Electronic Supplemental Material

O'Neill et al., The Benefits of Reduced Anthropogenic Climate changE (BRACE): A synthesis

Climatic Change, 2017

Risk definition

We define risk as the potential for harm arising from the combination of climate-related hazards and the exposure and vulnerability of society and ecosystems that experience them, and impacts as a particular realization of that potential (Intergovernmental Panel on Climate Change, 2014).

Choice of RCPs and SSPs

The choice to compare impacts between the RCP8.5 and 4.5 forcing pathways was motivated by several factors. RCP8.5 was an attractive choice for a high pathway given that it is near the upper end of forcing scenarios in the literature and the only RCP that does not assume any mitigation is undertaken. It therefore provides a useful benchmark against which to measure the benefits of mitigation. In addition, a large initial condition ensemble of climate model runs (Kay et al., 2015), described further below, was available, allowing for better analysis of extreme events and natural variability. RCP4.5 was a useful representative of a lower forcing pathway given that the mitigation efforts required to achieve it are generally considered feasible and moderate even if climate policies are not ideal and not all technologies are acceptable (Blanford et al., 2014; van Ruijven, 2016), with costs substantially lower than those estimated to be required to achieve lower pathways (Clarke et al., 2014). While it is important for the research field as a whole to investigate the consequences of a wide variety of future forcing pathways, our focus in this project on RCP4.5 avoids questions about the difficulty or even feasibility of scenarios reaching a maximum warming of 2°C or lower (including RCP2.6) (Sanderson et al., 2016). It also helps fill a gap in the literature on forcing levels in the middle of the RCP range (van Ruijven, 2016).

The two SSPs (SSP3 and SSP5) were chosen in order to span a range of uncertainty in societal determinants of climate change impacts. SSP3 describes a world with relatively pessimistic development trends, little investment in education or health, fast growing population, and increasing inequalities, and a priority placed on regional security concerns. In contrast, SSP5 envisions relatively optimistic trends for human development, with substantial investments in education and health, rapid economic growth, low population growth, and well-functioning institutions, although it also assumes an energy intensive, fossil-based economy.

Production of CESM ensembles

CESM ensembles were produced with version 1.1 of CESM (Hurrell et al., 2013), which includes version 5 of the Community Atmosphere Model (CAM5) (Neale et al., 2012) and version 4 of the Community Land Model (CLM4.0) (Lawrence et al., 2011), and has a horizontal resolution of 0.9375˚x 1.25˚. Ensemble members for RCP8.5 were produced by slightly perturbing atmospheric conditions at the surface in 1920, with all members following historical plus future forcing according to the RCP8.5 scenario (Kay et al. 2015). Ensemble members for RCP4.5 were produced by selecting a subset of 15 of the 30 RCP8.5 ensemble members in 2005, and then imposing forcing according to the RCP4.5 scenario through 2080 (Sanderson et al., 2016). Ensemble members for the RCP8.5 fixed aerosol simulations were produced by selecting a subset of 16 of the 30 RCP8.5 ensemble members in 2005, and then imposing forcing that is identical to RCP8.5 except keeping aerosol emissions and atmospheric oxidants fixed at their 2005 level (Xu et al., 2015). Many of the BRACE studies report results for the 2060-80 period, during which time GMT averages about +3.7˚C relative to pre-industrial in RCP8.5 and +2.5˚C in RCP4.5. These warming levels are calculated as the ensemble mean change of average temperature over the period 2061-2080 compared to that over the period 1986-2005, to which we add 0.6° (for the global mean numbers) or 0.9° (for the land-only numbers) obtained on the basis of the change between 1850-1900 and 1986-2005 from, respectively, HadCRUT4 (Morice et al., 2012) and CRUTEM4 data (Jones et al., 2012).

Supplemental References

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Table S1: Summary of CESM simulations used in each BRACE study. Definitions: CESM-LE = RCP8.5 Large Ensemble (Kay et al., 2015); CESM-ME = RCP4.5 Medium Ensemble (Sanderson et al., 2015); CESM-LE-FA = RCP8.5 Large Ensemble with Fixed Aerosols, i.e. aerosols fixed at 2005 levels (Xu et al., 2015); CAM5-HR = High resolution (25 km) time slice simulations runs with the Community Atmosphere Model version 5, driven by sea surface temperatures from CESM projections of RCP4.5 and RCP8.5. Bias correction or use of single ensemble members is indicated where relevant. For full citations, see main paper.

Study	CESM-LE	CESM-ME	CESM-LE-FA	CAM5-HR
Sanderson et al., 2015	X	X		
Alexeeff et al., 2016	X	X		
Fix et al., 2016	X	X		
Tebaldi & Wehner, 2016	X	X		
Lehner et al., 2016	X	X		
Oleson et al., 2016	X Bias corrected	X Bias corrected		
Xu et al., 2015	X	X	X	
Lin et al., 2016	X	X	X	
Jones et al., submitted	X Bias corrected	X Bias corrected		
Anderson et al., 2016a				
Anderson et al., 2016b	X Bias corrected	X Bias corrected		
Marsha et al., 2016	X Downscaled, Bias corrected	X Downscaled, Bias corrected		
Monaghan et al., 2016	X Downscaled, Bias corrected	X Downscaled, Bias corrected		
Levis et al., 2016	X Single member*	X Single member*		
Ren et al., 2016	X Single member*	X Single member*		
Tebaldi & Lobell, 2015	X	X		
Bacmeister et al., 2016	X 3 members, SSTs Bias corrected	X 1 member, SSTs Bias corrected		X
Done et al., 2015	X	X Single member		
Gettelman et al., 2017	X 3 members, SSTs Bias corrected	X 1 member, SSTs Bias corrected		X

* These simulations were from a small ensemble of CCSM4 runs produced for CMIP5 (Meehl et al. 2012). CCSM4 differs from CESM1(CAM5), used for the large and medium ensembles of RCPs 8.5 and 4.5, primarily in the atmospheric component (CAM4 in CCSM4, CAM5 in CESM1(CAM5)). Among other differences, the equilibrium climate sensitivities in CAM5 vs CAM4 are 4.1 vs 3.2 C, and the transient climate sensitivities are 2.3 vs 1.7 C (Hurrell et al., 2013).

Table S2: Selected results by topic for impacts and avoided impacts in the BRACE project. All results global and for the time period 2061-2080 unless otherwise indicated.

Impact	RCP8.5	RCP4.5	RCP4.5 vs 8.5	Notes
Extreme events				
US urban heat/cold waves (Oleson et al., 2015)	41-99 heat wave days per year (relative to 4.5-6.5 recent) 0-3.0 cold wave days per year (relative to 4.5-6.5 recent)	21-53 heat wave days per year (relative to 4.5-6.5 recent) 0.5-4.5 cold wave days per year (relative to 4.5-6.5 recent)	Heat/cold wave days reduced by about half	Heat and cold wave days for urban areas only. Ranges represent the max and min results over ensemble members and over seven sub-regions. Recent period defined as 1981-2005.
Hottest day (or 3-day period) of the year measured by minimum or maximum daily temperatures (Tebaldi and Wehner, 2015)	>2 degree increase in 20-year events over 96%, 98%, 98% and 100% of land for the 1-day max, 3-day max, 1-day min and 3-day min temperature metrics, respectively; >4 degree increase over 67%, 81%, 57% and 72% of land, for the same metrics.	>2 degree increase in 20-year events over 76%, 99%, 60% and 82% of land for the 1-day max, 3-day max, 1-day min and 3-day min temperature metrics, respectively; >4 degree increase over 7%, 55%, 2% and 8% of land, for the same metrics.	Intensity of 20-year events reduced substantially: >1 °C reduction over 94%, 94%, 94% and 96% of land area for the 1-day max, 3-day max, 1-day min and 3-day min temperature metrics, respectively; >2 °C reduction over 56%, 53%, 50% and 49% of land, for the same metrics.	Results are for temperatures in 2075 compared to a reference period of 1996-2005.
	Current 20-year events occur every year in 47%, 60%, 61% and 79% of the land area for the 1-day max, 3-day max, 1-day min and 3-day min temperature metrics, respectively.	Current 20-year events occur every year in 11%, 18%, 13% and 26% of the land area for the 1-day max, 3-day max, 1-day min and 3-day min temperature metrics, respectively.	Area in which current 20-year events occur every year reduced by 77%, 67%, 79% and 70% for the 1-day max, 3-day max, 1-day min and 3-day min temperature metrics, respectively.	

	Area-averaged return period for current 20-year event reduced to 3, 2, 2, and 1 year for the 1-day max, 3-day max, 1-day min and 3-day min temperature metrics, respectively.	Area-averaged return period for current 20-year event reduced to 9, 6, 8, and 5 years for the 1-day max, 3-day max, 1-day min and 3-day min temperature metrics, respectively.	On average RCP4.5 has an area-average return period for current 20-year events that is 5, 4, 6 and 4 years longer than the return period in RCP8.5 for the 1-day max, 3-day max, 1-day min and 3-day min temperature metrics, respectively.	
Summer temperature records (Lehner et al., 2016)	Globally averaged likelihood for a summer warmer than historical record: 80%	Globally averaged likelihood for a summer warmer than historical record: 41%	Likelihood of summer temperature warmer than historical record reduced by half (about 39 percentage points)	Likelihood calculated at each grid point, then globally averaged. By definition the likelihood of exceeding the historical record in the recent period is 0%, because the threshold of exceedance is based on the historical record itself. This applies as well to the metrics in the next two rows.
	Population (land area) at >70% risk of exceeding historical record: 79% (76%)	Population (land area) at >70% risk of exceeding historical record: 23% (29%)	Population benefits disproportionately compared to just land area	

	13-40% of land area experiences a new record summer	5-27% of land area experiences a new record summer	Land area experiencing a new record reduced by one-third to one-half (33-62%).	Ranges represent averages over the 2060-80 period of upper and lower bound of distribution across ensemble members.
US extreme precipitation (Fix et al., 2016)	1% Annual Exceedance Probability Level increases 0-29% (mean 15%) over all grid cells. Increase is 5-29% (mean 15%) over the 96% of cells with statistically significant differences.	1% Annual Exceedance Probability Level increases 0-23% (mean 10%) over all grid cells. Increase is 6-23% (mean 12%) over the 72% of cells with statistically significant differences.	1% Annual Exceedance Probability Level changes by -15% to +8% (mean -4%) over all grid cells. Change is -15% to -4% (mean -8%) over the 34% of cells with statistically significant differences.	AEP level is the amount of daily rainfall with a 1 % chance of being exceeded in a given year. Results for RCP8.5 and RCP4.5 are for a single future year (2070) compared to a single current year (2005), while comparison between the two RCPs is for the year 2070.
Aridity (Lin et al., 2015)	Global aridity index decreases 7% (drying)	Global aridity index decreases 4% (drying)	Drying reduced by about half	Results are for ensemble means; uncertainty is small at the global level (+/- 2 SD range about 1 percentage point). Results vary substantially at the regional level, ranging from small increases in the aridity index to >20% reduction (drying).

Health				
US high-mortality heat waves (Anderson et al., 2016b)	40-85 high mortality heat waves during 20 year period across 82 communities (relative to 4-7 recent)	29-55 high mortality heat waves during 20 year period across 82 communities (relative to 4-7 recent)	Number of high mortality heat waves reduced by 7-28 (14-37%).	Ranges of high mortality heat waves represent the range over ensemble members and across four different heat wave models, assuming no adaptation. Range for reduction in heat waves is the difference in ensemble means over four heat wave models. Adaptation strongest determinant of outcome.
	39-136 Million Person-Days per year (MPD/yr) of population exposure, no adaptation (relative to 1-3 MPD/yr recent)	20-64 MPD/yr, no adaptation (relative to 1-3 MPD/yr recent)	Exposure reduced by about half (21-70 MPD, or 42-57%) with no adaptation.	Ranges of exposure represent the range over ensemble members, across four different heat wave models, and across two population scenarios, assuming no adaptation. Range for reductions in exposure is the difference in ensemble means over four heat wave models and two population projections.

Global population exposure (Jones et al., submitted)	~220-790 billion person days/year of exposure to heat waves (relative to 15 billion person days/year recent)	~100-350 billion person days/year of exposure to heat waves (relative to 15 billion person days/year recent)	Population exposure to heat waves reduced by about half	Ranges represent the range for 2061-2080 across two population scenarios and the 95% interval over ensemble members and interannual variability.
Houston heat wave mortality (Marsha et al., 2016)	~5115-8103 heat-related deaths/yr (relative to ~1608/yr recent)	~5018-7955 heat-related deaths/yr (relative to ~1608/yr recent)	Climate change effect on heat-related mortality reduced by about half, but small effect compared to mortality changes driven by demographics and income	Ranges of heat-related deaths represent the range across two SSPs and the 25th-75th percentile range over ensemble members.
Exposure to dengue, Zika, chikunguna and yellow fever virus vector mosquito (Monaghan et al., 2016)	~6300-8900 M/yr experience any level of exposure (relative to ~3800 recent).	~6000-8600 M/yr experience any level of exposure (relative to ~3800 recent)	Exposure at any level reduced by ~3% of total global population, however small effect compared to changes due to population.	Ranges of exposure represent the range in ensemble means of exposure across two different population projections, for all four mosquito occurrence types (i.e., levels of exposure) combined.
	For ~1780-2250 M/yr, exposure increases by at least one occurrence type.	For ~1230-1500 M/yr, exposure increases by at least one occurrence type.	Net reduction of about one-third (~650-875 M/yr) in number who experience increase in exposure of at least 1 occurrence type.	Ranges of exposure represent the range in ensemble means of exposure across two different population projections, for the net number of people experiencing a change in exposure of at least one occurrence type. Positive value indicates that more people are exposed to more (rather than less) suitable conditions for mosquito occurrence.

Agriculture				
Economic impacts on agriculture (Ren et al., 2016)	With CO_2 fertilization, regional and global mean changes: yield: +28% to +163% (mean +84%, +102% in 2 SSPs) crop price: -17% to +247% (mean +46%, +98% in 2 SSPs)	With CO_2 fertilization, regional and global mean changes: yield: 30% to 161% (mean +72%, +87% in 2 SSPs) crop price: -13% to +263% (mean +58%, +113% in 2 SSPs)	With CO_2 fertilization, the regional range of yield and price outcomes is affected very little.	Results are for yields and prices as calculated in the iPETS economic model for the aggregate crop sector. They include the effect of non-climate-related productivity changes, the effect of climate and CO_2 change on potential yield (Levis et al., 2015), and economic adjustments to potential yield changes. Ranges are over the 9 iPETS regions and two SSPs, expressed as percentage changes relative to 2004.
	Without CO_2 fertilization, regional and global mean changes: yield: -14% to +108% (mean +17%, +29% in 2 SSPs) crop price: 67% to 414% (mean +141%, +219% in 2 SSPs)	Without CO_2 fertilization, regional and global mean changes: yield: -2% to +125% (mean +30%, +42% in 2 SSPs) crop price: 33% to 322% (mean +115%, +186% in 2 SSPs)	Without CO_2 fertilization, yields are somewhat higher and crop price increases are reduced by a quarter to a half.	
Crop yields (empirical) (Tebaldi & Lobell, 2015)	With CO_2 fertilization, global yield changes: wheat: -4 to -12% (mean -8%) maize: -22 to -31% (mean -27%)	With CO_2 fertilization, global yield changes: wheat: -4 to -9% (mean -7%) maize: -13 to -18% (mean -15%)	With CO_2 fertilization, about half the net decline in maize yield is avoided, wheat yield decline is similar in both scenarios.	Results for 2070 (relative to 1996 climate). Range represents the 25th-75th percentile of the distribution over CESM ensemble members.
	Without CO_2 fertilization, global yield changes: wheat: -27 to -36% (mean -32%) maize: -27 to -36% (mean -32%)	Without CO_2 fertilization, global yield changes: wheat: -22 to -16% (mean -19%) maize: -22 to -16% (mean -19%)	Without CO_2 fertilization, about 40% of the decline in both maize and wheat yields is avoided	

	Days of exposure to daily temperatures above critical threshold: Wheat: 23-26 (mean 24); relative to ~8 recent Maize: 18-20 (mean 19); relative to 4-5 recent	Days of exposure to daily temperatures above critical threshold: Wheat: 15-17 (mean 16); relative to ~8 recent Maize: 10-13 (mean 12); relative to 4-5 recent	Exposure to extreme heat reduced by about a third.	Results for 2061-2080 and represent the ensemble range and mean of the average global exposure over the current cropland area for each crop in number of days. Recent period defined as 1993-2012.
	Chance of major slowdown in yield (>5% loss over 10 yrs) with CO_2 fertilization: Wheat: 2% chance (relative to 4% recent) Maize: 35% chance (relative to 10% recent)	Chance of major slowdown in yield (>5% loss over 10 yrs) with CO_2 fertilization: Wheat: 1% chance (relative to 2% recent) Maize: 8% chance (relative to 9% recent)	Chance of major slowdown in maize yield (>5% loss over 10 yrs) reduced by three-fourths. Chance of slowdown in wheat yield is small in both cases.	Results for 2060-2070. Recent period defined as 2000; results for recent period vary slightly between RCPs due to differences in outcomes across ensembles.
Potential crop yields (CLM) (Levis et al., 2016; Ren et al., 2016)	With CO_2 fertilization, regional and global mean yield changes: all crops: +2 to +26% (mean +11%) wheat: +14 to +160% (mean +24%), maize: -18 to +4% (mean 0%)	With CO_2 fertilization, regional and global mean yield changes: all crops: 0 to +14% (mean +6%) wheat: +9 to +86% (mean +16%) maize: -12 to +6% (mean -1%)	With CO_2 fertilization, about one-third the net benefit to global mean wheat yield in RCP8.5 is lost; little change to maize yields.	Results are based on Ren et al. for 2061-2080 relative to 1986-2005, and assume current cropland distribution and fertilizer rates held constant at current levels according to FAO (see Ren et al., 2016, for the method of deriving yield from CLM runs). Results are crop area-weighted averages. Ranges are over the 9 iPETS regions, mean is the global area-weighted average.

	Without CO_2 fertilization, regional and global mean yield changes: all crops: -1 to -21% (mean -12%) wheat: -3 to -23% (mean -15%) maize: -1 to -23% (mean -9%)	Without CO_2 fertilization, regional and global mean yield changes: all crops: -15 to +1% (mean -7%) wheat: -15 to +2% (mean -8%) maize: -17 to +4% (mean -6%)	Without CO_2 fertilization, about half the net decline in global mean wheat yield, and one-third the decline in maize yield, is avoided.	
	With CO_2 fertilization, global yield increase 43% for C3 crops; no significant change for C4 crops. Without CO_2 fertilization, global yield decreases 20% for C3 crops, 14% for C4 crops.	With CO_2 fertilization, global yield increases 23% for C3 crops; no significant change for C4 crops. Without CO_2 fertilization, global yield decreases 10% for C3 crops, 7% for C4 crops.	With CO_2 fertilization, about half the net benefit to C3 yields in RCP8.5 is lost. Without CO_2 fertilization, about half the net decline in C3 and C4 yields is avoided.	Results are from Levis et al. for 2081-2100 and assume the current spatial distribution of crop types. They include nitrogen fertilizer and irrigation according to CLMcrop default assumptions, which are generally substantially more optimistic than current and projected management assumed in Ren et al. (2016). Yield results are therefore more optimistic than in Ren et al.

Tropical Cyclones				
Tropical cyclone activity (Bacmeister et al., 2016)	Global, all tropical cyclones: track density of 4.2-5.9 h/yr/grid (relative to 5.3-7.0 today)	Global, all tropical cyclones: track density of 4.9-5.9 h/yr/grid (relative to 5.3-7.0 today)	No significant difference between scenarios; both indicate declines relative to present.	Future results are for 2070-2090 and represent 1st to 99th percentile ranges over eight ensemble members for RCP8.5 and one member for RCP4.5. Results for recent are for 1979-2005 or 1979-2012 and represent the 1st to 99th percentile ranges across four ensemble members. Distributions derived from 2000 bootstrapped 20-year samples. Units are hours of storm activity per year per 4x4 degree grid box (h/yr/grid).
	Global, category 4/5 storms: track density of 0.05-0.14 h/yr/grid (relative to 0.01-0.05 today)	Global, category 4/5 storms: track density of 0.05-0.11 h/yr/grid (relative to 0.01-0.05 today)	No significant difference between scenarios; both indicate increases relative to present.	
Atlantic tropical cyclone damage potential (Done et al., 2016)	Damage potential declines; 3-10 years per decade of low damage potential (relative to 2-7 years today)	Damage potential declines; 10 years per decade of low damage potential (relative to 2-7 years today)	No significant difference between scenarios.	Results are for 2071-2080 for the N Atlantic basin, based on physical index of cyclone damage potential calculated from the RCP8.5 ensemble and for a single ensemble member for RCP4.5. Ranges for recent and RCP8.5 represent the 95% interval over the ensemble.

Economic damage from tropical cyclones (Gettelman et al, submitted)	Global: ~$170 billion/yr (relative to ~$67 billion/yr recent)	Global: ~$190 billion/yr (relative to ~$67 billion/yr recent)	Difference between RCP4.5 and RCP8.5 is not statistically significant. In both scenarios future global damages increase relative to recent.	Future damages represent annual mean insured losses based on climate over the 2061-2080 period and 2070 projected assets based on SSP5. Climate simulations for both RCPs assume the same type of surface-atmosphere coupling (1 degree). The standard deviation of the estimate of mean damage for RCP8.5 is ~$33 billion/yr, based on five simulations with different coupling assumptions. Recent damages are based on climate simulations for 1975-2013 and 2015 assets.
	US: ~$12 billion/yr (relative to ~$13 billion/yr recent)	US: ~$12 billion/yr (relative to ~$13 billion/yr recent)	Difference between RCP4.5 and RCP8.5 is not statistically significant.	

Figure S1: Models and methods employed in the BRACE project. Numbers of papers associated primarily with the methods in each box are shown in parentheses.

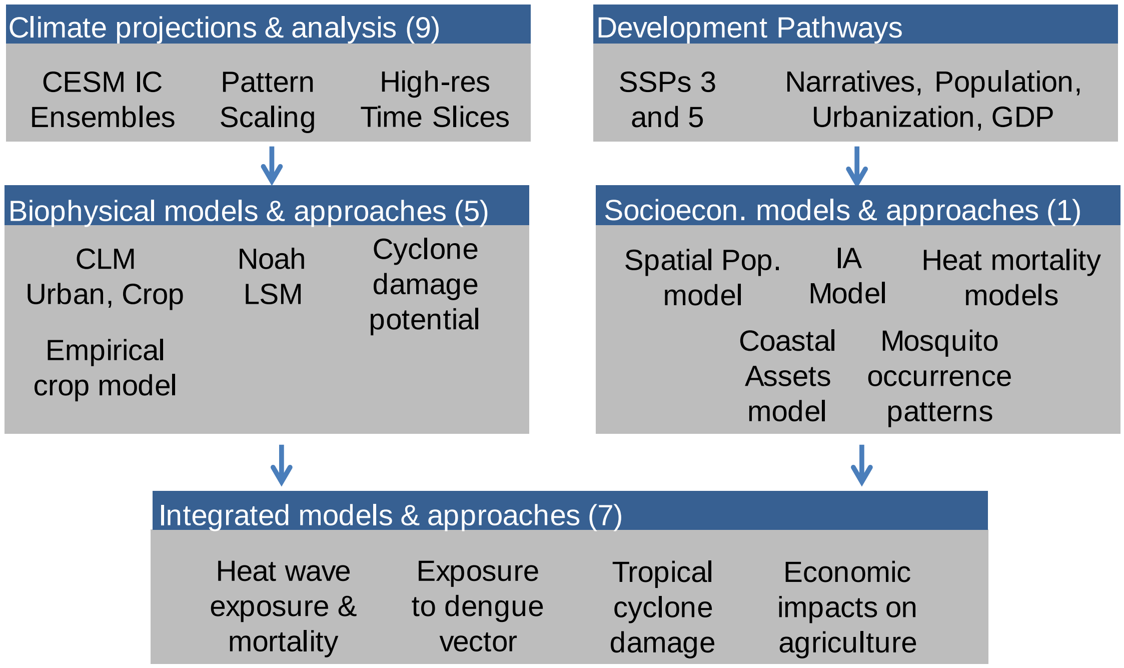
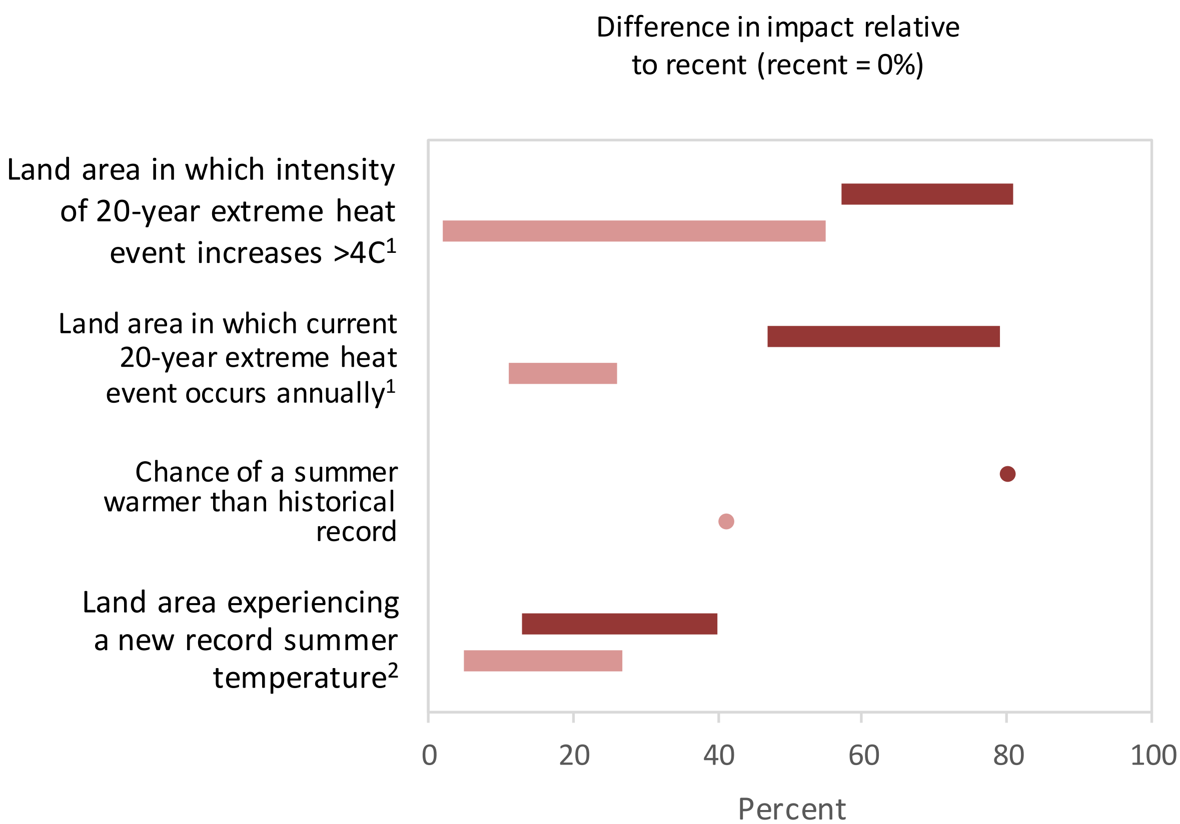


Figure S2: Analogously to Figure 1 in the main text, differences between RCP8.5 and RCP4.5 for impacts related to (a) extreme events and (b) agriculture. Bars show uncertainty ranges for impacts in RCP8.5 (red) and RCP4.5 (pink) for the late 21st century relative to a recent period (2061-80 relative to 1986-2005 unless otherwise indicated). Panel (a) shows the *difference* in outcomes relative to recent (where recent = 0) while panel (b) show the *ratio* in outcomes relative to recent (where recent = 1.0). Ranges are defined differently for each impact (see Table S2 and notes to each panel); they are comparable between RCPs for a given impact but not across impacts. In panel (b), yield outcomes based on CLM and the empirical model have been made as comparable as possible. Both show results for 2061-2080 relative to a 1986-2005 recent period, assume current spatial distribution of crops, and either explicitly (CLM) or implicitly (empirical) assume fixed fertilizer and irrigation over time (for CLM-based estimates, fertilizer is fixed at 2005 levels).

(a)

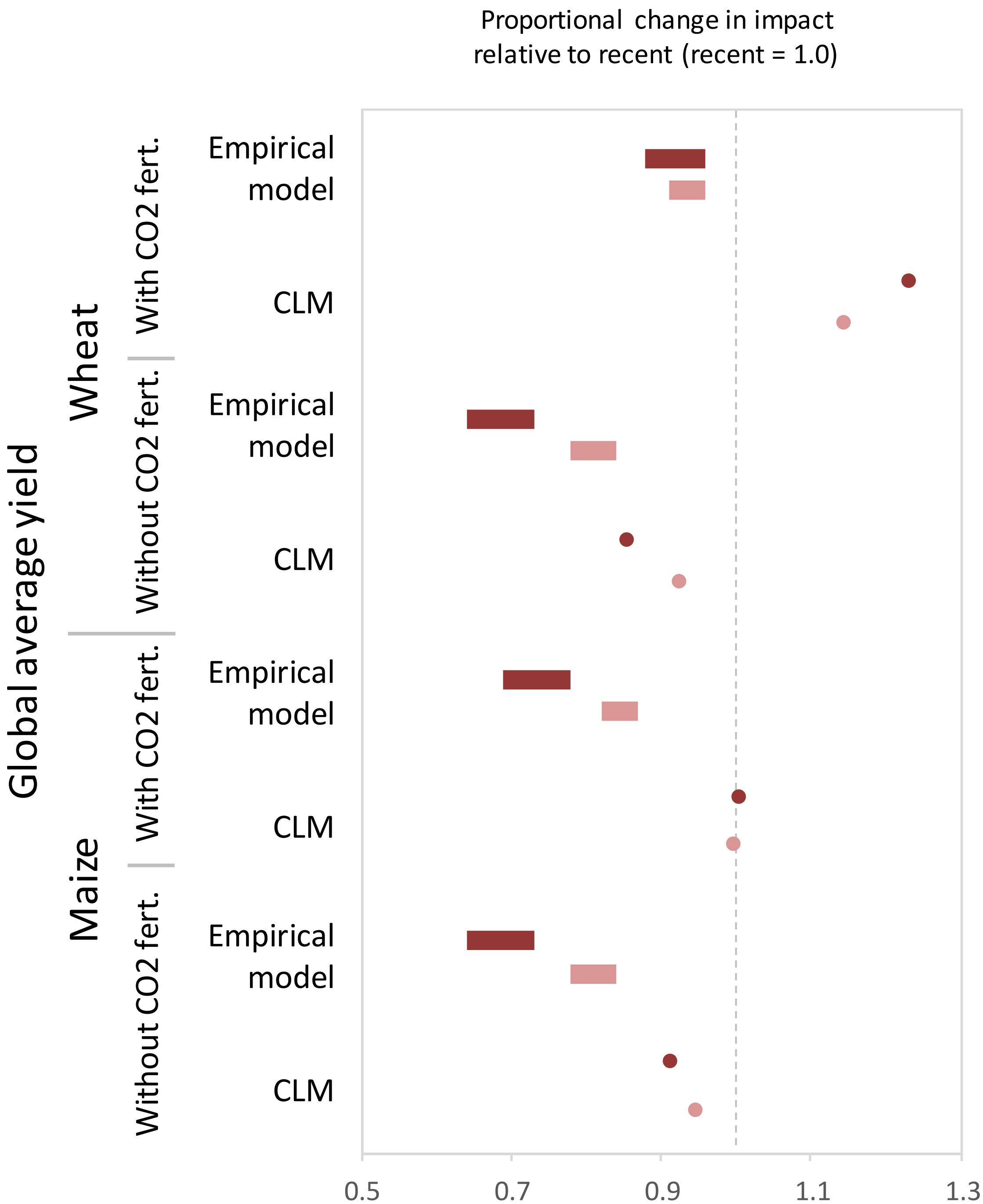


Ranges defined over:

[1] Four different metrics of 20-year events (1 or 3 day, min or max temperature)

[2] 2060-80 average of upper and lower bound of range of CESM ensemble members

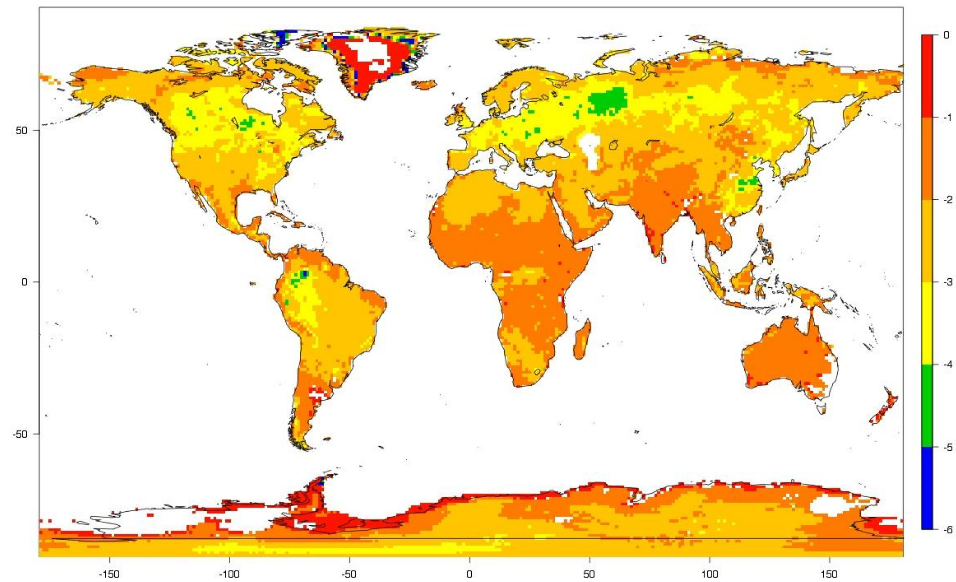
(b)



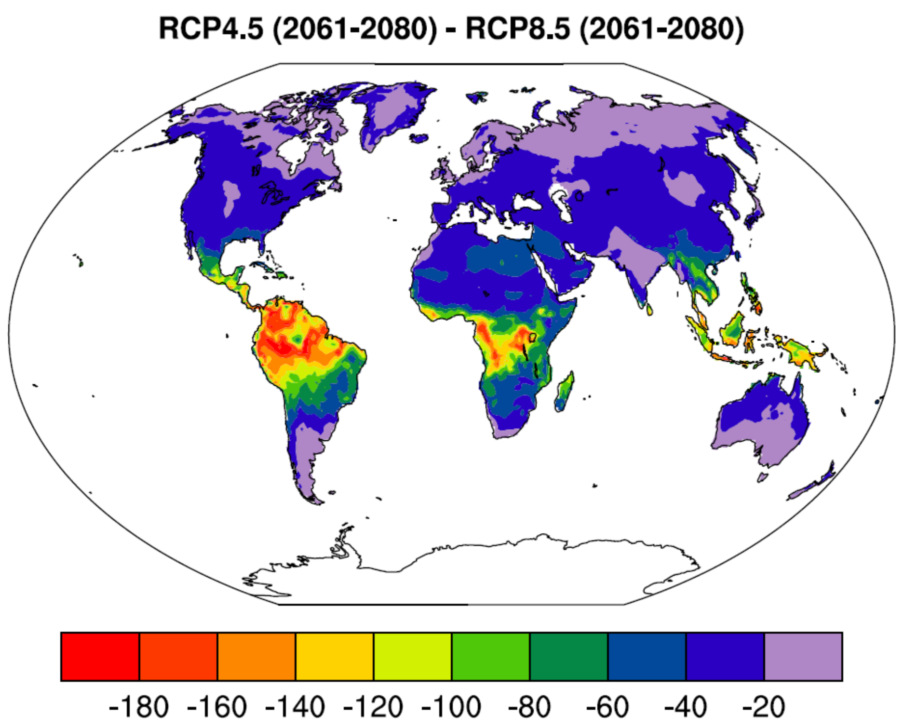
Ranges for all empirical model results defined over 50% interval of CESM ensemble members.

Figure S3: Maps of avoided impacts by sector.

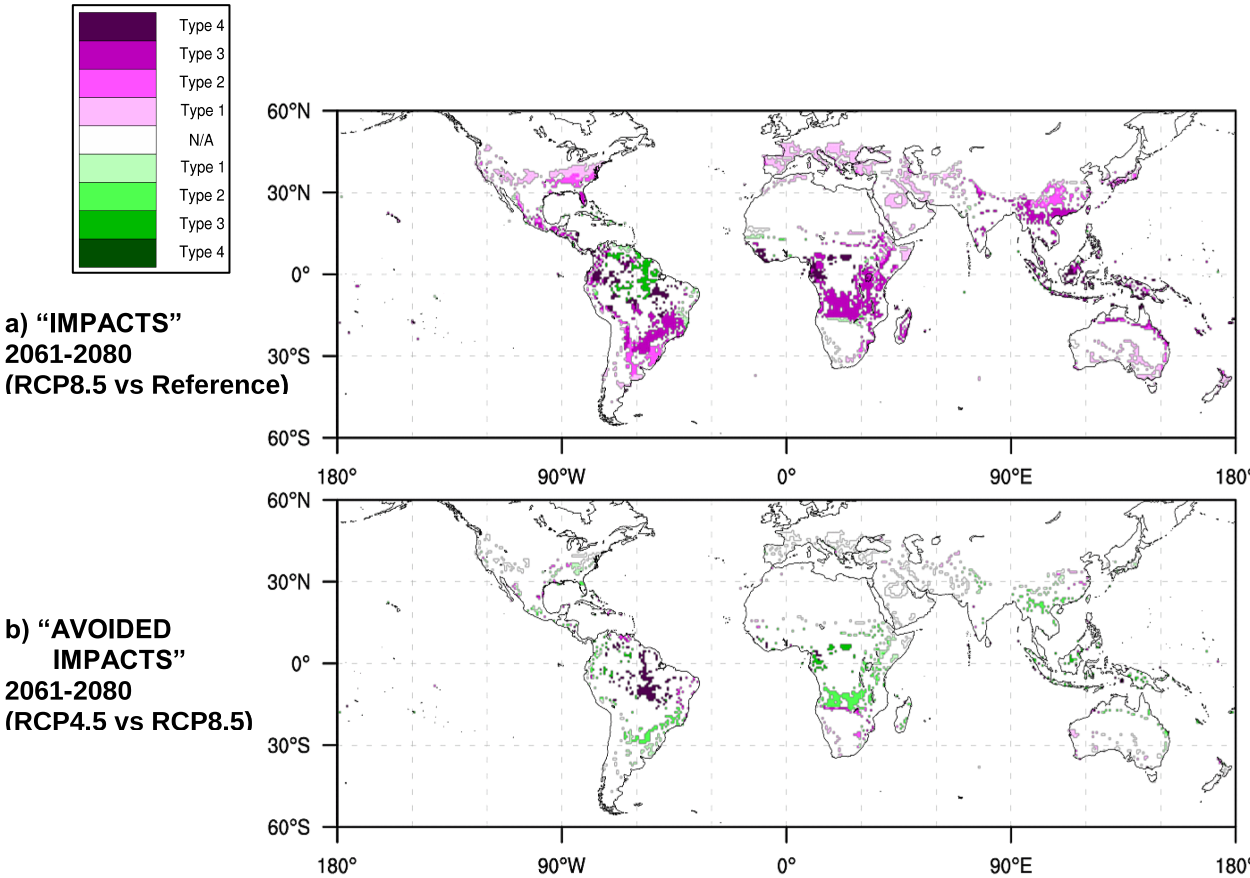
Difference in return value of 20-year event, annual max of daily high temperature, RCP4.5 vs RCP8.5 (degrees C). Tebaldi and Wehner, 2016.



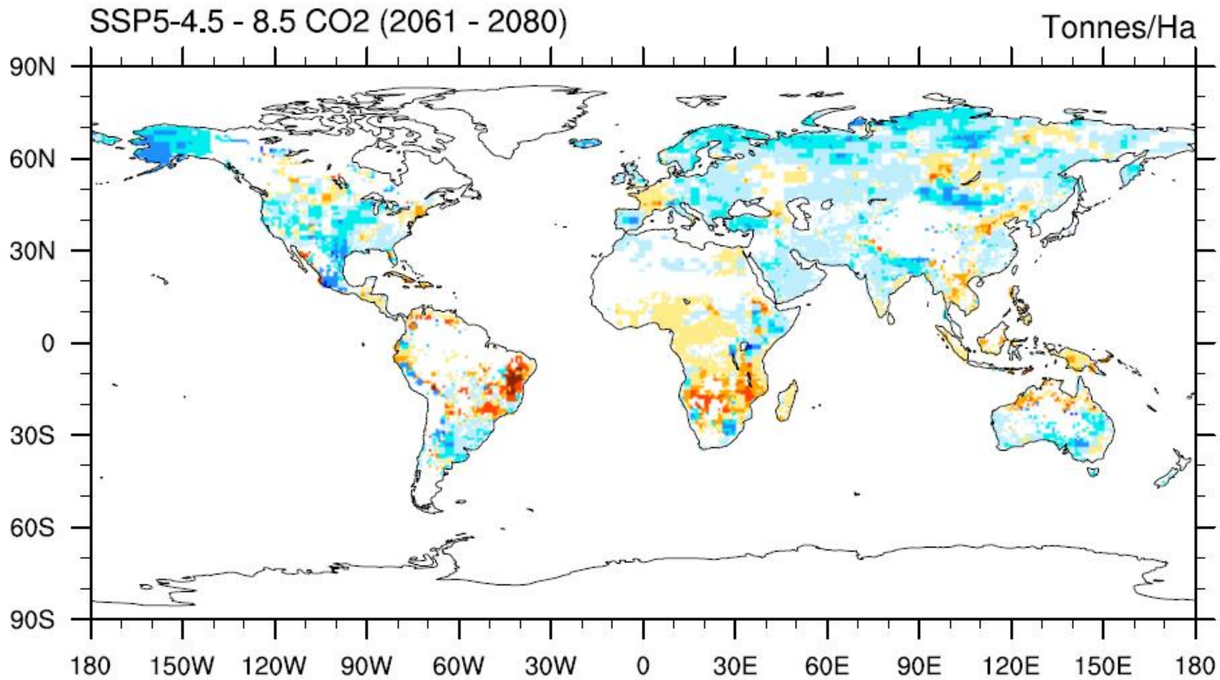
Difference in heat wave days per year. Oleson et al., 2015.



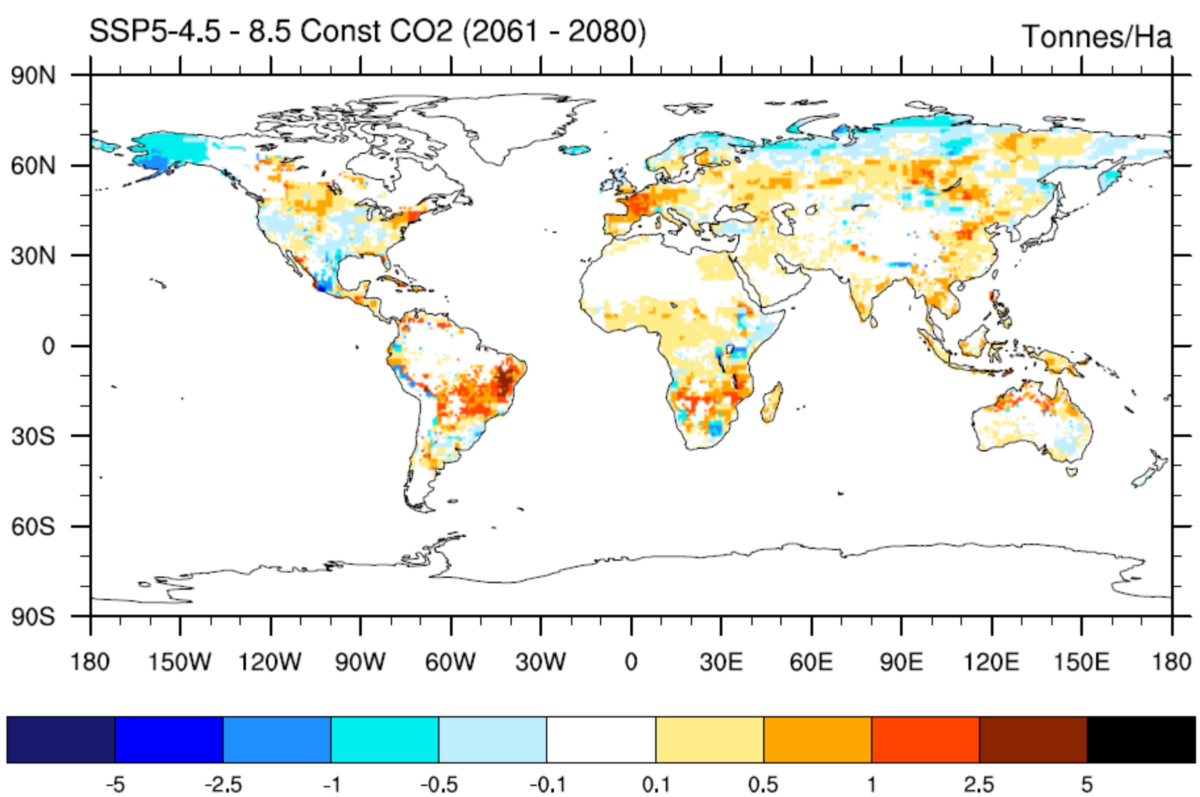
Change in area of Dengue mosquito vector occurrence (green shades = area loss by occurrence type, purple shades = area gain by occurrence type). Monaghan et al., 2016.



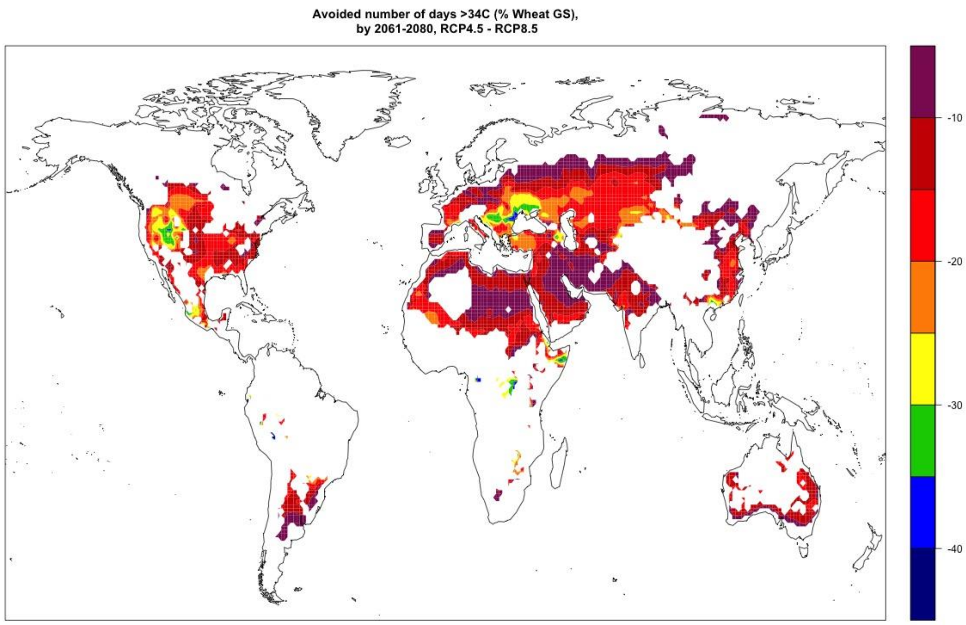
Change in potential crop yield (CLM), with CO2 fertilization.



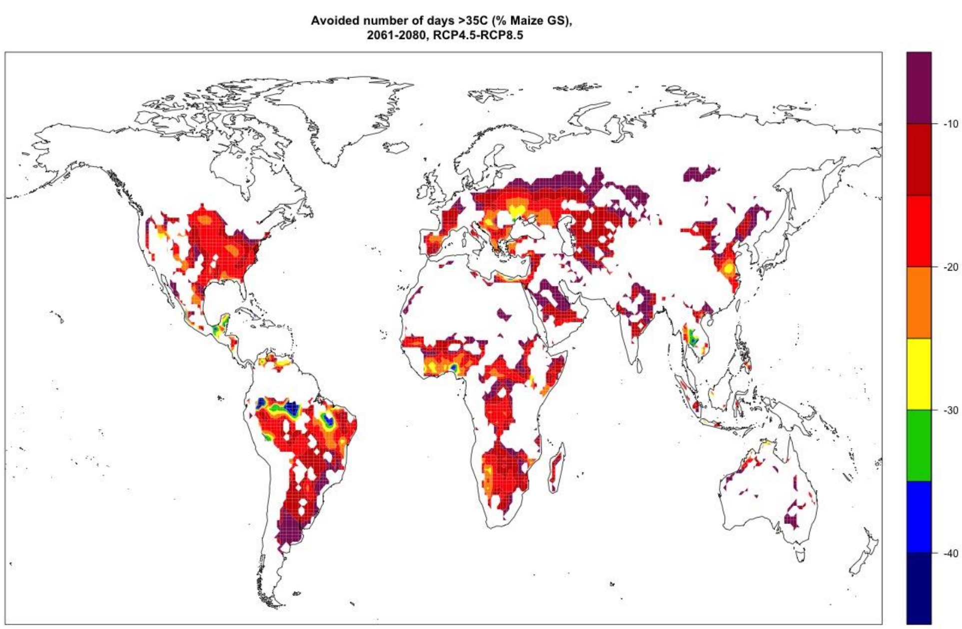
Change in potential crop yield (CLM), without CO2 fertilization.



Difference in number of days above critical temperature threshold for wheat as a percentage of the growing season, for all cells with non-zero fraction of cropland in 2070 and at least 5% difference. Tebaldi and Lobell, 2015.



Difference in number of days above critical temperature threshold for maize as a percentage of the growing season, for all cells with non-zero fraction of cropland in 2070 and at least 5% difference. Tebaldi and Lobell, 2015.



Difference in Aridity Index. Lin et al., 2015.