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Migration and Global Environmental Change

SR8: The possible impacts of high levels of climate change in 2060 and implications for migration

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Contents

Introduction

Anthropogenic climate change has the potential to affect nearly all aspects of society, both positively and negatively (IPCC, 2007a). One adaptation response to severe climate impacts is migration, either within or across national borders (e.g. McLeman and Smit, 2006; Tacoli, 2009; Bardsley and Hugo, 2010; Feng *et al.*, 2010; Gemenne, 2011). Whether migration in response to climate change, or, more generally, environmental stress, is actually chosen as an adaptation option depends on many factors, discussed in more detail elsewhere (e.g. Julca and Paddison, 2010; Kolmannskog and Trebbi, 2010; Martin, 2010; Warner *et al.*, 2010; Marchiori and Schumacher, 2011; Piguet, 2011). Indeed, where regional effects of climate change are beneficial, climate change may act as a ‘pull’ rather than a ‘push’ factor (Piguet, 2011).

The purpose of this paper is to evaluate the potential impacts of high levels of climate change by 2060 on three key environmental push factors that, if sufficiently strong, could trigger or contribute to migration. The study looks specifically at the 2060 time horizon, as requested for the Foresight Migration and Global Environmental Change Project. Additionally, this horizon is particularly pertinent, as it is a time at which many population growth scenarios suggest global population will peak, producing a particularly sensitive climate–environment–population nexus. The paper focuses on ‘high-end’ climate change, enabling the exploration of a worst-case scenario that would result in the absence of meaningful efforts to reduce greenhouse gas emissions between now and 2060.

The paper begins with an assessment of the potential for continued high greenhouse gas emissions through to the middle of the century, and the range of global and regional climate changes that would be associated with a specific high-end emissions scenario, namely the IPCC Representative Concentration Profile 8.5 (RCP 8.5). The paper then presents an assessment of the geographical impacts of climate change for three key environmental push factors that could affect migration: water resources, agriculture and food security, and sea-level rise (SLR). In each case general issues and vulnerabilities are discussed, along with identification of key regions with high vulnerability. This is followed by a quantitative analysis, on a country-by-country basis, of the nations most at risk from joint impacts of climate change on water, agriculture and SLR. Next, the potential for environmental tipping points to induce rapid changes in environmental ‘triggers’ by 2060 is assessed. Finally, results are synthesised to provide an overall picture of the potential scale of climate-driven stresses on migration by analysing the number of people at risk by 2060 in the three sectors – water, food, SLR – under a mid-range (SRES A1B) population scenario.

The plausibility of high emissions through to 2060

In this section we evaluate the plausibility of high-end emissions, similar to and beyond the IPCC SRES A1FI and RCP 8.5 scenarios. There are two underlying assumptions to this analysis: (i) sufficient fossil fuels exist at affordable prices to maintain emissions on a high-emission pathway; (ii) there is insufficient control on emissions to prevent fossil fuels dominating the global energy mix.

There are significantly differing views on the total available and affordable fossil fuels. However, across the range of estimates in the literature there is sufficient carbon locked up in the portfolio of conventional and unconventional fossil fuels to follow, if not exceed, an RCP 8.5-style emissions pathway. Moreover, although there is an absolute physical limit to the total quantity of fossil fuels, in practice the availability relates, in significant part, to the price of the fuel and hence the maximum cost of extraction/recovery.

The history of fossil fuels is littered with concerns about a future economic crisis being triggered by the price of crude (typically a proxy for fossil fuels). In the 1970s and 80s prices fluctuated wildly, with US$30/barrel considered prohibitive, yet Western economies weather such prices through a mix of elasticity of demand and prices falling back. More recently, prices have risen to highs of almost US$150/barrel and now fluctuate between US$80 and US$100.

Opportunities for significant low or no cost improvements in efficiencies typically offer scope to compensate for very high increases in energy prices. In this regard, the technical and institutional lock in to fossil fuels can continue with barrel prices in the US$200–600 mark. This opens up massive unconventional reserves, deep sea and Arctic exploration, as well as a wealth of previously prohibitively expensive secondary and tertiary recovery techniques.

Despite on-going international negotiations, there remains a gulf between discussions on temperature targets and actual mitigation policies. The absence of any meaningful post-2012 emission constraints, the low aggregate voluntary reductions associated with the Copenhagen Accord (Rogelj *et al.*, 2010; UNEP, 2010) and the likelihood that the USA will now not sanction significant emission cuts within the current and possibly the next political cycle increase the possibility of emissions rising unchecked for many more years. In addition, the last two decades have witnessed little progress in decoupling economic growth from carbon emissions and there remains little to indicate any substantial decoupling in the near-to-medium future (Friedlingstein *et al.*, 2010; Garnaut, 2011).

A1FI, RCP 8.5 and beyond – a brief foray into the numbers

Table 1 shows headline figures for CO_2 emissions for the SRES A1FI and newer RCP 8.5 scenarios. Whilst both the A1FI and the RCP 8.5 scenario represent the apparent high end of emissions, the annual growth rate assumed for the 2010–20 period (~2.6% from Table 1) is lower than the 5% the International Energy Agency estimates for 2010 (IEA, 2011). Although emissions in the recent economic downturn dropped by ~1.3%, the scale of emission reduction was not as great as had been anticipated, in significant part because the emissions of China and India continued to rise (Kone and Buke, 2010). Emissions are anticipated to have risen back to a long-term trend 3% and 4%[1] from 2010 (Friedlingstein *et al.*, 2010; Garnaut, 2011), at least for the next 5 years or so.

[1] The lower of these numbers assumes an improvement in carbon intensity of ~1.7% p.a., whilst the higher number assumes an intensity improvement of around 1% p.a.

Table 1: Emissions growth and decade-end emission under the A1FI scenario, and the corresponding decade-end emission for RCP 8.5

Decade	Typical growth in emissions p.a.	A1FI emissions in end year ($GtCO_2$)	RCP 8.5 in end year ($GtCO_2$)
2010 to 2020	~2.6%	41	*~42*
2021 to 2030	~2.7%	54	*~49*
2031 to 2040	~2.5%	68	*~59*
2041 to 2050	~2.2%	85	*~70*
2051 to 2060	~0.9%	92	*~81*
2061 to 2070	~0.8%	100	*~92*
2071 to 2080	~0.7%	107	*~97*
2081 to 2090	~0.2%	109	*~103*
2091 to 2100	~0.2%	111	*~104*

With recent trends in mind, and with the assumptions outlined earlier, weak or no effective constraints on carbon emissions would suggest there is scope for emissions to rise at over 4% p.a. for the coming decade, if not longer. Given that the aim of this document is to consider explicitly the upper bounds of reasonable emissions profiles, and in light of the analysis above, a 3–4% annual increase in emissions out to 2025/30 is certainly plausible[2]. Moreover, a recent hypothetical study taking plausible variations on the A1FI assumptions with regard to population growth, per capita primary energy demand and fuel mix illustrates how moderate changes to input parameters results in emissions by 2100 between two and four times higher than the levels within A1FI (Sanderson *et al.*, 2011)

[2] Disaggregating global to Annex 1 and non-Annex 1 suggests even a higher emission profile could be plausible. Non-Annex 1 emissions grew at 6% between 2000 and 2008. If this was allied with a 1% p.a. reduction in emissions from Annex 1, and given non-Annex 1 emissions increasingly dominate total emissions, the net global growth rate would be even higher (possibly 5% or more).

Beyond 2030, the range of issues that drive emissions becomes more speculative – but certainly China and India do not, typically, envisage their emissions peaking till around 2030 (Kone and Buke, 2010). If the assumptions about Asian industrialisation extending beyond current nations is even partially realised, the A1FI growth for 2030–40 again looks relatively conservative.

Consequently, a plausible outlier of emissions growth could include 4% p.a. to 2030 and 3% to 2040. Even if emissions subsequently drop to the much lower annual growth rates assumed in A1FI from 2030 out to 2100, this brief analysis suggests plausible emission scenarios can be constructed with emissions well in excess of those in either A1FI or RCP 8.5.

Global and regional changes in climate in 2060 under high-end emissions scenarios

Taking the RCP 8.5 as a plausible high-end emissions scenario, a range of global and regional climate changes are possible. At the global scale two key factors are in play (Hawkins and Sutton, 2009). First, uncertainties in biogeochemical cycling, especially the carbon cycle, mean that a given emissions scenario can results in a range of atmospheric GHG concentrations (Friedlingstein *et al.*, 2006). Second, uncertainties in feedbacks in the climate system, such as cloud, water vapour and snow/ice albedo, mean that even if atmospheric concentrations of GHG and aerosols are known, the warming response is uncertain. The range of possible global temperature changes associated with RCP 8.5 has been estimated by the Met Office Hadley Centre (2010) using the MAGICC simple climate model, which accounts for these uncertainties (see Figure 1). By 2060, RCP 8.5 would result in a best estimate change in global temperature of 2.17°C over 2010 global temperature (3.25°C over preindustrial temperatures), with a 90% confidence interval of 1.52–3.02 (2.6–4.1 over preindustrial).

These temperature ranges are used as the starting point for the remainder of the analysis. For reference to previous scenarios, these 2060 RCP 8.5 5th, 50th and 95th percentile temperature changes correspond quite closely to the IPCC Fourth Assessment central estimates of global temperatures at 2100 for the SRES B1, A1B and A2 emissions scenarios.

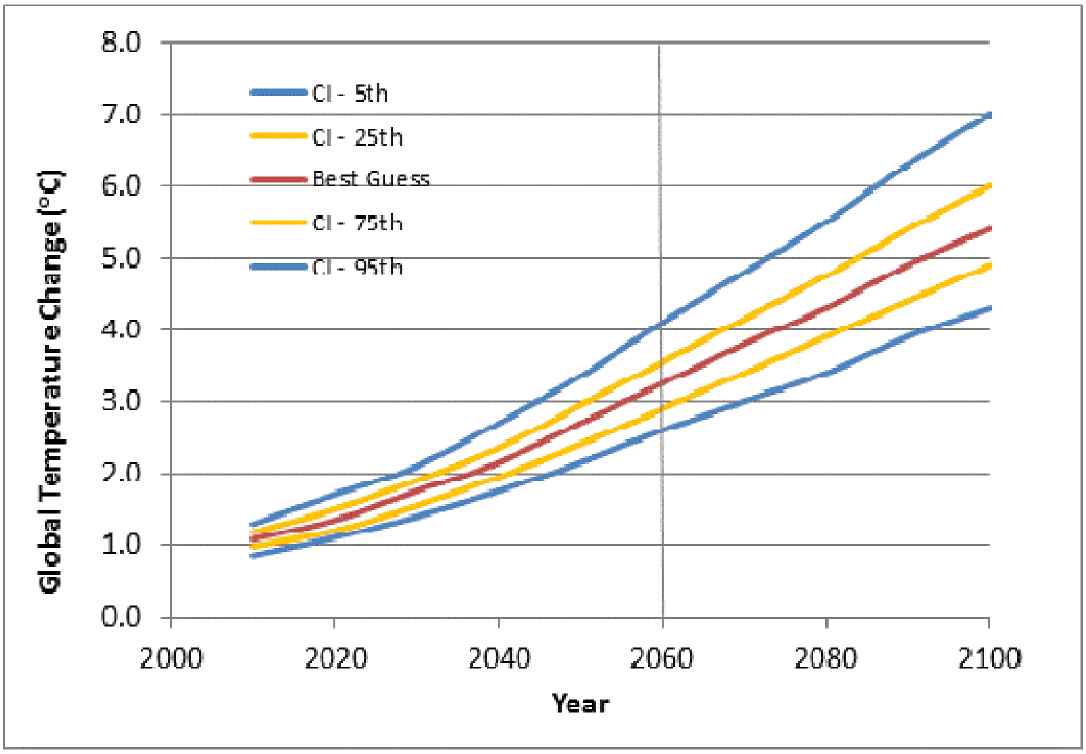

Figure 1: Range of global temperature changes from preindustrial levels resulting from the RCP 8.5 emissions scenario, simulated by the MAGICC simple climate model, taking into account uncertainties in ocean heat uptake, carbon cycle response in a warming climate and climate sensitivity (Met Office Hadley Centre, 2010)

Regional changes in temperatures and precipitation associated with RCP 8.5 5th, 50th and 95th percentiles were examined by extracting GCM results from the CMIP3 archive. For each GCM simulation under the SRES A2 emissions scenario, the date on which an individual GCM global mean temperature reached the 2060 RCP temperature was identified, and the pattern of changes relative to 2010 was determined. The patterns of change for temperature and precipitation are, as might be expected, similar to those reported by the IPCC AR4, with the key difference that the high-end emissions result in larger changes at the 2060 time horizon (Figure 2). For temperature, changes relative to the global mean temperature are broadly similar for the three RCP 8.5 percentiles, implying that the regional changes become amplified in absolute temperature terms. For precipitation, the areas in the subtropics subject to drying become larger and more intense as one moves from the low to the high RCP 8.5 global temperatures. Therefore, for both temperature and precipitation, regional impacts are likely to be non-linearly amplified for higher global temperatures.

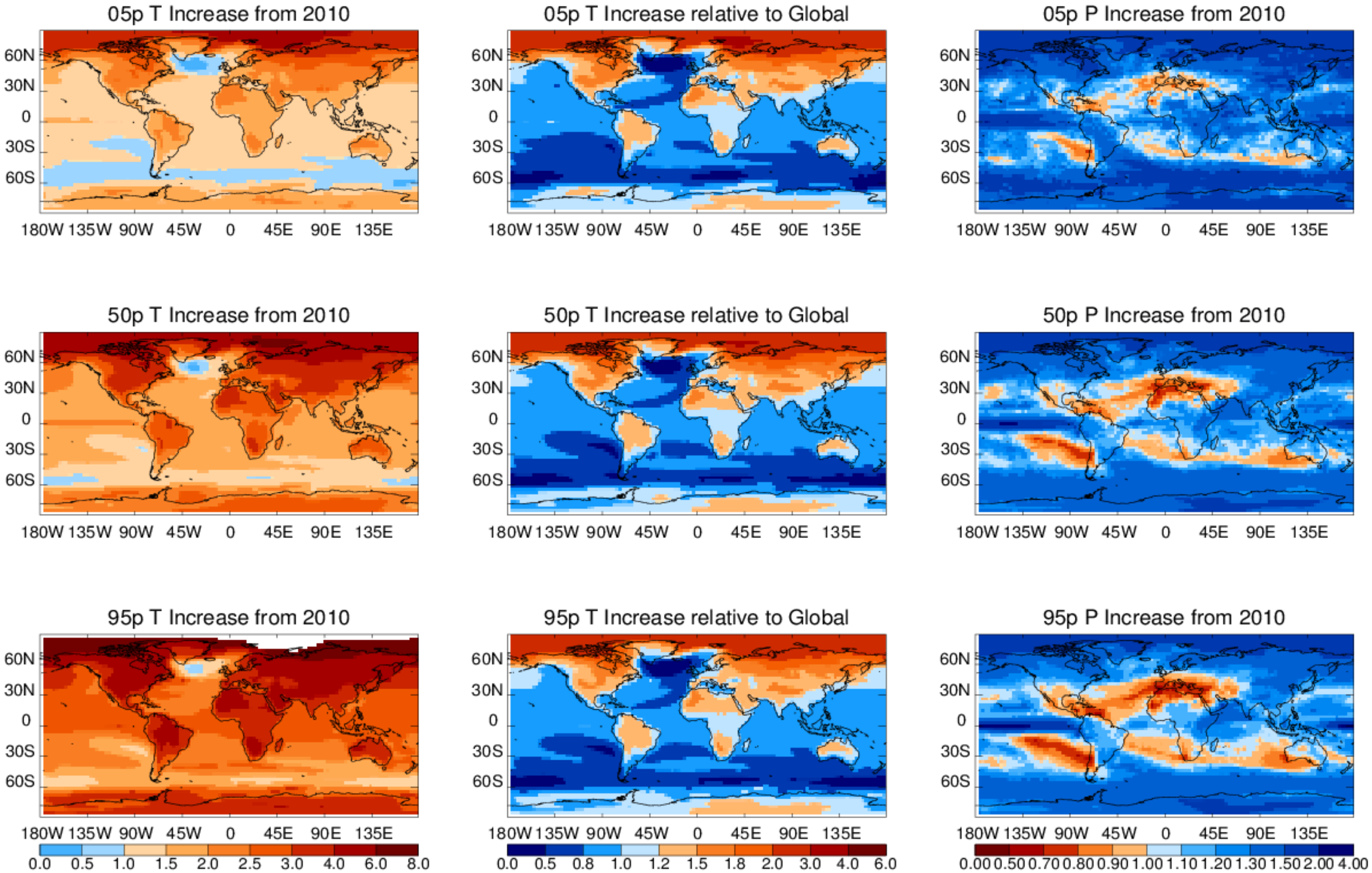

Figure 2: The GCM ensemble mean pattern of change of annual temperature (left) and precipitation change (right) at the 5th, 50th and 95th percentiles of RCP 8.5 global temperature change in 2060, relative to 2010 temperatures. The central panel shows the ratio of local changes in temperature relative to the global mean temperature change associated with each RCP 8.5 percentile

Implications for environmental factors potentially affecting migration

Water

Water is rather unique in that both excess and shortage can cause stress and harm (Grey and Sadoff, 2007), and potentially drive migration. Climate change can alter both these facets, both directly and indirectly. Reductions in water availability are driven by the changes in the net balance between precipitation and evaporation. Evaporative demand is projected to increase due to a warmer atmosphere, but any changes in evaporation would be mediated by soil moisture and perhaps improved plant water use efficiency under elevated CO_2 concentrations. Precipitation increases would act to offset enhanced evaporative losses, and if large enough, increase water availability; decreases in precipitation would act with evaporation to decrease water availability. Without technical or behavioural changes, water demand is also likely to increase with climate change, especially irrigation demands. Changes in precipitation intensity and duration will also affect flood frequency and magnitude. Water stress, water security and related issues merit a full review on their own, and are beyond the scope of this report; therefore we address only the most direct effects of high-end climate change on water availability, identifying major river basins where climate change will be a significant driver of water stress.

A widely used index of water stress, initially used by Falkenmark and Widstrand (1992), and by others with various modifications, relates mean annual runoff to population; lower per capita runoff is taken to indicate higher first-order water stress[3]. Unsurprisingly, stress ‘hotspots’ are generally located in arid and semi-arid regions or in more humid regions with high population densities. More nuanced versions of this index, such as the ratio of actual withdrawals to available water resources (Vorosmarty *et al.*, 2000; Alcamo *et al.*, 2003) or the percentage of a river basin or country’s territory affected by oversubscription of water (epi.yale.edu), show similar geographical patterns. Several studies have explored the sensitivity of water stress to climate change using similar indices (e.g. Arnell, 2000; Vorosmarty *et al.*, 2000; Alcamo *et al.*, 2007; Arnell *et al.*, 2011; Fung *et al.*, 2011).

Water stress hotspots under high-end climate change in 2060

To specifically explore the potential implications of high-end climate change we build on the work of Fung *et al.* (2011), who used the Mac-PDM water balance model (Gosling and Arnell, 2011, and references therein) to contrast the possible impacts on water availability under 2 and 4°C global warming. Mean water availability (runoff) in 2060 is determined for the 5th, 50th and 95th percentiles of global temperature change relative to 2010 in 112 major river basins, by driving

[3] First-order water stress relates to the absolute amount of water available. This may be moderated by second-order factors, such as infrastructure and governance, that hamper access to this potentially available water.

Mac-PDM with the temperature and rainfall changes from each of the GCMs analysed for Figure 2. The inputs from each GCM are for the 30-year period centred on the time that the GCM warms by the corresponding percentile of RCP 8.5 2060 global mean temperature. Water stress in each basin is then calculated as catchment mean runoff per capita under four spatially explicit UN population scenarios – high fertility, low growth, medium growth and high growth[4].

When climate change alone is considered as a driver of water stress[5], by holding population at 2010 levels, 54% of river basins globally experience increased water stress under the 50th percentile RCP 8.5 climate changes, and 24% experience significant (>10%) increases in water stress (Table 2). The distribution of increased stress varies geographically, with most of Africa, South America, Australia, southern Europe and the USA and Mexico showing increased stress, and northern latitudes showing reduced stress (Figure 3). For higher levels of global temperature change, the number of basins showing increased stress is larger, and stress changes are also larger. In most regions, at least half of the river basins negatively affected by climate change are already considered moderately or highly stressed (Table 2) according to the analysis by Alcamo *et al.* (2000) for the World Commission on Water.

When population growth is considered either alone or in combination with climate change, it is clear that water stress in many river basins in low- and middle-income countries is likely to be more sensitive to population than climate change (Figure 3). This corresponds to previous studies that have taken into account the interactions of climate change and population change on water stress (Vorosmarty *et al.*, 2000; Arnell, 2004; Scholze *et al.*, 2006; Alcamo *et al.*, 2007; Arnell *et al.*, 2011; Gosling *et al.*, 2011); changes in demand, driven mainly by population growth, but also by urbanisation and industrialisation, would be the primary driver of future water stress, except in a few areas such as the Mediterranean region, where rainfall decreases could be particularly large. Elsewhere, if runoff were reduced, it would act to exacerbate population-driven water stress rather than be the primary driver of water stress. In some areas, climate change could actually act to reduce population-related stress, by increasing runoff. However, increased rainfall and runoff would often lead to larger flood events, a potential push factor for migration (Piguet *et al.*, 2010).

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[4] National population scenarios are from projections by DESA (2007), combined with distributions of rural and urban populations from CIESIN (2004, 2005).

[5] Excluding the effects of climate change on demand, but including the direct effects of evapotranspiration, and holding population constant at present-day levels.

Table 2: Percentage of major river basins showing an increase (>0%) or significant increase (>10%) in potential water stress (WSI, after Fung *et al.*, 2011) due to climate change alone, under the 5th, 50th and 95th percentiles of the RCP 8.5 2060 global temperature change. Figures in brackets show the percentage of basins with an increasing WSI and categorised as highly or moderately stressed in 2000 by Alcamo *et al.* (2000)

Change in WSI	Increase by >0%						Increase by >10%					
Percentile RCP 8.5	5th		50th		95th		5th		50th		95th	
Africa	23	(14)	68	(23)	64	(23)	9	(5)	32	(14)	32	(14)
Asia	7	(7)	23	(17)	20	(17)	0	(0)	0	(0)	0	(0)
Australasia	0	(0)	40	(20)	40	(20)	0	(0)	20	(20)	20	(20)
Europe	41	(22)	59	(41)	67	(48)	22	(11)	41	(22)	52	(33)
N America	42	(37)	58	(42)	68	(47)	32	(26)	32	(26)	37	(26)
S America	78	(11)	100	(11)	89	(11)	22	(11)	22	(11)	33	(11)
Global	29	(17)	54	(28)	54	(30)	14	(9)	24	(14)	29	(17)

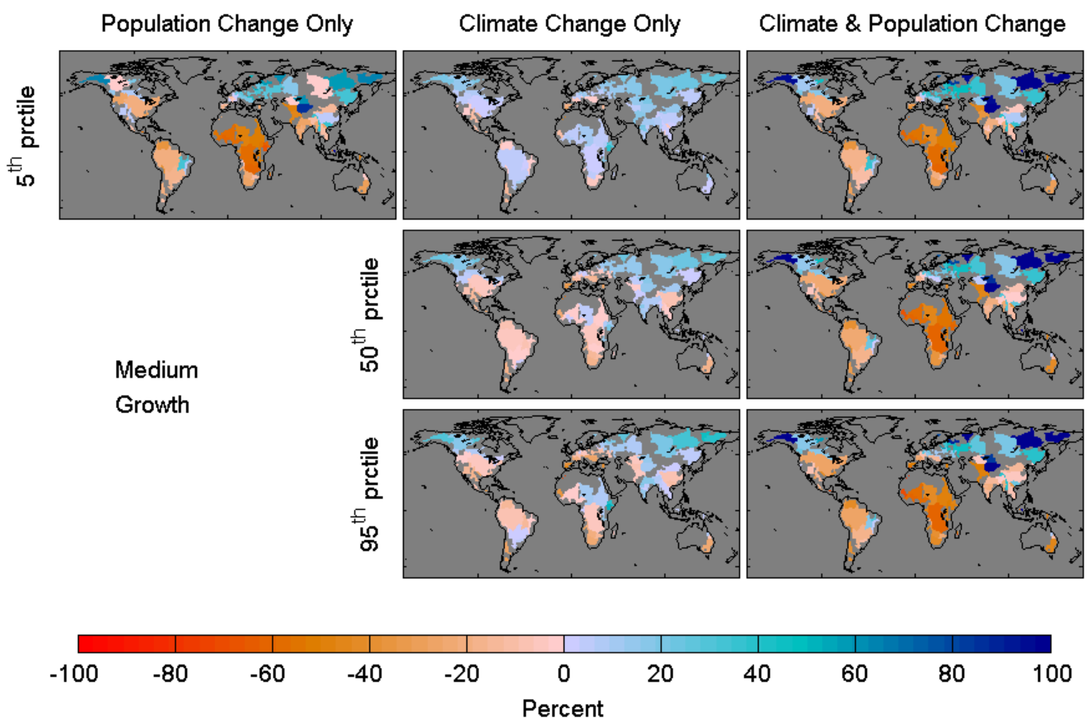

Figure 3: Mean changes in water stress index (per capita runoff) in 112 major river basins, under different combinations of climate change (5th, 50th and 95th percentile of RCP 8.5 climate change in 2060) with the UN medium-growth population scenario

A similar study by Arnell (2004) investigated the number of people living in water-stressed river basins under climate change and population growth scenarios. Under a similar population scenario to the medium-growth scenario illustrated in Figure 3, in the absence of climate change approximately 60% of the global population was projected to be living in moderately or highly stressed river basins in 2055, whereas only 53% of the global population was classed as living in water stressed *countries*. This illustrates a general problem with using country-level water stress indicators, in that many have population concentrated in a few river basins, and river basin stress can be higher than country-averaged stress. When climate change is considered (Table 3), under the A2 emissions and population scenario, climate change in 2055 does not significantly change the total number of people living in moderately to highly stressed catchments, although the distribution between stressed categories does vary, particularly between high and moderate stress (1,000 m^3/cap/ann).

Arnell also identifies, on a regional basis, the balance between the numbers of people switching from no or moderate water stress into a high or extreme stress situation (Table 4). While there is variation between results for different climate models, some regions can be identified as particularly vulnerable to a net switch of a high water stress situation: northern and southern Africa, Mashriq, Southeast Asia and Great Mekong, Europe, the USA, the Caribbean and Meso-America.

Table 3: Percentage change in the number of people experiencing water stress with climate change, relative to without climate change in 2055 under the A2 emissions and population scenario. Stress is defined in cubic metres per capita per annum (> 1,700 = unstressed, 1,000–1,700 = moderately stressed, 500–1,000 = highly stressed, < 500 = extreme stress) (data from Arnell, 2004)

Stress level (m^3/cap/ann)	GCM							
	HadCM3	ECHAM	CGCM	CSIRO	GFDL	CCSR	Mean	SD
>1,700	−4.4	0.2	−2.1	−0.7	−9.7	7.4	−1.5	5.2
1,000–1,700	9.8	46.7	−3.2	58.6	21.6	−14.1	19.9	25.8
500–1,000	12.2	−23.4	8.9	−7.0	13.0	−1.8	0.3	12.9
<500	−10.8	−12.9	−2.3	−34.5	−12.6	1.5	−12.0	11.5
<1,700	2.289	−0.104	1.092	−0.247	5.033	−3.824	0.7	2.7

Table 4: Millions of people in catchments that shift into and out of water stress in different world regions, under the A2 population and emissions scenario. Stress is defined as catchment average runoff <1,000 m^3/cap/ann. Data adapted from Arnell (2004), taking the mean and standard deviation from six GCMs reported individually in the original work

	Into stress		Out of stress		Into vs out of stress	
	Mean	SD	Mean	SD	Difference	Ratio
Northern Africa	197	70	74	69	123	2.7
Western Africa	57	48	72	36	−14	0.8
Central Africa	18	24	20	20	−2	0.9
Eastern Africa	68	58	123	52	−55	0.6
Southern Africa	46	33	29	25	18	1.6
Mashriq	132	32	19	22	113	7.0
Arabian Peninsula	35	75	229	111	−193	0.2
Central Asia	56	57	54	50	2	1.0
South Asia	373	305	1794	318	−1421	0.2
Southeast Asia	4	4	2	2	2	2.6
Greater Mekong	41	32	6	7	34	6.5
North-west Pacific	404	329	477	336	−74	0.8
Australasia	0	0	0	0	–	–
Western Europe	142	61	13	25	129	10.8
Central Europe	125	25	0	0	125	–
Eastern Europe	21	5	1	1	20	21.3
Canada	7	2	0	0	7	–
USA	87	30	13	11	74	6.7
Caribbean	12	17	8	13	4	1.5
Meso-America	71	37	33	27	38	2.1

	Into stress		Out of stress		Into vs out of stress	
	Mean	SD	Mean	SD	Difference	Ratio
South America	31	22	21	15	10	1.5

Other factors

Annual average water stress figures hide a range of other potential impacts that may in specific circumstances be very important. For example, changes in seasonality, or reduced dry-season flows, even with no reduction in mean annual runoff, can cause temporary stress, especially in areas where there is limited infrastructure to store water from the wet season (Taylor, 2009). In semi-arid areas, drier conditions can lead to smaller water courses becoming ephemeral (de Wit and Stankiewicz, 2006), adding to difficulties in water access for rural communities.

An important caveat with all assessments of hydrological response to climate change concerns the large spread in projected changes in precipitation from different GCMs over many areas of the globe. While a relatively consistent picture of increasing precipitation in high latitudes and strong drying in the Mediterranean emerges from GCM projection, there is little consensus on even the direction of precipitation change over most of the tropics and subtropics (IPCC, 2007b: 16, figure SMP-7). For the analyses presented in Figure 3, areas with little or no change in ensemble mean water stress reflect this lack of consensus rather than a clear sign of 'no change'. Some indication of the magnitude of climate model uncertainty is evident in Tables 3 and 4, where the spread of impacts across six models is shown.

The results presented here do not consider the effects of elevated CO_2 on plant water use efficiency, and hence soil moisture and runoff (Field *et al.*, 1995). A study using the Hadley Centre land-surface model (Gedney *et al.*, 2006) has suggested that elevated CO_2 has played a role in continental-scale observed changes in runoff, moderating the effects expected by observed precipitation changes. While there is considerable uncertainty about the long-term effects of CO_2 fertilisation on both plant growth and water use efficiency, there is likely to be some non-zero reduction in plant water use. So the results presented here, and those of many other studies where CO_2 effects are not considered, are likely to underestimate increases in runoff and overestimate decreases in runoff (Betts *et al.*, 2007). However, the relative ranking of changes in stress across catchments in unlikely to vary much, as the offsetting effects of CO_2 are broadly similar in different catchments.

Also not considered fully in Figure 3 and Table 2 are countries that do not have a major river basin, which includes much of the Middle East and North Africa, all small island states and Western Australia. These countries are however included in Tables 3 and 4, and in a later section looking at combined risk across water, agriculture/food and coastal inundation.

Agriculture and food security

The combination of increasing temperatures, shifting rainfall amounts and patterns, and increasing variability will clearly have impacts on crop and livestock agriculture. At mid to high latitudes, crop productivity may increase slightly for local mean temperature increases of up to 1–3°C, depending on the crop (although changes in rainfall patterns and amounts could well offset this benefit), while at lower latitudes, productivity of crops *currently* grown is projected to decrease for even relatively small local temperature increases of 1–2°C (IPCC, 2007a). Livestock production will likely also suffer via a range of impacts, including those mediated through animal feed, a critical constraint on livestock production in the tropics, much of which is derived from crop residues in smallholder systems.

A wide variety of methods has been applied to the problem of estimating the impacts of climate change on agricultural production in different parts of the world, with considerable variation in results, for many reasons: differences in climate models used, in emission scenarios used, in methods of downscaling and in the methods used to evaluate impacts themselves.

Here we synthesise results from some key studies that have used climate change scenarios corresponding approximately to 5th, 50th and 95th percentiles of the RCP 8.5 scenario. Many studies on agricultural impacts with AR4 data go out to 2030 or 2050 only, with corresponding global temperature increases of about 1.5°C over current, equivalent to the 5th percentile of possible temperature increases under RPC 8.5 by 2060. An example is shown in Table 5, from Nelson *et al.* (2010), where results are from crop model simulations, driven by synthetic daily data associated with a downscaled future climatology, and suggest interesting regional and crop-specific differences. The authors argue that properly targeted agricultural productivity investments will be able to mitigate the impacts of climate change and enhance sustainable food security, and that international trade will play an essential role in compensating for various climate change effects.

Table 5: Simulated yield changes (%) due to climate change to 2050: MIROC 3.2 medres model, scenario A1B (data from Nelson *et al.*, 2010: Table 5)

Region	Maize		Rice		Wheat	
	Irrigated	Rain-fed	Irrigated	Rain-fed	Irrigated	Rain-fed
Developed	−12.3	−29.9	−13.3	−12.8	−11.6	−9.0
Developing	−5.2	−3.5	−11.9	0.1	−13.4	−10.4
Low-income developing	−3.4	−0.5	−9.1	−1.6	−12.6	−18.0
Middle-income developing	−5.3	−4.1	−12.5	−0.7	−13.4	−10.0

	Maize		Rice		Wheat	
World	−7.2	−12.0	−12.1	0.1	−13.2	−9.9

Another study (Jones and Thornton, 2009) suggests that temperature shifts similar to the 5th percentile of RCP 8.5 may have severe impacts on crop and livestock productivity in some places, to the point at which existing livelihood strategies of rural people may be seriously compromised. These places include parts of Africa that are already marginal for crop production; as these become increasingly marginal, livestock may provide an alternative to cropping. Substantial changes to people's livelihoods and agricultural systems may be required if food security is to be improved and incomes raised. Schlenker and Lobell (2010) used completely different methods (a panel analysis of historical crop production and weather data) to arrive at substantially similar conclusions for sub-Saharan Africa at the middle of this century – if anything, their analysis is more pessimistic than that carried out with simulation models.

At the 'warmer' end of the spectrum, other impacts work has been done for much higher temperature changes, beyond even the 95th percentile of possible temperature increases under RCP 8.5 by 2060. The yield estimates from Cline (2007) shown in Table 6 refer to a global temperature increase of 4.95°C over current by the 2080s. As might be expected, even aggregated yield reductions are substantial, particularly without carbon fertilisation effects. As another example, impacts of a global temperature of 5°C over pre-industrial are shown in Table 7 for three crops in sub-Saharan Africa (Thornton *et al.*, 2011). These results suggest serious regional declines for both maize and beans, the latter being a much more temperature-sensitive crop. Other results from this study indicate that rain-fed cropping south of latitude 18°S would be difficult if not impossible in such a climate because of the high risk of crop failure each year.

Note that there is still considerable uncertainty as to the likely magnitude of any carbon fertilisation effect on future crop yields. This is particularly so in developing countries, where yields are frequently limited by water, farming practice and fertiliser inputs rather than CO_2. More generally, field-based studies indicate that 'real world' effects of CO_2 may be only 50% of those achieved in laboratory studies for C_3 plants, and even lower for C_4 plants (Long *et al.*, 2006). This is of particular concern for African countries as many of the current cereal crops are C_3 plants (maize, millet, sorghum).

Table 6: Summary country-based estimates for impact of global warming on world agricultural output potential by the 2080s. All changes in per cent, relative to late twentieth century (from Cline, 2007)

	Without carbon fertilisation	With carbon fertilisation
Global	−23.6	−12.1

	Without carbon fertilisation	With carbon fertilisation
Industrial countries	−6.3	7.7
Developing countries	−25.8	−14.7
Africa	−27.5	−16.6
Asia	−19.3	−7.2
Middle East–North Africa	−21.2	−9.4
Latin America	−24.3	−12.9

Table 7: Simulated yield changes in sub-Saharan Africa for three crops grown on cropland and pastureland to the 2090s. Variation between four different climate models and three emission scenarios is shown by the coefficient of variation (CV) (data from Thornton *et al.*, 2011)

	Mean % change in production	CV of change in production %
Maize (C4)	−24	19
Beans (C3)	−71	34
Brachiaria decumbens*	−7	15

**Indicator grass species*

For the median temperature increase under RCP 8.5 to 2060 of 2.17°C, the possible impacts on crop yields can be estimated from crop temperature responses, such as in Table 8 (from Easterling *et al.*, 2007). As before, this aggregation hides a great deal of spatial variation, as evidenced by the large standard errors in Table 8, but it is clear that with the median temperature increase, all crops could suffer mean yield decreases (these yield declines are for the situation in which no adaptation occurs). These results again show that sub-Saharan Africa is particularly at risk, with its relatively low dependence on wheat and rice but high dependence on maize.

Table 8: Per cent yield changes at low latitudes for different local temperature changes, estimated from Easterling *et al.* (2007: Figure 5.2). SE is the standard error of estimate for the best-fit polynomial to the data, estimated from the original figures. Individual studies contributing to this table reflect a range of precipitation changes and CO_2 fertilisation effects

	Temperature change			
	+1.52°C	+2.17°C	+3.02°C	SE
Maize	−3.1	−7.6	−16.6	15.8
Wheat	+0.5	−7.4	−18.3	15.4
Rice	−3.8	−7.8	−11.5	9.7

What might such results mean for food security in the future? In relation to agricultural production, even the 5th percentile of possible temperature changes under RCP 8.5 to 2060 is likely to bring about considerable shifts in cropping patterns in developing countries, and marginal environments are likely to become even less suitable for cropping, with serious implications for livelihood options in such places. It should be noted that in the modelling approaches indicated above, the impacts of climate change on agricultural systems and rural households are very likely to be underestimated; they generally exclude secondary climate change effects via the impacts of pests, weeds and crop and livestock diseases; similarly, potential changes in climate variability have not been accounted for, although we know they already can have enormous implications for households and livelihoods (Matlon and Kristjanson, 1988). With median and higher temperature increases, these impacts will obviously be exacerbated. In any event, if climate change reduces food production, either regionally or locally, this would affect incomes of, and food prices faced by, poor households, in turn affecting other components of food security such as food accessibility and utilisation (perhaps via health impacts, for example), as well as food availability.

Impacts could be felt well beyond crop production systems. In the mixed crop–livestock systems of the tropics, for example, crop residues are a critical dry-season feed resource. The projected negative impacts on crop yields outlined above may have serious knock-on effects on the amount of crop residues that are produced. Food-feed crops are particularly important in South Asia and southern Africa, regions home to large human populations which depend to varying degrees on livestock for their livelihood and food security.

For the pasturelands and rangelands, there are few, if any, comprehensive studies of climate change impacts that include an assessment of the likely changes in water, carbon and nutrient cycling (McKeon *et al.*, 2009); the interactions of these factors with plants, livestock grazing and land management practices are complex, and appropriate models are lacking. In rangeland systems in general, increases in temperature, which are likely to result in a decrease in forage production, may exacerbate or reduce the effects of changes in rainfall, while at the same time, the effects of increased CO_2 concentrations may enhance forage production and water use efficiency (Morgan *et al.*, 2011). Impacts are uncertain and will depend on the specifics of each situation. The rangelands of East Africa, for example, may experience some ecosystem service benefits through increased precipitation, but impacts on the region's livestock are complex: in one modelling study, all simulations showed future increases in tropical woody vegetation at the expense of grasslands (Doherty *et al.*, 2010). This is supported by experimental work on southern African tree species that occur in grasslands (Kgope *et al.*, 2010). The increases in climate variability and extreme events that could occur will only compound pastoralists' food insecurity. Some argue that traditional pastoralists in the region face a dismal future, as climate variability and change would render their environment increasingly unsupportive of them (Blackwell, 2010). Particularly in the warmer futures, alternative livelihood options for pastoralists could be required if their food security is to be preserved or enhanced.

In all estimates of possible impacts of climate change on agricultural production and food security, there is a wide range of uncertainty, in terms both of possible impacts and adaptive capacity. For example, in some areas, rainwater harvesting may make rain-fed crops more resilient to within-season water stress (Rappold, 2005). Similarly, heat- and drought-resistant crops might be developed; the analysis here clearly demonstrates the need for adaptation. More work is required to try to reduce these uncertainties, particularly in relation to simulation modelling approaches as well as in approaches based on empirical relationships between agricultural productivity and climate variables using large data sets. At the same time, impacts need to be evaluated at the household level. The development of dynamic frameworks for household vulnerability to food security, building perhaps on a conceptual model such as that of McLeman and Smit (2006), could lead to much more robust estimates of true climate thresholds beyond which households that depend on cropping and/or livestock keeping may be forced into radical adaptation responses to preserve their food security, such as migration to urban areas or even more to benign climatic zones altogether.

Sea-level rise

SLR at any location is a function of global and local factors (Nicholls and Cazenave, 2010). Global factors are thermal expansion of warming oceans and inputs of melt from land-based iced stores, primarily mountain glaciers, small ice caps and the Greenland and Antarctic ice sheets. Local and regional effects will mediate globally averaged SLR; these include vertical movement (isostatic, tectonic and local subsidence) and gravitational effects (Mitrovica *et al.*, 2009; Bamber and Riva, 2010). The IPCC 4th Assessment Report projects increases in global sea level in 2100 for a range of emissions scenarios. As a first-order approximation, these can be related to 2060 temperature change under RCP 8.5, by assuming that the 5th, 50th and 95th percentiles of RCP 8.5 2060 global temperature change, and hence SLR, are equivalent to those for the B1, A1B and A2 scenarios in 2100

(Table 2). These estimates do not include dynamic ice sheet responses, which could add significantly to these levels in 2100, with a total SLR of up to 2 m, but with a very low likelihood of a rise above 1 m (Nicholls *et al.*, 2011). Whether significant dynamic ice sheet responses 'kick in' by 2060, even with higher-end temperatures, is uncertain; therefore, these 2100 values may be overestimates. However, observed SLR has been at a rate near the top end of multi-model estimates, and empirically based projections for the twenty-first century suggest rates faster than those projected by models (Rahmstorf, 2007; Vermeer and Rahmstorf, 2009).

Table 9: Potential global SLR (excluding dynamic ice sheet response) in 2060 derived from ranges from IPCC AR4 2100 projections, and an empirical model (Vermeer and Rahmstorf, 2009) for global temperature changes equivalent to the 5th, 50th and 95th percentile of RCP 8.5 in 2060

RCP 8.5 2060	SRES 2100	IPCC SLR likely range (m)	Empirical SLR estimate (m)
5th percentile	B1	0.18–0.38	0.50
50th percentile	A1B	0.21–0.48	0.60
95th percentile	A2	0.23–0.51	0.65

Impacts of SLR on the coastal zone will be mediated by (i) changes in other climate processes (Nicholls *et al.*, 2007), including storm frequency and intensity, wave climate, runoff and sediment supply, water temperature and CO_2 acidification; and (ii) the types of human use of the coastal environment (Dasgupta *et al.*, 2007) and local adaptation capacity (Nicholls and Cazenave, 2010). Nonetheless, Nicholls *et al.* (2007) identify coastal environments that are particularly vulnerable to SLR as deltas/estuaries (especially populated mega-deltas) and coral reefs (especially atolls); also potentially vulnerable are low-lying coastal wetlands, small islands, sand and gravel beaches and soft rock cliffs, depending on other local influences.

Population at risk

Coastal areas are among the most densely populated regions in the world. In 1990, some 190 million people lived in areas subject to a large-magnitude (1:1000 year) coastal flooding (Nicholls *et al.*, 2007), with the large majority of these located in the Asian mega-deltas. The impacts of SLR on these populations will result from the interplay between potential exposure – defined here as the areas at risk of flooding if there is no added protection over and above that existing today – and the amount of protection that is added. Nicholls *et al.* (2011) evaluated potential exposure under two global SLR scenarios for 2100 – 0.5 m and 2.0 m – assuming population grows according to the SRES A1B population scenarios. The most vulnerable areas under a 0. m SLR are South, Southeast and East Asia, with 24, 12 and 18 million people at risk, respectively (Figure 4). For a 2-m SLR, the populations at risk more than double, but new vulnerabilities also emerge, notably in north-western Europe and the Atlantic coast of North America, as existing defences become susceptible to failure. While a 2-m SLR can largely be ruled out for 2060, the particular regions at risk for intermediate SLR will remain the same. Further, the A1B population scenario peaks at about 9 billion in 2060, then declines to about 7 billion in 2100; thus, the absolute number of people at risk for a given SLR will be largest at 2060.

Dasgupta *et al.* (2007) undertook a more nuanced analysis of potential SLR impacts for 84 developing countries, across several metrics: total area, population, GDP, urban land extent, agricultural land extent and wetland area. The top 10 countries impacted by a 1-m SLR in each of these categories differ slightly, but many are common across all or nearly all categories: Vietnam, the Bahamas and Egypt are particularly vulnerable.

Figure 4: Relative vulnerability of coastal deltas as shown by the indicative population potentially displaced by current sea level trends to 2050 (extreme = >1 million; high = 1 million to 50,000; medium = 50,000 to 5,000) (from Nicholls *et al.*, 2007: Figure 6.6)

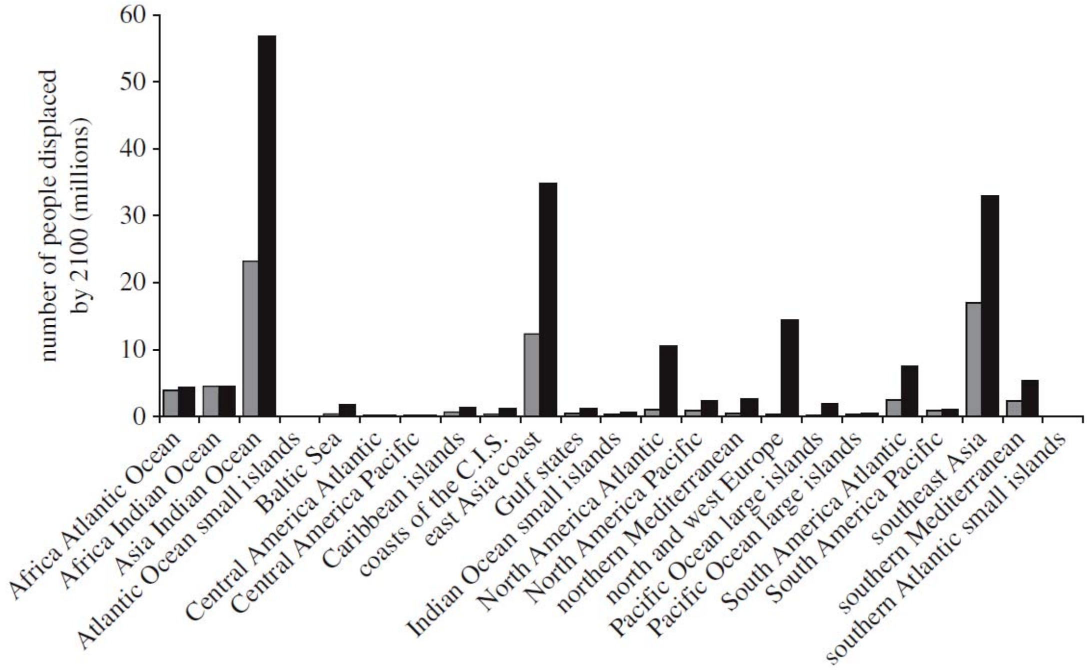

Figure 5: Population potentially at risk of displacement at 2100, for a global SLR of 0.5 m (grey) and 2.0 m (black), under the SRES A1B population scenario (from Nicholls *et al.*, 2011)

Table 10: The 10 most vulnerable countries, according to different impact criteria (Dasgupta *et al.*, 2007)

Rank	Area	Population	GDP	Urban extent	Agric. extent	Wetlands
1	Bahamas	Vietnam	Vietnam	Vietnam	Egypt	Vietnam
2	Vietnam	Egypt	Mauritania	Guyana	Vietnam	Jamaica
3	Qatar	Mauritania	Egypt	Fr. Guiana	Suriname	Belize
4	Belize	Suriname	Suriname	Mauritania	Bahamas	Qatar
5	Puerto Rico	Guyana	Benin	Egypt	Argentina	Bahamas
6	Cuba	Fr. Guiana	Bahamas	Libya	Jamaica	Libya
7	Taiwan	Tunisia	Guyana	UAE	Mexico	Uruguay
8	The Gambia	UAE	Fr. Guiana	Tunisia	Myanmar	Mexico
9	Jamaica	Bahamas	Tunisia	Suriname	Guyana	Benin
10	Bangladesh	Benin	Ecuador	Bahamas	Taiwan	Taiwan

Earth system tipping points

In addition to the incremental impacts on water, agriculture and coastal environments, there is a possibility that tipping points or thresholds in specific systems or environments can be crossed. Lenton *et al.* (2008) define a 'tipping element' as a component of the earth system that is at least regional in extent, which might undergo an large alteration or switch in state for a relatively small incremental perturbation. In the climate change context, a tipping element is one that remains in a state similar to the present as climate change proceeds in a largely monotonic manner, but then tips into a new state once climate change reaches some threshold. The Amazon forest, Atlantic thermohaline circulation (THC) and South Asian monsoon are examples of the tipping elements proposed by Lenton *et al.* (2008). Changes in environmental conditions, or the impacts on ecosystems services that people depend on, after an Earth system tipping point is reached could therefore be triggers for migration.

To evaluate potential impacts of tipping points in 2060, two factors need to be considered: first, the equivalent global temperature threshold at which the tipping point will occur; and, second, the time scale over which the tipping element responds. Table 11 lists major tipping elements identified by Lenton *et al.* (2008), along with additional elements suggested by other authors; the table also includes the suggested global warming threshold for each element, and the time scale over which the response will occur.

Comparing these thresholds against the 95th percentile of global temperature for RCP 8.5 (~3.0°C above present) suggests that only a few tipping points may be reached under high-end climate change in 2060: Arctic summer sea ice, Greenland ice sheet (GIS) and tropical reef systems. Arctic sea ice loss could have significant impacts on Arctic ecosystems and the communities that depend on these ecosystem services, and may lead to migration away from Arctic coastal regions if traditional lifestyles become unsustainable. Conversely, the opening of north-west and north-east ocean shipping routes, and the opening of the Arctic to petroleum and mineral exploration, may lead to job creation and inward migration. While irreversible melt of the GIS could be triggered by 2060, the effects on SLR will only be felt decades to centuries after this threshold, owing to the relatively slow response times, and will not be a significant influence in 2060, or indeed most likely the entire twenty-first century. Tropical coral reef systems are extremely vulnerable to climate change of 3°C or lower, with more frequent temperature-driven coral bleaching events potentially leading to declines in living coral cover, reducing reef diversity. The coupling of loss of ecosystem services from reef systems with inundation from SLR would affect small island developing states (SIDS) particularly heavily. Boreal and Amazon forest systems are thought be vulnerable to changes of 3°C or greater; if these thresholds are at the low end of their estimated ranges, the effects of shifts in these large ecosystems might appear under high-end climate change in 2060. It must be emphasised that the exact locations of the tipping points outlined above are uncertain; these uncertainties are illustrated to some extent in Table 11, but even the ranges given there are in many cases tentative.

Table 11: Summary of tipping points or potential threshold responses to progressive climate change. Rate of impact is the time scale of response once the tipping point is reached, expressed as annual (A), decadal (D) or centennial (C). ND indicates no tipping point temperature has been defined

Tipping point/threshold	Description	Global T over 1990s (°C)	Rate of impact	Reference
Tundra species	No shifts in S range, but temperatures affect colonisation/regeneration, so once current populations are gone, shifts could occur; N shifts are occurring. No projections.	ND	D–C	Doak and Morris (2010)
Human tolerance to heat extremes	35°C for extended period; need warming of 7°C over today to make this start to occur.	7	D	Sherwood and Huber (2010)
Dust	Bodele likely to become bigger dust source, but no threshold; unclear on impacts, both at surface (dust storms) and in feedbacks to regional climate.	ND	D–C	Washington *et al.* (2009)
Arctic summer sea ice	Positive feedbacks, albedo, leading to accelerated warming. Potential effects on ecosystem function, and livelihoods of local communities. Opening of NW passage in summer, with possible socioeconomic effects on region and also competing shipping routes.	0.5–2.0	D	Lenton *et al.* (2008), and references therein

West Antarctic ice sheet	Grounding line retreat due to rising ocean temperature, collapse and possibly enhanced outward flow. SLR of up to 5 m.	5	C	Lenton *et al.* (2008), and references therein
Greenland ice sheet	Accelerated surface warming, mass balance loss and surface elevation decreases provide positive feedback. Complete loss leading to an SLR of ~6 m.	1.0–2.0	C	Lenton *et al.* (2008), and references therein
Atlantic THC	Freshening of N Atlantic Ocean due to high-latitude ice and permafrost melt and enhanced precipitation. Cooler conditions over N Atlantic and NW Europe, possibly enhanced warming in S and Tropical Atlantic; possible effects on tropical rainfall, including reduced W African monsoon.	3.0–5.0	D, C	Lenton *et al.* (2008), and references therein
ENSO	Switch to more intense, persistent or more frequent El Niño (or La Niña) conditions. Large impacts of rainfall in the tropics and subtropics, with El Niño tending to cause drought over much of S Asia, S Africa, parts of S America, Australia, SW USA/Mexico; La Niña can induce above-average rainfall in same regions, but signal outside of Pacific is not as strong.	3.0–6.0	A, D	Lenton *et al.* (2008), and references therein

Indian monsoon	Weakening of Indian monsoon due to land-surface albedo changes and/or Asian brown cloud reducing surface heating; climate models generally show enhanced monsoon, but do not represent these effects well (albedo) or at all (brown cloud). Feedback through drought increasing surface albedo.	ND	A, D	Lenton *et al.* (2008), and references therein
West African monsoon	Enhanced warming strengthens the W African monsoon, with enhanced rainfall leading to a greening of the Sahel/Sahara; greening reduces albedo, further enhancing surface warming. Results from climate models are equivocal on whether GHG emissions will enhance W African rainfall. Additionally, the land-surface effects will be mediated by tropical Atlantic ocean temperature changes, as well as ENSO.	3.0–5.0	D	Lenton *et al.* (2008), and references therein

Amazon rainforest	Reduced precipitation, and therefore soil moisture, especially in dry season, leads to loss of moist tropical tree species, replacement by deciduous or savanna species. Possible positive feedbacks where moisture recycling over Amazon is reduced, further reducing rainfall, and albedo changes reduce surface heating, and hence convection. Threshold may be lowered if other factors come into play – fire and more intense drought periods. Threshold may be higher if plant water use efficiency improves under elevated CO_2.	3.0–5.0	D–C	Lenton *et al.* (2008); Nobre and Borma (2009)
Boreal forest	Increased water stress, increased peak summer heat stress causing increased mortality, vulnerability to disease and subsequent fire, as well as decreased reproduction rates, could lead to large-scale dieback of the boreal forests, and replacement by Steppe grasslands, as temperate forests could be slow to colonise. Very uncertain threshold, due to complex interplay of processes. Recent work shows changes in forest composition, with larch (higher albedo) being replaced by evergreen needle leaf (lower albedo).	3	D–C	Lenton *et al.* (2008), and references therein; Shuman *et al.* (2011)

Compost-bomb instability in drying organic soils	Enhanced microbial decompositon, heating faster than heat can be dissipated, local soil heating, feedback, even burning. Organic soils only.	10 (L)	D	Luke and Cox (2011)
Local large water body drying	Lake Titicaca cools local area, and supports precipitation; warming and drying could evaporate lake, leading to local drying and heating. Possibly a feature in other regions where lakes affect regional climate, but no data.	1–2 (L)	C	Bush *et al.* (2010)
Tropical coral reef systems	Coral bleaching caused by warm water events. Sea surface temperature (SST) anomalies 1–2°C greater than the usual summer maximum, sustained for several weeks, can cause coral breakdown of corals' symbiosis with the dinoflagellate algae which reside in coral tissue. Future ocean warming may increase the frequency and severity of coral bleaching events, leading to declines in living coral cover, reef complexity and populations of other reef-dwelling organisms; switches to algal dominated reef systems with low biodiversity may occur.	0.7–2.7	D	Donner *et al.* (2011)

Agricultural and water tipping points?

Several studies of agriculture and food production suggest that, without adapted crops and farming systems, tipping point-like thresholds may exist. For example, Schlenker and Roberts (2009) demonstrate that maize, soyabean and cotton yields in the USA show a sharp inflection in yield when mean temperatures rise above a (crop-specific) threshold; these inflections occur at temperatures below those associated with the upper range for RCP 8.5 in 2060. Burke *et al.* (2009) map out crop–climate thresholds for key African foods – maize, millet, sorghum – and show that for a global mean temperature change of 2.3°C (approximately the RCP 8.5 50th percentile), only 2–3% of area in each African country will have climatic conditions similar to those where these crops are currently grown. For many Sahelian countries, there will be crop–climate conditions for which there are no analogues over the whole of Africa. As noted above, Thornton *et al.* (2011) show that for higher climate changes (global temperature change of 5°C over preindustrial, ~4°C over 2010), the high risk of crop failure each year in southern Africa may make rain-fed cropping impossible. While these thresholds are not tipping points in the strict sense, they suggest the existence of thresholds beyond which current agricultural modes become impossible, and the possibility of tipping points in societal response.

Identifying tipping points or critical thresholds in water resource systems is even more problematic; indeed, there is very little discussion in the literature on water tipping points. At the household scale, a figure of 20–50 litres per person per day is considered necessary to meet basic needs (World Water Assessment Program, 2011), and failure to meet this need could constitute a tipping point that triggers movement away from an area simply to survive. The most direct link to climate change would likely be in rural areas that are not connected to large rivers or water resource systems; for example, de Wit and Stankiewicz (2006) showed how decreased precipitation could increase the number of ephemeral rivers in much of subtropical Africa, which could lead to permanent or at least periodic loss of access to water by rural communities. In areas connected to a water resource system, as is the case for most urban areas, climate-driven tipping points in basic water delivery could occur through competing demands for water from industry and agriculture. Assessments that look at the ratio of withdrawals to available water under climate change provide an indication of areas where these conflicts might arise, but do not consider the potential for demand-side management to alleviate the problem.

In the case of both water and agriculture, more research is needed on the nature and mechanisms of tipping points, and in particular the relationship between frequency of failure and climate variability.

Detecting tipping points and critical thresholds

Despite uncertainty about the nature and location of bifurcation points and tipping points in physical and ecological systems, there is an emerging theoretical literature that suggests that system behaviour might change as a critical threshold is approached (e.g. van Nes and Scheffer, 2007; Biggs *et al.*, 2009; Dakos *et al.*, 2010). These generic behaviour changes can potentially be observed even if the underlying mechanisms are not understood, as an emergent property of a complex system as it nears a critical state. A ‘critical slowing down’ of a range of modelled systems has been noted, where a system becomes slower in recovering from perturbations when it approaches a tipping point (e.g. van Nes and Scheffer, 2007), perhaps also with increased autocorrelation and variance in system-state diagnostics.

This raises the possibility that careful monitoring of ecosystems and ecosystem service diagnostics could provide early warning signals of ‘approaching’ tipping points and thresholds. This has yet to be demonstrated in real systems, and remains an area of active research. There is also the possibility that the same theoretical approach could be applied to coupled social–ecological systems, such as farming and food production, where one might expect similar ‘critical slowing’ in recovery from periodic climate variations, or indeed other perturbations, as crop–climate thresholds such as those proposed by Burke *et al.* (2009) are approached.

Combined vulnerabilities and implications for migration

While the impacts of climate change in any one sector have the potential to impact on migration patterns, interactions between sectors mean that vulnerability to multiple factors may lead to joint impacts that are larger than the sum of the individual components. Here we rank countries by their joint relative vulnerability to climate change-induced SLR, agricultural production and water stress.

- For SLR, we use the same data as Nicholls *et al.* (2011), but calculate population at risk of inundation due to an SLR of 45 cm in 2060. A SLR of 45 cm is near the upper limit of rises under RCP 8.5 in 2060, excluding the possible effects of ice sheet dynamics. We express population as both absolute numbers of people at risk, and the proportion of total population in the country. Population numbers are based on the SRES A1B scenario.

- Agricultural impacts are taken from Cline (2007: Table 5.8), who calculates country-scale changes in agricultural output for the 2080s relative to the late twentieth century, using a combination of Ricardian and process-based modelling. Although the original analysis estimated changes with and without CO_2 fertilisation, we use the non-CO_2 results, on the basis that in the relatively low-input production systems that predominate in the lower latitudes, nutrients are often limiting and any beneficial impacts of increased CO_2 concentrations on plant growth may not be seen.

- Water stress is based on the river basin data presented earlier, where we use the per cent change in stress in 2060 under the mid-range population scenario and the 50th percentile RCP 8.5 global warming. Where a country has more than one river basin, we take an area-weighted average of the stress changes across all the basins. Some counties, particularly in arid areas and small island states, do not have a major river basin within their borders; here we estimate the change in stress using projected changes in runoff averaged across the country.

Results for *each* sector are standardised across countries, allowing for relative magnitude of impacts between sectors to be assessed in a consistent manner. For SLR, coastal countries are ranked into percentiles; inland countries are not ranked. For agriculture and water, countries also ranked into percentiles, but all countries with changes greater than 40% in magnitude are assigned a common ranking of zero (for least impact) or 1 (for maximal impact). Although the results are specific to the modelling approach used, and to the specific emissions scenario used, the relative ranking within each sector will be relatively insensitive to these specifics, providing a reasonably robust ranking of countries most vulnerable to multiple stresses.

Information on the current situation with regard to water stress and food security is also included, on the basis that changes due to climate change will be more severely felt if stress in already high. For water, two water shortage indices from the Yale Environmental Performance Index project are used. The Water Stress Index is calculated as the percentage of a country's territory affected by oversubscription of water resources, where oversubscription is defined as water use greater than 40% of available water[6]. The Water Scarcity Index measures the extent to which country average water use exceeds the recommended level of 40% of available water[7]; a value of zero implies that water use is less than or equal to 40% of available surface water, a value greater than 1 implies that all available water is currently used, and that water is imported or is derived from other sources such as fossil ground water or desalination. Countries are ranked into percentiles for each index. An overall ranking is then defined first using the Scarcity Index, as data are available for more countries. If no scarcity data are available then a country is given an overall ranking based on its Stress Index percentile. Where data are not available for either index, overall ranking is left undefined.

For agriculture and food security, the percentage of population aged 5 and under that is malnourished is used as an indicator of general food insecurity. These data were downloaded from the Millennium Development Goals Indicator site, and are transformed into a single value as a weighted average of data for the last 20 years, where more weight is given to more recent data. Countries are then ranked into percentiles, and these are used to indicate relative present-day food insecurity.

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[6] EPI Water Stress Index uses data from the University of New Hampshire's Water Systems Analysis Group.

[7] EPI Water Scarcity Index used data from FAO's AQUASTAT.

Finally, countries are ranked by severity of future joint impact on pairs of sectors: water–agriculture, water–SLR and agriculture–SLR. Full results are shown in the Appendix. Figure 6 shows the 30 countries most vulnerable to joint impacts across two sectors. These are all middle- and low-income developing nations, with high representation from the wider Caribbean region[8], West Africa and North Africa.

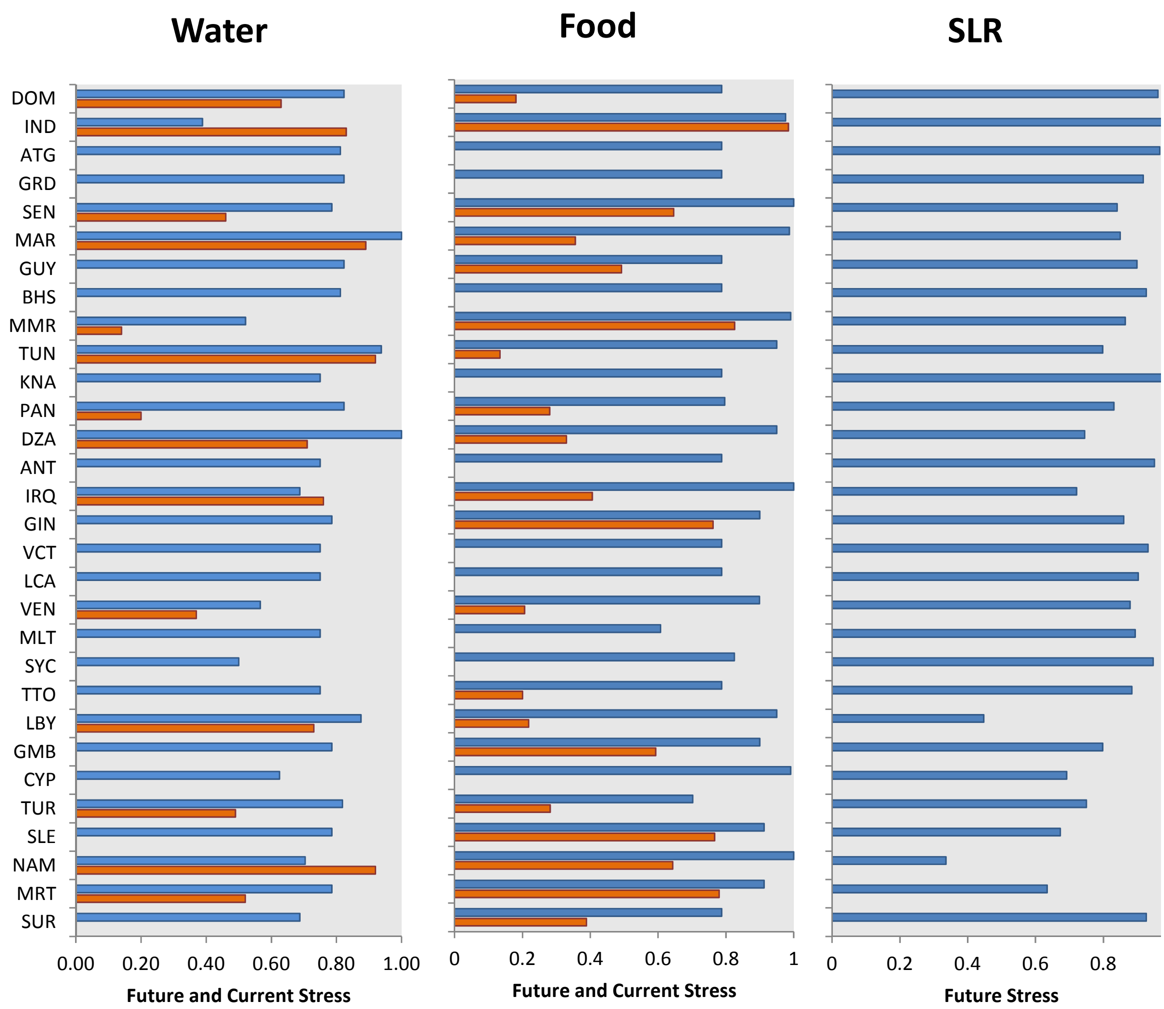

Figure 1: The 30 countries 'most vulnerable' to at least two climate change impacts. Bars show standardised severity of impact for sea level rise (SLR), agricultural production (Agric) and water stress (Water). Severity of impact ranges from 0 (low) through to 1 (most severe) impact. See text for further details on ranking process. Brown bars show present-day stress, again standardised across countries; absence of a brown bar means no data available on current stress. Country codes and related country names can be found in the Appendix

[8] Caribbean SIDS, Cuba, Central America, and the Caribbean coast of South America.

Myanmar and India are also in the list, due to agricultural impacts and SLR, despite the reduction in water stress under the 50th percentile RCP 8.5 climate change projections. The results confirm many other assessments, summarised in the 2007 IPCC assessment report, that low- and middle-income countries in the tropics and subtropics are – in general – most vulnerable to climate change, while warming, coupled with increases in precipitation, will tend to benefit mid-latitude countries.

Implications for displacement

The focus of this report has been to explore the potential for climate change, and specifically ‘high-end’ climate change, to impact on resources and society in ways that might trigger migration. This narrow lens plainly needs to be considered in a wider context of other pressures that might affect migration, detailed in other reports for the Foresight Project. Nonetheless, it is clear that climate change is a potentially significant factor that cuts across other socioeconomic drivers.

In the tropics and subtropics, climate change will potentially affect food production negatively across most countries. These changes in production may be ameliorated by CO_2 fertilisation, but remain negative in almost all cases; CO_2 effects may be less beneficial than previously thought because of water, nutrient and farm practice limitations, which are widespread at lower latitudes. The impacts on agriculture discussed here do not directly incorporate adaptation, for example through development of new, more resilient and more productive crops, improved agricultural practice and expansion of irrigation. In some areas, such as southern Africa, frequency of crop failure (assuming no adaptation) may rise to a level at which migration off lands becomes a necessity. While food security might be maintained through imports from less affected areas, and areas that benefit from climate change, alternative livelihood sources would have to be developed to ‘pay’ for these imports; if patterns of the past are repeated, this will most likely occur via migration to urban areas and other countries with higher earning potential (e.g. Tacoli, 2009; Feng *et al.*, 2010).

A recent vulnerability assessment of the global tropics from a food security perspective indicates clearly that for a wide range of indicators of exposure to climate change, the major problem areas remain sub-Saharan Africa and South Asia, through their combination of high exposure, high sensitivity and generally low coping capacity (Ericksen *et al.*, 2011). It seems that particularly in these highly vulnerable areas, the 2060 temperature increases associated with RCP 8.5 could exceed thresholds that might bring about serious societal problems, certainly in terms of enforced changes in livelihoods and rural–urban migration, at the very least. The causes of the food price spikes of 2008–09 and in late 2010–early 2011 are complex, but increasingly volatile climate may already be contributing to food price rises and social unrest in some countries.

Many of the countries projected to experience agricultural stress are also subject to potential reductions in water availability, due to both increased demand for water and climate-driven reductions and/or alterations in the seasonality of river flows. As with food, water security depends in part on national and local capacity to store, redistribute and use water efficiently, and many low- and middle-income countries have low capability in this respect. Water stress may also be exacerbated by rural–urban migration, with the consequent concentration of water demand, and sanitation issues, in a few rapidly growing urban areas.

Developed countries are relatively robust to SLR in 2060, as a result of investment in existing defences in low-lying areas, though there are exceptions. SLR will potentially have serious consequences for two main categories of developing country: SIDS and nations that have large deltas or coastal wetlands. Many SIDS, especially in the Caribbean, are projected to have increased water stress and reduced agricultural production, alongside SLR and impacts of coastal ecosystems. The combination of stresses here may well make livelihoods unsustainable. The large majority of low- and middle-income countries, however, have minimal defences, so without investment in protection, coastal populations become increasingly at risk to permanent inundation and coastal erosion, and an unmanageably high frequency of flooding.

It is difficult to quantify the potential number of people at risk from climate change using the data presented here, which are necessarily broad-scale, or indeed any projections for 2060. Within any individual country there will be a range of impacts and vulnerabilities that are geographically specific. In addition, the data used here do not directly consider interactions between different impacts, where manageable impacts from one sector may become unmanageable in the face of combined impacts from other sectors.

Nonetheless, there are 30 countries, all low- and middle-income, with more than 1 million people at risk from SLR in 2060, and a global total of some 420 million, or ~5% of world population under the scenario used. Several SIDS are particularly vulnerable, with more than 50% of the population at risk from SLR: Kiribati, Marshall Islands, Tonga, St Kitts and Nevis, Maldives, Tuvalu, Antigua and Barbuda, and the Dominican Republic.

For water, 29 countries are projected to experience large water stress increases (>20%) due to climate change in 2060, representing a total population of ~500 million. A further 70 countries will experience less severe increases (5–20%) in water stress, corresponding to an additional 1.2 billion people.

Turning to food and agriculture, there are 106 countries, with a total population of 4.2 billion in 2060 (48% of global population), that are likely to experience severe (>20%) reductions in food production in the absence of any adaptation. Similarly, a further 64 countries, with a population of 3.9 billion, will experience moderate reduction (5–20%) in food production.

Looking at joint water and food production stress, 44 countries are projected to experience severe (>20%) reductions in both these resources due to climate change in 2060, with a total population of 400 million. A further 50 countries are projected to experience at least moderate (5–20%) reductions in the two resources, corresponding to an additional 1.28 billion people.

The figures quoted above are dependent on a number of assumptions, including population growth, a high-end climate change, the individual modelling approaches used to assess impacts, that country scale impacts affect all in a country equally and that adaptation does not occur. Nonetheless, even if they are used as ball-park figures, it is clear that climate change has the potential to severely affect the land and resources on which hundreds of millions of people depend, and to act as an additional – but perhaps not dominant – stressor to billions.

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Appendix A: Country-by-country ranking of potential climate impacts in 2060 across three key sectors: sea level rise, agricultural production and water stress

Country				Children <5 malnourished		EPI water stress	SLR				Agriculture		Water		Pair-wise ranking		
Rank	Code	Name	Population in 2060 (millions)	% total	% rank	% rank	Population at risk	% rank	% total	% rank	% change	% rank	% change	% rank	Agric–water	Agric–SLR	Water–SLR
1	DOM	Dominican Republic	12.3	4.0	0.18	0.63	55	0.49	49.5	0.96	-23	0.79	−25.8	0.82	66	45	11
2	IND	India	1,569.9	46.2	0.98	0.83	26,667	0.98	1.7	0.67	−38	0.98	8.9	0.39	50	11	99
3	ATG	Antigua and Barbuda	0.1	..	..	..	58	0.49	56.0	0.97	−23	0.79	−25.0	0.81	67	44	14
4	GRD	Grenada	0.1	..	..	..	23	0.38	15.6	0.92	−23	0.79	−25.8	0.82	69	49	15
5	SEN	Senegal	22.3	19.1	0.65	0.46	1,539	0.84	2.5	0.75	−52	1	−22.8	0.79	16	20	30
6	MAR	Morocco	60.9	8.6	0.36	0.89	1,806	0.85	3.2	0.78	−39	0.99	−57.0	1.00	17	24	16
7	GUY	Guyana	1.3	12.3	0.49	0	147	0.60	11.2	0.90	−23	0.79	−25.8	0.82	65	51	17
8	BHS	Bahamas	0.4	..	..	0	93	0.53	21.1	0.93	−23	0.79	−25.0	0.81	67	48	18
9	MMR	Myanmar	59.1	30.4	0.83	0.14	1,955	0.87	3.4	0.79	−39	0.99	−1.7	0.52	37	21	79
10	TUN	Tunisia	21.0	3.4	0.13	0.92	802	0.80	1.2	0.63	−36	0.95	−35.0	0.94	24	31	23
11	KNA	St Kitts and Nevis	0.1	..	..	..	40,189	0.99	64.4	0.98	−23	0.79	−20.0	0.75	62	42	23
12	PAN	Panama	4.1	6.3	0.28	0.2	1,437	0.83	2.4	0.74	−24	0.80	−25.8	0.82	53	50	24

Country				Children <5 malnourished		EPI water stress	SLR				Agriculture		Water		Pair-wise ranking		
Rank	Code	Name	Population in 2060 (millions)	% total	% rank	% rank	Population at risk	% rank	% total	% rank	% change	% rank	% change	% rank	Agric–water	Agric–SLR	Water–SLR
13	DZA	Algeria	65.8	8.1	0.33	0.71	460	0.75	0.7	0.57	−36	0.95	−57.0	1.00	26	37	27
14	ANT	Netherlands Antilles	0.3	..	..	..	13,594	0.95	23.5	0.94	−23	0.79	−20.0	0.75	63	46	26
15	IRQ	Iraq	49.6	10.0	0.41	0.76	352	0.72	0.7	0.57	−41	1.00	−15.0	0.69	27	32	60
16	GIN	Guinea	19.1	24.3	0.76	0	196	0.63	6.7	0.86	−32	0.90	−22.8	0.79	35	31	28
17	VCT	St Vincent and the Grenadines	0.2	..	..	..	8,682	0.93	13.9	0.91	−23	0.79	−20.0	0.75	64	48	28
18	LCA	St Lucia	0.2	..	..	..	3,426	0.90	5.5	0.84	−23	0.79	-20.0	0.75	66	51	31
19	VEN	Venezuela	34.4	4.5	0.21	0.37	2,273	0.88	3.5	0.79	−32	0.90	−5.3	0.57	47	32	61
20	MLT	Malta	0.4	..	..	0	2,974	0.89	5.3	0.83	−9	0.61	−20.0	0.75	102	79	32
21	SYC	Seychelles	0.1	..	..	..	13,307	0.95	21.7	0.93	−26	0.83	0.0	0.50	62	33	76
22	TTO	Trinidad and Tobago	2.0	4.4	0.20	0	2,322	0.88	3.6	0.80	−23	0.79	−20.0	0.75	67	53	33
23	LBY	Libyan Arab Jamahiriya	11.7	5.0	0.22	0.73	41	0.44	0.4	0.45	−36	0.95	−30.0	0.88	34	68	61
24	GMB	Gambia	3.0	18.1	0.59	0	105	0.56	3.5	0.80	−32	0.90	−22.8	0.79	38	38	34
25	CYP	Cyprus	17.3	..	..	0	305	0.69	1.8	0.67	−39	0.99	−10.0	0.63	35	39	74
26	TUR	Turkey	151.4	7.1	0.28	0.49	467	0.75	0.7	0.58	−16	0.70	−25.5	0.82	96	87	36
27	SLE	Sierra Leone	11.2	24.9	0.77	0	283	0.67	0.5	0.50	−33	0.91	−22.8	0.79	37	48	47

Country				Children <5 malnourished		EPI water stress	SLR				Agriculture		Water		Pair-wise ranking		
Rank	Code	Name	Population in 2060 (millions)	% total	% rank	% rank	Population at risk	% rank	% total	% rank	% change	% rank	% change	% rank	Agric–water	Agric–SLR	Water–SLR
28	NAM	Namibia	4.1	19.8	0.64	0.92	12	0.34	0.0	0.28	−46	1.00	−16.3	0.70	38	72	97
29	MRT	Mauritania	6.2	26.8	0.78	0.52	212	0.63	0.4	0.47	−33	0.91	−22.8	0.79	38	52	51
30	SUR	Suriname	0.6	9.5	0.39	0	8,207	0.93	13.0	0.91	−23	0.79	−15.0	0.69	67	48	38
31	MEX	Mexico	143.7	4.7	0.21	0.81	317	0.70	0.6	0.54	−35	0.94	−14.5	0.68	41	43	68
32	LSO	Lesotho	5.2	15.1	0.55	0	0	0.00	0.0	0.00	−46	1.00	−15.8	0.70	44	95	120
33	PRT	Portugal	10.8	..	..	0.38	302	0.69	0.5	0.52	−10	0.62	−29.2	0.86	100	96	37
34	MDV	Maldives	0.4	32.4	0.84	0	244	0.66	58.4	0.98	−26	0.83	5.0	0.44	72	30	89
35	VIR	United States Virgin Islands	0.1	..	..	..	1,249	0.82	1.9	0.69	−23	0.79	−20.0	0.75	70	59	40
36	ESH	Western Sahara	0.6	..	..	..	1	0.27	0.0	0.26	−33	0.91	−25.0	0.81	47	90	87
37	ECU	Ecuador	18.1	9.4	0.39	0.6	489	0.76	2.7	0.75	−29	0.86	−3.3	0.54	56	47	81
38	CAF	Central African Republic	8.8	21.1	0.69	0.04	0	0.00	0.0	0.00	−60	1.00	−4.4	0.55	51	95	141
39	SWZ	Swaziland	2.3	7.6	0.31	0.26	0	0.00	0.0	0.00	−46	1.00	−11.2	0.64	48	95	131
40	ZAF	South Africa	100.3	31.5	0.83	0.94	83	0.51	0.1	0.36	−33	0.92	−13.5	0.67	49	63	88
41	BWA	Botswana	3.9	12.9	0.50	0.79	0	0.00	0.0	0.00	−47	1.00	−6.1	0.58	50	95	138
42	URY	Uruguay	5.1	..	..	0	134	0.59	0.2	0.41	−43	1.00	1.4	0.48	47	46	120

Country				Children <5 malnourished		EPI water stress	SLR				Agriculture		Water		Pair-wise ranking		
Rank	Code	Name	Population in 2060 (millions)	% total	% rank	% rank	Population at risk	% rank	% total	% rank	% change	% rank	% change	% rank	Agric–water	Agric–SLR	Water–SLR
43	AGO	Angola	29.4	37.0	0.90	0.3	963	0.81	3.3	0.78	−26	0.82	−12.5	0.66	59	49	58
44	GNB	Guinea-Bissau	2.9	18.8	0.62	0	12	0.33	0.1	0.30	−32	0.90	−22.8	0.79	50	86	83
45	TZA	Tanzania	80.1	23.0	0.74	0.41	1,902	0.86	3.0	0.77	−24	0.80	3.3	0.46	75	46	98
46	SDN	Sudan	71.2	34.0	0.86	0.4	0	0.26	0.0	0.25	−56	1.00	0.0	0.50	53	80	146
47	PER	Peru	37.1	5.2	0.27	0.56	704	0.78	1.2	0.63	−31	0.88	−3.2	0.54	56	43	79
48	PRI	Puerto Rico	5.9	..	..	0	721	0.79	1.2	0.63	−24	0.80	−20.0	0.75	60	54	43
49	BMU	Bermuda	0.1	..	..	..	45	0.45	46.3	0.96	−23	0.79	−20.0	0.75	71	45	26
50	CZE	Czech Republic	0.8	2.1	0.09	0.21	15	0.36	1.8	0.68	−8	0.60	−30.0	0.88	111	103	36
51	THA	Thailand	80.8	12.9	0.52	0.35	1,060	0.82	1.7	0.66	−26	0.83	−2.8	0.53	63	45	78
52	VNM	Viet Nam	101.8	31.2	0.84	0.23	12,265	0.94	18.6	0.92	−15	0.69	−6.1	0.58	99	67	53
53	LBN	Lebanon	7.4	3.9	0.22	0.39	183	0.62	2.5	0.74	22	0.23	−20.0	0.75	145	122	48
54	PHL	Philippines	94.2	26.3	0.79	0.23	1,561	0.85	2.6	0.75	−23	0.79	10.0	0.38	85	50	115
55	MOZ	Mozambique	46.5	24.4	0.79	0.46	6,169	0.92	10.8	0.89	−22	0.77	−7.0	0.59	87	60	54
56	BDI	Burundi	16.5	38.9	0.92	0	0	0.00	0.0	0.00	−60	1.00	0.1	0.50	59	95	164
57	MTQ	Martinique	0.6	..	..	..	157	0.61	0.3	0.43	−27	0.84	−20.0	0.75	56	65	62
58	ESP	Spain	43.3	..	..	0.84	126	0.57	0.2	0.40	−9	0.61	−30.2	0.88	106	111	48

Country				Children <5 malnourished		EPI water stress	SLR				Agriculture		Water		Pair-wise ranking		
Rank	Code	Name	Population in 2060 (millions)	% total	% rank	% rank	Population at risk	% rank	% total	% rank	% change	% rank	% change	% rank	Agric–water	Agric–SLR	Water–SLR
59	BOL	Bolivia	11.7	7.2	0.32	0.15	0	0.00	0.0	0.00	−43	1.00	-2.8	0.53	54	95	150
60	BRB	Barbados	0.4	..	..	0.95	38	0.44	9.2	0.88	−23	0.79	−20.0	0.75	73	53	33
61	LBR	Liberia	5.6	21.6	0.74	0	0	0.00	0.0	0.00	−32	0.90	−22.8	0.79	57	108	105
62	CHL	Chile	22.4	0.7	0.01	0.54	494	0.76	2.2	0.71	−24	0.81	−13.1	0.66	62	55	62
63	ZWE	Zimbabwe	29.1	12.8	0.53	0.64	0	0.00	0.0	0.00	−38	0.97	−7.0	0.59	58	101	137
64	IRN	Iran	154.0	11.7	0.50	0.74	131	0.58	0.1	0.32	−29	0.86	−15.0	0.69	58	65	74
65	PRY	Paraguay	7.6	2.8	0.11	0.67	0	0.00	0.0	0.00	−43	1.00	−1.8	0.52	56	95	156
66	HND	Honduras	8.9	12.4	0.51	0.18	49	0.47	0.5	0.53	−23	0.79	−25.8	0.82	74	89	55
67	ZMB	Zambia	21.9	19.7	0.66	0	0	0.00	0.0	0.00	−40	1.00	−2.7	0.53	59	98	151
68	BGD	Bangladesh	199.4	49.3	0.99	0.36	18,653	0.96	9.4	0.89	−22	0.77	7.8	0.40	102	55	98
69	GAB	Gabon	2.9	8.8	0.39	0	27	0.39	1.0	0.61	−32	0.90	−2.5	0.53	59	57	101
70	KWT	Kuwait	4.2	..	..	0.98	96	0.54	2.3	0.72	−22	0.78	−20.0	0.75	85	78	50
71	MLI	Mali	26.6	30.0	0.80	0.47	0	0.00	0.0	0.00	−36	0.95	−8.0	0.60	60	103	136
72	SLV	El Salvador	8.9	7.9	0.35	0	43	0.45	0.5	0.51	−24	0.80	−25.8	0.82	63	83	58
73	UKR	Ukraine	52.3	2.5	0.10	0.7	1,948	0.86	3.0	0.77	−5	0.57	−9.6	0.62	126	94	57
74	SYR	Syria	33.3	10.0	0.41	0.95	30	0.42	0.0	0.29	−27	0.84	−20.0	0.75	61	84	82

Country				Children <5 malnourished		EPI water stress	SLR				Agriculture		Water		Pair-wise ranking		
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75	GLP	Guadeloupe	0.7	..	..	..	28	0.39	4.2	0.82	−23	0.79	−20.0	0.75	75	60	40
76	PAK	Pakistan	229.1	34.8	0.87	0.82	293	0.68	0.5	0.51	−30	0.88	2.8	0.46	69	54	114
77	ISR	Israel	13.7	..	..	0.98	6	0.30	0.0	0.28	−27	0.84	−20.0	0.75	63	96	94
78	ABW	Aruba	0.1	..	..	..	10	0.32	7.4	0.87	−23	0.79	−20.0	0.75	75	54	35
79	BLZ	Belize	0.3	5.2	0.27	0	16	0.37	4.7	0.82	−17	0.71	−20.0	0.75	98	76	40
80	NIC	Nicaragua	7.0	8.4	0.34	0	83	0.52	0.1	0.37	−24	0.80	−25.8	0.82	64	82	56
81	GRC	Greece	11.5	..	..	0.27	233	0.64	2.0	0.70	−8	0.60	−15.0	0.69	116	103	62
82	JOR	Jordan	14.2	3.5	0.21	0.98	0	0.25	0.0	0.25	−27	0.84	−20.0	0.75	65	101	99
83	HTI	Haiti	11.9	18.8	0.64	0.09	100	0.55	0.8	0.59	−23	0.79	−20.0	0.75	76	83	64
84	AUS	Australia	21.1	..	..	0.88	122	0.56	0.6	0.54	−27	0.83	−4.0	0.55	67	71	100
85	CMR	Cameroon	35.3	16.5	0.56	0	2,231	0.88	6.3	0.85	−20	0.75	−0.3	0.50	99	67	82
86	REU	Réunion	1.0	..	..	0	287	0.68	0.5	0.50	−26	0.83	−4.0	0.55	69	61	87
87	BEN	Benin	14.3	22.8	0.74	0	0	0.00	0.0	0.00	−32	0.90	−5.0	0.56	69	108	140
88	IDN	Indonesia	272.2	24.2	0.77	0.01	10,421	0.94	3.8	0.81	−18	0.72	2.3	0.47	106	63	87
89	GUF	French Guiana	0.2	..	..	0	17	0.37	7.4	0.88	−23	0.79	−15.0	0.69	77	54	44
90	DMA	Dominica	0.1	..	..	..	25	0.38	0.2	0.40	−23	0.79	−25.8	0.82	77	103	69

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91	COL	Colombia	60.8	5.4	0.30	0.22	406	0.73	0.7	0.56	−23	0.79	−5.7	0.57	74	62	76
92	GTM	Guatemala	15.7	19.8	0.67	0	25	0.38	0.2	0.38	−23	0.79	−25.8	0.82	78	105	71
93	NER	Niger	24.5	42.4	0.99	0.77	0	0.00	0.0	0.00	−34	0.93	1.2	0.48	72	104	168
94	MDG	Madagascar	36.8	37.2	0.91	0.44	165	0.62	0.4	0.49	−26	0.83	−1.0	0.51	72	66	108
95	COM	Comoros	1.6	23.7	0.77	0	35	0.43	2.2	0.71	−26	0.83	−1.0	0.51	74	58	97
96	GNQ	Equatorial Guinea	1.1	13.4	0.58	0	0	0.00	0.0	0.00	−32	0.90	−2.5	0.53	73	108	152
97	KHM	Cambodia	13.8	34.8	0.88	0	14	0.36	0.1	0.34	−27	0.84	−1.8	0.52	74	90	130
98	CIV	Côte d'Ivoire	5.6	17.5	0.63	0.13	10	0.33	0.2	0.39	−23	0.79	−25.8	0.82	79	104	70
99	MYS	Malaysia	27.7	16.7	0.63	0.05	620	0.77	2.2	0.72	−23	0.78	6.0	0.43	102	71	114
100	MWI	Malawi	25.9	22.1	0.77	0.49	0	0.00	0.0	0.00	−31	0.89	−2.7	0.53	77	111	151
101	TGO	Togo	10.9	20.7	0.72	0	0	0.00	0.0	0.00	−32	0.90	0.3	0.50	77	108	165
102	PNG	Papua New Guinea	5.1	18.1	0.68	0.11	1,421	0.83	2.4	0.73	−18	0.73	2.2	0.47	107	73	97
103	GEO	Georgia	5.3	2.5	0.14	0.32	49	0.46	0.9	0.61	−8	0.60	−15.0	0.69	120	111	72
104	ROU	Romania	20.6	3.7	0.26	0.57	244	0.66	0.4	0.48	−7	0.58	−14.9	0.69	128	112	70
105	PSE	Occupied Palestinian Territory	8.1	..	..	0.86	83	0.52	0.1	0.36	−23	0.79	−20.0	0.75	81	91	71

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106	BRA	Brazil	251.2	3.5	0.23	0.17	3,203	0.90	1.3	0.64	−17	0.71	−3.1	0.54	104	68	67
107	TCD	Chad	17.9	32.5	0.85	0.53	0	0.00	0.0	0.00	−32	0.90	3.7	0.45	80	108	175
108	MUS	Mauritius	3.0	13.0	0.61	0	0	0.24	0.0	0.24	−26	0.83	−4.0	0.55	81	107	132
109	OMN	Oman	5.3	11.3	0.55	0.85	525	0.77	0.9	0.60	−22	0.78	5.0	0.44	105	73	111
110	JAM	Jamaica	3.9	4.3	0.27	0	14	0.35	0.4	0.45	−23	0.79	−20.0	0.75	82	98	78
111	LKA	Sri Lanka	30.1	21.4	0.75	0.55	705	0.79	1.1	0.62	−20	0.75	10.0	0.38	114	75	121
112	COG	Congo	6.9	11.8	0.60	0	158	0.61	2.3	0.73	32	0.10	−4.4	0.55	156	124	79
113	NZL	New Zealand	4.3	..	..	0.07	903	0.81	1.6	0.65	2	0.47	−3.0	0.54	145	108	77
114	QAT	Qatar	1.4	4.8	0.29	0.61	406	0.74	0.7	0.56	−22	0.78	0.0	0.50	101	76	98
115	ETH	Ethiopia	148.1	38.3	0.90	0.59	0	0.00	0.0	0.00	−31	0.89	7.4	0.41	88	111	184
116	NLD	Netherlands	16.9	..	..	0.69	349	0.72	0.6	0.55	−7	0.59	−4.1	0.55	129	104	81
117	FRA	France	63.5	..	..	0.33	147	0.60	0.2	0.42	−7	0.58	−12.2	0.65	131	117	81
118	CHN	China	1219.7	11.1	0.53	0.61	24,376	0.97	2.0	0.69	−7	0.59	3.1	0.46	131	77	85
119	DJI	Djibouti	1.6	23.7	0.76	0.68	98	0.54	6.1	0.85	−17	0.71	5.0	0.44	119	76	103
120	TWN	Taiwan	22.4		#N/A	0	482	0.75	0.8	0.58	−7	0.59	−3.0	0.54	130	100	83

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121	STP	Sao Tome and Principe	0.4	11.6	0.60	0	0	0.00	0.0	0.00	−23	0.79	−20.0	0.75	92	132	113
122	POL	Poland	35.1	..	..	0.3	233	0.65	0.4	0.47	−5	0.56	−6.9	0.59	144	122	83
123	EGY	Egypt	146.1	8.5	0.43	0.75	2,037	0.87	1.4	0.64	11	0.36	−0.4	0.50	154	106	82
124	PRK	North Korea	22.2	21.0	0.74	0.24	842	0.80	3.8	0.81	−7	0.59	3.5	0.46	132	93	103
125	AND	Andorra	0.1	..	..	0	0	0.00	0.0	0.00	−9	0.61	−32.2	0.90	119	157	94
126	AFG	Afghanistan	33.1	38.9	0.90	0.43	0	0.00	0.0	0.00	−25	0.81	0.9	0.49	95	121	167
127	ARG	Argentina	54.8	3.5	0.32	0.69	127	0.58	0.2	0.41	−11	0.64	−9.2	0.61	116	107	87
128	BHR	Bahrain	1.4	7.6	0.43	0.96	29	0.40	2.1	0.70	−22	0.78	−2.0	0.53	101	80	94
129	BFA	Burkina Faso	27.9	32.4	0.85	0.45	0	0.00	0.0	0.00	−24	0.80	0.3	0.50	96	122	165
130	ITA	Italy	62.7	..	..	0.58	79	0.50	0.1	0.35	−7	0.59	−12.5	0.66	129	124	90
131	TLS	Timor-Leste	1.1	41.1	0.92	0	30	0.41	2.7	0.76	−18	0.73	0.3	0.50	111	79	97
132	CUB	Cuba	4.1	3.4	0.32	0.77	12	0.34	0.3	0.43	−9	0.61	−14.9	0.69	123	127	93
133	ARE	United Arab Emirates	5.5	..	..	0.86	239	0.65	0.4	0.46	−21	0.76	−1.0	0.51	108	89	103
134	KOR	South Korea	44.9	..	..	0.37	369	0.73	0.8	0.59	−9	0.62	5.0	0.44	126	93	115
135	SOM	Somalia	21.9	27.8	0.81	0.97	320	0.70	0.5	0.52	−17	0.71	19.2	0.26	127	91	135

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136	ALB	Albania	2.9	10.2	0.54	0	7	0.31	0.2	0.42	−9	0.61	−14.9	0.69	124	128	94
137	SVN	Slovenia	1.8	..	..	0	30	0.41	0.0	0.30	−5	0.56	−14.9	0.69	144	144	96
138	YEM	Yemen	37.1	41.6	0.97	0.96	126	0.57	0.2	0.39	−22	0.78	−4.0	0.55	101	93	98
139	SGP	Singapore	4.6	3.3	0.33	0	99	0.55	0.2	0.38	−22	0.78	6.0	0.43	114	96	138
140	SCG	Serbia and Montenegro	9.6	1.8	0.19	0.25	50	0.47	0.1	0.32	−9	0.61	−8.0	0.60	122	120	98
141	BGR	Bulgaria	7.7	..	..	0.84	5	0.30	0.1	0.31	−5	0.56	−14.9	0.69	145	154	106
142	SAU	Saudi Arabia	45.1	5.3	0.35	0.91	82	0.51	0.1	0.37	−22	0.77	3.0	0.46	114	102	133
143	USA	United States of America	397.6	1.3	0.07	0.66	268	0.67	0.4	0.48	−6	0.57	−1.2	0.51	140	112	100
144	BIH	Bosnia and Herzegovina	3.1	2.9	0.21	0	0	0.25	0.0	0.26	−5	0.56	−14.9	0.69	147	159	111
145	BRN	Brunei Darussalam	0.4	..	..	0	5	0.29	1.1	0.62	−18	0.72	5.0	0.44	122	96	127
146	AZE	Azerbaijan	7.7	9.3	0.46	0.8	0	0.00	0.0	0.00	−6	0.57	−20.0	0.75	141	169	113
147	ARM	Armenia	3.6	3.2	0.22	0.98	0	0.00	0.0	0.00	−9	0.61	−20.0	0.75	128	159	113
148	MCO	Monaco	0.0	..	..	..	0	0.00	0.0	0.00	−9	0.61	−20.0	0.75	128	159	113
149	DEU	Germany	89.3	1.1	0.04	0.53	135	0.59	0.2	0.38	−3	0.54	−2.2	0.53	154	129	104
150	NGA	Nigeria	264.8	30.3	0.80	0.28	53	0.48	0.1	0.33	−19	0.73	1.2	0.48	118	108	130

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151	CAN	Canada	44.1	..	..	0.1	677	0.78	1.5	0.65	−2	0.53	8.8	0.39	158	110	119
152	RUS	Russia	150.6	..	..	0.15	222	0.64	0.4	0.46	−8	0.60	14.1	0.32	145	109	141
153	BEL	Belgium	11.0	..	..	0.9	13	0.35	0.1	0.35	−7	0.58	−4.1	0.55	141	144	119
154	RWA	Rwanda	14.1	20.9	0.79	0	0	0.00	0.0	0.00	−22	0.77	−2.1	0.53	120	144	153
155	KEN	Kenya	72.8	17.6	0.70	0.48	321	0.71	0.4	0.49	−5	0.57	8.6	0.39	151	109	126
156	JPN	Japan	131.4	..	..	0.31	433	0.74	0.3	0.44	−6	0.57	10.0	0.38	152	106	126
157	MKD	Macedonia	1.8	1.9	0.18	0	0	0.00	0.0	0.00	−9	0.61	−15.0	0.69	127	156	122
158	HUN	Hungary	9.3	..	..	0.72	0	0.00	0.0	0.00	−5	0.56	−14.9	0.69	152	174	126
159	MDA	Moldova	4.5	3.2	0.19	0.93	0	0.00	0.0	0.00	−9	0.61	−14.9	0.69	132	159	126
160	ERI	Eritrea	8.5	36.6	0.90	0	8	0.32	0.1	0.34	−17	0.71	0.0	0.50	126	129	140
161	CRI	Costa Rica	121.5	..	..	0	2	0.27	0.0	0.25	−15	0.68	−2.1	0.53	128	137	138
162	GBR	United Kingdom	63.8	..	..	0.34	201	0.63	0.3	0.44	−4	0.55	2.2	0.47	157	124	118
163	IRL	Ireland	3.9	..	..	0	33	0.42	0.8	0.60	−4	0.54	2.0	0.48	158	128	121
164	NOR	Norway	4.8	..	..	0	320	0.71	0.5	0.53	11	0.36	12.5	0.34	168	121	133
165	SVK	Slovakia	4.9	..	..	0	0	0.00	0.0	0.00	−5	0.56	−10.7	0.63	154	174	132
166	CHE	Switzerland	7.8	..	..	0	0	0.00	0.0	0.00	−5	0.56	−10.2	0.63	154	174	132

Country				Children <5 malnourished		EPI water stress	SLR				Agriculture		Water		Pair-wise ranking		
Rank	Code	Name	Population in 2060 (millions)	% total	% rank	% rank	Population at risk	% rank	% total	% rank	% change	% rank	% change	% rank	Agric–water	Agric–SLR	Water–SLR
167	SMR	San Marino	0.0	..	..	..	0	0.00	0.0	0.00	−7	0.59	−10.1	0.63	141	164	133
168	LVA	Latvia	2.6	..	..	0	46	0.46	1.8	0.68	10	0.38	8.0	0.40	165	122	128
169	UGA	Uganda	50.7	19.0	0.79	0.08	0	0.00	0.0	0.00	−17	0.71	2.3	0.47	135	150	172
170	BTN	Bhutan	3.1	13.1	0.67	0	0	0.00	0.0	0.00	−17	0.72	7.6	0.41	137	148	185
171	NPL	Nepal	35.8	41.4	0.94	0.06	0	0.00	0.0	0.00	−17	0.72	7.6	0.41	137	148	185
172	HRV	Croatia	36.2	..	..	0	0	0.00	0.0	0.00	−14	0.68	0.3	0.50	138	154	165
173	GHA	Ghana	47.2	18.5	0.81	0	0	0.00	0.0	0.00	−14	0.68	0.3	0.50	138	154	165
174	ISL	Iceland	0.3	..	..	0.06	5	0.29	1.7	0.66	10	0.38	5.0	0.44	165	124	122
175	LIE	Liechtenstein	0.0	..	..	..	0	0.00	0.0	0.00	−5	0.56	−4.1	0.55	157	174	143
176	LUX	Luxembourg	0.4	..	..	0	0	0.00	0.0	0.00	−5	0.56	−4.1	0.55	157	174	143
177	HKG	Hong Kong	6.2	..	..	..	4	0.28	0.1	0.31	−8	0.60	10.0	0.38	151	142	171
178	DNK	Denmark	5.7	..	..	0.16	34	0.43	0.6	0.55	11	0.36	10.0	0.38	171	138	146
179	COD	Dem. Rep. Congo	9.4	30.8	0.87	0	0	0.00	0.0	0.00	−5	0.56	−3.5	0.54	158	174	146
180	AUT	Austria	8.8	..	..	0	0	0.00	0.0	0.00	−5	0.56	−3.5	0.54	159	174	147
181	BLR	Belarus	10.6	1.3	0.07	0.12	0	0.00	0.0	0.00	−7	0.59	−1.3	0.52	152	166	157
182	EST	Estonia	1.5	..	..	0.19	7	0.31	0.5	0.50	11	0.36	10.0	0.38	174	143	151

Country				Children <5 malnourished		EPI water stress	SLR				Agriculture		Water		Pair-wise ranking		
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183	TKM	Turkmenistan	4.1	10.5	0.62	0.77	0	0.00	0.0	0.00	11	0.36	−1.1	0.51	175	184	158
184	SWE	Sweden	9.6	..	..	0.02	29	0.40	0.0	0.29	11	0.36	9.8	0.38	176	153	160
185	LTU	Lithuania	3.8	..	..	0.29	3	0.28	0.1	0.33	10	0.38	8.0	0.40	174	159	165
186	FIN	Finland	5.6	..	..	0.03	1	0.26	0.0	0.27	11	0.36	13.5	0.33	180	167	179
187	MNG	Mongolia	2.4	8.7	0.50	0.42	0	0.00	0.0	0.00	−6	0.57	10.2	0.37	168	169	193
188	TJK	Tajikistan	5.8	14.9	0.82	0.51	0	0.00	0.0	0.00	11	0.36	2.0	0.48	181	185	169
189	UZB	Uzbekistan	22.9	8.9	0.60	0.87	0	0.00	0.0	0.00	12	0.35	2.0	0.48	182	186	169
190	KGZ	Kyrgyzstan	4.6	5.5	0.44	0.65	0	0.00	0.0	0.00	11	0.36	5.7	0.43	185	185	181
191	KAZ	Kazakhstan	16.8	5.1	0.38	0.62	0	0.00	0.0	0.00	11	0.36	11.5	0.36	189	185	193
192	SLB	Solomon Islands	0.4	11.5	0.71	0	7,532	0.92	12.2	0.90	..	..	5.0	0.44	..	..	95
193	CPV	Cape Verde	1.0	..	..	..	65	0.50	6.4	0.86	..	..	0.5	0.49	..	..	90
194	FJI	Fiji	0.9	6.9	0.50	0	51	0.48	5.6	0.84	..	..	0.0	0.50	..	..	87
195	PYF	French Polynesia	0.3	..	..	..	70	0.50	27.8	0.95	..	..	0.0	0.50	..	..	76
196	KIR	Kiribati	0.1	..	..	..	84	0.53	92.0	1.00	..	..	6.0	0.43	..	..	91
197	LAO	Laos	6.6	35.9	0.80	0	0	0.00	0.0	0.00	..	..	−1.8	0.52	..	..	155
198	MAC	Macao	0.4	..	..	..	0	0.25	0.0	0.27	..	..	10.0	0.38	..	..	175

Country				Children <5 malnourished		EPI water stress	SLR				Agriculture		Water		Pair-wise ranking		
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199	NRU	Nauru	0.0	..	..	..	21,268	0.97	36.9	0.95	..	..	5.0	0.44	..	..	90
200	NCL	New Caledonia	0.2	..	..	0	2,900	0.89	5.0	0.83	..	..	−8.0	0.60	..	..	55
201	VUT	Vanuatu	0.2	11.2	0.75	..	5,647	0.91	8.6	0.88	..	..	−7.0	0.59	..	..	54
202	FSM	Micronesia	0.6	..	..	..	1,533	0.84	2.7	0.76	..	..	5.0	0.44	..	..	104
203	MHL	Marshall Islands	0.1	..	..	..	45,461	1.00	81.1	0.99	..	..	5.0	0.44	..	..	87
204	PLW	Palau	0.0	..	..	..	13,910	0.96	23.6	0.94	..	..	6.0	0.43	..	..	95
205	TON	Tonga	0.1	..	..	..	42,545	0.99	66.4	0.99	..	..	−5.0	0.56	..	..	50
206	TUV	Tuvalu	0.0	1.6	0.33	..	37,049	0.98	57.3	0.97	..	..	5.0	0.44	..	..	89
207	WSM	Samoa	0.2	1.7	1.00	..	4,317	0.91	7.1	0.87	..	..	7.0	0.41	..	..	102

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