# Climate Damages in IAMs

AERE Summer Conference Workshop

May 29th, 2019

# Outline

- Damage functions – what are they and why do we need them?

- Current representation of climate damages in cost-benefit IAMs

- Opportunities to improve damages
  - Climate impact literature
  - Coordinated multi-model / multi-sector efforts
  - Reduced-form approaches: sector-specific and top-down

- Two applied examples
  - Improving the agriculture sector damage function using the climate impacts literature
  - Incorporating empirical estimates of growth-rate damages into the SCC

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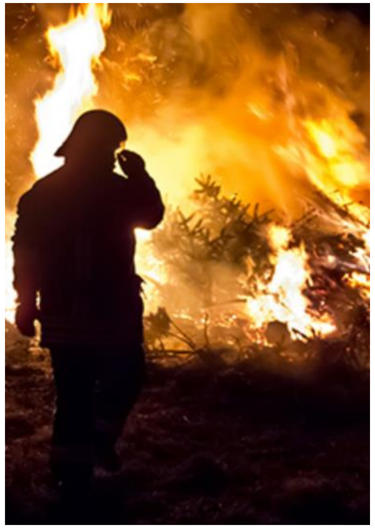
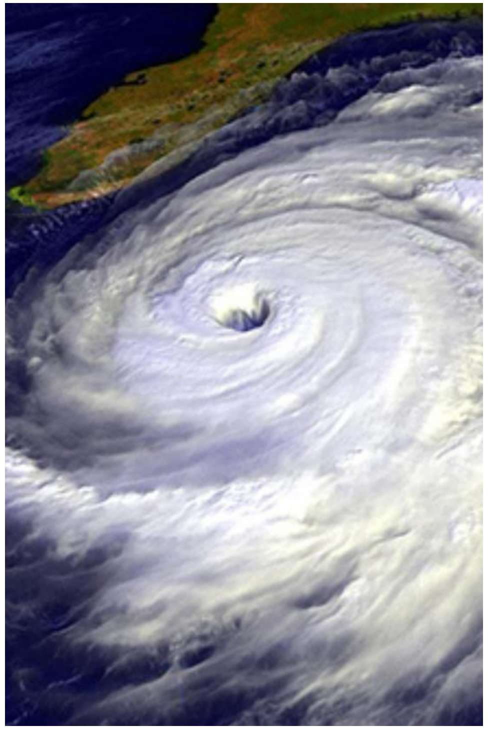
# The SCC as Accounting Exercise





- A ton of $CO_2$ emitted today affects many systems, around the world, for centuries
- The SCC is essentially an accounting exercise that quantifies these changes and converts them into common units through valuation and discounting
- Climate damages are ***the whole point*!**

# Damage Functions

- In current cost-benefit IAMs, climate change effects are not represented structurally
- Instead, they include a reduced-form relationship between climate impacts and global temperature
- Why?
  - Computational reasons?
  - Path dependency?
  - Cross-disciplinary problems?

$$Damages_t = \boldsymbol{f}(\Delta T_t)$$

This little guy has a LOT of work to do!

# Damage Functions

- Damages should include the costs and benefits of private adaptation (i.e. the value function)
- Damages can be resolved by region and sector (typically assume additive separability)
- Generally damage functions are giving equilibrium rather than transition costs

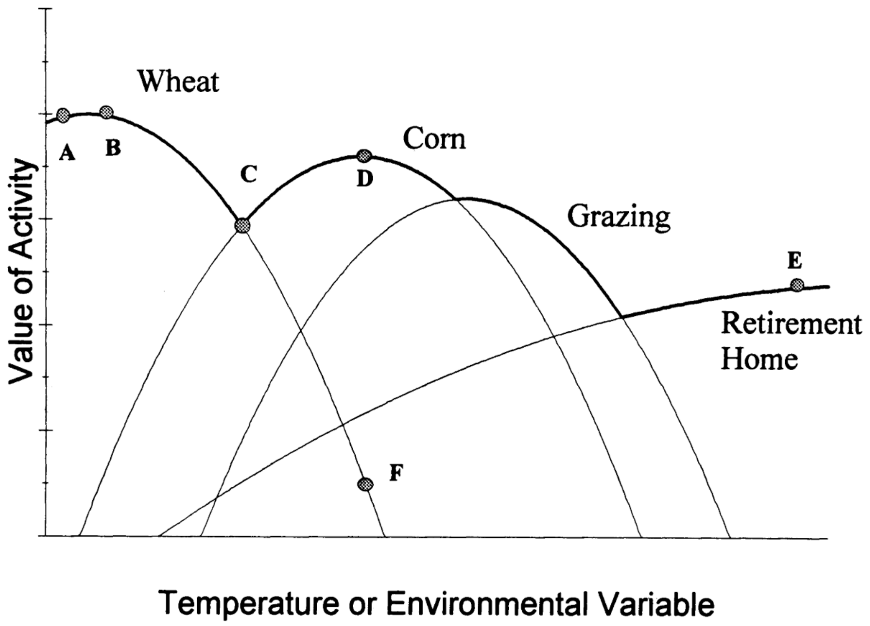



FIGURE 1. BIAS IN PRODUCTION-FUNCTION STUDIES

Mendelsohn, Nordhaus and Shaw, 1994

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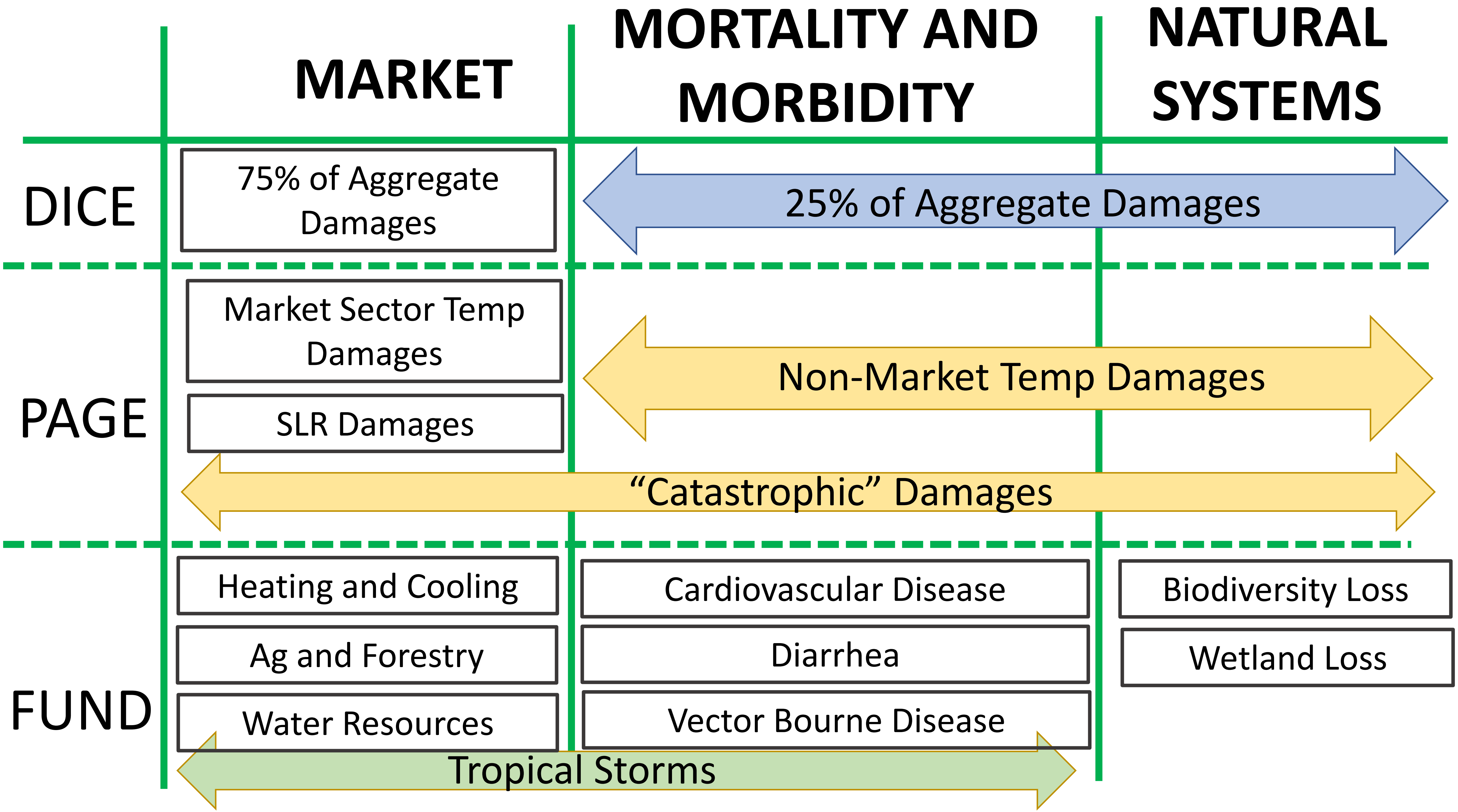
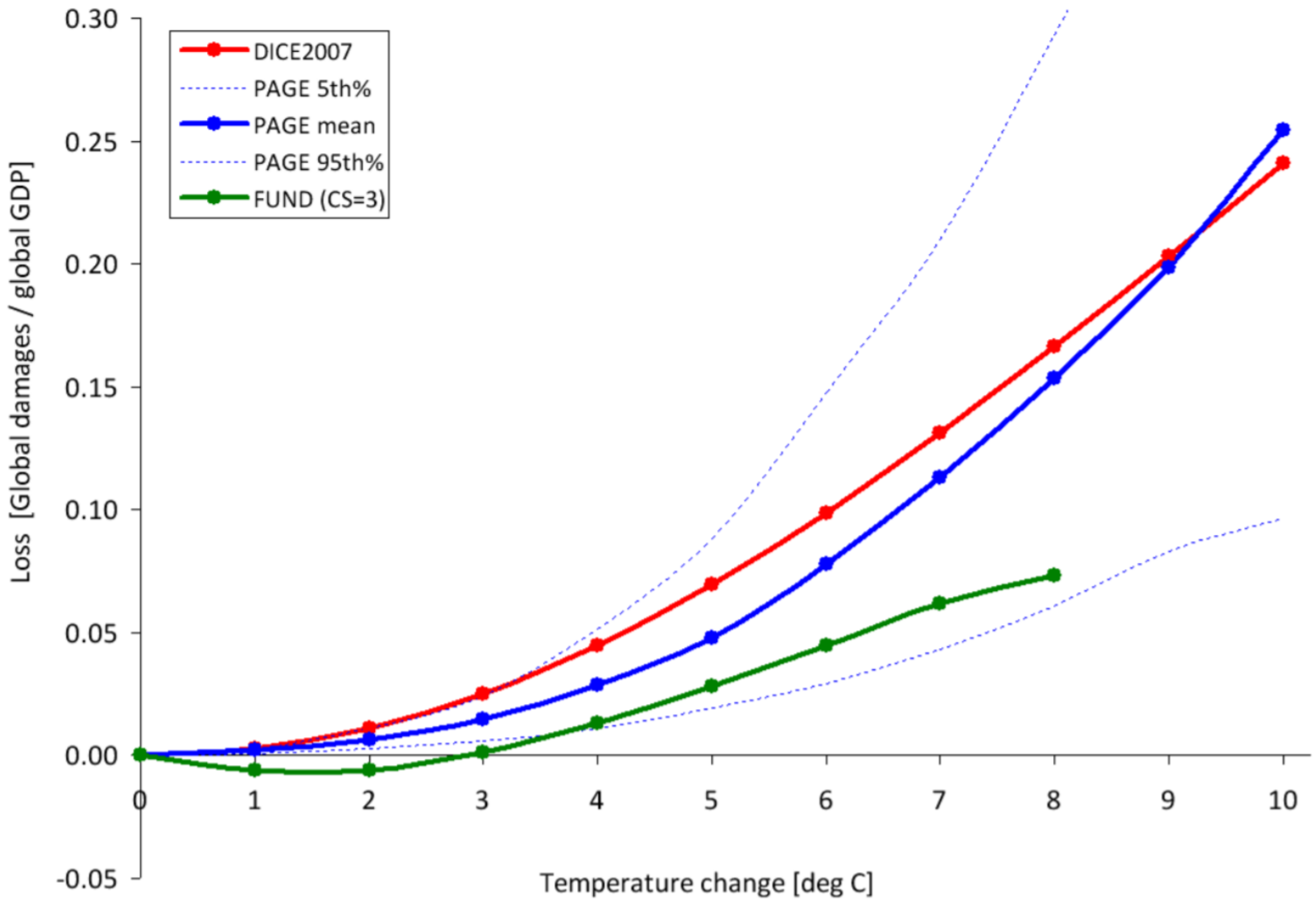

MARKET
MORTALITY AND MORBIDITY
NATURAL SYSTEMS
DICE
75% of Aggregate Damages
25% of Aggregate Damages
PAGE
Market Sector Temp Damages
SLR Damages
Non-Market Temp Damages
"Catastrophic" Damages
FUND
Heating and Cooling
Ag and Forestry
Water Resources
Cardiovascular Disease
Diarrhea
Vector Bourne Disease
Biodiversity Loss
Wetland Loss
Tropical Storms

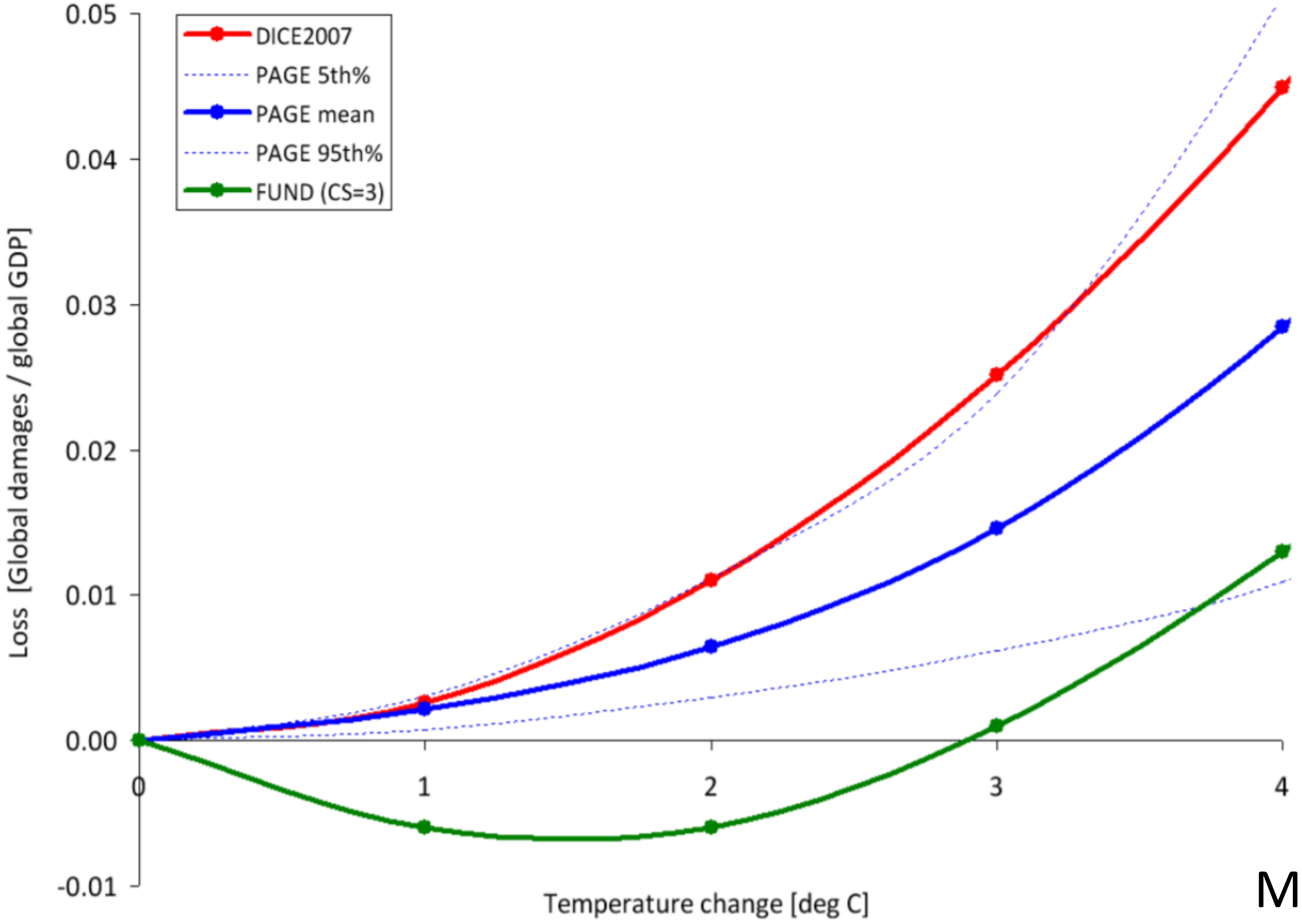
**Figure 1A: Annual Consumption Loss as a Fraction of Global GDP in 2100 Due to an Increase in Annual - Global Temperature in the DICE, FUND, and PAGE models[5]**




Model differences in representing climate damages

IAWG, 2010

Figure 1B: Annual Consumption Loss for Lower Temperature Changes in DICE, FUND, and PAGE -

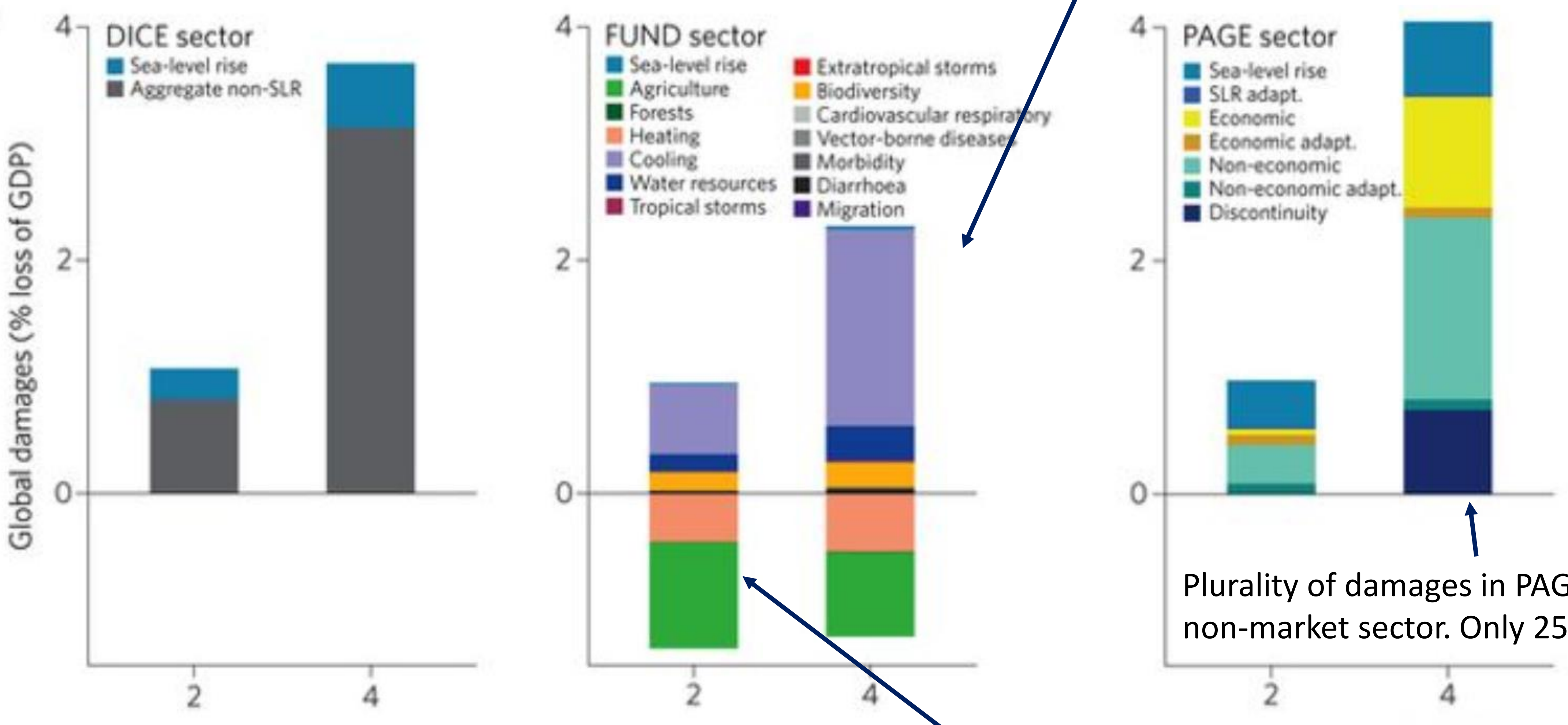



Model differences in representing climate damages

IAWG, 2010

# Individual damage sectors in each model

Almost all negative impacts in FUND come from increased cooling costs




Plurality of damages in PAGE from non-market sector. Only 25% in DICE

FUND shows large benefits from agriculture and reduced energy for heating

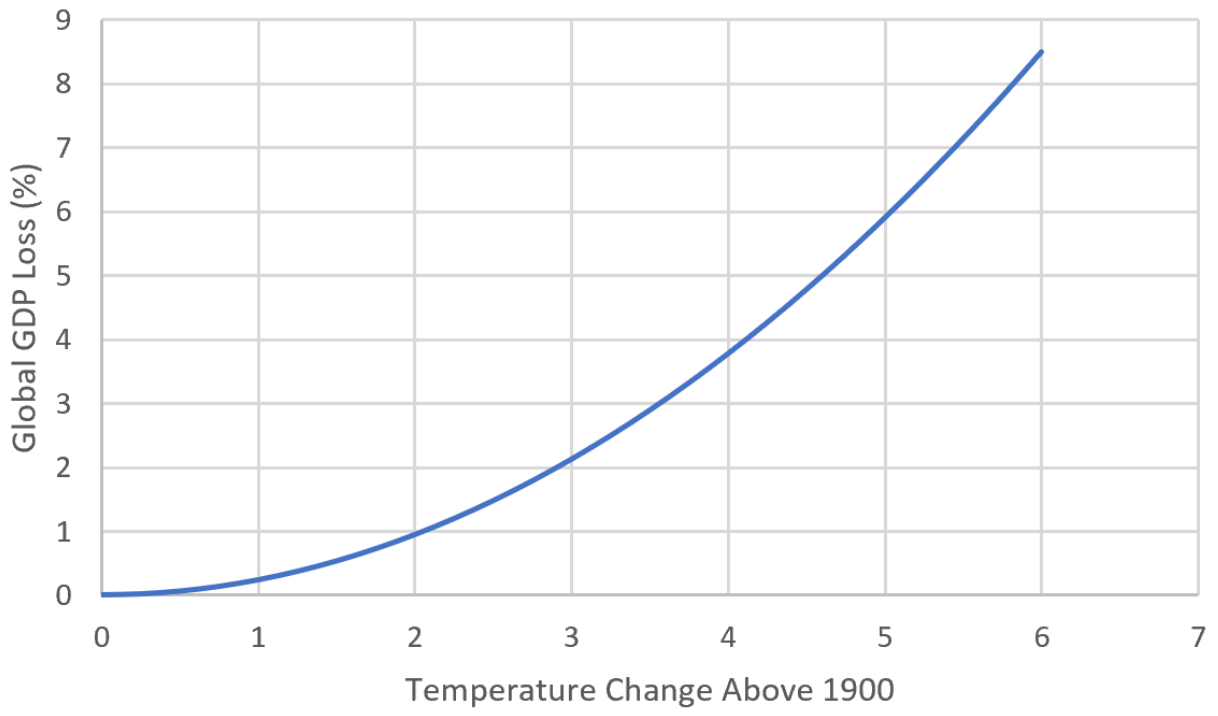
Diaz and Moore, 2017

# Model-Specific Damages

1. DICE 2016R2

$$D_t = Y_t \theta_1 \Delta T_t^{\theta_2}$$

- $\Delta T$ warming since 1900
- Calibrated to 2.1% of global income at 3 degrees of warming, 8.5% at 6 degrees based on




Nordhaus, 2017

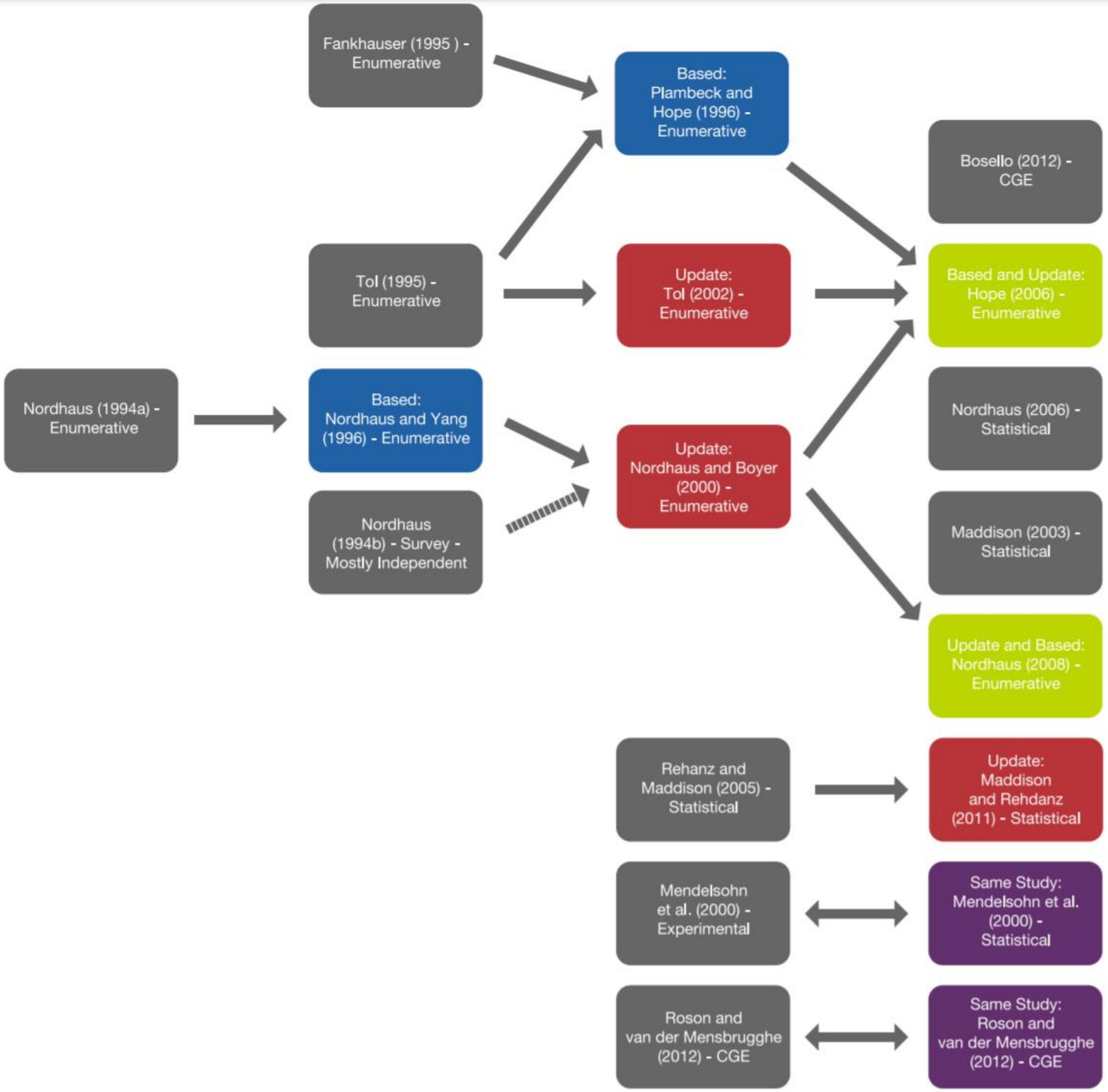
# Model-Specific Damages

1. DICE 2016R2

- Current calibration is based on a ‘non-systematic research study’ of 36 estimates of the sensitivity of global GDP to temperature change from 27 studies (Nordhaus and Moffatt, 2017)
  - These include damage functions in previous versions of DICE, as well as current versions of FUND, WITCH, and PAGE (Nordhaus has authored 10 of the 36 estimates)

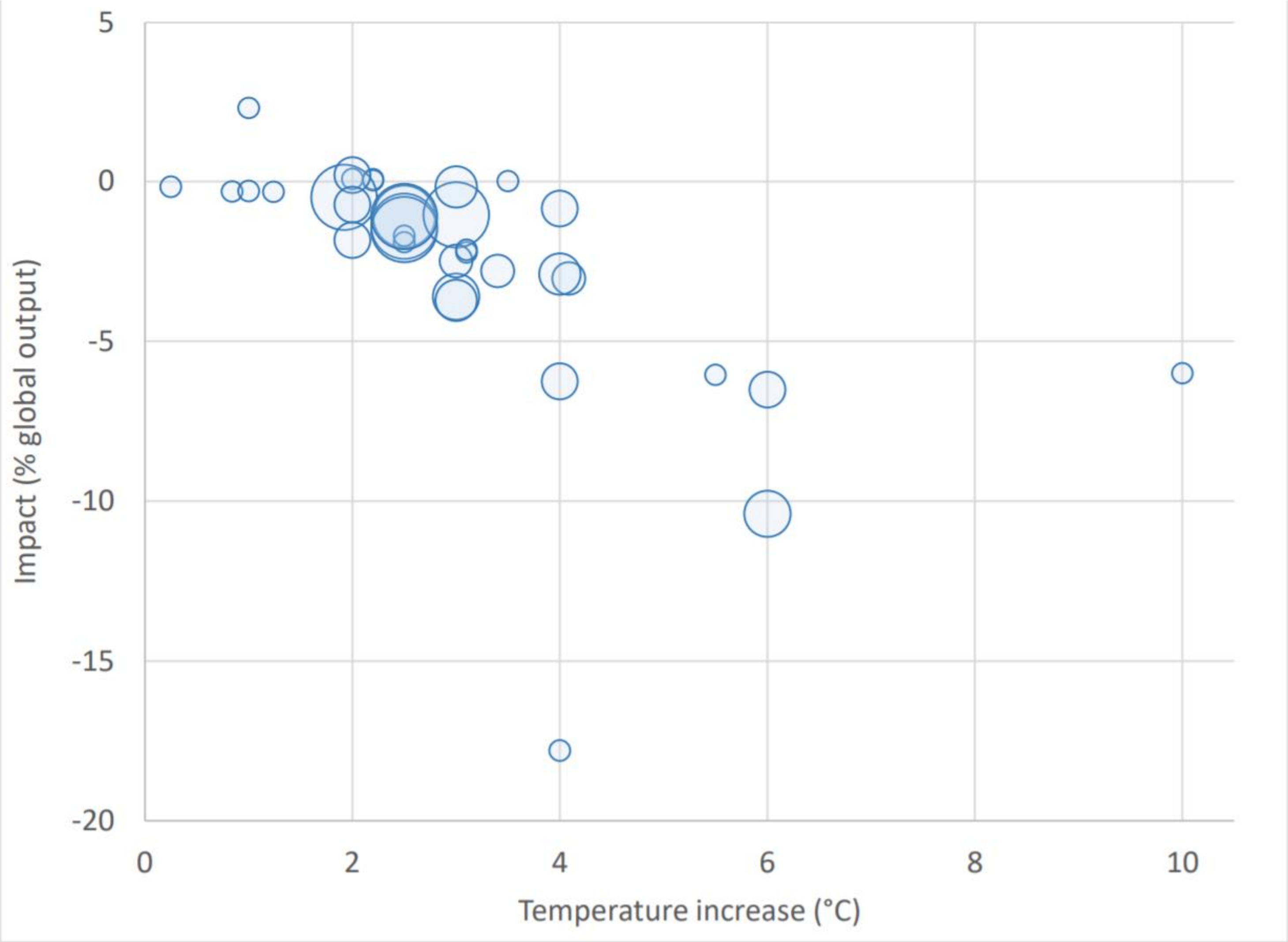
- Weighting of studies between 0 and 1 based on subjective assessment of quality

- Add 25% for omitted categories of damages (ecosystems, mortality)




Dependencies involved in damage estimates included in Tol (2014) meta-analysis

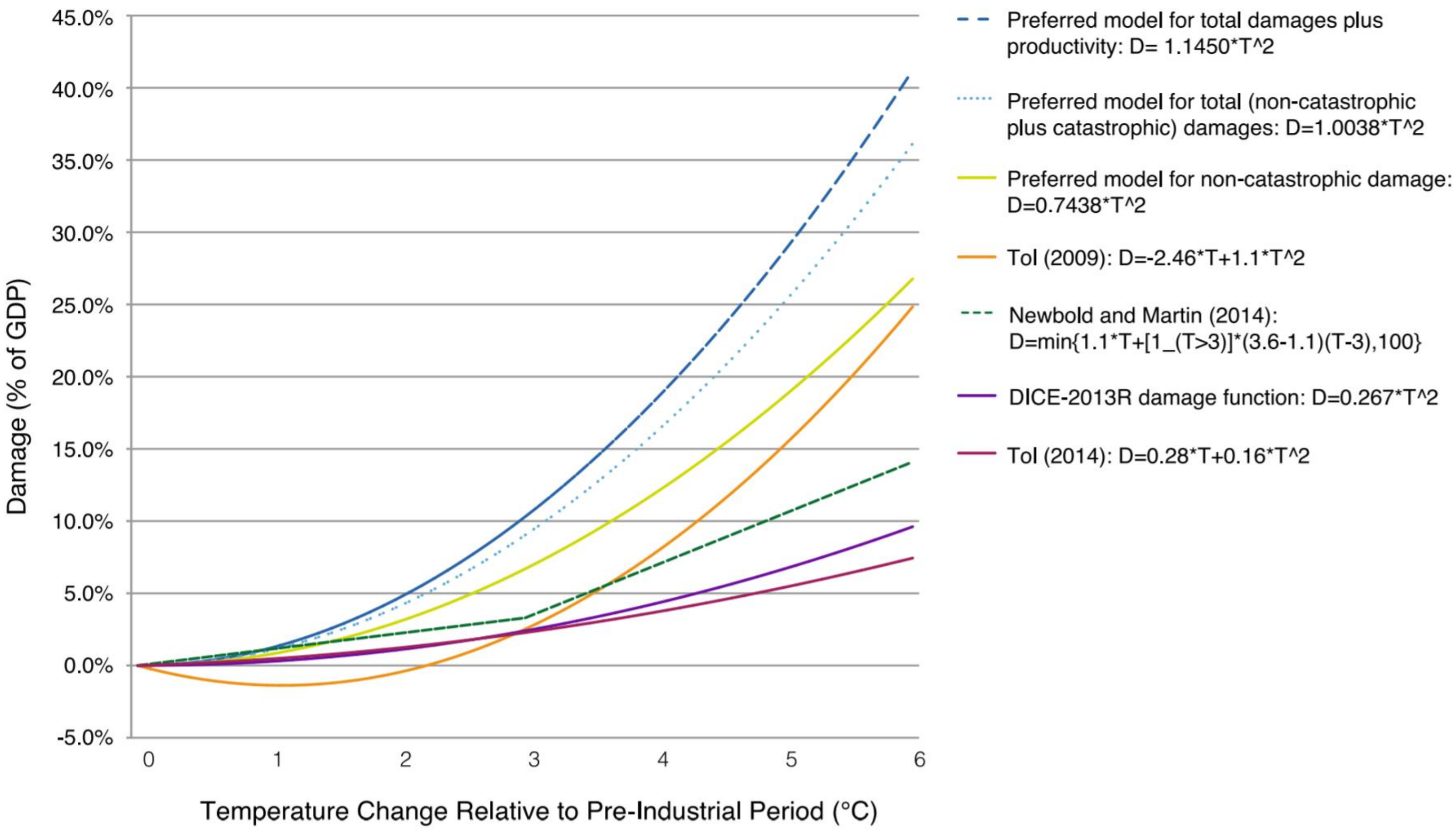
Howard and Sterner, 2017




Individual Estimates of Global Climate Change Impacts Included in DICE Damage Function Calibration.
Size = Weighting Based on Quality Assessment

Nordhaus and Moffatt, 2017

# A Wrinkle…




- Howard and Sterner did exactly the same exercise and came up with very different numbers
- Differences due to:
  - Weightings
  - Studies included
  - Methodological Control Variables

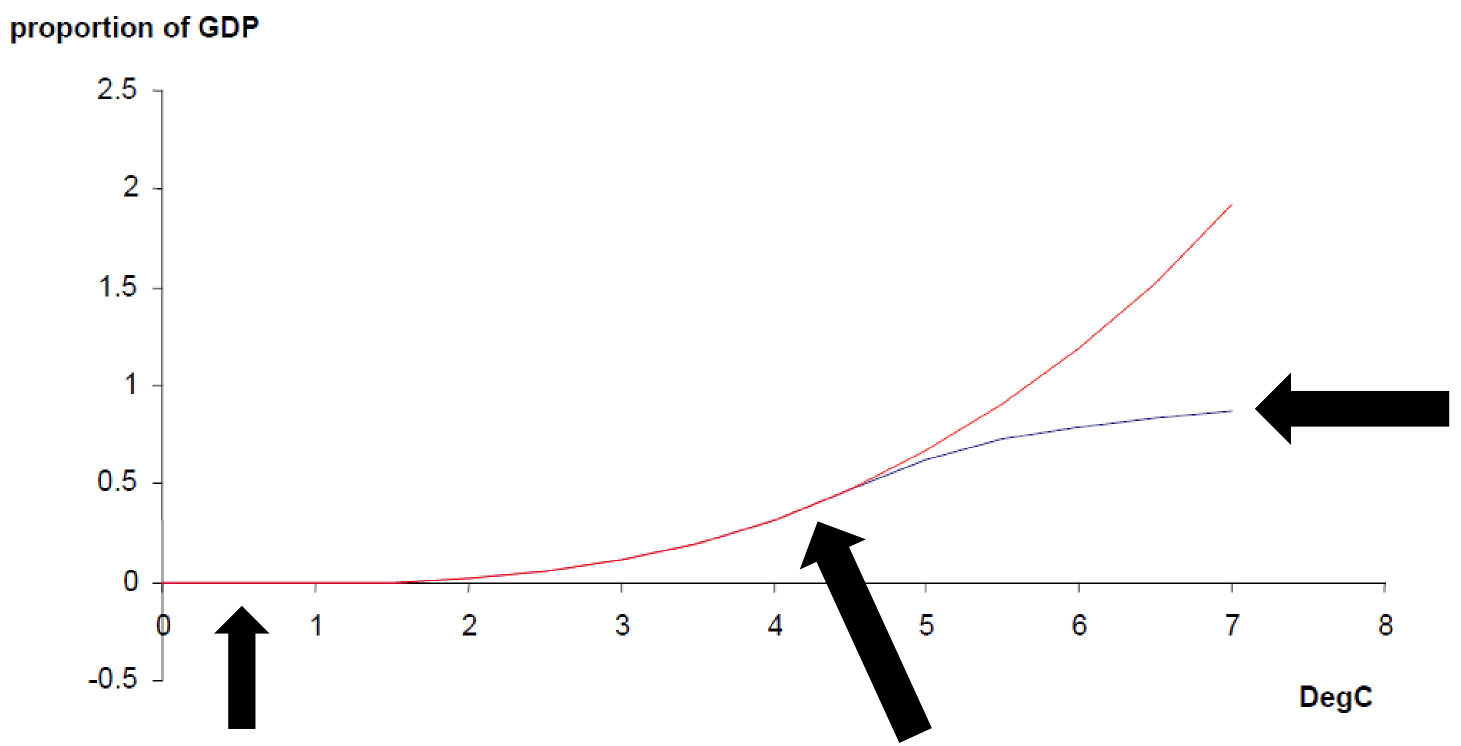
Howard and Sterner, 2017

# Model-Specific Damages

2. PAGE09

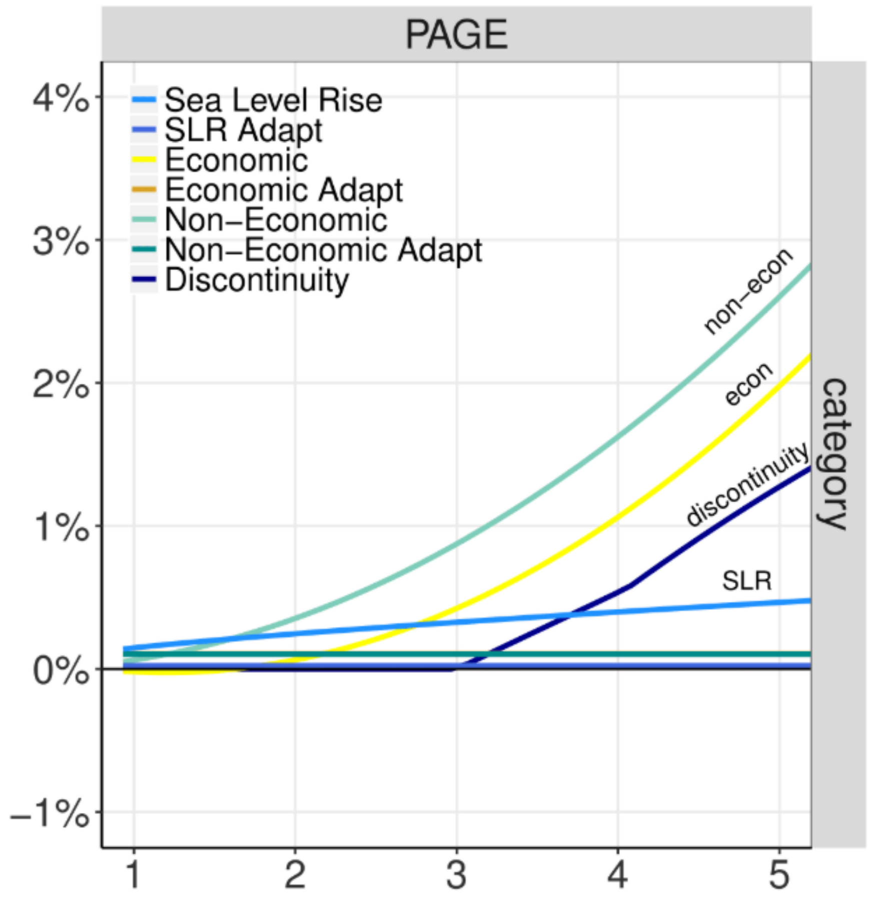
- Damages in PAGE are fairly complex functional forms that include:
    1. Possibility of initial benefits at small levels of warming
    2. A “tolerable” amount of warming below which damages are zero
    3. Exponential increase in damages above the tolerable level
    4. Logarithmic approach to a saturation point below 100% of GDP
    5. Income elasticity of damages (in some sectors, generally small)

- Explicit representation of adaptation models:
    1. Increase in “tolerable” window below which impacts are zero and decrease in damages above window
    2. Gradual ramp up of adaptation policy over time
    3. Costs of adaptations that change endogenously




Tolerable Window / Very Small Initial Benefits

Damages Exponentially Increasing Above Tolerable Window




Hope 2011

Rose, Diaz and Blanford, 2017

# Model-Specific Damages

2. PAGE09

- Complex functional forms for damages and adaptation mean that there are lots of parameters describing impacts
  - Adaptation parameters: 7 parameters for 3 sectors for 8 regions = 168 parameters
  - Impact parameters: 5 parameters for 4 sectors ≈ 20 parameters
  - Note that impact parameters are *not* region-specific

- Few of these can be quantitatively traced to the scientific literature

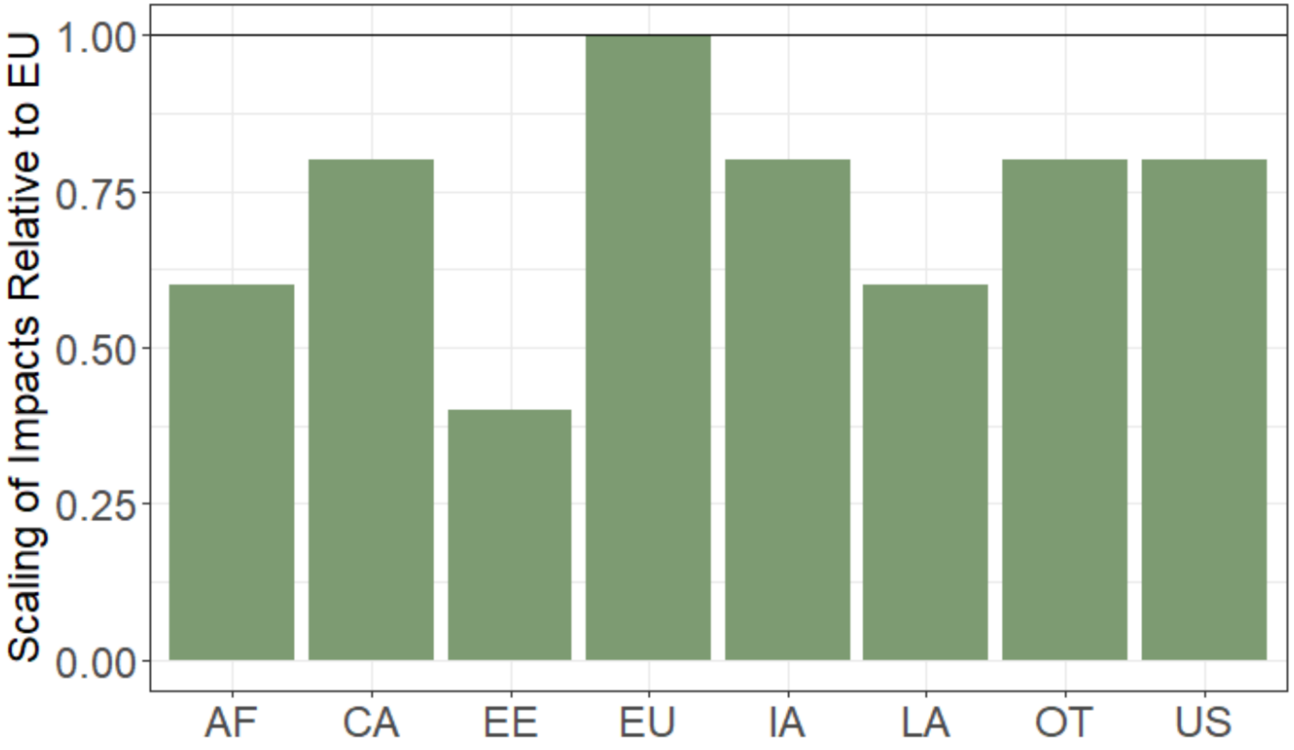
- Calibration is for the EU region only, for 1 point on the damage function (3°C)

- Referenced studies for calibrations are almost all previous IAM damages (DICE, MERGE, PAGE, and FUND)

# Model-Specific Damages

2. PAGE09

- Impact parameters are not region-specific
- Instead damages are extrapolated to other regions mainly based on relative coastline length (?) and per-capita GDP (some sectors)
- Many impact and adaptation parameters in PAGE have uncertainty bounds (triangular distribution)
- Justification for these uncertainty bounds is not documented




Scaling of Damages Between the EU and Other Regions in PAGE09 (WINCF Parameter)

# Model-Specific Damages

3. FUND 3.7 / 3.9

- FUND has by far the richest representation of climate impacts by sector and region – both market and non-market

- References to original sectoral studies in model documentation and original estimation of parameters and income elasticities in Tol (2002)

- Bottom-up damage estimation vs DICE's top-down damages

# Model-Specific Damages

3. FUND 3.7 / 3.9

- Functional forms vary somewhat by sector. Characteristic damage function (space cooling):

$$SC_{t,r} = \alpha_r Y_{1990,r} \left(\frac{T_t}{1.0}\right)^{\beta} \left(\frac{y_{t,r}}{y_{1990,r}}\right)^{\epsilon} \left(\frac{P_{t,r}}{P_{1990,r}}\right) \Big/ \prod_{s=1990}^{t} AEEI_{s,r}$$

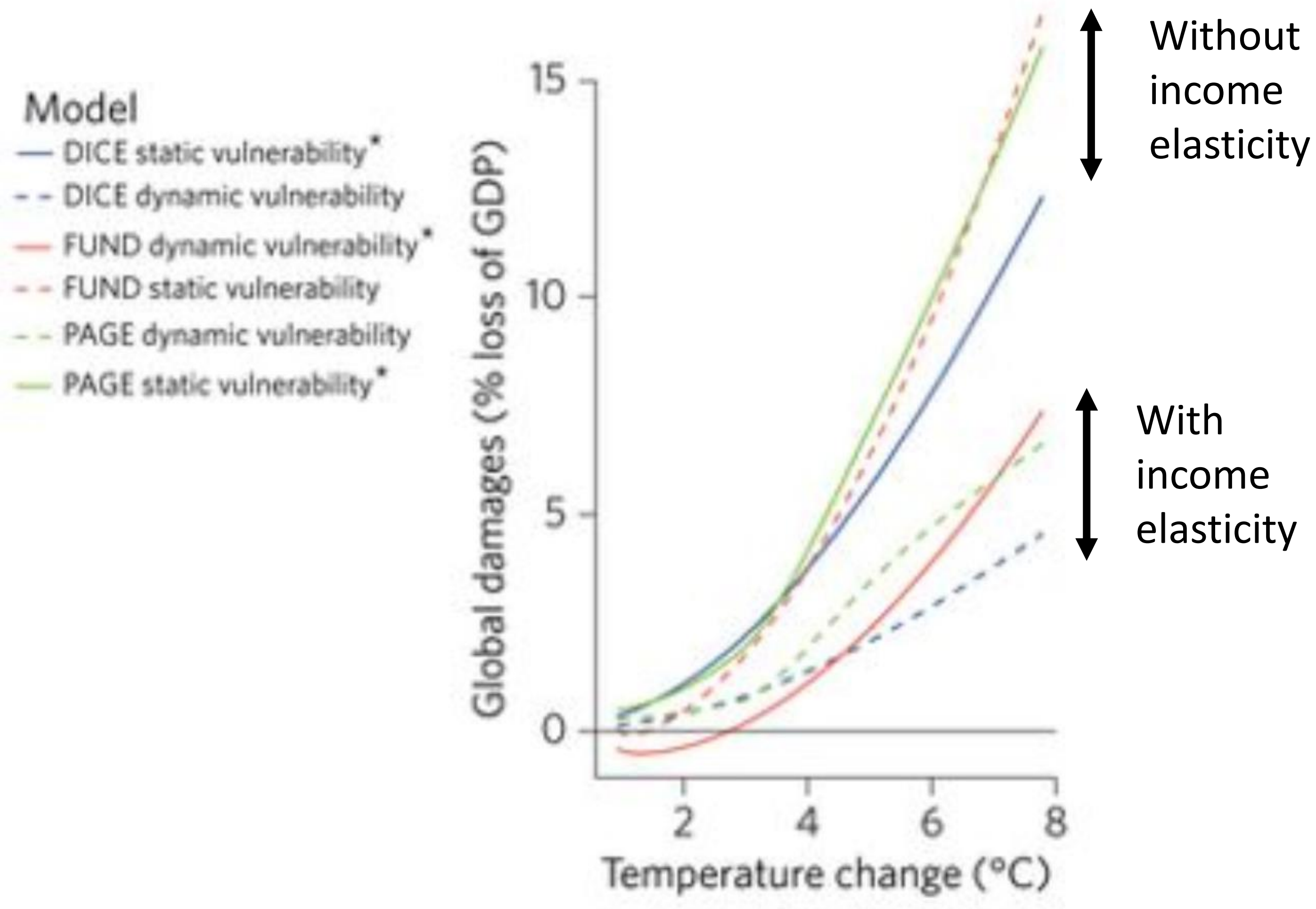
Technical improvement in energy efficiency

Region-specific damage parameter at baseline from Downing et al (1995)

Increase in damages with warming (β=1.5)

Income elasticity of damages (ε=0.8)

# Model-Specific Damages




Diaz and Moore, 2017

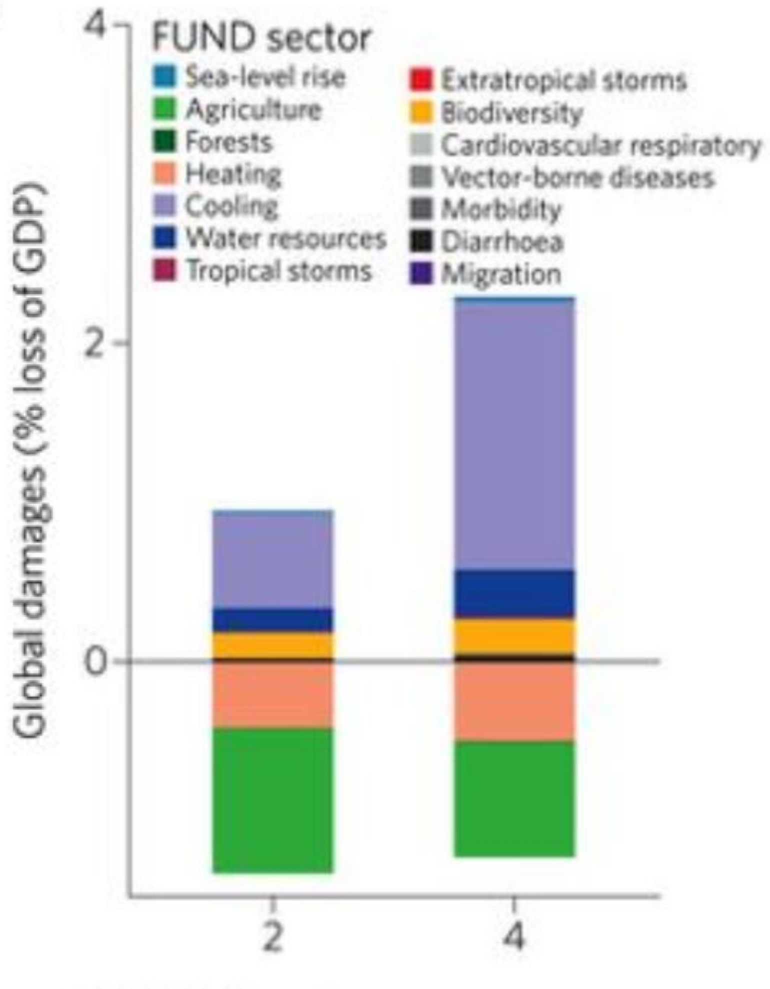
- Income elasticity of damages in FUND is an important characteristic
  - In some sectors (storm damage, vector borne mortality, diarrhea) ε<0
  - In most others ε<1
- Without income elasticity of damages aggregate FUND damages look a lot like the other models
- Empirical basis of at least some elasticity parameters is cross-sectional regressions of countries

# Model-Specific Damages

- FUND has many damage sectors, but only a couple contribute substantively to the SCC
  - Agriculture and space heating  (benefits)
  - Space cooling (damages)

- Main issue with damages in FUND is that they (mostly) haven't been updated since model was first developed in the late 1990s

- Scientific developments since then, as well as improved empirical methods are not represented




Diaz and Moore, 2017

# Summary: Existing Damages in IAMs

- DICE
  - Top-down representation of aggregate effects of temperature on GDP
  - Documented calibration using a meta-analysis, but results seem to be sensitive to arbitrary analytical decisions
  - No documented basis for 25% increase in damages to capture non-market effects
- PAGE
  - Ad-hoc representation of damages, adaptation costs and benefits, with very limited scientific basis
  - Parametric uncertainty is important in PAGE, but no documented basis for parameter distributions
- FUND
  - Bottom-up representation of damages, reflecting characteristics of each sector
  - Important role of income elasticity of impacts in determining damages
  - Calibrations mostly rely on a small number of very old studies. Many parameters are “expert guesses”

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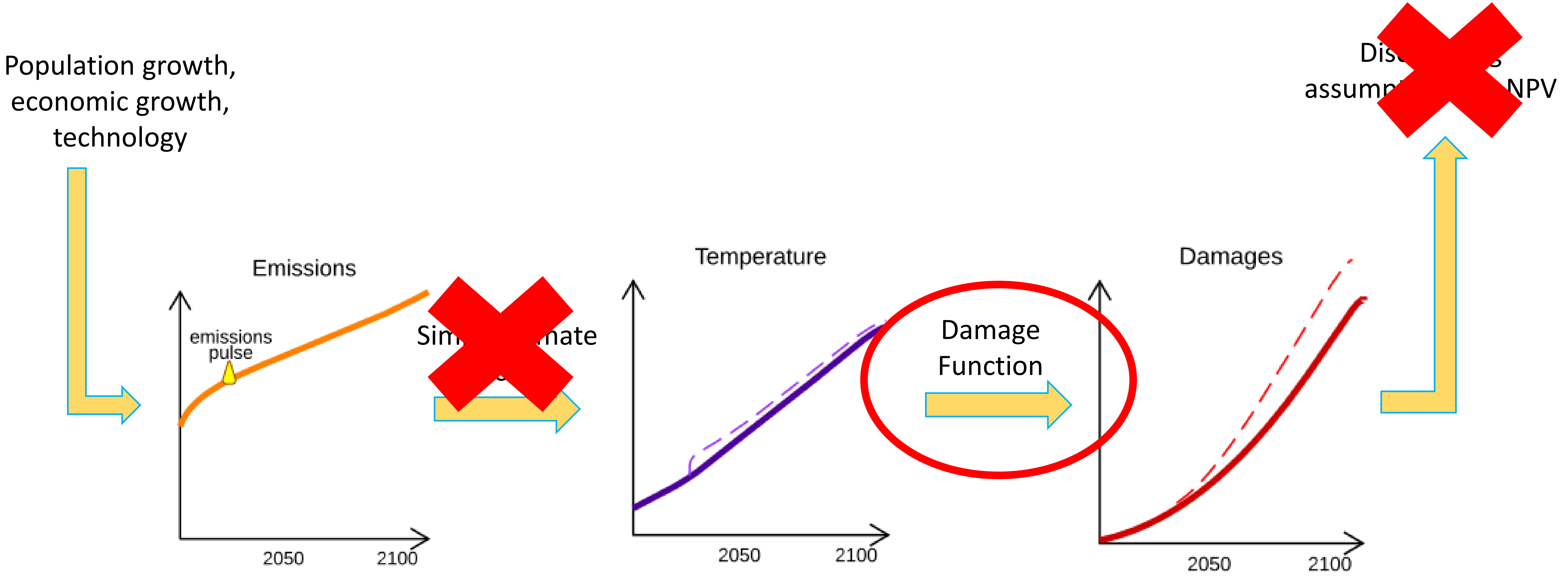
# Why Improve Damage Representation in IAMs?

1. ***Accuracy***: If we are using the SCC for policy analysis, it should accurately reflect our best understanding of climate change damages. (Ignoring current science risks using a SCC that is not fit for purpose and potentially vulnerable to legal challenge.)

2. ***Efficiency***: We spend a lot of time and money on studies of climate change impacts. Those efforts should be informing policy.

3. ***Knowledge***: Developing climate damages requires standardizing across studies, considering the whole globe, and converting impacts in different sectors to comparable units. Given the disparate (disorganized?) nature of much impact science, this can be a valuable exercise in and of itself.

# Where Can We Improve IAMs For Policy Analysis?



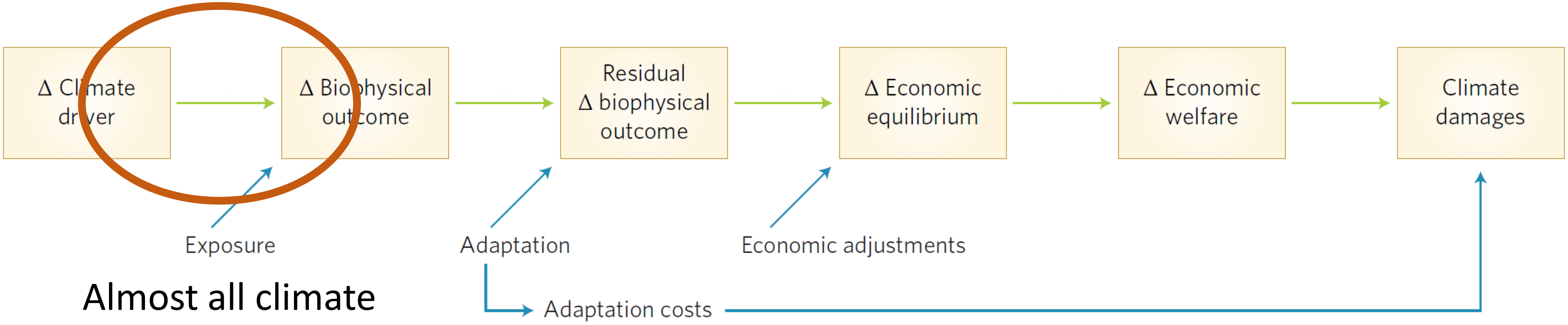

Add 1 Extra Ton of Emissions to a Baseline Emissions Scenario

Model the Effect of this Extra Ton on Global Temperature

Model the Additional Monetized Damages

Diaz, 2014

# Improving Damages is Not Straightforward




Almost all climate change impact studies

Diaz and Moore, 2017

# Improving Damages is Not Straightforward

- For a damage function we would like to know:
  1. The costs of damages
  2. Globally
  3. For a particular level of temperature change
  4. Including equilibrium economic adjustments, adjustment costs, and the costs and benefits of adaptation
  5. Using consistent socio-economic scenarios

- In contrast, most studies of climate impacts estimate:
  1. Biophysical changes rather than costs
  2. For a subset of regions (or parts of a sector)
  3. For emissions scenarios, not levels of temperature change
  4. Not including adaptation
  5. Using various socio-economic assumptions (if applicable)

# Sources for Improving Damages: Pros and Cons

**General Climate Impacts Literature**

e.g. IPCC results, literature review / meta-analysis

**Pros**

- Captures largest possible set of studies, reflecting full epistemic uncertainty
- Tying results to IPCC may be useful in some contexts

**Cons**

- Very difficult to standardize / compare across studies
- Regional or sectoral coverage may be limited

**Coordinated Sectoral / Regional Modeling Projects**

e.g. AgMIP, BRACE, CIRA, PESETA, ISIMIP

**Pros**

- Comparable outputs using standardized socio-economic and emissions scenarios
- Often characterize multiple sources of uncertainty (e.g. climate, process)

**Cons**

- Impacts not often monetized
- Limited representation of adaptation
- Limited sectoral / geographic coverage
- Report effects of emissions scenarios, not temperature change

# Sources for Improving Damages: Pros and Cons

**Detailed Process IAMS**

e.g. GCAM, AIM, MESSAGE, IGSM

**Pros**

- Global in scope
- Standardized and consistent socio-economic and emissions projections
- Include multiple margins of adjustment
- Can capture spillovers across sectors
- Models can produce welfare-relevant metrics

**Cons**

- Historically model developers have reported biophysical outcomes rather than welfare changes

**Reduced Form Empirical Approaches**

e.g. Global Impacts Lab; Dell, Jones and Olken (2012)

**Pros**

- Calibrated to observed effect of climate / weather variation
- Relatively inexpensive to implement
- Integrate over multiple impact pathways, some of which may be missing from process-based (structural) models

**Cons**

- Not all impacts amenable to this approach ($CO_2$ fertilization, ocean acidification)
- Many studies report biophysical outcomes rather than welfare changes
- Adaptation and general equilibrium adjustments may not be captured

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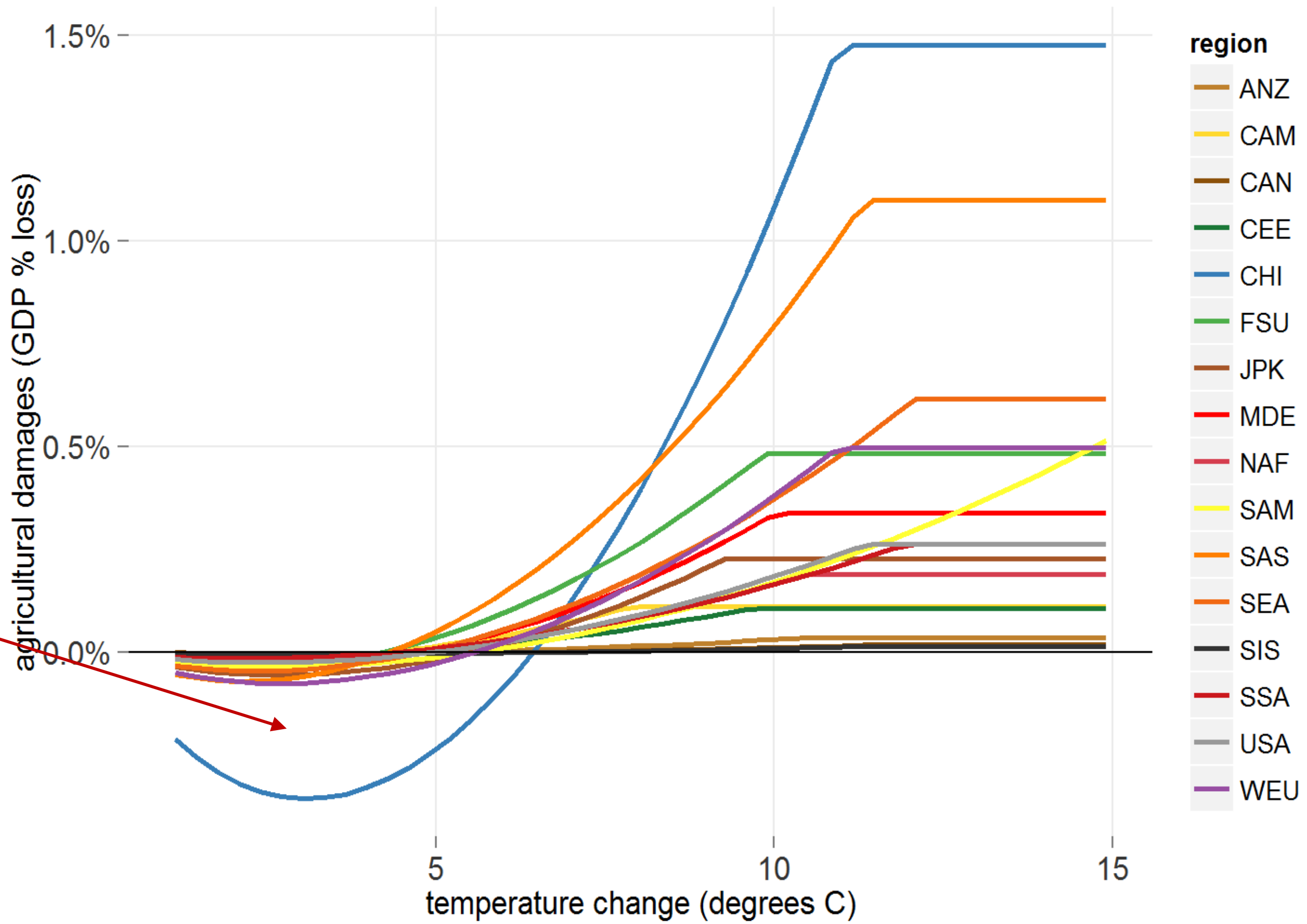
# Example: Improving Agriculture in the SCC

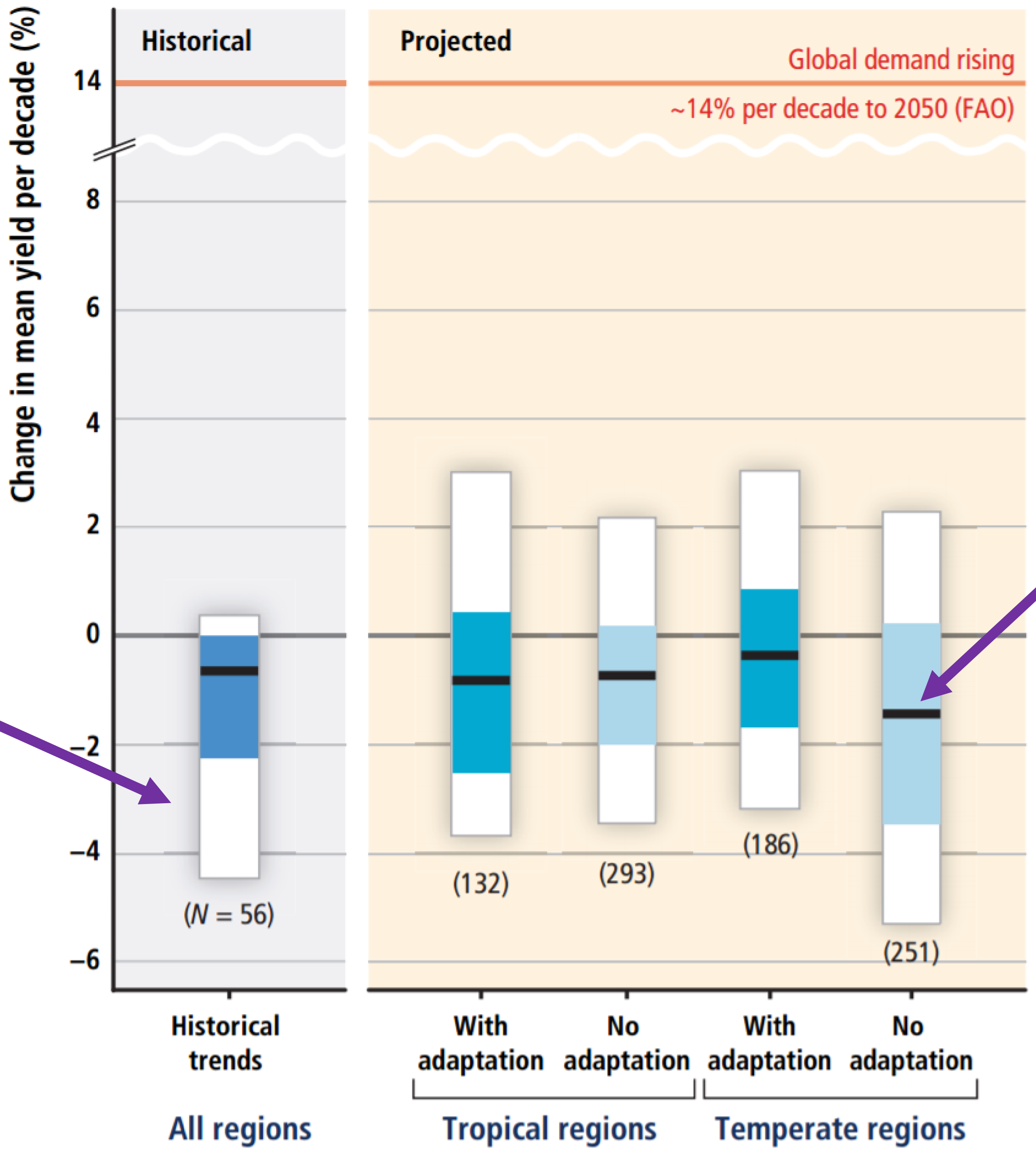
Universal benefits up to ~4-5 degrees of warming




FUND Damage Functions, Agriculture Sector

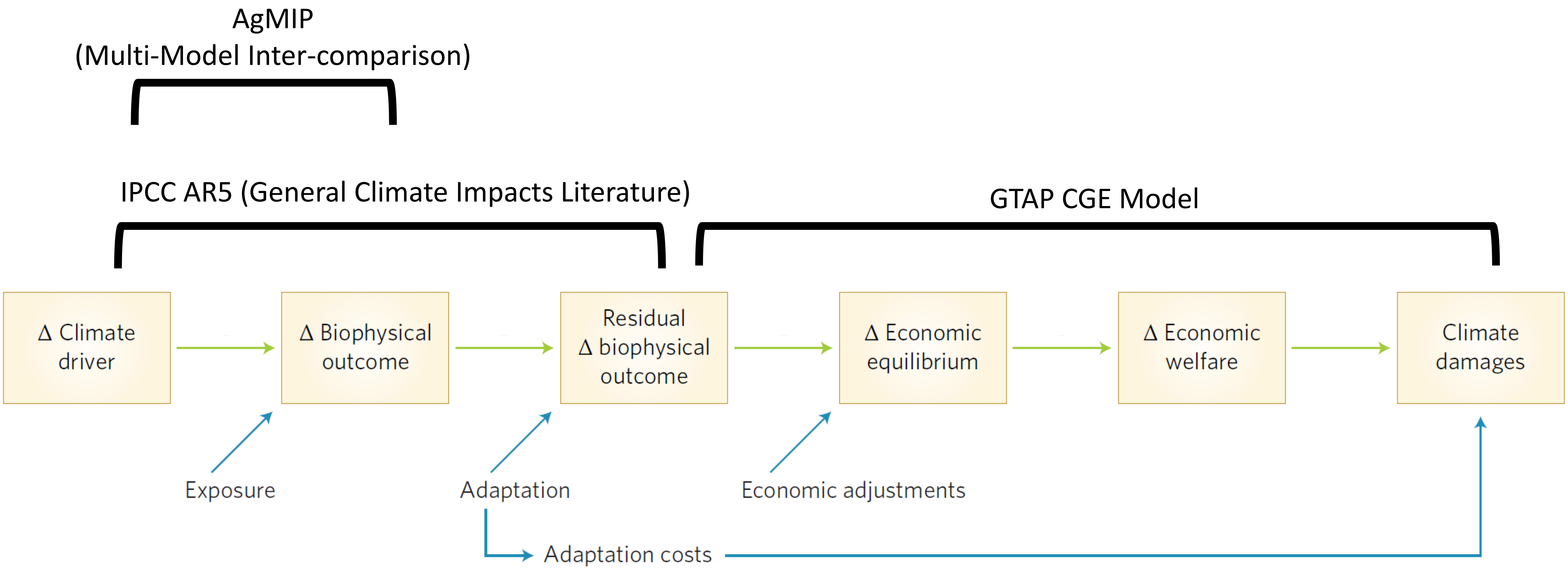
**References:** Fischer, Frohberg, Parry, & Rosenzweig, 1996; Kane, Reilly, & Tobey, 1992; Morita et al., 1994; Reilly, Hohnmann, & Kane, 1994; Tsigas, Frisvold, & Kuhn, 1996

Climate change has already had a negative effect on agriculture




Future climate change will likely have a negative effect on agriculture in all regions

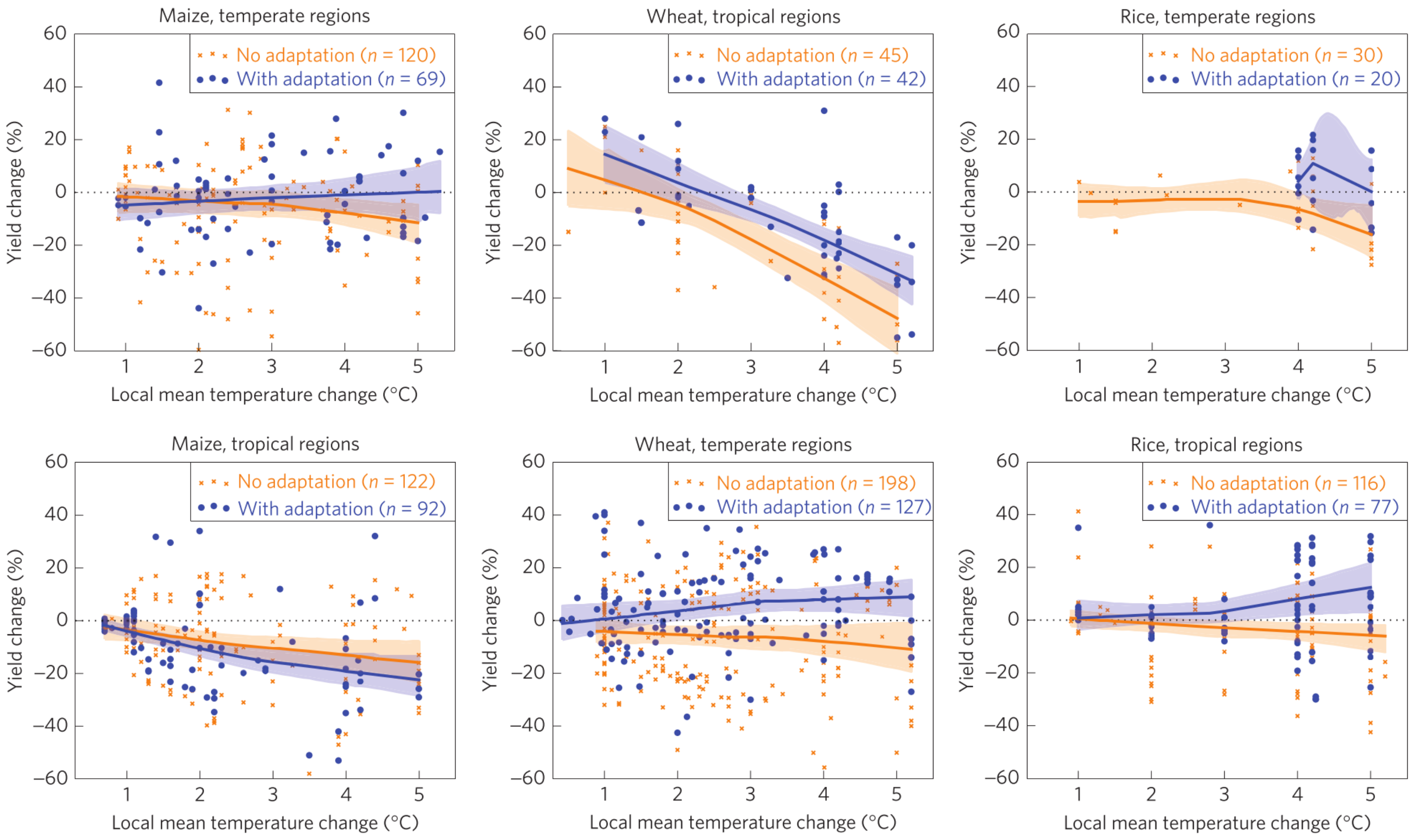
IPCC, 2014 p. 506



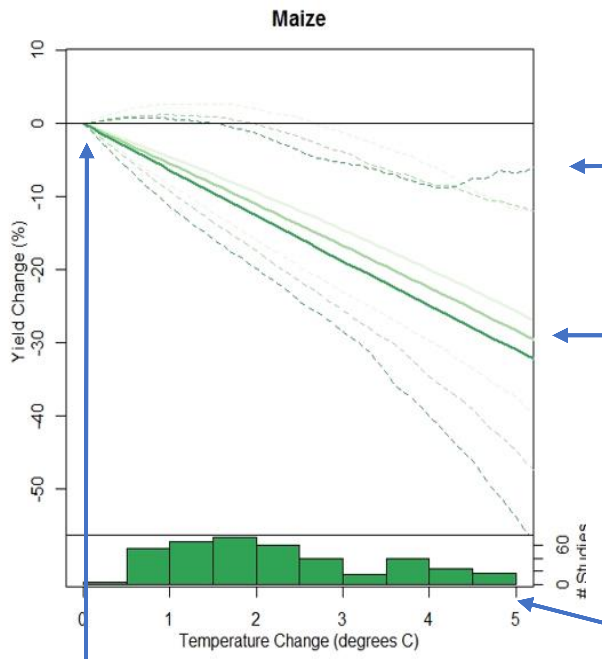

Diaz and Moore, 2017

# 1. Meta-Analysis

- Database of 1,010 point-estimates of yield change in response to temperature change compiled for IPCC AR5
- From 56 studies using 28 different models
- Wheat, rice, maize, soybeans
- Process-based and empirical
- Data on: temp change, rainfall change, CO2 change, adaptation, region
- Merge with average growing season temperature data




Challinor et al. (2014) and IPCC (2014)

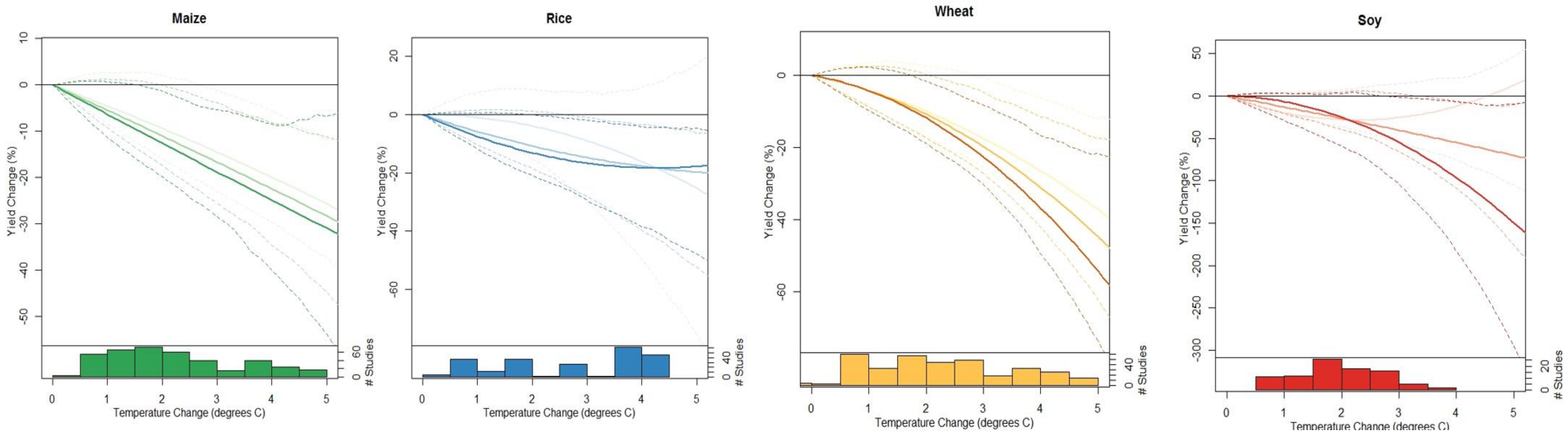



95% confidence intervals based on block-bootstrap

Lightest = 25th percentile of growing season temperature
Middle = 50th percentile
Darkest = 75th percentile

Number of data-points for estimation

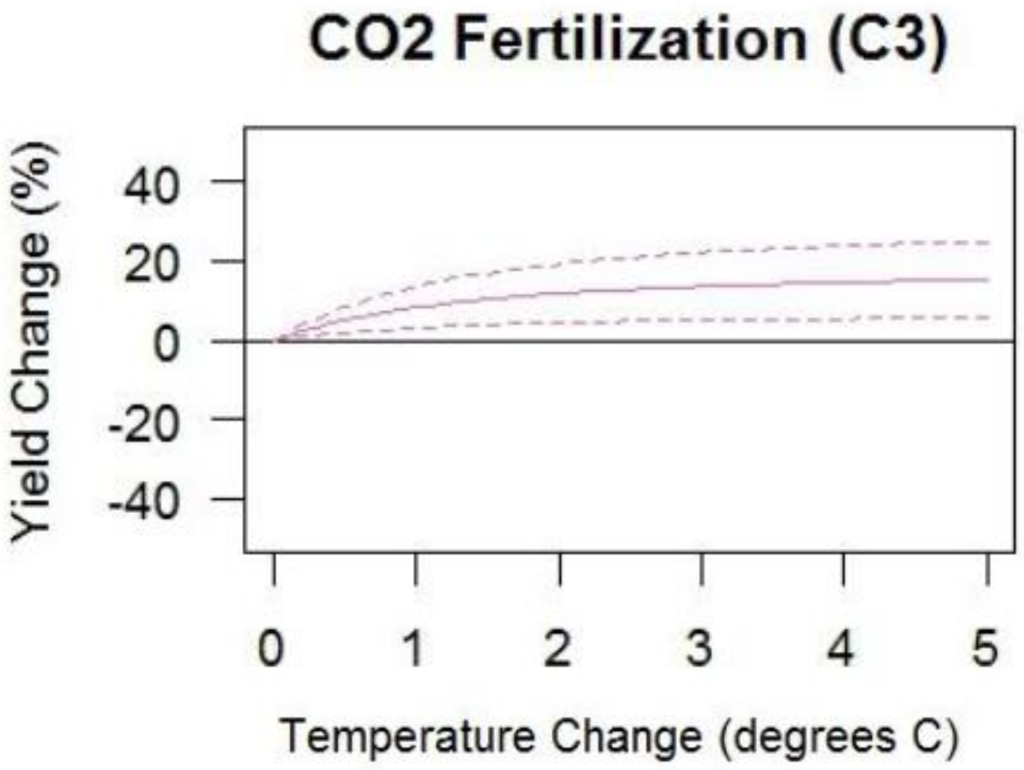
Temperature response not including $CO_2$

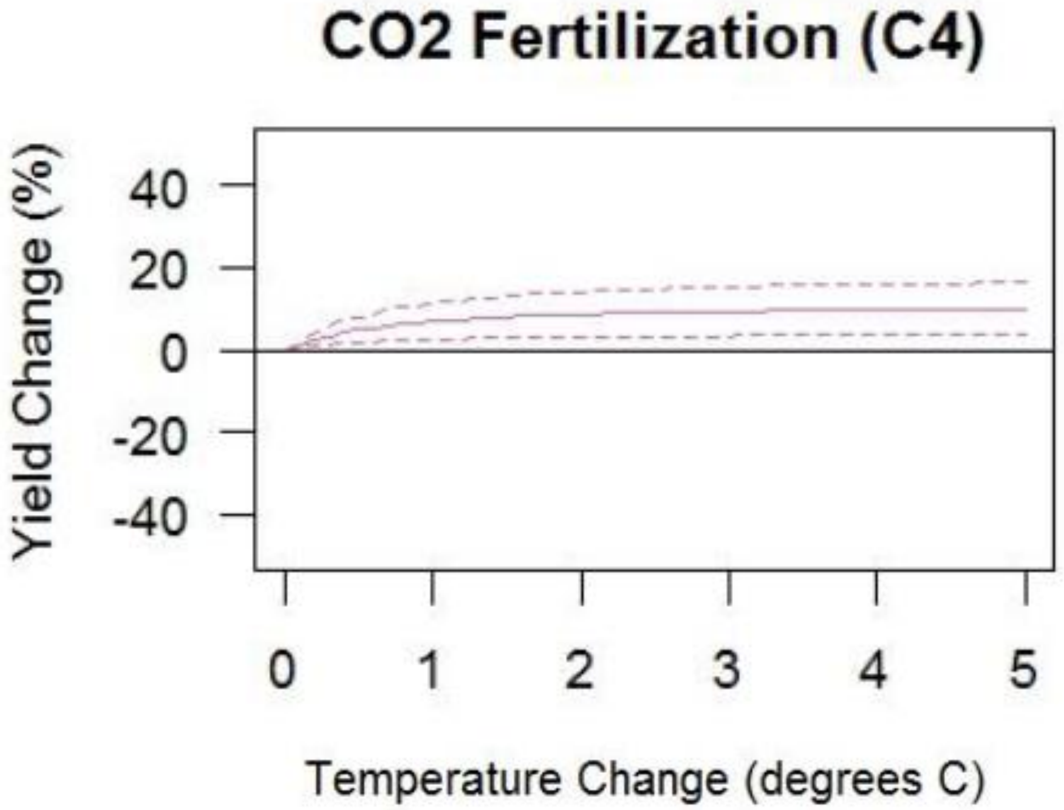



- Declines in yield with warming for all crops, even at low levels of warming
- Impact is smaller, though not positive, in cooler regions
- Largest declines for wheat and soy

Moore, Baldos, Hertel and Diaz, 2017

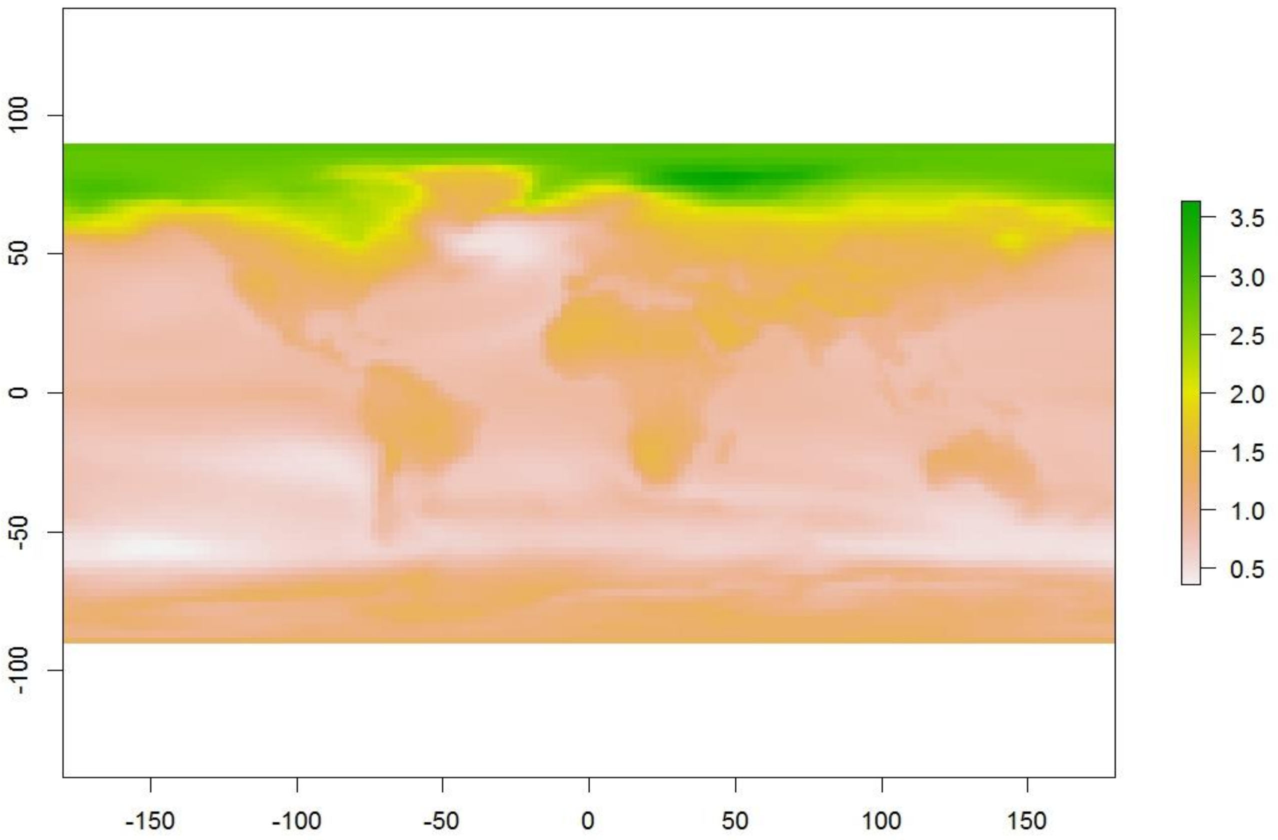
# CO2 Fertilization




- Estimated effect for a doubling of $CO_2$ is 11.5% for $C_3$ crops and 8.5% for $C_4$

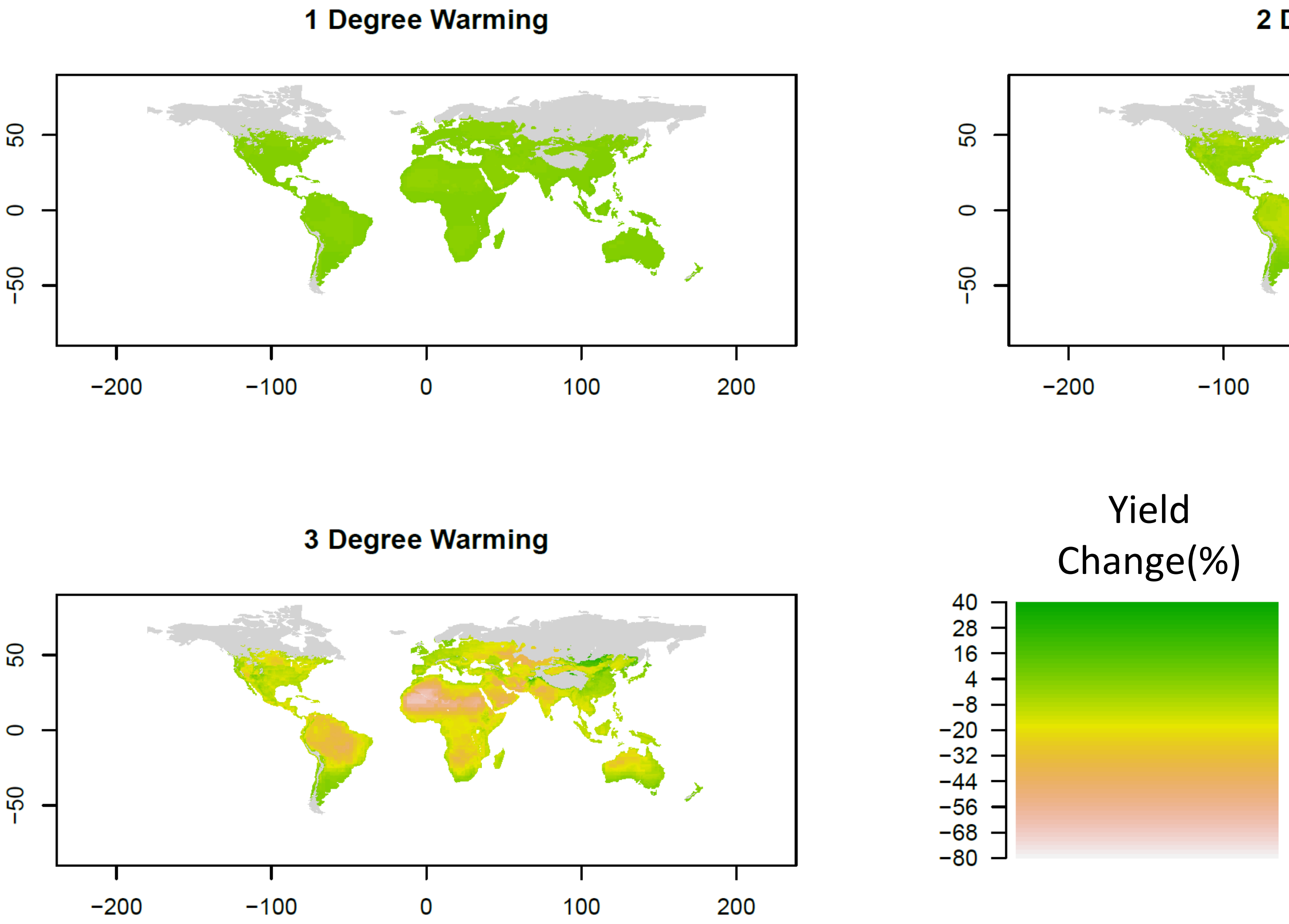
# Gridded Global Yield Change




Pattern scaling between local and global temperature change, based on RCP 8.5

- Use response functions to extrapolate yield responses to a global grid
- Local response depends on pattern scaling of local to global temperature (CMIP5 ensemble) and baseline temperatures

# Gridded Global Yield Change




Gridded wheat yields, including adaptation and $CO_2$ fertilization

Moore, Baldos, Hertel and Diaz, 2017

# 2. Global Gridded Crop Model Inter-comparison

- Part of the Agricultural Modeling Inter-comparison and Improvement Project (AgMIP)
- 6-7 process-based crop models run on 0.5° global grid with 5 climate models
- Extract yield changes for specified levels of global temperature change
- Average over crop and climate models for GGCMI ensemble average
- Preferred results use a restricted AgMIP ensemble that only includes models that represent nitrogen stress (i.e. low fertilizer environments)

# Welfare Consequences of Yield Changes

- GTAP run with 140 regions, 14 commodities (9 agricultural)
- Computable general equilibrium (CGE) model solves for changes in prices, production and consumption given changes in productivity
- Detailed representation of agricultural trade network and market distortions
- Yield shocks aggregated to regional level and introduced as Hicks-neutral shift in the production function
- Economic adaptations (crop switching, intensification, trade adjustments, product substitution) are accounted for here

# Welfare Consequences of Yield Changes

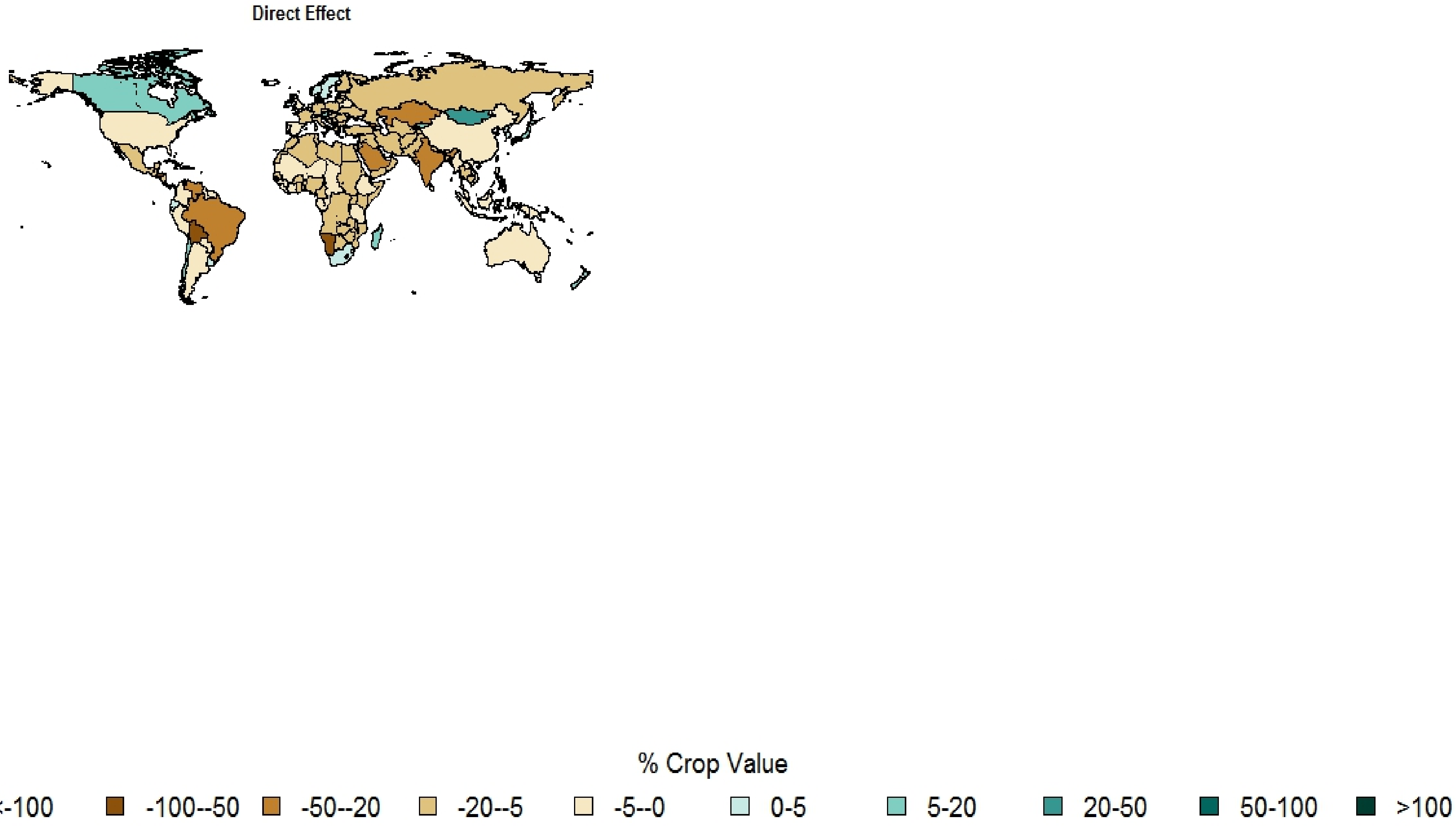
- Yield changes affect regional welfare in three ways:

  1. Direct productivity effect
     - How much do you get for the same set of inputs?

  2. Terms of trade effect
     - How does the price of imports change relative to the price of exports?

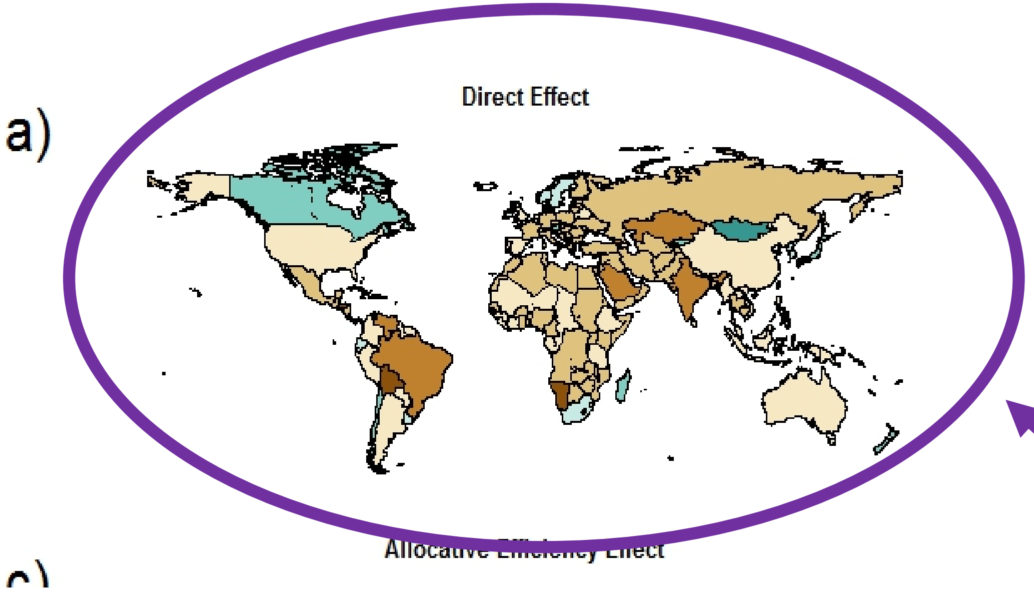
  3. Allocative efficiency
     - How do effects of climate change interact with existing market distortions (eg taxes and subsidies?)

- Welfare changes are normalized by the value of affected sectors to give % change a)




# Welfare Change, 3° Warming (Meta-Analysis)

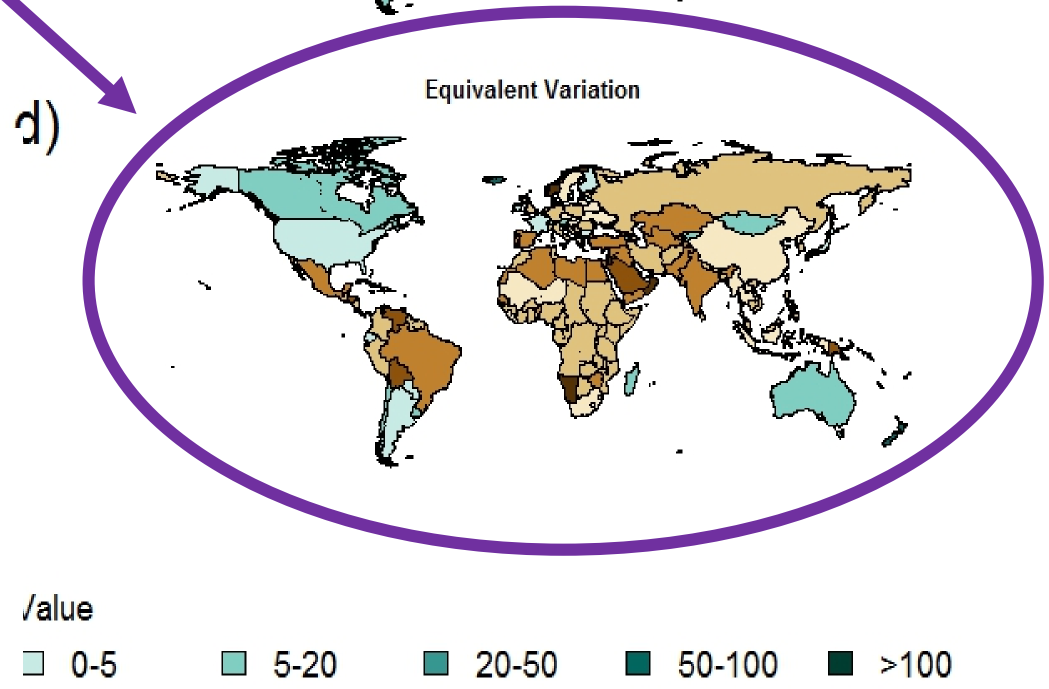
Moore, Baldos, Hertel and Diaz, 2017




Changes in Yield =/= Changes in Welfare

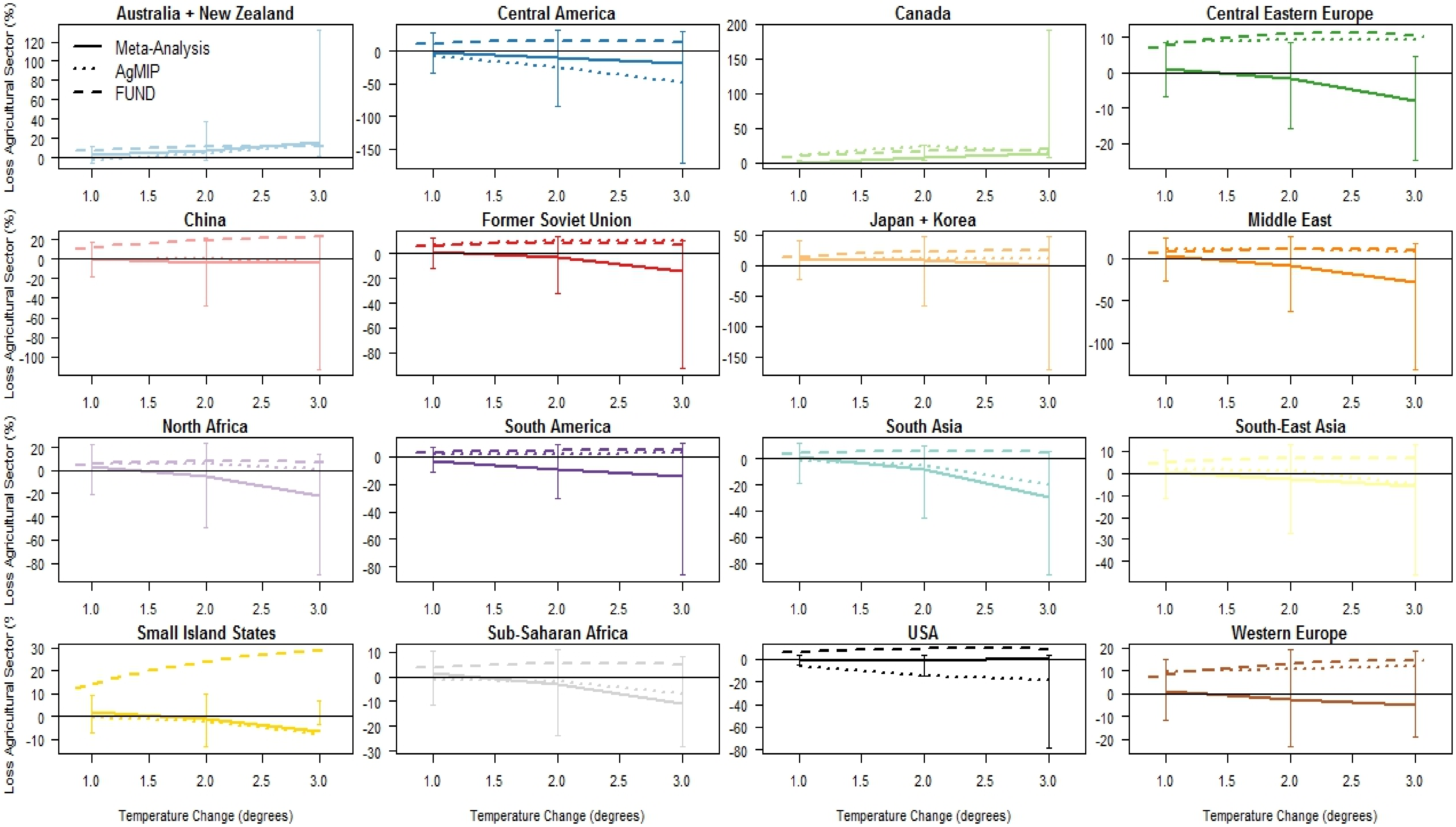
Terms of Trade Effects are Smaller

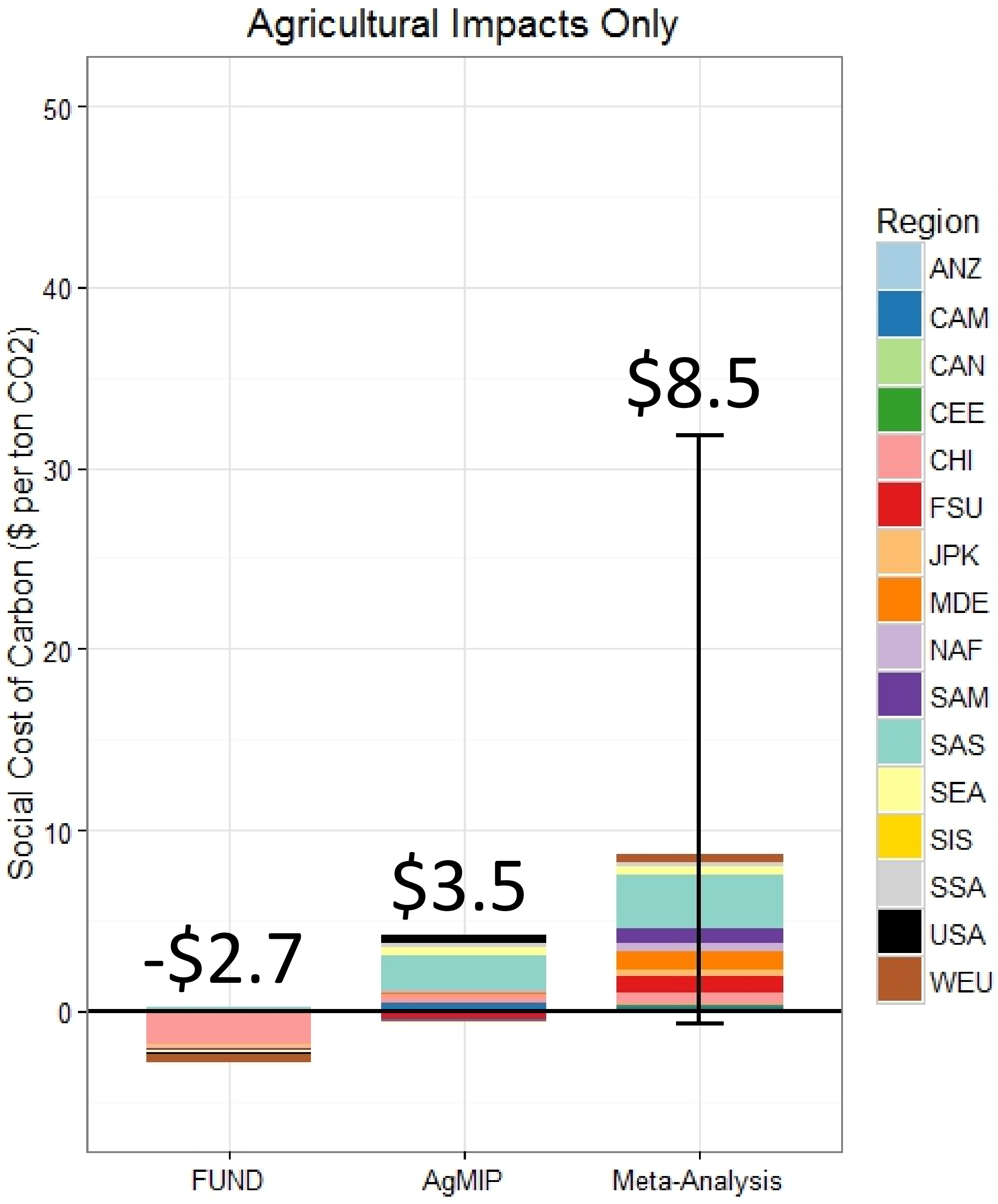
1) At larger regional aggregations
2) For smaller global net changes in productivity




Welfare Change, 3° Warming (Meta-Analysis)

Moore, Baldos, Hertel and Diaz, 2017


Australia + New Zealand
Central America
Canada
Central Eastern Europe
China
Former Soviet Union
Japan + Korea
Middle East
North Africa
South America
South Asia
South-East Asia
Small Island States
Sub-Saharan Africa
USA
Western Europe
Meta-Analysis
AgMIP
FUND
Loss Agricultural Sector (%)
Temperature Change (degrees)

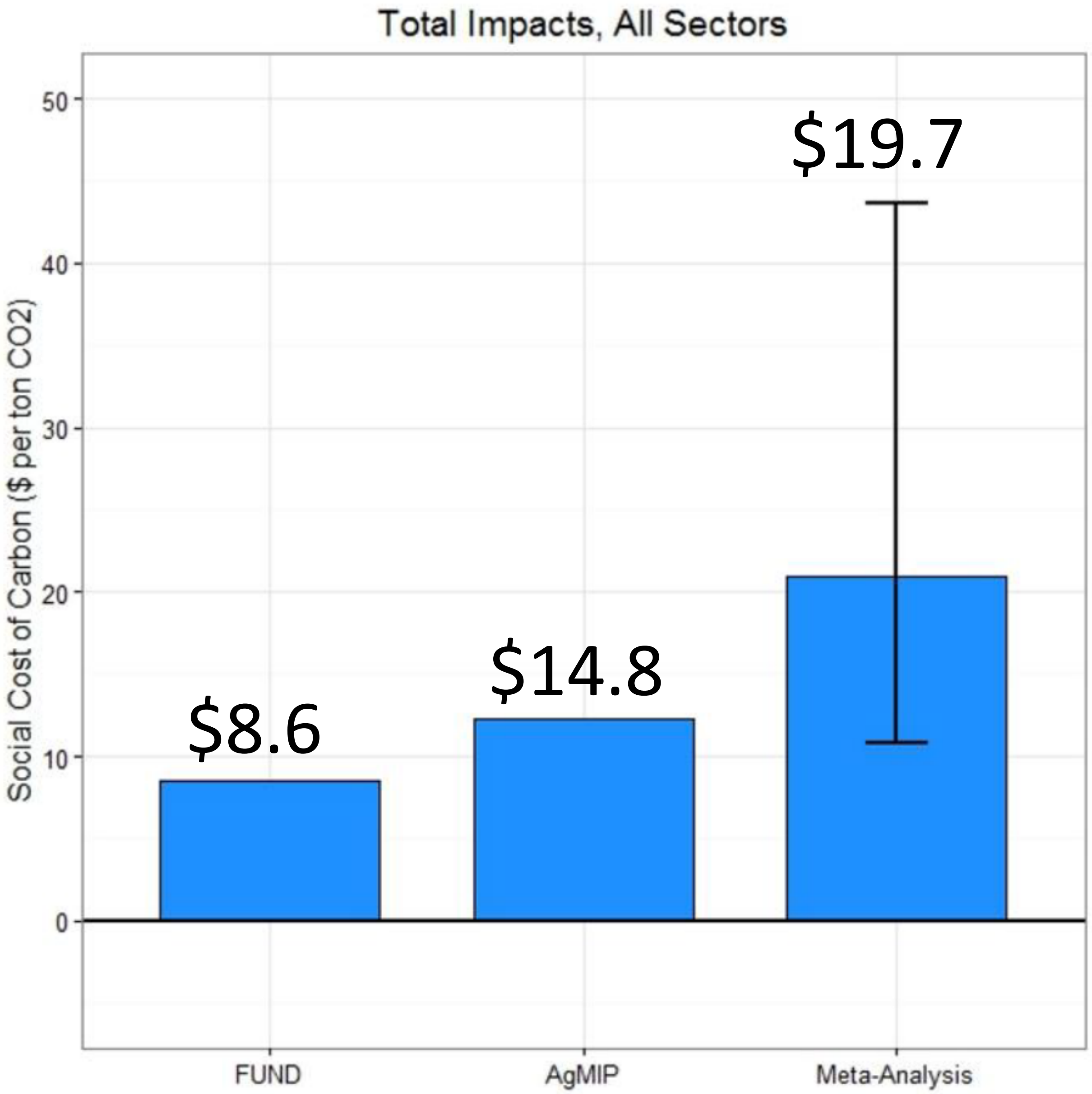



- Existing FUND damages show global net benefits from climate change impacts on agriculture

- Both updated damage functions show net costs

3% constant discount rate

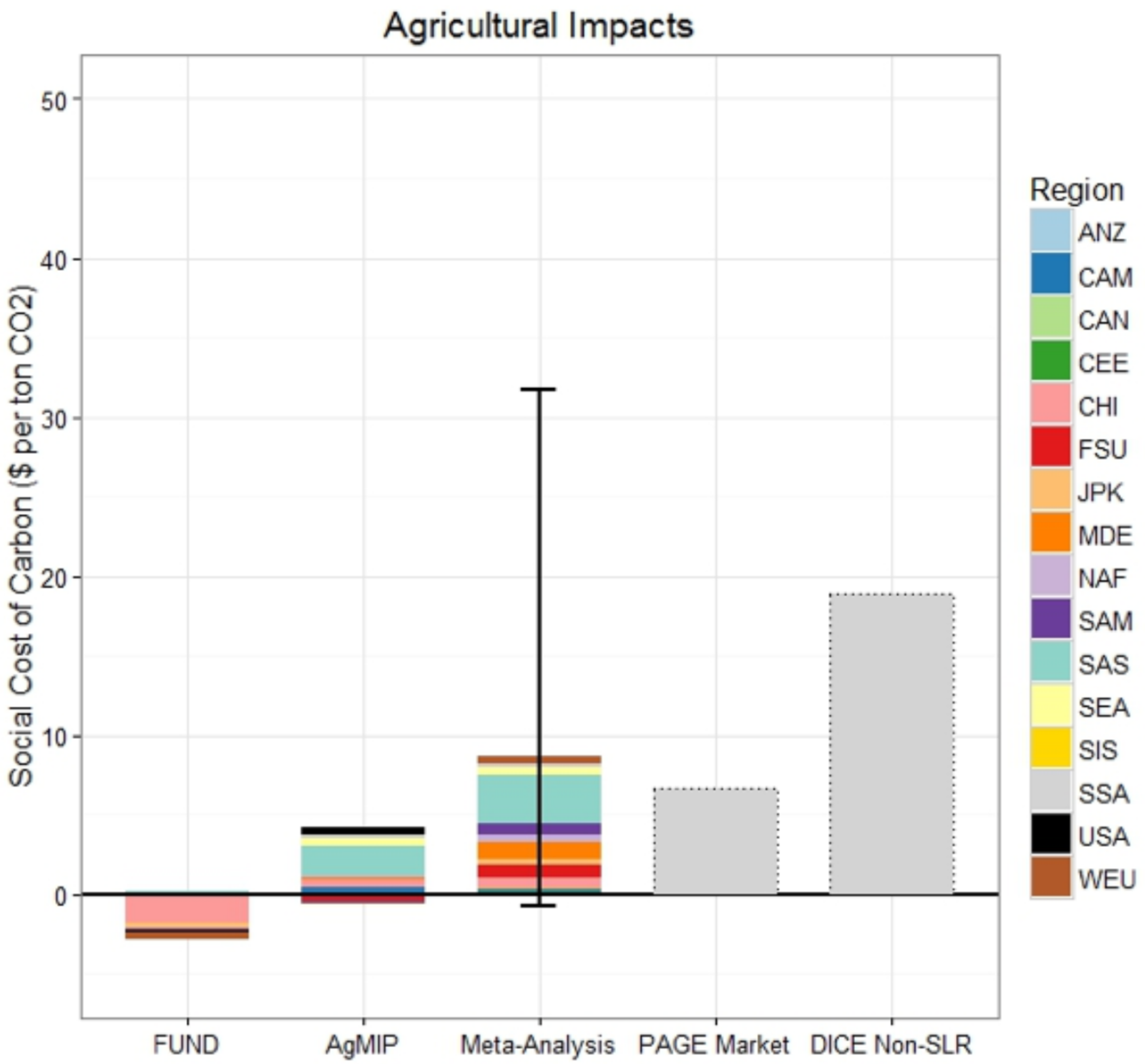
Moore, Baldos, Hertel and Diaz, 2017




- This has a large effect on the *total* SCC
- Increases between 72% (AgMIP) and 129% (Meta-Analysis)
- Error bars include the AgMIP estimate but not the FUND result

Moore, Baldos, Hertel and Diaz, 2017

# What About Other Models?



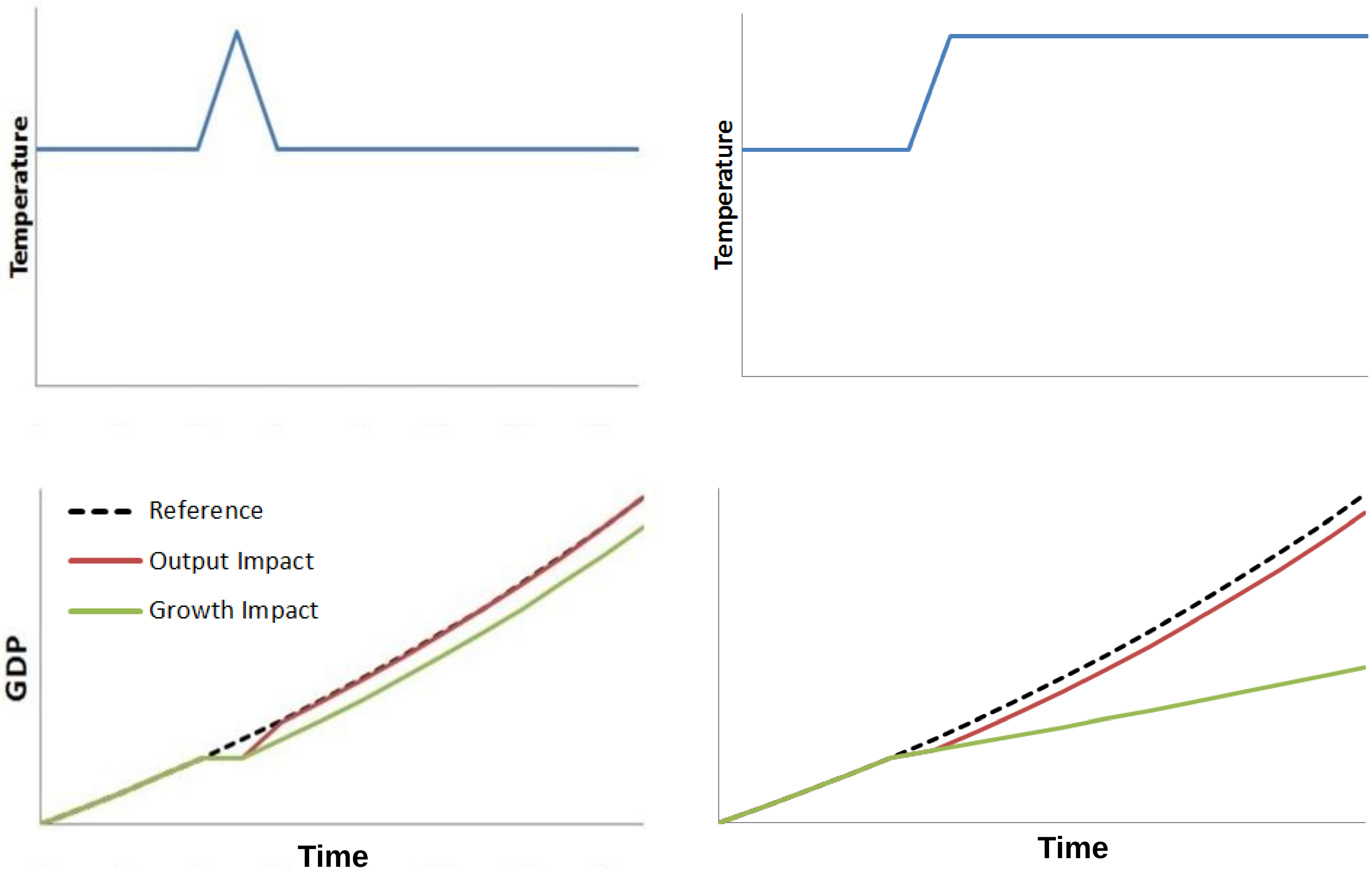

- Standardized socio-economics, climate, and discounting modules mean we can do an apples-to-apples comparison with damage functions in other models
- Our meta-analysis estimate is *larger* than all market damages in PAGE
- Agriculture comprises 19% - 45% of non-SLR damages in DICE

# Lessons Learned

- Even for a relatively "organized" damage sector like agriculture, a lot of work involved in producing a damage function
- Regional damage functions enter IAMs independently, but shouldn't be thought of as independent – conditional on impacts in other regions, through GTAP modeling step
- Difficult to standardize socio-economic projections / assumptions across modeling steps without an integrated model
- Original motivation was SCC, but this work also:
  - Systematically compared yield impacts across process-based and empirical yield models (Moore, Baldos and Hertel, ERL 2017)
  - Compared AgMIP and IPCC yield changes
  - Decomposed terms of trade effects (Baldos, Hertel and Moore, accepted, AJAE)
  - Provided global gridded yield changes for multiple crops and global welfare changes (hosted on Figshare)

# Example: Reduced-Form Empirical Growth Rate Impacts in DICE

- Damages in current IAMs mostly model temperature as having an effect on productivity (i.e. level of output), but not affecting the underlying growth path of the economy (i.e. growth of output)
- There are reasons to think that climate damages could affect growth as well as levels (e.g. impacts to capital stock, diversion of public resources affecting technical progress)
- This is critical in determining economic damages

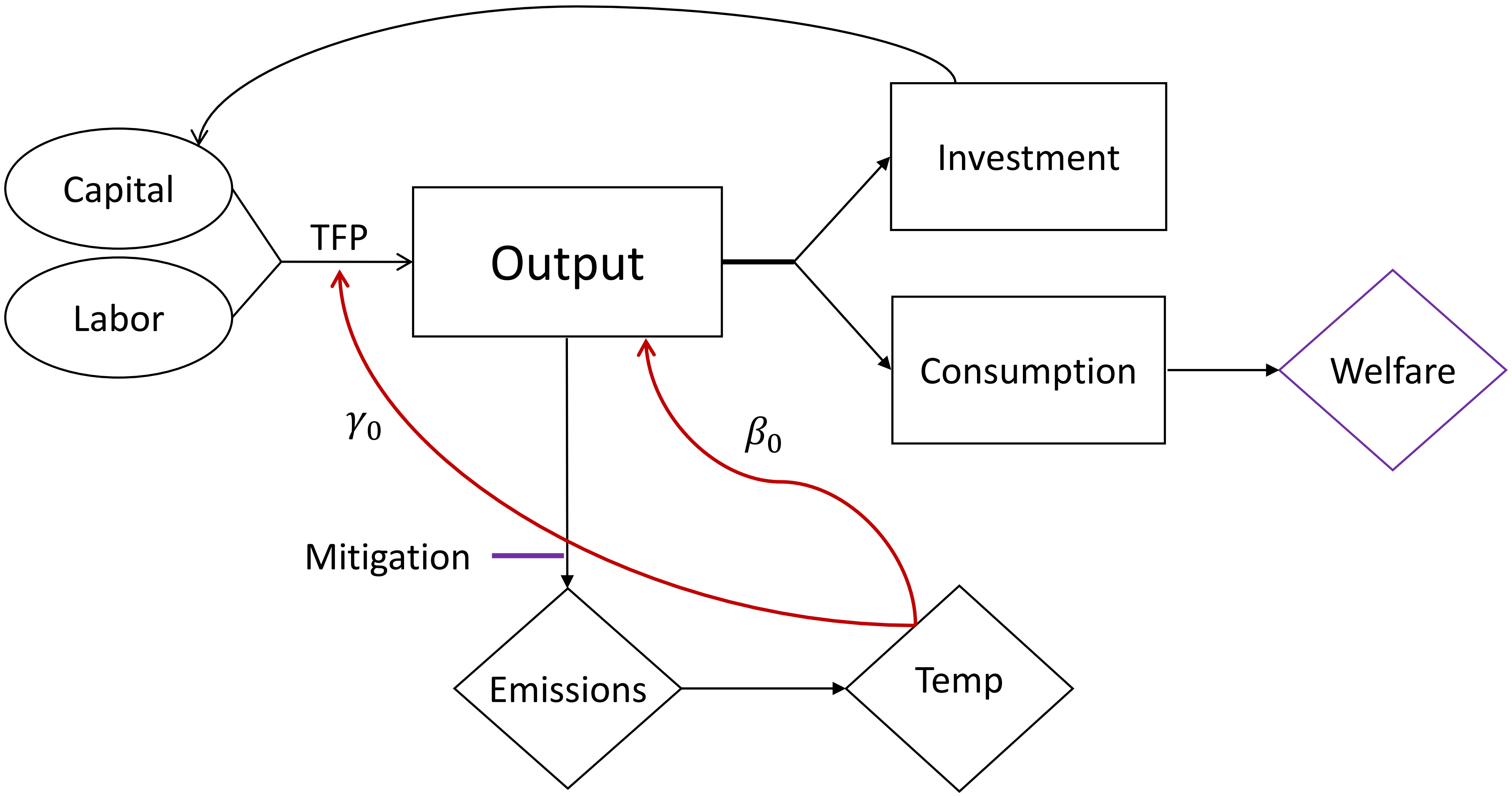


Temperature
Temperature
Reference
Output Impact
Growth Impact
GDP
Time
Time

# Empirical Findings

| | **Effect One Degree Temp Increase on GDP Growth Rates** $(\gamma_0)$ | **Effect One Degree Temp Increase on GDP Growth Levels** $(\beta_0)$ |
|---|---|---|
| **Poor** | -1.171 pp | -0.426 pp |
| **Rich** | -0.152 pp | 0.371 pp |

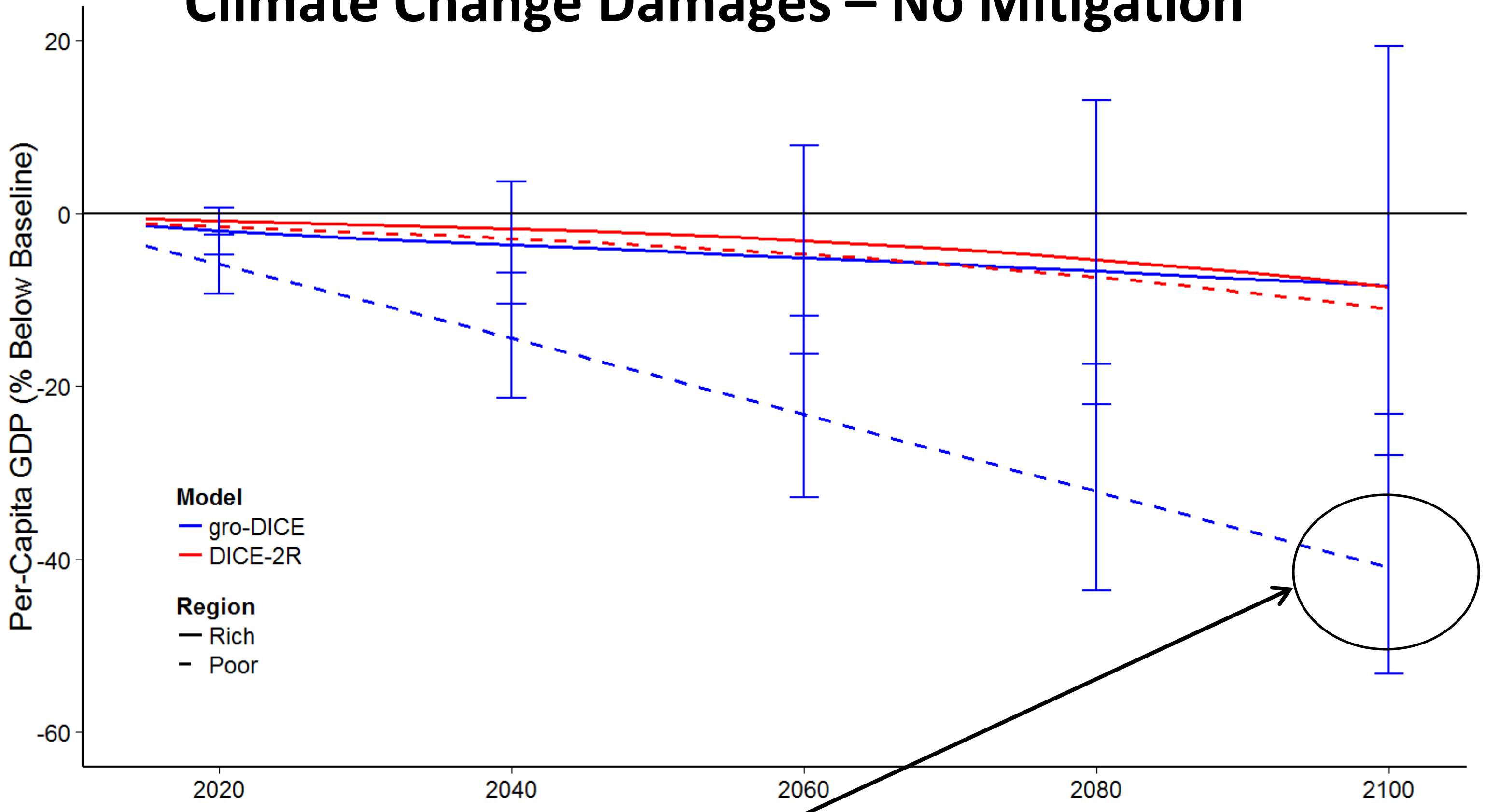
- Dell, Jones and Olken (2012) use panel regression model with lagged temperature terms to distinguish output and growth effects
- Large, negative, significant effects on growth in poor countries
- Some growth effects in rich countries, although not significantly different from zero
- Warming has different effects on GDP levels in poor and rich countries




1. Split DICE into 2 regions using RICE parameterization

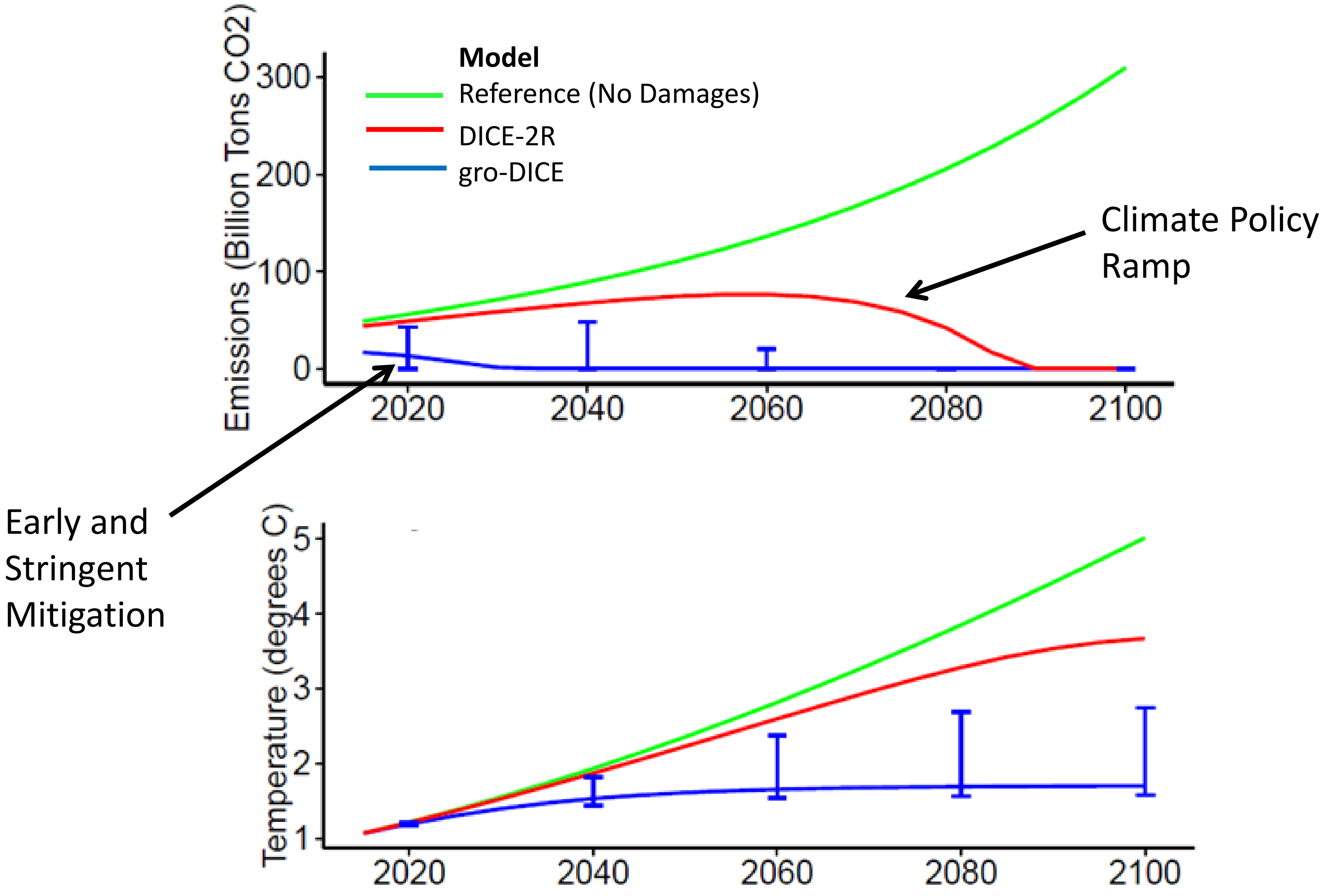
2. Add growth impact pathway and calibrate damage parameters to DJO results (accounting for existing DICE growth effects via capital stock)

# Climate Change Damages – No Mitigation



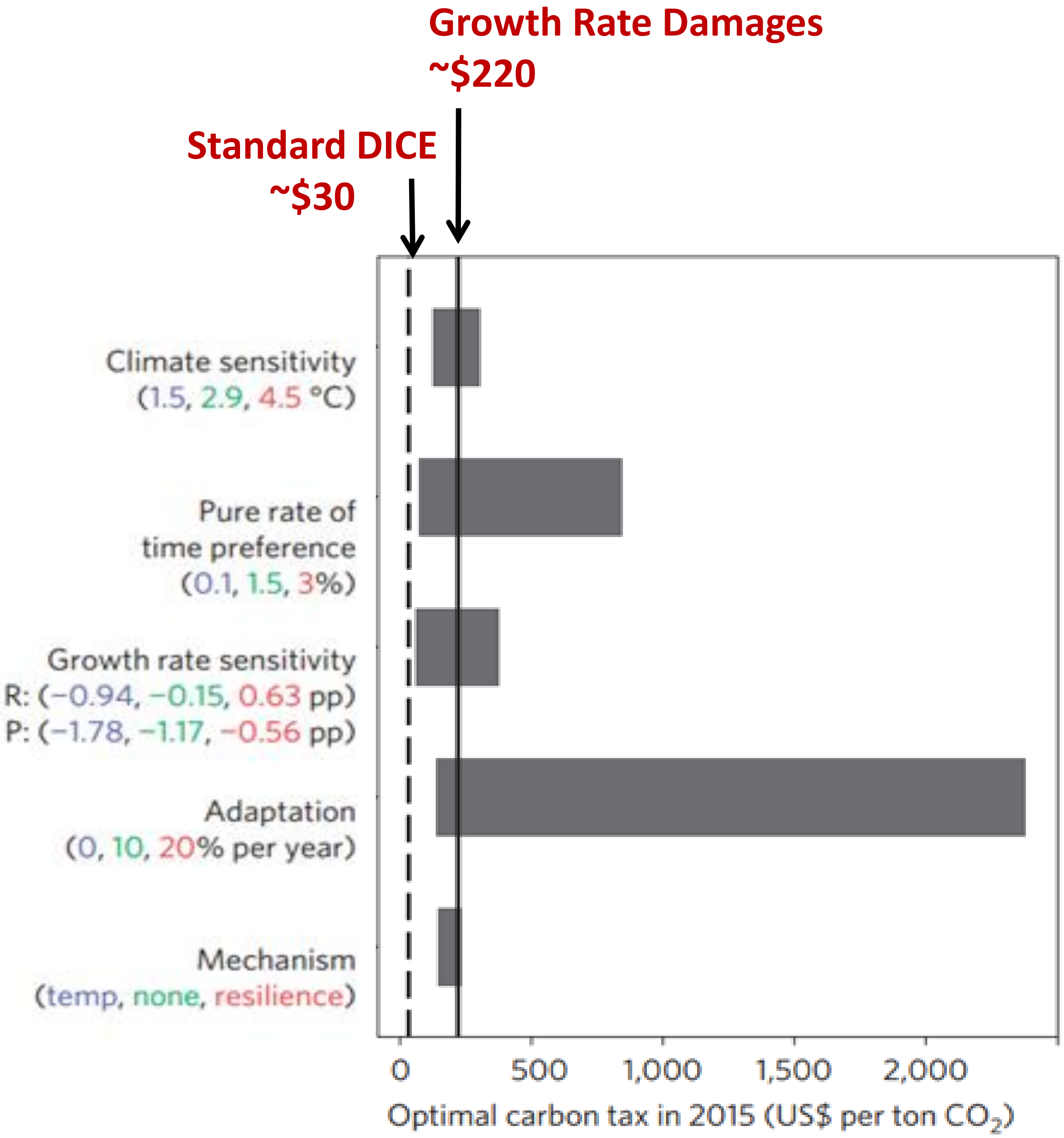

- 40% Below Baseline
- Average Annual Growth Rate Cut from 3.2% to 2.6%

Error Bars = DJO Estimate +/- One Standard Error = 68% Confidence Interval




Error Bars = DJO Estimate +/- One Standard Error = 68% Confidence Interval

Moore and Diaz, 2015




Moore and Diaz, 2015

# Lessons Learned

- Respecting empirical findings required substantial alterations to the DICE model
  - Convert from one to two regions
  - Calibrate parameters to match empirical findings

- Close collaboration between empiricists and modelers essential for accurate translation of findings

- Growth rate effects are important in determining the SCC – more empirical work needed

# Thank you!

Questions?