0.05-0.8 million in commercial coastal fisheries by 2050[120] are estimated. Globally, 20-25% of the fish caught by developing nations come from coral reefs[121] and 6 million people fish in coral reef systems[122]. Glacier meltwater supports a number of unique mountain ecosystems and social systems, in particular in Central Asia and S America. As glaciers melt, initially streamflow may increase as a result of accelerated melting, after which flow declines again, as seen in the Cordillera Blanca of Peru[123], while at the same time the melting creates an associated risk of potentially damaging Glacial Lake Outburst Floods as meltwater collects behind barriers and suddenly breaches them. In central Asia there is potential for loss of large (but uncertain) fractions of central Asian glacier cover by 2100 if temperatures rise by approximately 2-4°C above pre-industrial levels in the second half of the 21st century, potentially creating water security issues in downstream populations dependent on glacier melt[124, 125, 126, 127]. In S. America, glacier melt-dependent areas are at risk of water resource stress under 2°C warming above pre-industrial levels in the second half of the 21st century (and even higher risks under 4°C warming), with several studies projecting river flow declines of between 20 and 40% by the end of the century[123].

3.3.3. Limitations to risk judgments

Studies often do not consider the benefits of adaptation designed to reduce species and ecosystem impacts, such as interventions to increase ecosystem resilience or design of protected areas to facilitate movement in response to warming. In addition, studies frequently do not consider the potential negative effects on species and ecosystems of adaptation to other impacts. For example if an area warms and dries, biodiversity and agriculture will both tend to move into the same cooler, wetter areas, and the ability of natural systems to track climate change will be impeded by human efforts to adapt.

4. RFC2: Risks from extreme events

4.1. *Transition from Undetected to Moderate risk at recent temperatures.*

AR5 WGI found it *very likely* that human influence has contributed to changes in the global scale frequency and intensity of daily temperature extremes (ref. 17, 10.6.1.1) and also increased the probability of occurrence of heat waves in some locations (ref. 17, Section 10.6.2). AR5 assessed *medium confidence* in attribution of intensification of heavy precipitation over Northern Hemisphere land areas with sufficient data (ref. 17, Section 10.6.1.2). In developing countries where urban infrastructure is expanding and population is growing, the intensification of the urban heat island effect is increasing the risk of heat stress[43]. In other areas, such as Germany and Japan, the susceptibility of people exposed to heat stress is generally increasing due to the aging population[43]. Vulnerability, exposure, and resulting mortality from extreme heat is currently widespread[128], as is vulnerability and exposure of property and people to heavy precipitation. Accordingly, such risks were judged to be sufficiently high currently to provide additional support for the assessment of a transition to Moderate risk.

4.2. *Transition to High risk at 1.6 °C above preindustrial*

On average, the frequency and intensity of heavy precipitation events over land will *likely* increase over much of the world, particularly the Northern Hemisphere and East Africa with exceptions for Central America, the Mediterranean Basin, Australia and South Africa[129] (ref. 42, Section 11.3.2.5.2; ref. 77, Table SPM.1).

5. RFC3: Distributional Impacts

5.1. Transition from Undetected to Moderate risk at recent temperatures

Climate change has also been shown to have played a major role in the decline of fruit-bearing trees in the Sahel[14, 130] and a minor role in the spread of bluetongue virus in European sheep[131].

5.2. *Transition to High risk between 1.6 and 2.6°C above preindustrial*

Many studies project significant reductions in yields of wheat, maize, millet and sorghum in Africa and S. Asia by the 2050s[55, 57], corresponding to global temperature of approximately 1.5-2C above pre-industrial levels (based on temperature response to SRES scenarios[132]). Many studies project significant negative impacts of climate change on crops and livestock in Central and S America[123]. For example with around 2 °C warming above pre-industrial (SRES A2 scenario, 2050s), ref. 133 projects that 80% of all crops grown in Colombia will be negatively affected in 60% of the current cultivated area. Ref. 134 projects reductions in yields of crops important to large food-insecure populations in Africa (e.g., maize yield change of -21.4 ± 8.6%) and S Asia (e.g., rice yield change of -4 ± 2%) by the 2030s with approximately 1.6°C warming relative to preindustrial (a somewhat lower level of global warming).

Regarding water resources, projected decreases for warming of 2.3°C[58, 59] include annual mean discharge losses of between 10-30% in European Mediterranean areas, parts of the southern USA, and central S America, and losses of 30-50% in African Mediterranean areas, parts of Western Australia and Southern Africa. "Severe" impacts, defined as a reduction in water resources of more than 20% and/or more than one standard deviation of the current natural variability, would affect about 8% and 14% of the global population at 1.7°C and 2.7°C respectively above pre-industrial levels[59] with areas surrounding the Mediterranean (Middle East, N. Africa, S. and E. Europe) most consistently affected. Ref. 135 reports that for warming of 2.0°C above pre-industrial around 8% of the population is projected to experience new or increased water stress compared to the present day. Ref. 58 find that water scarcity (defined as a water crowding index below 1000 m^3/capita/yr) increases rapidly in N., W., and E. Africa, Central Asia, Central America and Mashriq as temperatures rise by about 1°C above pre-industrial, and continues to increase as temperatures rise to about 2.0°C above pre-industrial. Use of additional groundwater resources to compensate for projected reduced surface water availability may be problematic in many areas since it is projected that for around 2.0°C warming, by the end of the century 24% of the projected population will incur >10% decrease in groundwater resources[136]. Using water storage to adapt may be physically infeasible in some areas, and is likely to be financially infeasible in many others: a global study found that it would cost approximately $12bn/yr to increase global water storage by ~35% by 2050 in order to maintain water supplies[137].

5.3. *Transition to Very High Risk at 4.6° C above preindustrial*

Risks of flooding, water scarcity and human health impacts contribute to this judgment. The proportion of the global population exposed to a 20th century 100 year fluvial flood is projected to be three times higher for warming of around 4°C above pre-industrial levels (RCP8.5, 2100[75]) than for warming of approximately 1.6°C above pre-industrial (RCP2.6, 2100[75])[138], or 14 times higher than present day exposure; whilst a multi-model study projects increases in flood frequency over half the land surface, and decreases in one third[139]. Runoff in the Nile and Ganges basins are projected to increase by up to 150% and 80% respectively under warming of around 4°C above pre-industrial levels. Ref. 59 project that the population exposed to a severe reduction in water resources would increase to 15% with 4°C warming above pre-industrial. Regionally, water stress is projected to increase further, particularly in West Africa, Central America, Brazil, USA, Eastern Europe and East Asia, as global temperatures increase from around 2°C above pre-industrial to around 4°C above pre-industrial, associated with projected runoff reductions of up to 90% in the Amazon and 75% in the Danube & Mississippi[140].

With 4°C warming important tipping points for health impacts related to heat stress, such as heat stroke and fatal occupational heat stroke, may be exceeded in many parts of the world. In S.E. Asia, for example, such impacts may occur as regional temperatures increase by 4-7°C[39, 141, 142, 143, 144], with associated decreases in labor productivity both indoors and outdoors[145].

5.4. *Limitations to risk judgments*

Civil conflict is an example of a type of impact beyond those in the food and water sectors for which literature is sparse and difficult to relate to specific levels of GMT. Empirical studies do suggest that extremes of temperature and precipitation increase the relative risk of civil conflict[146]; since the absolute risk of civil conflict is highest in poorer countries, and since civil conflict reduces economic growth[147], this effect will most severely impact the poor.

Agricultural impacts are sensitive to assumptions regarding CO_2 fertilization. Food prices, which strongly influence food security, are very likely to increase by 2050 in response to climate change if CO_2 fertilization effects do not occur, but are only about as likely as not to increase if they do (ref. 53, 7.4.4). In addition, a concurrent effect of this process is a reduction in the protein and nutrient content of wheat, rice, maize, barley, potato, soybean and peas, meaning the contribution that yield makes to food security per ton of crop harvested may decrease at higher CO_2 levels[53, 148]. Regarding the role of heat extremes in crop yield impacts, warming is projected to triple the exposure of crops to drought[149], for 4° C relative to preindustrial) and extreme heat[150], for wheat and maize at 3.5° C warming. A recent study[151] found that extreme heat at anthesis is projected to double climate change-induced global losses of maize yield, and to halve projected increases in wheat yield (due to an assumption of CO_2 fertilisation effects in this particular model) for a warming of 4.3°C above pre-industrial levels (RCP8.5, 2080s; ref. 75, Table 12.2). The extreme 2003 and 2010 summers in Europe and Russia respectively are known to have reduced grain yields by 20-30%[152, 153].

As noted in the main text, the limitations to adaptation to agricultural impacts that play a role in the judgment of Very High Risk do not consider a number of adaptation options. The adaptation limits refer only to incremental agronomic adaptations such as changes in cultivars and planting dates, which are projected to fall short of offsetting the negative effects on yield for local increases in temperature exceeding 3°C in tropical areas (ref. 53, 7.5.1.1.1).

6. RFC4: Global Aggregate Impacts

6.1. Transition from Undetected to Moderate risk

While detection and attribution of globally aggregated impacts on socio-ecological systems has not been achieved, detection and attribution *has* been accomplished for global biophysical impacts such as changes in the cryosphere or global crop yields. It has also been established for widespread species impacts such as earlier onset of spring events (flowering, breeding, etc.) and poleward and upward movement of the geographic ranges of many species[86, 154]; changes in phenology in plants, birds, amphibians, mammals, and freshwater plankton[14, 155, 156, 157, 158, 159]; changes in distribution[14, 89, 158, 160, 161, 162]; and increases in the prevalence of disease[163]. More recently, endemic species turnover in Mexico has been detected and attributed to climate change[164]. It is not surprising that species extinctions have not yet been attributed to climate change[86], since it generally takes decades for a species to become completely extinct, and extinction commonly occurs as a result of a combination of factors[165].

In addition, individual studies have begun to find relationships between climate trends and economic growth rates in developing countries[166, 167], even if global aggregate economic damages are not yet attributable to climate change.

6.2. Moderate risk at 1.6-2.6°C above preindustrial (and transition from Undetected to Moderate risk between current temperatures and 1.6 °C)

6.2.1. Definition of "increasing risk of extinction"

In the IPCC Fourth and Fifth Assessment Reports and in this paper, 'increased risk of extinction' reflects that the literature indicates a future increased risk of extinction, but does not go as far as projecting actual extinction rates. The proportions of species that are thought to be *exposed* to this increased risk are quantified in much of this literature, but this does not imply actual extinction within a defined period, such as the date at which they become exposed. This literature referring to increased risk of extinction includes (but is not completely limited to) studies which show that species are projected to lose large proportions of their historic geographic range once climate has changed (in other words, their climatic niche is largely lost). Once a species is confined to a small area it becomes more vulnerable to extinction – for example as a result of a disease outbreak, an extreme weather event such as a prolonged drought, or due to local land use change caused by humans fragmenting or completely removing their habitat. Thus the International Union for the Conservation of Nature (IUCN) criteria for classifying a species as critically endangered includes geographic range as one of the key criteria, alongside factors related to population size and population dynamics (http://www.iucnredlist.org/static/categories_criteria). Having a limited geographic range does not necessarily mean that a species will in fact become extinct within a period shorter than it would otherwise have lasted, as extinction depends on many other factors, such as population dynamics, other effects of climatic change such as the impacts of extreme weather events, and climate effects mediated through interactions with other species (eg its predators, prey or pollinators) as well as non-climate drivers. The combined outcome of these factors might act to exacerbate or reduce the potential for extinction, and are not included in most of the quantifications of increased extinction risk found in the literature.

6.2.2. *Impacts on biodiversity at 1.6-2.6° C warming relative to preindustrial*

There have been many studies on the potential impacts of climate change on the ranges of a number of species with varying levels of warming. AR4 concluded that approximately 20-30% of plant and animal species assessed are likely to be at increased risk of extinction for warming of 2-3°C above preindustrial[29]. A recent meta-analysis of 131 published projections found that extinction risk increased from 2.8% (current) to 5.2% at 2°C, 8.5% at 3°C and 16% at ~4°C across both widespread and endemic species[32]. However, endemic species were found to have a 6% higher extinction risk in this study. Differences between the levels of increases in extinction risk between studies stem almost entirely from assumptions about how much range loss equates to increased risk of extinction. Ref. 69, in an assessment of 48,786 widespread animal and plant species across the globe, projected that with a warming of 2°C above pre-industrial levels by the 2080s, more than half of the potential range would be lost for 23+/-4% of the plants and 13+/-3% of animals studied globally, allowing for realistic dispersal rates. The species distribution models on which the global assessments in refs. 69 and 32 were largely based cannot be applied to narrowly-restricted species, which in Sub-Saharan amphibians, for example, make up 54% of species and 92% of threatened species[168]. Therefore these estimates may under-represent the total risk.

Other studies that inform this risk judgment have found similar risks to Western Hemisphere birds, substantial impacts on specific animal and plant species ranges, and projected turnovers of large fractions of marine species assemblages. To date a minimum of 66,000 species have been examined (exact number larger but unobtainable as there are overlaps in species between different studies). The types of studies include species distribution models (also called ecological niche models), mechanistic models, expert judgment with or without traits-based analysis, and species area curves. These models include almost all birds, amphibians, and warm-water corals, large numbers of plants as well as mammals, reptiles and butterflies[27, 32, 69]. For example, 23-25% of Western Hemisphere birds are projected to be at increased risk of extinction under approximately 1.6°C of warming above preindustrial[169]. The numbers of species at increasing risk of extinction varies widely in the literature owing to differences in modeling technique, assumptions about dispersal, endemic (RFC 1) versus widespread (RFC 4) species and, especially, thresholds used to establish increasing risk of extinction[32]. Globally, even with a more restricted definition of threshold of change to classify a species as under increased extinction risk, this translates to a near doubling of current extinction risk with 2°C above pre-industrial. However, increased extinction risk is not the only consideration when looking at biodiversity and, in particular, its provision of ecosystem services. Large-scale losses of widespread and common species[69] implies significant erosion of ecosystem services operating through predation, pollination, carbon removal, subsistence, etc. There are also projected large turnovers of up to 60% in marine species assemblages (for 1.8 – 2.4°C of warming above pre-industrial levels; corresponding to SRES A1B, B1 and A2 in the 2050s), combined with shrinkage of fish body weight of 14–24%[170, 171].

6.2.3. *Economic damages between 0 and 3°C of warming above pre-industrial levels*

Economic impacts are not an important factor at low levels of warming for global aggregate impacts because studies point to the combination of winners and losers from limited levels of warming. Winners include countries with presently cool climates that may experience increases in agricultural or forest production, reductions in the number of cold-related deaths, and decreases in energy expenditures for heating. Losers include countries with presently hot climates, or with high vulnerability to moderate changes in hazard distribution (e.g. low-lying areas and small islands), and people living in extreme poverty who are vulnerable to any kind of environmental change. Some assessments indicate that, on average, these impacts cancel out for low levels of warming. As warming increases, negative impacts are driven by, for example, increased heat-related mortality and morbidity, decreased labor productivity, increased energy demand for cooling, coastal flooding, crop loss, ecosystem damage, and the potential for catastrophic impacts.

Few studies assess global aggregate damages due to climate change at levels of warming close to the present level. Estimates of global economic damages generally project small negative impacts around 1°C warming above pre-industrial levels[70, 172, 173] (although two older studies project small positive impacts). One study[173] found that 1°C of warming caused ~2% ± 1% (1σ) increase in global GDP due to impacts on agriculture, forestry, biodiversity, sea level rise, human health, energy demand, water resources. The benefits arise from the benefits of assumed CO_2 fertilization to agriculture and forestry after allowing for adaptation, from the reduction in the number of cold deaths, and from reduction in heating demand. Note that CO_2 fertilization is itself uncertain in magnitude, and that its effects might be negated by the effects of climate change upon the frequency and intensity of extreme weather such as heatwaves[151] and/or by increases in agricultural pests and diseases. That study also found that costs of climate change at 1°C fall disproportionately on poorer regions, especially Africa and South/Southeast

Asia. Another study[172] examined the effects of 1°C warming using a quite different methodology, assessing a cross-country panel of self-reported happiness, and finding a decrease in happiness equivalent to a 0.4% loss of GDP from 1°C of warming. Based on these studies, we conclude that the globally aggregated economic effect of 1°C of warming is small.

The estimate cited in the main text of 0-3% impact on GDP for warming of 1.9-3° C relative to preindustrial is based on studies that either enumerate and add different impacts or examine multiple impacts in a model of the full economy[45, 174, 175, 176, 177, 178, 179]. (Note that the limits of the 0-3% GDP range do not coincide with the limits of the 1.9-3°C range; most estimates in the Tol (2009, 2014) analysis are for either 2.5 or 3.0°C, and these span the range.). Many estimates depend on a large number of disputable assumptions (see section 6.4 below).

6.3. Transition to High risk around 3.6°C above preindustrial

Impacts on biodiversity at 3.6 C warming relative to preindustrial. The judgment for this risk transition is supported by many of the same studies used to support the judgment of Moderate risk at lower temperatures, as well as an assessment of 48,786 species which showed potential range losses of >50% for 57+/-6% of plants and 34+/-7% of animals studied. Results from the global assessment of 16,857 species[69] indicated even higher risks at a global temperature rise of 2.9-3.4°C above pre-industrial levels (A2, 2090), with extinction risks applying to approximately 26 - 62% of the birds, 30-58% of the amphibians and 42-65% of corals studied. Extinction risks are estimated to increase to 32-34% for Western Hemisphere birds[169]. Furthermore, 10-20% of natural vegetation has been projected to be at severe risk of ecosystem transformation (and hence disruption of ecosystem services) under a global temperature rise of approximately 3°C above pre-industrial levels[174].

A species does not need to be considered globally extinct for its decline to have an impact on ecosystem services. The local loss of one or more species will also impact a range of ecosystem services. Where many species potentially lose large fractions of their range, but are not considered at risk of extinction, this may ultimately have an even greater impact on ecosystem services at a global level. For example, for a temperature rise of 3.6°C above preindustrial, it was estimated that >50% of the potential range would be lost for 57+/-6% of plants and 34+/-7% of animals studied, allowing for realistic dispersal rates[69]. For a temperature rise of 3.6°C above preindustrial the figures increase to 57+/-5% of plants and 34+/-7% of animals studied. Such biodiversity loss amongst widespread and common species implies a major erosion of ecosystem functioning and services[180, 181].

A recent global analysis showed that species that are widespread geographically, not only endemics (which have tended to be the focus of many previous studies), are at risk of high levels of range loss meaning that they would disappear from many of the areas they currently inhabit[69]. 32-34% of Western Hemisphere birds are projected to be at risk of extinction under approximately 3°C of warming above preindustrial[169]. Furthermore, 10-20% of natural vegetation has been projected to be at severe risk of ecosystem transformation (and hence disruption of ecosystem services) under a global temperature rise of approximately 3°C[182]. While all of these studies use a range of taxa-specific dispersal rates (also, rate of climate change above), paleoecological evidence shows that dispersal in response to climate change is species-specific and that climate changes in the past led to what are known as non-analogue communities; that is, assemblages of species that are different than currently occurring assemblages. This ultimately means that the interactions with ecosystem services (e.g., seed dispersal, pollination and predation, especially of insect pests) between natural and agricultural systems will be different than current.

Together this evidence results in a transition to high risk for aggregate global biodiversity at 3°C above pre-industrial levels (Figure S2).

Economic damages. There are too few studies of aggregate economic damages to provide support for the judgment of risks above 3°C relative to pre-industrial. Ref. 183, as aggregated by ref. 184, found losses of happiness at 3.2°C equivalent to 12.4% of global GDP (or 11.5% as aggregated in ref. 70), while ref. 178 found losses of 6.1% of GDP at 5.4°C warming relative to pre-industrial, driven primarily by labor productivity decline (or 4.6% of GDP as aggregated by ref. 70).

The combination of the evidence about impacts on aggregate global biodiversity and the economy is taken to result in a transition to high risk at 3.6°C, given that risks to the economy in the literature do not reach the 'High' level for any level of warming assessed, and hence the 'High' risk point for the combination of economic and biodiversity-related impacts is placed at a larger temperature change than it would have been were it based upon a biodiversity assessment alone (see Supplemental Figure S2).

6.4. *Limitations of estimates of global aggregate economic impacts*

Economists have long used benefit-cost integrated assessment models (IAMs) to estimate the global aggregate economic impacts of climate change, employing simplified representations of the physical impacts of climate change upon a range of sectors and regions[177, 178, 185, 186, 187, 188]. For example, some IAMs include simple representations of the global aggregate impacts of climate-change induced sea level rise, the effects of climate change upon crop yields and the agricultural economy, and effects of climate change upon water resources.

There are significant weaknesses in aggregate economic damage estimates, as has been noted by numerous authors[71, 189, 190, 191]. IAMs may not capture the full range of uncertainties in the projection of climate change and its impacts. For example FUND[188] assumes positive effects of CO_2 fertilisation on crops, whereas debate continues about whether such effects are likely to manifest in the field[53], and meanwhile observations have already detected negative impacts of global climate change on yields of maize and wheat[54, 192]. No benefit-cost IAM has the temporal resolution to explicitly include the impacts of individual extreme weather events, meaning that they are likely to underestimate the magnitude of damages from climate change[189, 193].

Further, IAMs omit several key processes[190, 194], including impacts upon ecosystem services, which then impact upon the economy. Non-market interactions between impacts are excluded[30], and there is an assumption that loss of ecosystem services (including for example water purification, watershed preservation, flood prevention, carbon sequestration, crop pollination, coastal protection, regulation of pests and diseases, recycling of waste nutrients[195]) can be fully compensated for by market services[196, 197, 198]. Another key issue omitted from many integrated models is a representation of large-scale singular events and their economic consequences, which a small number of studies are beginning to explore[74, 186, 199].

New approaches to assessing aggregate impacts use risk assessment frameworks, aggregating risks across sectors globally using physical metrics such as numbers of people at increased risk of various kinds of impacts, instead of using economic methods of aggregation. These are based on much more detailed physical process-based or econometric modelling of the impacts of climate change in multiple sectors globally[200, 201] or nationally (e.g., in the USA[202, 203]). These studies overcome some of these limitations and can explicitly include effects of extreme weather events such as storm surges and heat waves, but also do not provide comprehensive estimates of the total aggregate economic risk across all key impact categories.

7. RFC 5: Risks associated with large-scale singular events

7.1. Transition from Moderate to High risk between 1.6 and 3.6°C above preindustrial

Drawing on AR5 WGI chapter 13 (ref. 76, 13.4, 13.5), AR5 WGII Chapter 19 placed the transition from Moderate to High risk of a multi-meter sea level rise between 1.6-4.6 C above preindustrial based on modeling of the sensitivity of the Greenland ice sheet to future warming and paleoclimatic evidence of large sea level rise due to contributions from both Greenland and Antarctic ice sheets during the Last Interglacial (LIG). Modeling studies indicate a threshold for complete loss of GIS in the 1.0 (low confidence)-4.0 (medium confidence) °C range while paleoclimatic evidence supports a partial loss of GIS during the LIG when global mean temperature was less than 2 °C above preindustrial levels. However, WGI had low confidence in the lower end of the temperature range which was determined by one study[204] which placed the threshold for complete loss of GIS around 1C compared to preindustrial. Furthermore, the relevance of the LIG analog is limited by differences in the paleo orbital forcing compared to future greenhouse gas forcing. In this paper, the transition from moderate to high risk is slightly modified to 1.6-4.0C to take the differences in confidence levels into account.

The role of the West Antarctic Ice Sheet (WAIS) entered into the Chapter 19 judgment in assessing the gradient of risk within the 1.6-4.6C range, with particular reference to studies supporting LIG sea level rise in the range of 6-9m[189, 205, 206], a range which would require substantial contribution of both ice sheets. One comprehensive post-AR5 review of evidence from paleo-sea levels supports such a large LIG sea level rise[207]. Other post-AR5 studies provide additional evidence of an accelerating contribution from WAIS currently[84] with the potential for a loss equivalent to a 3m or larger sea level rise in a multi-century timescale[83, 208]. Refs. 84 and 208 are not specific as to the relation of possible rapid loss to future temperatures but additional evidence in this regard (for example, see ref. 209) could support revision of the RFC 5 risk to include the Very High risk category.

The judgment that there is a more rapid increase in risk between 1.6°C and 2.6°C reflects additional risk of a very large sea level rise based on the LIG ice loss from both ice sheets [196, 205, 206, 207] (ref. 57, Section 5.6.2), when GMT was no more than 2°C warmer than preindustrial levels. This assessment of risk is based primarily on the *magnitude* and *irreversibility* of such sea level rise and the widespread exposure and vulnerability of coastal settlements and ecosystems to such a rise. However, the slower the rate of rise, the more feasible becomes adaptation to reduce vulnerability and exposure.

7.2. *Rate of ice sheet loss and associated risk*

Particularly with regard to rate of change, the assessment of risk associated with RFC5 is not well-characterized. “Abrupt” is a relative term: Disintegration of an ice sheet may be abrupt in a geological sense but, if stretched over a millennium or more, sufficiently slow to allow human and societal adjustment on a timescale as occurs routinely for large scale social reorganizations for economic reasons. On the other hand, there is no evident way to quantify cultural losses from permanent loss of (current and future) antiquities to the sea no matter how slowly they occur. In addition, multi-meter sea level rise of the magnitude associated with ice sheet loss stretching over a few centuries, while very slow compared to many other climate system changes, could seriously challenge adaptive capacity and, as a result, be viewed as abrupt.

8. Additional Metrics

8.1. Rate of climate change: limits to adaptation

Successful (and in some cases unsuccessful) natural adaptation of organisms to past changes in global mean temperature of similar magnitudes to those projected over the next century resulted mostly from their movement. The unassisted rate of movement of populations of organisms across the landscape – whether by migration in the case of mobile organisms, or by successive cycles of growth, propagule production, dispersal, and establishment for sessile organisms – has theoretical limits, borne out by observations. Paleoclimatic data show that on average, the rate of temperature rise during the emergence from the last glacial period was much slower than the rate currently observed and projected for this century (there may have been periods in the Younger Dryas where rates approached the current rate[210, 211]). Paleo-ecological data show that the realized migration rates of plants, vertebrates and invertebrates vary greatly, and extinctions occurred in many groups during past climate changes[86].

8.2. Rate of climate change: dependence of rate of change on topography

For example, for the RCP8.5 scenario, GMT change over the period 2050-2090 averages about 0.065°C/yr. This translates to a mean climate velocity in flat landscapes of about 70 km/decade, while in mountainous landscapes the rate of horizontal movement is less – averaging about 2.5 km/decade. The global average for all landscapes for the RCP8.5 scenario is about 20 km/decade.

8.3. Sea level rise: Transition to high risk

Additional examples include: For 20 cm of sea level rise, with local subsidence and without upgrade in coastal defenses, more than $1 trillion in assets could be lost annually in large cities alone [212]. For sea level rise between 20 and 60 cm, many ecosystems such as wetlands, coral reefs, estuaries and lagoons, and deltas would be at risk of widespread losses. Moreover, some vulnerability hotspots such as small islands would reach adaptation limits.

9. RFCs and the vulnerability of socio-ecological systems

Examples of dependence of impacts on societal conditions. For example, the population exposed to future water scarcity is sensitive to population growth assumptions[58], and sea-level rise impacts depend on future coastal development and on capacity to invest in protection[212, 213]. The ability of species to move can be impacted by barriers (e.g., cities, agriculturally transformed landscapes) that are linked to differing socio-economic assumptions. More recently, projections of global numbers of people at risk of hunger[101, 102] and water scarcity[214], as well as the health burden attributable to childhood undernutrition[215], have been found to depend more on changes in societal conditions than on climate change. Additionally, a projection of US population exposed to extreme heat found that demographic change was as important as climate change to outcomes[47].

10. Figure 3, main text

10.1. *Methodology*

Figure 3 is based on the numbers of people at risk of hunger reported in the scenarios described further in the extension to the Figure 3 Caption below and in Table S1. To normalize for the uncertainty in numbers of people at risk for a given climate outcome and level of exposure and vulnerability (E&V), we express all results as the difference in the number at risk relative to a benchmark case, defined as a medium E&V scenario with about 2.6 C warming. This normalization is applied within each subset of scenarios carried out with the same crop model and economic (or integrated assessment) model, climate model output, assumption about CO_2 fertilization, and assumption about adaptation. This normalization controls for principal factors that lead to uncertainty in risk outcomes for the benchmark case. However, results can be counter-intuitive in some cases. For example, subsets of scenarios that include explicit adaptation lead to smaller apparent benefits of lower climate change or E&V, because the main benefit of adaptation appears in the benchmark case to which other scenarios are normalized. In addition, subsets of scenarios that include the positive effects of CO_2 fertilization can lead to outcomes in which less climate change results in higher risks, because CO_2 levels are also lower and therefore its positive effects are lessened. Finally, some low E&V scenarios could lead to apparently reduced positive benefits of climate change (and associated CO_2 levels) simply because there are few people at risk of hunger even before climate change (and CO_2) effects are considered.

10.2. *Figure 3 caption*

The figure incorporates 24 scenarios from ref. 101: three different societal development pathways differentiated by exposure and vulnerability of socio-ecological systems (SSPs 1, 2 and 3), four different climate change outcomes for 2050 (RCP8.5, 6.0, 4.5 and 2.6, median of 8 GCMs each), and two adaptation assumptions (with and without). Two scenarios are included from ref. 102: a medium vulnerability societal future (SSP2) with two climate outcomes for 2050 (RCP8.5, RCP2.6, median of 12 different GCMs). These two scenarios are from the same author team as for ref. 91 but produce outcomes with substantially lower numbers of people at risk of hunger. The primary reason is that in ref. 92, changes in the within-country distribution of per capita calorie consumption are assumed, while the distribution is held fixed in ref. 91. This change leads to a substantial reduction in projected risk. Fourteen scenarios are included from ref. 103: four different development pathways (SRES A1FI, A2, B1, B2) with their associated climate outcomes in 2080 based on the HadCM3 model[216] with different crop yield models and assumptions about CO_2 fertilization (AEZ and DSSAT models with CO_2 fertilization, 4 scenarios each; AEZ and DSSAT models without CO_2 fertilization, 2 and 4 scenarios, respectively). A summary of quantitative outcomes for each scenario that is plotted in Figure 3 is provided in Supplementary Table 1.

For the results from ref. 101, all values are for 2050. Global Mean Temperature is from a corrected version of their Figure S7 provided by the author and represents the median of 8 GCMs. Global population is from Figure S6, and the change in hunger due to climate change is taken from Figure 5 as the median percent change in numbers of people at risk of hunger relative to a scenario with no climate change. The total population at risk of hunger is from Figure 3, summed from separate estimates for Developing and Transition countries.

For the results from ref. 102, all values are for 2050. Global Mean Temperature is from a corrected version of their Figure S8 provided by the author and represents the median of 12 GCMs. Global Population is from Figure S9 (the same as in ref. 101). The change in hunger due to climate change is taken from Figure 2 as the median change in numbers of people at risk of hunger relative to scenario with no climate change.

For the results from ref. 103, all values are for 2080. Global Mean Temperature is from HadCM3 results for these scenarios available from ref. 216. Population is taken from the SRES database at CIESIN. Numbers of people at risk of hunger are from Table 1 for 2080. Results for scenarios A1 and B1 with the AEZ-BLS impact model including CO_2 fertilization were not provided in that Table.

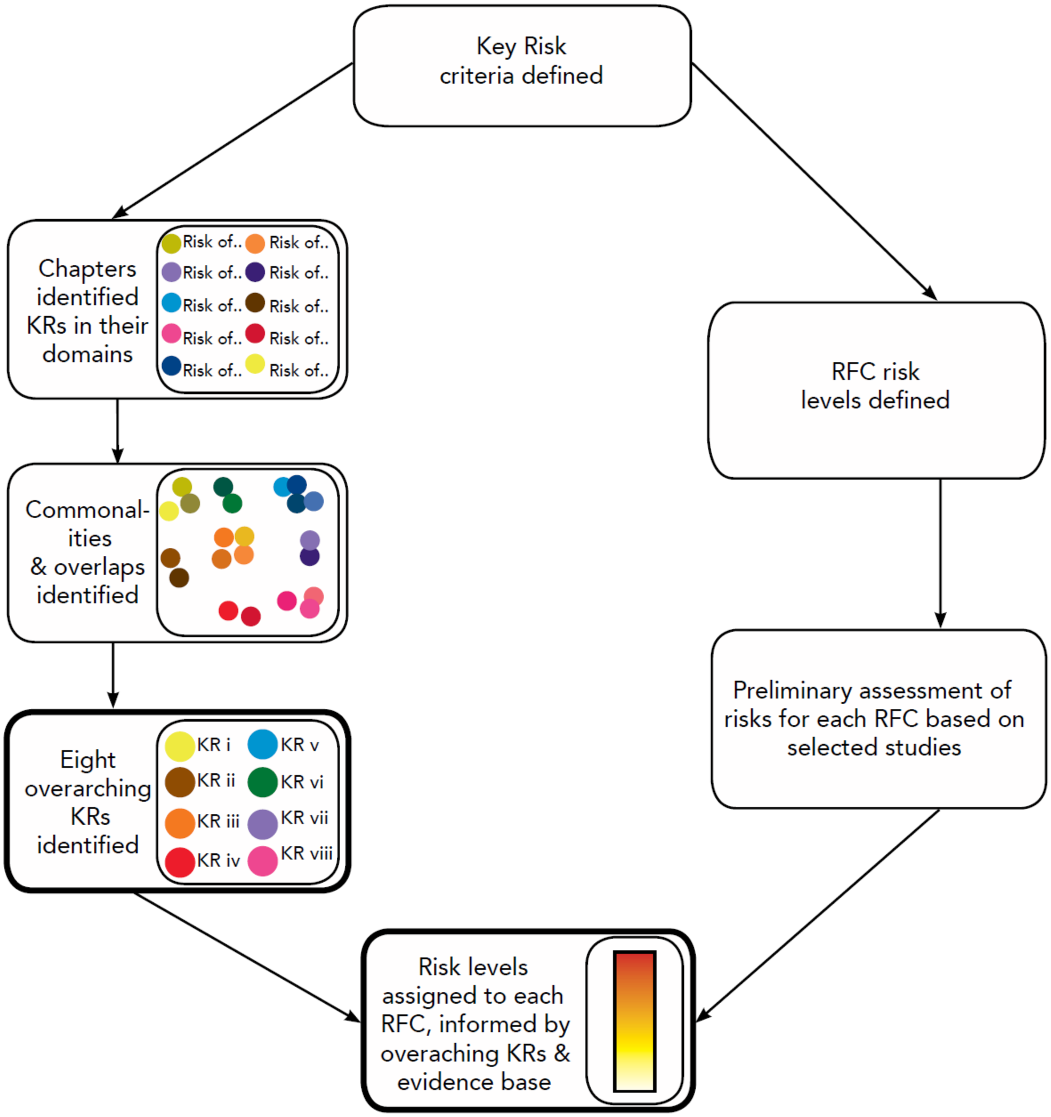
In general Fig. 3 and Supplementary Table 1 present results from different studies that have been harmonized to common categories of vulnerability and to a single scale of GMT. The vulnerability and GMT levels reported are approximate, as each study and scenario has its own approach to characterizing these factors.

Supplementary Table 1: Summary of scenario results supporting Figure 3 (a and b).

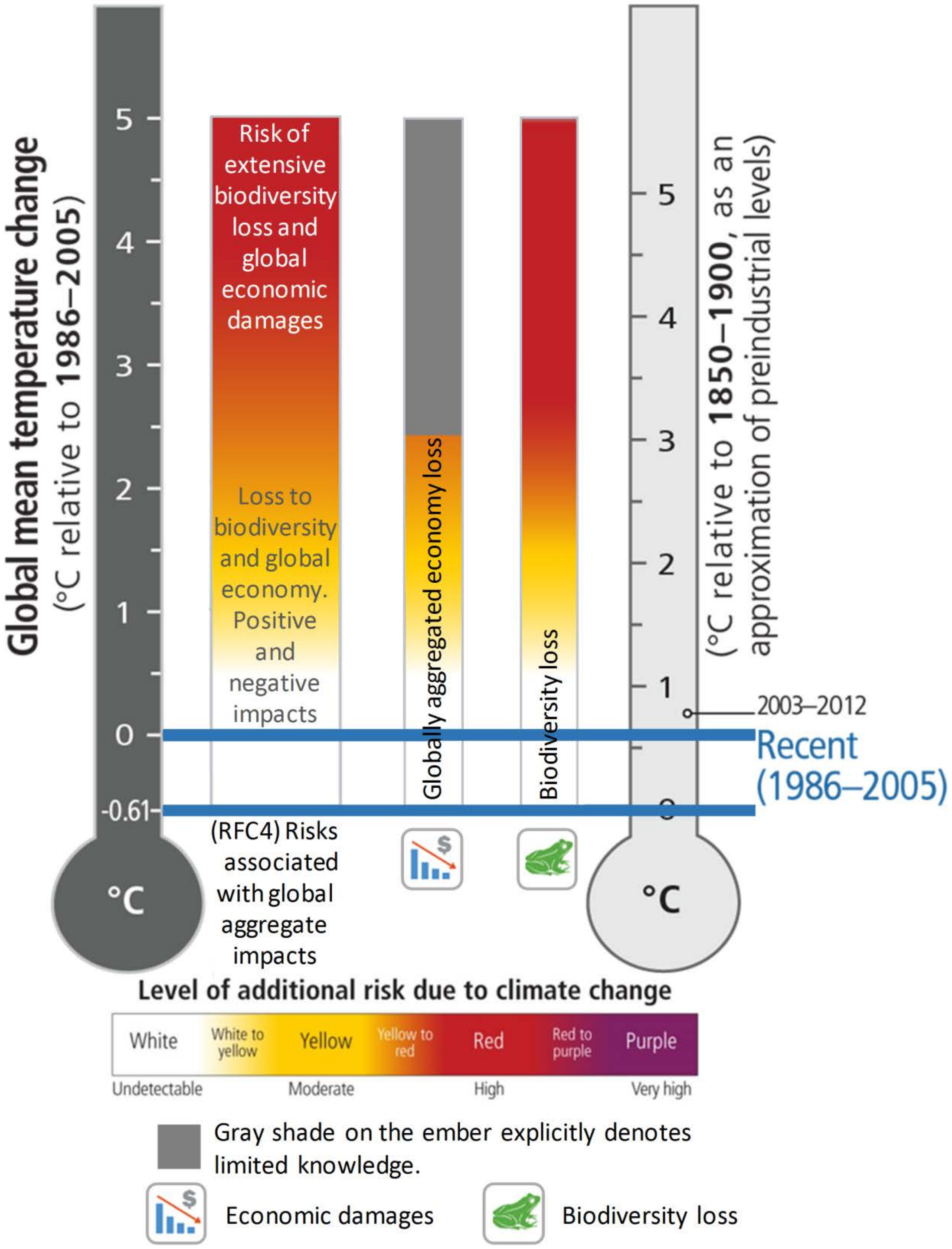
	Vulnerability	GMT	Total population at risk of hunger	Total pop at risk relative to SSP2-8.5	Additional pop at risk due to CC	Additional pop at risk compared to add'l pop at risk in SSP2-8.5
		C, rel. to 1981-2000	Millions	Millions	Millions	Millions
Hasegawa et al, 2014						
Current (2005)			830			
No climate change						
SSP1-Ref	L		400			
SSP2-Ref	M		530			
SSP3-Ref	H		940			
With climate change, without adaptation						
SSP1-8.5	L	2.1	452	-152	52	-22
SSP1-6.0	L	1.5	426	-178	26	-48
SSP1-4.5	L	1.6	435	-169	35	-39
SSP1-2.6	L	1.4	420	-185	20	-55
SSP2-8.5	M	2.1	604	0	74	0
SSP2-6.0	M	1.5	569	-36	39	-36
SSP2-4.5	M	1.6	578	-26	48	-26
SSP2-2.6	M	1.4	558	-47	28	-47
SSP3-8.5	H	2.1	1055	450	115	40
SSP3-6.0	H	1.5	1010	405	70	-5
SSP3-4.5	H	1.6	1026	421	86	11
SSP3-2.6	H	1.4	990	386	50	-24
With climate change, with adaptation						
SSP1-8.5	L	2.1	414	-136	14	-6
SSP1-6.0	L	1.5	409	-141	9	-11
SSP1-4.5	L	1.6	409	-141	9	-11
SSP1-2.6	L	1.4	404	-145	4	-15
SSP2-8.5	M	2.1	550	0	20	0
SSP2-6.0	M	1.5	544	-5	14	-5
SSP2-4.5	M	1.6	543	-7	13	-7
SSP2-2.6	M	1.4	536	-13	6	-13
SSP3-8.5	H	2.1	976	426	36	16
SSP3-6.0	H	1.5	968	419	28	9
SSP3-4.5	H	1.6	964	415	24	5
SSP3-2.6	H	1.4	952	403	12	-7
Hasegawa et al, 2015						
No climate change						
SSP2-Ref			90			
With climate change, without adaptation						
SSP2-8.5	M	2.1	92.2	0	2.2	0
SSP2-2.6	M	1.5	90.5	-2	0.5	-2

	Vulnerability	GMT	Total population at risk of hunger	Total pop at risk relative to SSP2-8.5	Additional pop at risk due to CC	Additional pop at risk compared to add'l pop at risk in SSP2-8.5
		C, rel. to 1981-2000	Millions	Millions	Millions	Millions
Schmidhuber & Tubiello, 2007						
No climate change						
A1	L		108			
A2	H		768			
B1	L		91			
B2	M		233			
Climate change, 2080, AEZ-BLS, with CO2 fertilization						
A1	L	3.7	136	-108	28	17
A2	H	3	885	641	117	106
B1	L	1.8	99	-145	8	-3
B2	M	2.1	244	0	11	0
Climate change, 2080, AEZ-BLS, without CO2 fertilization						
A1	L	3.7				
A2	H	3	950	693	182	158
B1	L	1.8				
B2	M	2.1	257	0	24	0
Climate change, 2080, DSSAT-BLS, with CO2 fertilization						
A1	L	3.7	136	-85	28	40
A2	H	3	742	521	-26	-14
B1	L	1.8	102	-119	11	23
B2	M	2.1	221	0	-12	0
Climate change, 2080, DSSAT-BLS, without CO2 fertilization						
A1	L	3.7	370	-14	262	111
A2	H	3	1320	936	552	401
B1	L	1.8	125	-259	34	-117
B2	M	2.1	384	0	151	0

Supplementary Figure 1: Process for assessing risks associated with Reasons for Concern in the IPCC Fifth Assessment Report. After criteria for key risks were defined, two branches of assessment were carried out: Working Group 2 chapters identified key risks in their domains, which were then synthesized into a set of eight overarching key risks (left branch in figure); Chapter 19 authors defined specific risk levels and used selected studies to make a preliminary assessment in terms of GMT (right branch). The two assessments were then merged to produce the final risk judgments.



Supplementary Figure 2: Decomposition of burning ember for RFC4 into two primary key risks.



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