Unavoidable Global Warming Commitment and Its Food Security Implications

Peter D. Carter, MD

28 July 2012

Summary

By combining all sources of unavoidable future warming, we find that (without drastic planetary emergency intervention) a global average temperature increase of 3°C from pre-industrial is unavoidable this century, which has grave implications for future world food security.

Rationale for Paper

According to the Lancet and University College London Institute for Global Health Commission (2009), climate change is "the biggest global health threat of the 21st century" due to effects that "put the lives and wellbeing of billions of people at increased risk," with food insecurity a "major threat" in this regard.

Global agricultural yield is projected to decrease above a 2°C global warming. According to the German Advisory Council on Global Change, "food production is expected to decline worldwide if warming of 2-4°C occurs" (WBGU 2009, 12).

Ramanathan and Feng (2008) calculate today's committed warming at 2.4°C, saying that "even the most aggressive CO_2 mitigation steps as envisioned now can only limit further additions to the committed warming, but not reduce the already committed GHGs warming of 2.4°C."

The aim of this paper is to provide a reliable, understandable, policy-relevant guide to unavoidable future global warming in order to establish the degree of urgency for mitigation and adaptation, particularly with respect to food security

Method

This paper relies on the 2007 IPCC Fourth Assessment Report and the National Research Council's 2011 Climate Stabilization Targets to provide a different yet complementary assessment approach via a simple estimation for calculating total unavoidable global warming commitment, linking this committed unavoidable temperature increase to projected crop yield changes.

There are several definitions in climate science for the term "commitment." The IPCC Fourth Assessment Report (2007) uses:

> three specific definitions of climate change commitment: (i) the "constant composition commitment" […] since the time [that] the composition of the atmosphere, and hence the radiative forcing, has been held at a constant value; (ii) the "constant emission commitment" […] since the time the greenhouse gas emissions have been held at a constant value; and (iii) the "zero emission commitment" since the time the greenhouse gas emissions have been set to zero. Climate change commitment as discussed here should not be confused with "unavoidable climate change" over the next half century, which would surely be greater because forcing cannot be instantly stabilized. (IPCC, 2007a)

For this paper, we therefore use the term "unavoidable global warming" to denote the actual total unavoidable warming, which will determine the committed unavoidable climate change and changes to crop yields.

As a baseline guide for indicating the urgency of today's climate change situation and for protecting food security, we include all unavoidable sources of warming; in particular, for policy relevance, we start with the time to atmospheric greenhouse gas stabilization.

Sources of Warming, in Sequence

From the climate science, we identify the following unavoidable warming sources that contribute to unavoidable future warming:

1. Duration of global warming;
2. Today's global emissions scenario;
3. Time from the fastest emergency reduction of emissions to atmospheric greenhouse gas stabilization.
4. Delayed warming from the ocean heat lag;
5. Deferred warming from unmasking of committed warming due to fossil fuel air pollution aerosol cooling.
6. Additional warming from positive climate system feedbacks resulting from the above.

1. Duration of Warming (> 1000 years)

Warming and its impacts are the product of temperature increase and time – like baking a cake at an even heat. The duration of warming is over 1000 years – practically "forever" in terms of food security. "Global average temperatures increase while CO_2 is increasing and then remains approximately constant until the end of the millennium despite zero further emissions" (Solomon 2009). "Climate changes that occur because of carbon dioxide increases are expected to persist for thousands of years even if emissions were to be halted at any point in time" (NRC 2011, 16). The significance of this is that we can afford no margin of error in protecting food security from the effects of global warming and climate change. Also, there will be increasing cumulative damage to agriculture, even after stabilization of global temperature, to consider.

2. Today's Global Emissions Scenario (A1FI – Worst-case, fossil-fuel-intensive, high emissions)

The world economy is tracking the IPCC's worst-case, fossil-fuel-intensive emissions scenario, A1FI. As Corinne Le Quéré reported in a December 4, 2011 University of East Anglia press release, "Global CO_2 emissions since 2000 are tracking the high end of the projections used by the Intergovernmental Panel on Climate Change." According to the Global Carbon Project (2011), "fossil fuel CO_2 emissions increased by 5.9% in 2010. These emissions were the highest in human history and 49% higher than in 1990."

For the A1FI emissions scenario, Betts et al (2011, 81, figure 9) project a warming of 5.5°C by 2100, including terrestrial carbon feedback as shown in Figure 1.

Figure 1. The high emissions IPCC scenario A1FI which is the current track showing the global average temperature projection by Betts et al including terrestrial carbon feedbacks .

Review. Global warming reaching 4°C 81

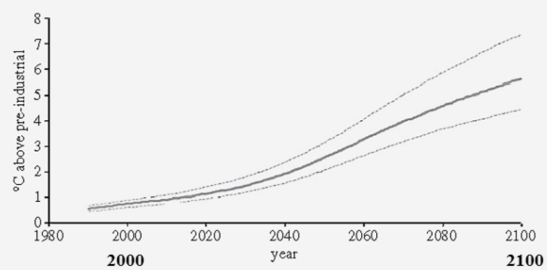


Figure 9. Global mean temperature change over the twenty-first century relative to pre-industrial, under the A1FI emissions scenario, projected with an ensemble of 729 simulations with the MAGICC SCM tuned against the HadCM3-QUMP and C4MIP ensembles. The central thick line shows the median projection, and the two dashed lines show the 10th and 90th percentiles of the frequency distribution of the 729 MAGICC experiments.

Betts, Richard A., Matthew Collins, Deborah L. Hemming, Chris D. Jones, Jason A. Lowe, and Michael G. Sanderson. 2011. "When could global warming reach 4°C?" *Phil. Trans. R. Soc. A 369*(1934), 67-84. doi:10.1098/rsta.2010.0292.

The International Energy Agency's *World Energy Outlook* (2011) shows that, according to global fossil fuel CO_2 emissions, the world energy situation is tracking the A1FI highest emissions scenario. The IEA, in its 2011 Fact Sheet commenting on this continued worst-case high emissions world energy track, said that "on planned policies, rising fossil energy use will lead to irreversible and potentially catastrophic climate change. Global energy-related emissions of carbon dioxide – the principal greenhouse gas – jumped by 5.3% in 2010 to a record 30.4 gigatonnes (Gt)."

The significance of today's worst-case, fossil-fuel-intensive global emissions trajectory is that it:

- means a longer time for decarbonization;
- increases greater "lock-in" global warming commitment from fossil fuel energy (IPCC 2007b);
- means continued deferred substantial warming from aerosol cooling;
- means a substantial unavoidable warming from large positive climate system feedbacks.

3. Time from Rapid Emissions Reduction to Virtual Zero Carbon (+0.4°C)

The most significant factor with respect to carbon dioxide is that 20% lasts in the atmosphere for 1000 years. "While more than half of the CO_2 emitted is currently removed from the atmosphere within a century, some fraction (about 20%) of emitted CO_2 remains in the atmosphere for many millennia" (IPCC 2007c).

The very long lifetime of a substantial amount of carbon dioxide emissions means that only zero carbon emissions can stabilize global temperature. "In fact, only in the case of essentially complete elimination of emissions can the atmospheric concentration of CO_2 ultimately be stabilized at a constant level" (IPCC, 2007c). According to the National Research Council (2011), "current representations of the carbon cycle and carbon-climate feedbacks show that anthropogenic emissions must approach zero eventually if carbon dioxide concentrations are to be stabilized in the long term" (63).

We, therefore, assume for this paper the decarbonization target of zero – or at least virtual zero – carbon emissions.

We assume in this paper that CO_2 emissions reduction is combined with corresponding emissions reduction of the other greenhouse gases.

> However, because emissions of these gases are expected to grow in the future if they are not mitigated, and because of the stringency of the requirement of near zero emissions of CO_2-equivalent, these gases could represent a significant future impediment to stabilization efforts. (NRC 2011, 65)

The earliest peak emissions contemplated now is 2020 (Schellnhuber & Klingenfeld 2011), as shown in Figure 2. The fastest rate of emissions reduction contemplated from a 2020 peak is 20 years (ibid). The 20-year decarbonization time frame from 2020 takes a 9% annual reduction in CO_2 emissions, according to a German government scenario (WBGU 2009).

Figure 2. Fairness and Physics H. Schellnhuber, on page 7, shows the most rapid emissions reduction peaking at 2020 reaching zero carbon at 2040 by a 9% emissions reduction. It is modified from WBGU Solving the Climate Dilemma

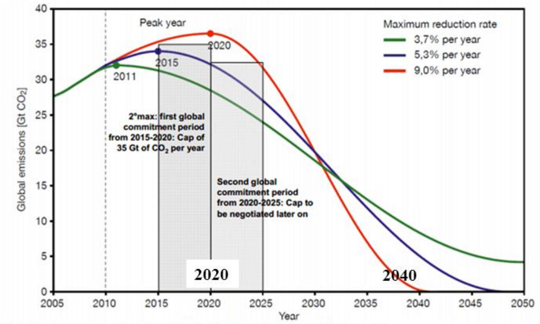


Figure 1. Source: modified from WBGU, *Solving the Climate Dilemma*, 16

Fairness and Physics – observing first principles in global climate policy
Hans Joachim Schellnhuber and Daniel Klingenfeld Page 7

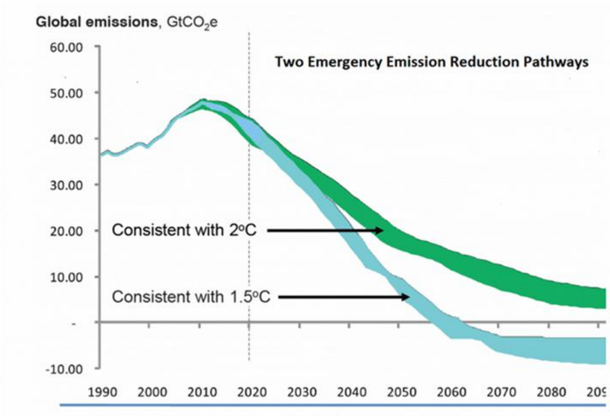
The fastest emissions reduction offered by the IPCC (2007) for mitigation is a 50% reduction by 2050.

> More stringent stabilization scenarios achieve more stringent climate targets…. [T]he most stringent scenarios (stabilizing at 445-490 ppm CO_2-eq) could limit global mean temperature increases to 2-2.4°C above pre-industrial, at equilibrium, requiring emissions to peak within 10 years and to be around 50% of current levels by 2050. (IPCC 2007d)

In the NRC's 2011 assessment documenting several published model results, all cases take until after 2050 to reach zero carbon emissions (64, figure 2.3; 68, figure 2.6). A "2ºC Emergency Pathway," proposed in the Greenhouse Gas Development Rights Framework (Baer et al, 2008), suggests that "global CO_2 emissions peak in 2013 and fall to 80 percent below 1990 levels in 2050."

A rapid emergency emissions reduction pathway proposed by Ecoequity (Athanasiou 2011) reaches zero carbon in 2060 as shown in Figure 3.

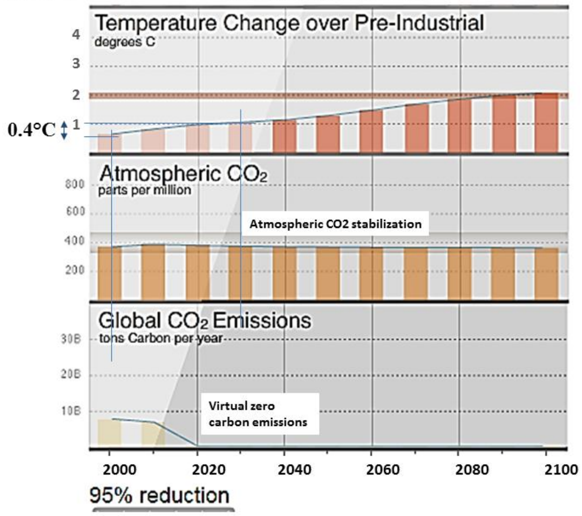
Figure 3 . A rapid emergency emissions reduction pathway proposed by Ecoequity (Athanasiou 2011) reaches zero carbon in 2060.



Tax Justice as Climate Justice Ecoequity
Tom Athanasiou, April 24, 2011

A climate momentum simulation (Climate Interactive 2010) conveniently gives us an example of a 95% reduction of emissions in 20 years and is a useful communication tool with policy relevance. It is based on multiple runs of the Climate Interactive C-ROADS model. According to the Climate Interactive site, "C-ROADS has undergone a scientific review from an independent team of respected climate scientists, climate modelers, and system dynamicists. The scientific review committee, chaired by Dr. Robert Watson, former Chair of the Intergovernmental Panel on Climate Change, recommend C-ROADS for widespread use." Figure 4 is a screen shot from the Climate Interactive site showing the model simulation result for a 95% reduction of CO2 emissions in 20 years that results in atmospheric CO_2 stabilization in 30 years. The temperature increase to atmospheric stabilization is 0.4°C.

Figure 4.



A 95% reduction of CO2 emissions by 2020.

We take 0.4ºC of warming from the Climate Interactive (2010) 30-years-to-virtual-zero-carbon model as our minimum unavoidable warming for the most rapid atmospheric stabilization. This is highly optimistic, especially considering IPCC projections:

> For the next two decades, a warming of about 0.2°C per decade is projected for a range of SRES emission scenarios. Even if the concentrations of all greenhouse gases and aerosols had been kept constant at year 2000 levels, a further warming of about 0.1°C per decade would be expected. (IPCC 2007e)

4. Delayed Warming from Ocean Heat Lag (+0.6°C)

The ocean heat lag is long established. "Models predict that, for the present day case of an increase in radiative forcing which is approximately steady, the realized temperature rise at any time is about 50% of the committed temperature rise" (IPCC 1990, xxvi). According to the NRC, "warming that occurs in response to a given increase in CO_2 is only about half the eventual total warming" (NRC 2011, 9).

For the ocean heat lag we include another 0.6°C by 2100. The IPCC provides this figure for committed warming by 2100 due to the ocean heat lag, saying that "the multi-model average warming for all radiative forcing agents held constant at year 2000, is about 0.6°C" (IPCCf 2007).

5. Deferred Warming Due to Air Pollution Aerosol Cooling (+0.4°C)

The combustion of fossil fuels emits air pollution acid aerosols, which are minute particles suspended in the air and which operate as global cooling agents.

> Because sulphate aerosols are very likely exerting a substantial negative radiative forcing at present, future net forcing is very sensitive to changes in sulphate emissions. One study suggests that the hypothetical removal from the atmosphere of the entire current burden of anthropogenic sulphate aerosol particles would produce a rapid increase in global mean temperature of about 0.8°C within a decade or two. Thus, the effect of environmental strategies aimed at mitigating climate change requires consideration of changes in both greenhouse gas and aerosol emissions. (IPCCg 2007)

According to the IPCC, "mean and median of the sulphate direct RF from grouping all these studies together are identical at –0.41 W m^{-2}. of radiative forcings" (IPCCh 2007), which is 25% of net anthropogenic forcing or a commitment of 0.4°C.

Ramanathan and Feng (2008) also pointed out that the aerosol cooling effect is a deferred global warming to future generations to be considered. Their paper found that with the effect of the ocean heat lag and aerosol cooling:

> "today's increase in the concentration of greenhouse gases since the preindustrial era has most likely committed the world to a warming of 2.4°C [with a] 90% possibility that the commitment as of 2005 can be as large as 4.3°C."

Their paper (Ramanathan and Feng 2008) considered several indicators of dangerous interference with the climate system, but not food security.

In our estimate of unavoidable global warming, we must assume virtual zero carbon emissions, ending the burning of fossil fuels for energy, aerosol unmasking of this warming is unavoidable. Stopping the release of the cooling aerosols would unmask the deferred warming. This would occur over a short-term period, so we apply the unmasking of +0.4°C by 2100.

Our unavoidable warming to this point is 2.2°C.

6. Additional Warming from Positive Feedbacks (+0.8°C)

NASA makes it clear that feedbacks in the climate system will contribute to rising temperatures:

> Greenhouse gases are only part of the story when it comes to global warming. Changes to one part of the climate system can cause additional changes to the way the planet absorbs

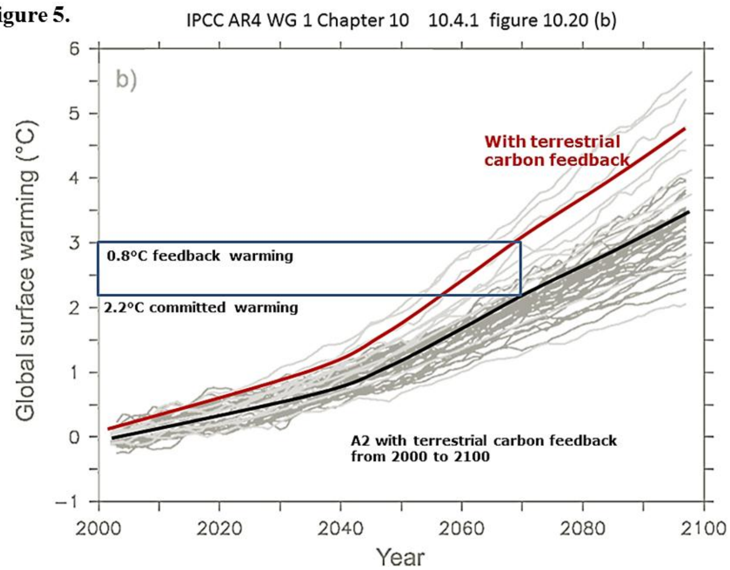
> or reflects energy. These secondary changes are called climate feedbacks. […] The primary feedbacks are due to snow and ice, water vapor, clouds, and the carbon cycle. (NASA 2012)

Such releases could add 2,000 GtC or more to the carbon directly put into the atmosphere by fossil-fuel burning and land-use change. If some of this stored carbon is released rapidly in the form of methane, it could lead to a pronounced transient warming spike above and beyond the more persistent warming caused by increases in atmospheric CO_2 (NRC 2011, 226).

Additional warming from positive climate feedbacks responding to warming this century is unavoidable. Included in carbon cycle models are the terrestrial carbon feedbacks comprised of warming soils and vegetation. In addition, but not included in the climate change assessment models as reported by McGuire et al (2009), are warming Arctic peatlands, the potential for methane to be released into the atmosphere from Arctic seafloor methane hydrates situated on shallow continental shelves, and methane from thawing permafrost. For the A2 high emissions scenario, the IPCC (2007e) records a carbon cycle terrestrial feedback warming of >1.5°C from pre-industrial by 2100: "For the A2 scenario, for example, the climate-carbon cycle feedback increases the corresponding global average warming at 2100 by more than 1°C [from 2000]."

To estimate unavoidable additional terrestrial feedback warming resulting from the total unavoidable warming we have already recorded (+2.2°C), we use the IPCC graph of the projected global temperature increase by 2100 of the A2 scenario with the carbon cycle model (IPCC 2007i, figure 10.20) shown in Figure 5.

Figure 5.



Our total warming up to 2100, up to this point and without feedbacks, is 2.2°C. From this, we derive the additional feedback temperature increase from the IPCC graph, which is 0.8°C. This gives us the unavoidable total warming from all unavoidable sources, which is 3.0°C by 2100, as shown in Table 1.

Table 1. **Unavoidable global warming from all sources of definite additional temperature increase by 2100**

Today's global average temperature increase from pre-industrial	**0.8°C**
Lag time from an emergency rapid greenhouse gas reduction to atmospheric greenhouse gas stabilization	**0.4°C**
Delayed warming due to ocean heat lag	**0.6°C**
Deferred additional temperature increase from committed unmasking of warming due to fossil fuel pollution aerosol cooling	**0.4°C**
Total committed warming at this point	**2.2°C**
Incurred additional temperature increase from climate carbon feedback resulting from the warming of 2.2° C	**0.8°C**
Grand total of unavoidable warming (that will last for over 1000 years)	**3.0°C**

As we have used individual warming source results of high confidence, we are confident that today's unavoidable warming, based on climate change assessments, is 3.0ºC.

Crop Yield Losses

The next phase of the exercise is to estimate the minimum or unavoidable changes to crop yields from this unavoidable global temperature increase.

Again we rely on the 2007 assessment of the IPCC and the National Research Council's Climate Stabilization Targets (2011), the latter including a thorough and up-to-date chapter on the projected effect of global warming and climate change on crop yields. The NRC presents climate crop model results for a range of staple crops grown in a range of national regions.

Both sources (IPCC and NRC) point out many potentially large adverse impacts to crop yields that are not captured by the climate crop models on which food security estimates are based.

> The results of such [computer model] simulations are generally highly uncertain due to many factors, including large discrepancies in GCM [different models] predictions of regional precipitation change, poor representation of impacts of extreme events and the assumed strength of CO_2 fertilisation. (IPCC 2007j)

We therefore assume, for two reasons, that the projected climate crop model changes in crop yields are minimums and tend to be underestimates that will increase as warming increases. First, as stated, is the large number of known adverse impacts on crop yields from global warming. For example, the IPCC (2007) assessment and recent research indicates that tropospheric (ground level) ozone, which is toxic to green plants, will increase with the increasing global temperature and will largely offset if not negate the potential CO_2 fertilization effect. "Ozone [air pollution] has significant adverse effects on crop yields, pasture and forest growth […] increasing ozone concentrations in future decades, with or without CO_2 increases, with or without climate change, will negatively impact plant production" (IPCC, 2007k). "[R]ecent research showed that tropospheric ozone results in significantly less enhancement of carbon-sequestration rates under elevated CO_2 because of the negative effects of ozone on biomass productivity" (IPCC 2007l). .

The crop yield change assessments define a decline in yields as a decline below today's (year 2000) baseline.

With respect to food security, the IPCC (2007) reported that modeling studies suggest crop yield losses with minimal warming in the tropics. Mid- to high-latitude crops benefit from a small amount of warming (about +2°C) but plant health declines with additional warming. Global production potential is threatened at +1.5 °C temperature change from pre-industrial (IPCC 2007m).

The food assessment chapter of the NRC is in keeping with the above, summarized by the results of the NRC chart, Loss of Crop Yields per Degree Warming (NRC 2011, 161, Figure 5.1), as shown in Figure 6.

> Several major crops and regions reveal consistently negative temperature sensitivities, with between 5-10% yield loss per degree warming estimated both by process-based and statistical approaches. For C3 crops, the negative effects of warming are often balanced by positive CO_2 effects up to 2-3°C local warming in temperate regions, after which negative warming effects dominate. Because temperate land areas will warm faster than the global average this corresponds to roughly 1.25-2°C in global average temperature. For C4 crops, even modest amounts of warming are detrimental in major growing regions given the small response to CO_2. (NRC 2011, 160)

Figure 6.

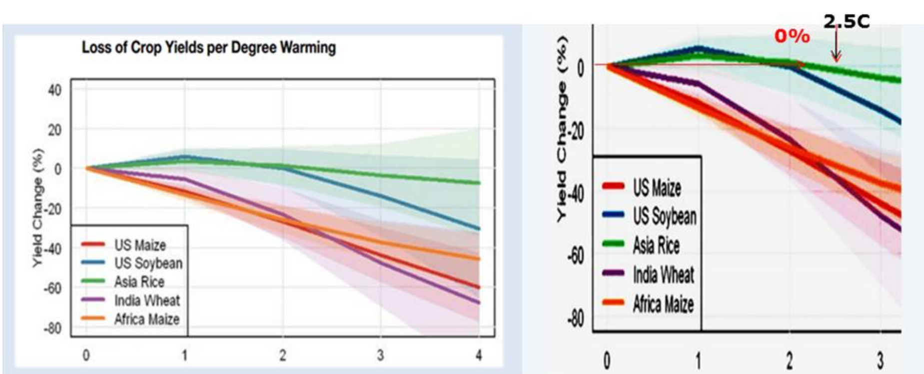


Figure 5.1 page 161 National Research Council Climate Stabilization Targets: Emissions, Concentrations, and Impacts over Decades to Millennia 2010

From the NRC climate crop model result graph we find:

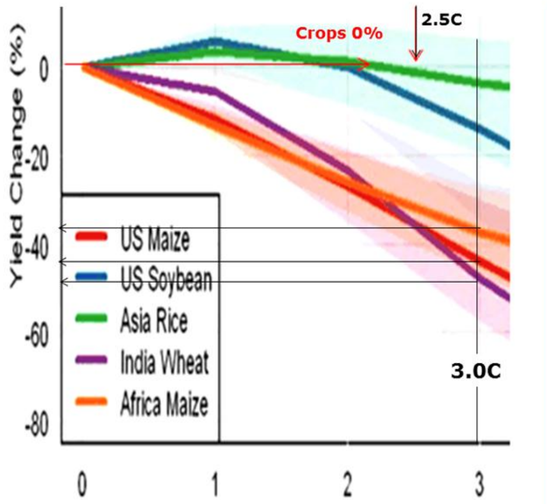
- Above 1°C, all crops in all regions are tipped into declining yields.
- Above 1°C, most crops in the most vulnerable regions have dropped below baseline yields.
- At 2.4°C, all crops in all regions have dropped below baseline yields.

- At 3°C, most crops have declined over a 20% to 47% range.

Greatest losses at 3.0°C, as shown in Figure 7, are to:

- India wheat: 47%
- US maize: 42%
- Africa maize: 35%

Figure 7.



National Research Council Climate Stabilization Targets: Emissions, Concentrations, and Impacts over Decades to Millennia 2010 Figure 5.1 page 161

What are the crop yield losses from today's 2°C target, which is a generally supported target and therefore a very longstanding definite policy commitment? The *2007 Bali Climate Declaration by Scientists* stated:

> "The prime goal of [the next round of focused negotiations for a new global climate treaty] must be to limit global warming to no more than 2ºC above the pre-industrial temperature, a limit that has already been formally adopted by the European Union and a number of other countries."

The greatest losses at 2ºC are to:

- US maize: 23%
- African maize: 23%
- India wheat: 21%

Conclusion

Unavoidable global warming and climate change, even if the world embarked on an all-out emergency climate change mitigation and fastest-possible emissions reduction response this year, will severely compromise world food security and food security in all regions.

Implications

The object of this exercise was to determine in general terms the degree of urgency for climate change mitigation in order to protect food security. We are confident that the result shows there is an extreme degree of urgency for food security protection. The findings indicate the need for the recognition that the world is in a committed, global, climate change emergency situation requiring drastic emergency interventions to mitigate unavoidable food security losses for the world and for all regions.

The current policy of targeting a 2°C warming will have severe impacts on world food security and food security in most if not all regions. However, today's unavoidable global warming is already far above the 2°C target. There is a need to recognize this.

The unavoidable warming of 3.0°C is projected to lead to large food production losses affecting all regions. This paper indicates that there is an urgent need to assess crop yield losses from committed global warming, which includes all sources of definite additional warming, and similarly from the high emissions scenario.

This is just the already committed warming up to 2100. The implications apply far beyond 2100 because the 3.0°C by 2100 commitment is committed to greatly increase further, because of further ocean heat lag and further carbon feedback warming.

There is an urgent need for a risk assessment to include all adverse effects, combined, on short- and very long-term food security from committed global warming and from the high emissions scenario.

> The expected impacts illustrated are useful as a measure of the likely direction and magnitude of average yield changes, but fall short of a complete risk analysis, which would, for instance, estimate the chance of exceeding critical thresholds. (NRC 2011, 160)

Discussion

Is our summation, from unavoidable sources of additional warming, a reliable guide to the urgency? We believe it is very policy relevant and in this sense a useful approach. Its sequential approach provides a clear understanding of the science behind commitment and is a means of making adjustments to the calculation.

Other estimates of realistically unavoidable global warming are consistent. In their article, Reframing the Climate Change Challenge in Light of Post-2000 Emissions Trends, Anderson and Bows (2008) conclude that ultimately, the latest scientific understanding of climate change allied with current emission trends and a commitment to "limiting average global temperature increases to below 4°C above pre-industrial levels" demands a radical reframing of both the climate change agenda, and the economic characterization of contemporary society. Ramanathan and Feng (2008) said commitment could be over 4.0°C.

Is there any overlap of the individual sources that reduce the summation? As they are distinct sources and processes, we do not see any overlap. Our estimates for the individual sources of additional warming commitment are all on the low side. We assume an immediate emergency response for decarbonization, which cannot happen, and the world economy is fixed on the highest IPCC (2007) emissions scenario, A1FI, which will further prolong the time to destabilization, at the same time increasing warming from other sources as already explained. The current policy of so-called "decarbonization" by lowering carbon intensity from fossil fuel emissions sources will not achieve zero or virtual zero carbon emissions. Only conversion to zero carbon sources can achieve this. "The highest rates of decarbonization of energy (up to 2.5% per year for the recent scenarios) are from scenarios that include a complete transition in the energy system away from carbon-intensive fossil fuels" (IPCC 2007n). The 0.4°C for atmospheric greenhouse gas stabilization is therefore very low.

We use the IPCC (2007f) 0.6°C for the commitment due to the ocean thermal lag, but this is taken from year 2000 and is based on an immediate constant radiative forcing at that time, and so our 0.6°C is certainly on the low side.

The value for positive carbon feedback is also low because, as Betts et al (2011) say, "the climate–carbon-cycle feedback can increase nonlinearly in strength for greater levels of climate change implying that the carbon-cycle feedback could be stronger" and it does not include the potentially large feedbacks from Arctic methane emissions, due to the fact, as reported by

McGuire et al (2009), that these are not as yet developed for inclusion in the temperature projecting models – but they are estimated to be potentially large.

Could our summation be missing any negative influences or feedbacks to the warming that would offset our numbers? We can find no offsetting interactions between the sources of warming. If anything, we think they might increase the warming. For example, the ocean heat lag would apply to the aerosol unmasked warming component but we chose to be conservative and to add the unmasking in after the ocean heat lag. There is one possible negative influence to warming resulting from the zero carbon measure of stopping fossil fuel emissions. This would be a partial offset from the reduction in black carbon (soot) emissions. An estimate of the net global warming effect of fossil fuel black carbon emissions and fossil fuel aerosol sulphate emissions would be helpful. However, the sulphate commitment of 0.4°C that we have applied is on the low side when compared to the 0.8°C research finding reported by the IPCC (2007g).

Could the large crop yield losses that we have found correlated with the unavoidable global temperature increases be less? Our crop yield losses that are median results from the models are optimistic:

> The existing literature identifies several prominent sources of uncertainty, including those related to the magnitude of local warming per degree global temperature increase, the sensitivity of crop yields to temperature, the CO_2 levels corresponding to each temperature level and the magnitude of CO_2 fertilization. The impacts of rainfall changes can also be important at local and regional scales, although at broad scales the modeled impacts are most often dictated by temperature and CO_2 because simulated rainfall changes are relatively small (Lobell and Burke, 2008). In addition, although the studies summarized in Figure 5.1 consider several of the main processes that determine yield response to weather, several other processes have not been adequately quantified. These include responses of weeds, insects, and pathogens; changes in water resources available for irrigation; effects of changes in surface ozone levels; effects of increased flood frequencies; and responses to extremely high temperatures. (NRC 2011, 160)
>
> Moreover, most crop modeling studies have not considered changes in sustained droughts, which are likely to increase in many regions (Wang, 2005; Sheffield and Wood, 2008), or potential changes in year-to-year variability of yields. The net effect of these

and other factors remains an elusive goal, but these are likely to push yields in a negative direction. (NRC 2011, 162)

These crop yield losses from the models do not account for the inevitable additive or synergistic combined impacts of the multiple adverse effects, nor does it account for cumulative damage to agricultural productivity over decades and centuries, which pertains because global warming lasts over 1000 years (NRC 2011).

Finally, the calculations for unavoidable warming and also for consequent unavoidable crop losses are derived from linear projecting climate models and linear projecting climate crop models, which may underestimate rate of warming and crop yield losses due no linear increases. "The climate system tends to respond to changes in a gradual way until it crosses some threshold: thereafter any change that is defined as abrupt is one where the change in the response is much larger than the change in the forcing" (IPCC 2007o). The climate crop models do not account for exceeding critical thresholds (NRC 2011, 160).

Therefore, we believe that our estimate of unavoidable global warming is, if anything, on the low side and that the unavoidable crop yield losses as unavoidable global warming progresses are on the low side.

References

Anderson, Kevin, and Alice Bows. 2008. Reframing the Climate Change Challenge in Light of Post-2000 Emission Trends. *Phil. Trans. R. Soc. A 366*(1882), 3863-3882. doi:10.1098/rsta.2008.0138

Athanasiou, Tom. 2011. "Tax Justice as Climate Justice." *Ecoequity*. Accessed July 25, 2012. http://www.ecoequity.org/2011/04/tax-justice-as-climate-justice/.

Baer, Paul, Tom Athanasiou, Sivan Kartha, and Eric Kemp-Benedict. 2008. The Greenhouse Development Rights Framework: The Right to Development in a Climate Constrained World. Berlin: Heinrich Böll Foundation.

Betts, Richard A., Matthew Collins, Deborah L. Hemming, Chris D. Jones, Jason A. Lowe, and Michael G. Sanderson. 2011. "When could global warming reach 4°C?" *Phil. Trans. R. Soc. A 369*(1934), 67-84. doi:10.1098/rsta.2010.0292.

Climate Interactive. 2010. Climate Momentum Simulation. Accessed July 25, 2012. http://climateinteractive.org/simulations/climate-momentum-simulation/climate-momentum.

Global Carbon Project. 2011. Carbon Budget 2010. Accessed July 25, 2012. http://www.globalcarbonproject.org/carbonbudget/10/hl-full.htm.

HLPE. 2012. Food Security and Climate Change: A Report by the High Level Panel of Experts on Food Security and Nutrition of the Committee on World Food Security. Rome: FAO.

International Energy Agency (IEA). 2011. World Energy Outlook. Fact Sheet. Accessed July 25, 2012. http://www.worldenergyoutlook.org/publications/weo-2011/.

IPCC. 2007. Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge, UK: Cambridge University Press.

IPCC. 2007a. "Long Term Climate Change and Commitment 10.7." In *Working Group 1: The Physical Science Basis,* edited by S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K. B. Averyt, M. Tignor and H. L. Miller.

IPCC. 2007b. "Development trends and the lock-in effect of infrastructure choices 3.1.3." In *Working Group III: Mitigation of Climate Change*, edited by B. Metz, O. R. Davidson, P. R. Bosch, R. Dave, and L. A. Meyer. http://www.ipcc.ch/publications_and_data/ar4/wg3/en/ch3s3-1-3.html.

IPCC. 2007c. "FAQ 10.3." In *Working Group 1: The Physical Science Basis*, edited by S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K. B. Averyt, M. Tignor and H. L. Miller. http://www.ipcc.ch/publications_and_data/ar4/wg1/en/faq-10-3.html.

IPCC. 2007d. "Mitigation and adaptation in the light of climate change impacts and decision-making under uncertainties." In *Working Group III: Mitigation of Climate Change*, edited by B. Metz, O. R. Davidson, P. R. Bosch, R. Dave, and L. A. Meyer. http://www.ipcc.ch/publications_and_data/ar4/wg3/en/tssts-ts-3-4-mitigation-and.html.

IPCC. 2007e. "Projections of Future Changes in Climate." In *Working Group 1: The Physical Science Basis,* edited by S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K. B. Averyt, M. Tignor, and H. L. Miller. http://www.ipcc.ch/publications_and_data/ar4/wg1/en/spmsspm-projections-of.html.

IPCC. 2007f. "Multi-Model Averages and Assessed Ranges for Surface Warming" (figure SPM.5). In *Working Group 1: The Physical Science Basis*, edited by S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K. B. Averyt, M. Tignor, and H. L. Miller. http://www.ipcc.ch/publications_and_data/ar4/wg1/en/figure-spm-5.html.

IPCC. 2007g. "Coupling Between Climate Change and Changes in Biogeochemical Cycles." In *Working Group 1: The Physical Science Basis*, edited by S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K. B. Averyt, M. Tignor, and H. L. Miller. http://www.ipcc.ch/publications_and_data/ar4/wg1/en/tssts-5-4.html.

IPCC. 2007h. "Sulphate Aerosol 2.4.4.1." In *Working Group 1: The Physical Science Basis*, edited by S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K. B. Averyt, M. Tignor, and H. L. Miller. http://www.ipcc.ch/publications_and_data/ar4/wg1/en/ch2s2-4-4-1.html.

IPCC. 2007i. "Carbon Cycle/Vegetation Feedbacks 10.4.1." In *Working Group 1: The Physical Science Basis*, edited by S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K. B. Averyt, M. Tignor, and H. L. Miller. http://www.ipcc.ch/publications_and_data/ar4/wg1/en/ch10s10-4.html#10-4-1.\

IPCC. 2007j. "Review of crop impacts versus incremental temperature change 5.4.2.2." In *Working Group II: Impacts, Adaptation and Vulnerability*, edited by M. L. Parry, O. F. Canziani, J. P. Palutikof, P. J. van der Linden, and C. E. Hanson. http://www.ipcc.ch/publications_and_data/ar4/wg2/en/ch5s5-4-2-2.html.

IPCC. 2007k. "Sensitivity to multiple stresses (Box 5.2)." In *Working Group II: Impacts, Adaptation and Vulnerability*, edited by M. L. Parry, O. F. Canziani, J. P. Palutikof, P. J. van der Linden, and C. E. Hanson. http://www.ipcc.ch/publications_and_data/ar4/wg2/en/ch5s5-2-2.html.

IPCC. 2007l. "Vulnerability of Carbon Pools 5.4.1.5." In *Working Group II: Impacts, Adaptation and Vulnerability*, edited by M. L. Parry, O. F. Canziani, J. P. Palutikof, P. J. van der Linden, and C. E. Hanson. http://www.ipcc.ch/publications_and_data/ar4/wg2/en/ch5s5-4-1-5.html.

IPCC. 2007m. “Important findings of the Third Assessment Report” section 5.1.3, Review of crop impacts versus incremental temperature change 5.4.2.2 In *Working Group II: Impacts, Adaptation and Vulnerability*, edited by M. L. Parry, O. F. Canziani, J. P. Palutikof, P. J. van der Linden, and C. E. Hanson. http://www.ipcc.ch/pdf/assessment-report/ar4/wg2/ar4-wg2-chapter5.pdf

IPPC. 2007n. "Carbon-free Energy and Decarbonization. 3.4.1." In *Working Group III: Mitigation of Climate Change*, edited by B. Metz, O. R. Davidson, P. R. Bosch, R. Dave, and L. A. Meyer. http://www.ipcc.ch/publications_and_data/ar4/wg3/en/ch3s3-4-1.html.

IPCC. 2007o. "Mechanisms producing thresholds and abrupt changes 8.7.1." In *Working Group 1: The Physical Science Basis*, edited by S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K. B. Averyt, M. Tignor, and H. L. Miller. http://www.ipcc.ch/publications_and_data/ar4/wg1/en/ch8s8-7.html

IPCC. 1990. First Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge, UK: Cambridge University Press.

Lancet and University College London Institute for Global Health Commission. 2009. "Managing the Health Effects of Climate Change." *The Lancet 373*. Accessed July 25, 2012. http://environmentportal.in/files/Managing%20the%20health%20effects%20of%20climate%20change.pdf

McGuire, D. A., L. G. Anderson, T. R. Christensen, S. Dallimore, L. Guo, D. J. Hayes, M. Heimann, T. D. Lorenson, R. W. MacDonald, and N. Roulet. 2009. "Sensitivity of the Carbon Cycle in the Arctic to Climate Change." In *Ecological Monographs 79*(4), 2009, pp. 523–555.

NASA. 2012. "How Much More Will Earth Warm?" In *Earth Observatory Features*. Accessed July 25, 2012. http://earthobservatory.nasa.gov/Features/GlobalWarming/page5.php.

National Research Council (NRC). 2011. Climate Stabilization Targets: Emissions, Concentrations, and Impacts Over Decades to Millennia (2010). Washington, DC: National Academies Press.

Ramanathan, V., and Y. Feng. 2008. "On Avoiding Dangerous Anthropogenic Interference with the Climate System: Formidable Challenges Ahead." Abstract. *Proceedings of the National Academy of Sciences* (September 17, 2008). doi:10.1073/pnas.0803838105.

Schellnhuber, H. J., and D. Klingenfeld. 2011. Fairness and Physics – Observing First Principles in Global Climate Policy. *Global Change, Peace & Security 23*(3): 427-433 (October 2011). Accessed July 25, 2012 at http://www.pik-potsdam.de/members/danielkl/documents/fairness-and-physics.Schellnhuber, H. J. 2008.

"Global Warming: Stop Worrying, Start Panicking?" Proceedings of the National Academy of Sciences (September 18, 2008). doi:10.1073/pnas.0807331105.

Solomon, Susan, Gian-Kasper Plattner, Reto Knutti, and Pierre Friedlingstein. 2009. "Irreversible Climate Change Due to Carbon Dioxide Emissions." Proceedings of the National Academy of Sciences (January 28, 2009). doi:10.1073/pnas.0812721106.

WBGU. 2009. Solving the Climate Dilemma: The Budget Approach. Berlin: German Advisory Council on Global Change. Accessed July 25, 2012. http://www.wbgu.de/en/special-reports/sr-2009-budget-approach/.