Climate Change Impacts on Agriculture: Understanding Global Effects on Yield and Welfare

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Climate Change Impacts on Agriculture: Understanding Global Effects on Yield and Welfare

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IATRC Theme Day Presentation, December 11^{th} 2016

Outline

- Motivation
- Global, multi-crop, multi-method yield response functions
- Welfare changes
- Implications for the social cost of carbon

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- **Motivation**
- Global, multi-crop, multi-method yield response functions
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Motivation – The Gap

- Climate change will have direct impacts on the agricultural sector
- Substantial scientific effort directed toward understanding how crop yield responds to changing temperature, rainfall, and CO_2
- Less work on understanding more policy-relevant impacts such as production, prices, consumption, and welfare
- This requires global, multi-crop estimates of productivity response to climate change
- Aggregating, synthesizing, and extrapolating results from the agronomic literature is extremely challenging

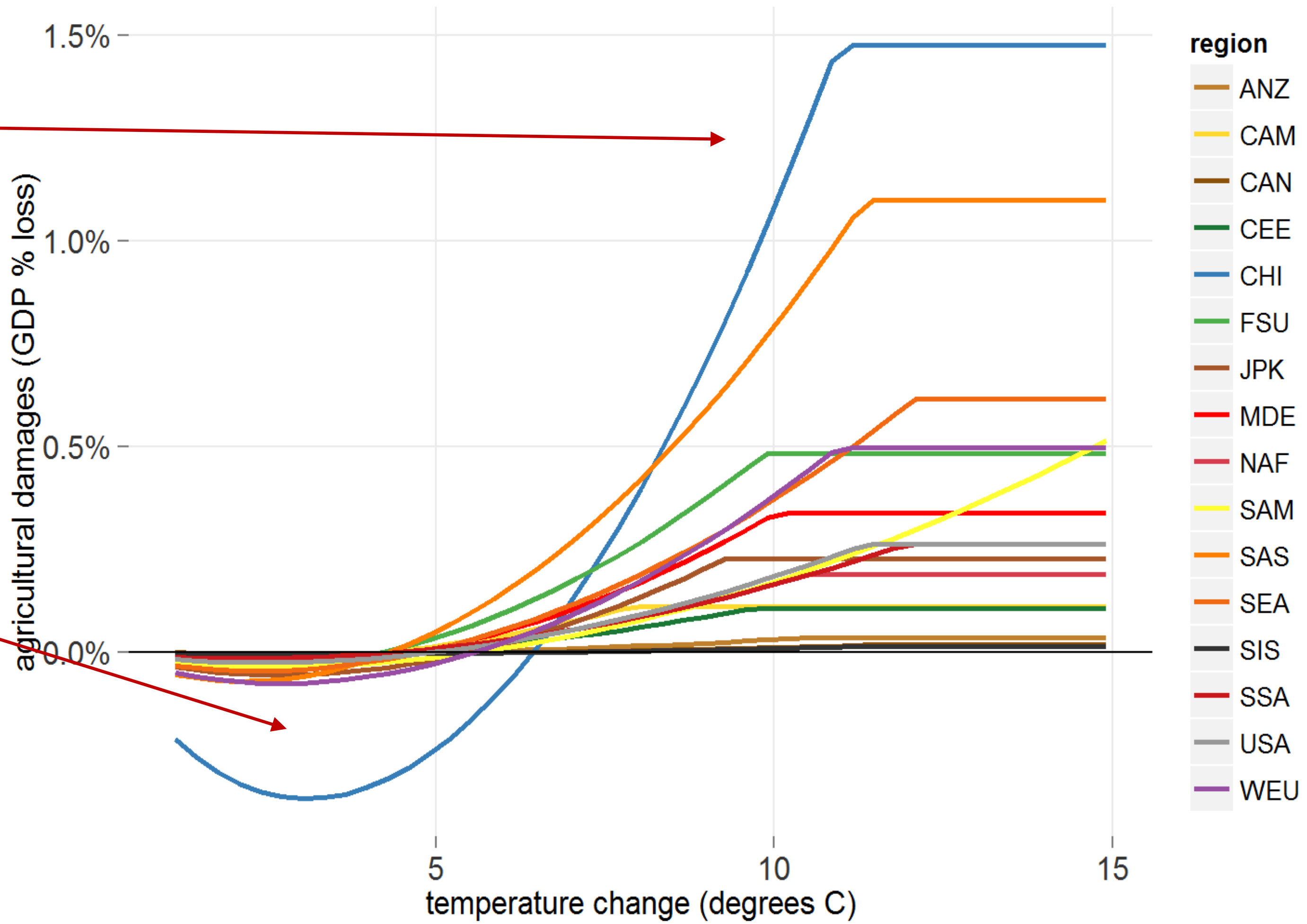
Motivation – The Need

- Global and regional welfare impacts are needed to improve estimates of the social cost of carbon (SCC)
- SCC is the marginal cost of an additional ton of CO_2 emissions
- Since 2010 used at the federal level for regulatory analysis of climate and energy policies, and increasingly at the state level
- Estimated using three integrated assessment models – DICE, PAGE, and FUND

Motivation – The Need

Damages capped at current fraction of agriculture in the economy

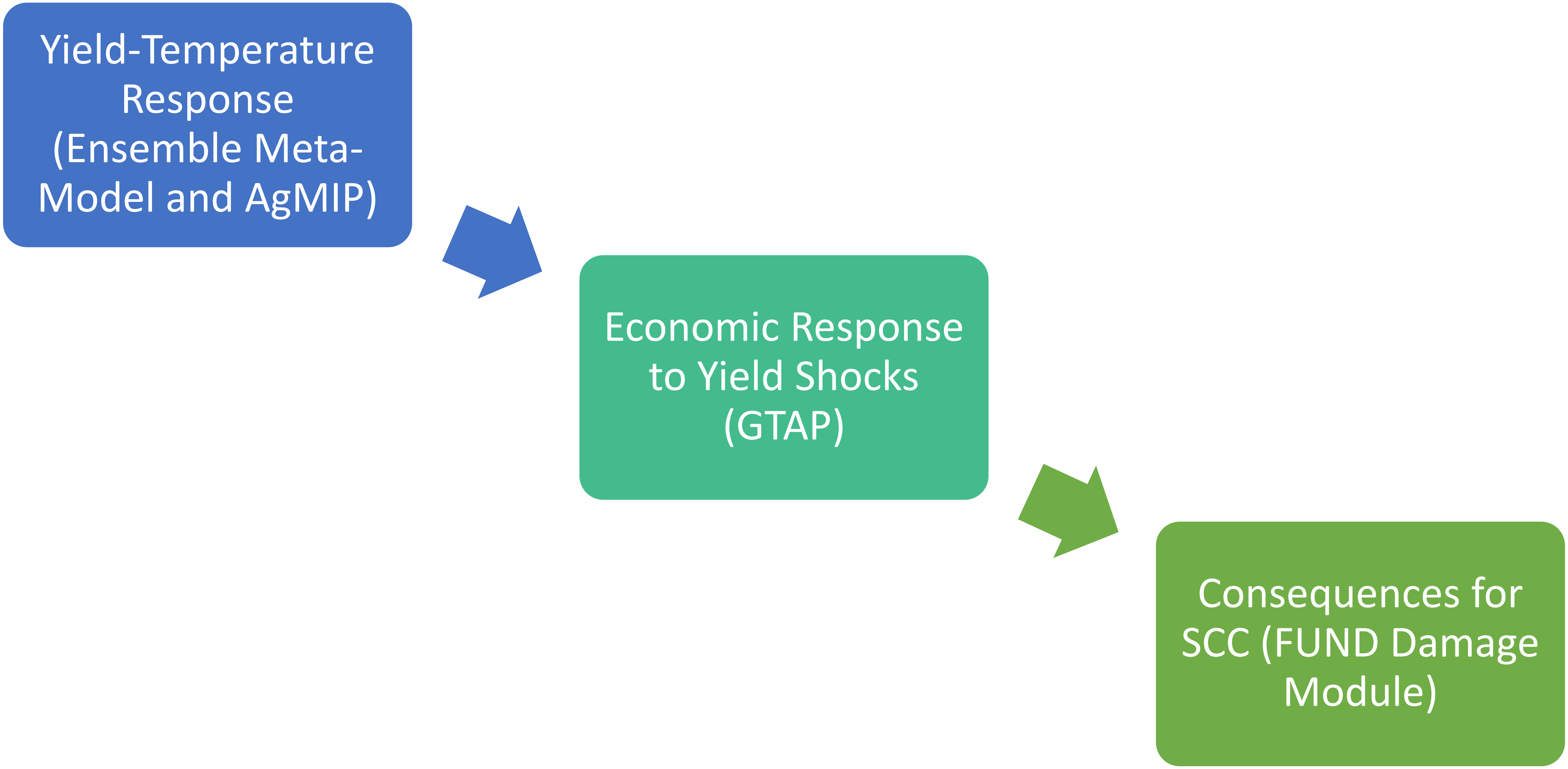
Universal benefits up to ~4-5 degrees of warming



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

Methodology Overview



Outline

- The research challenge
- **Global, multi-crop, multi-method yield response functions**
- Welfare changes
- Implications for the social cost of carbon

The Landscape of Climate-Crop Modeling

$$Yield = f(Temperature, Rainfall, CO_2 | Inputs, Soil \ldots etc)$$

Statistical Models

Process-Based Crop Models

Meta-Analysis

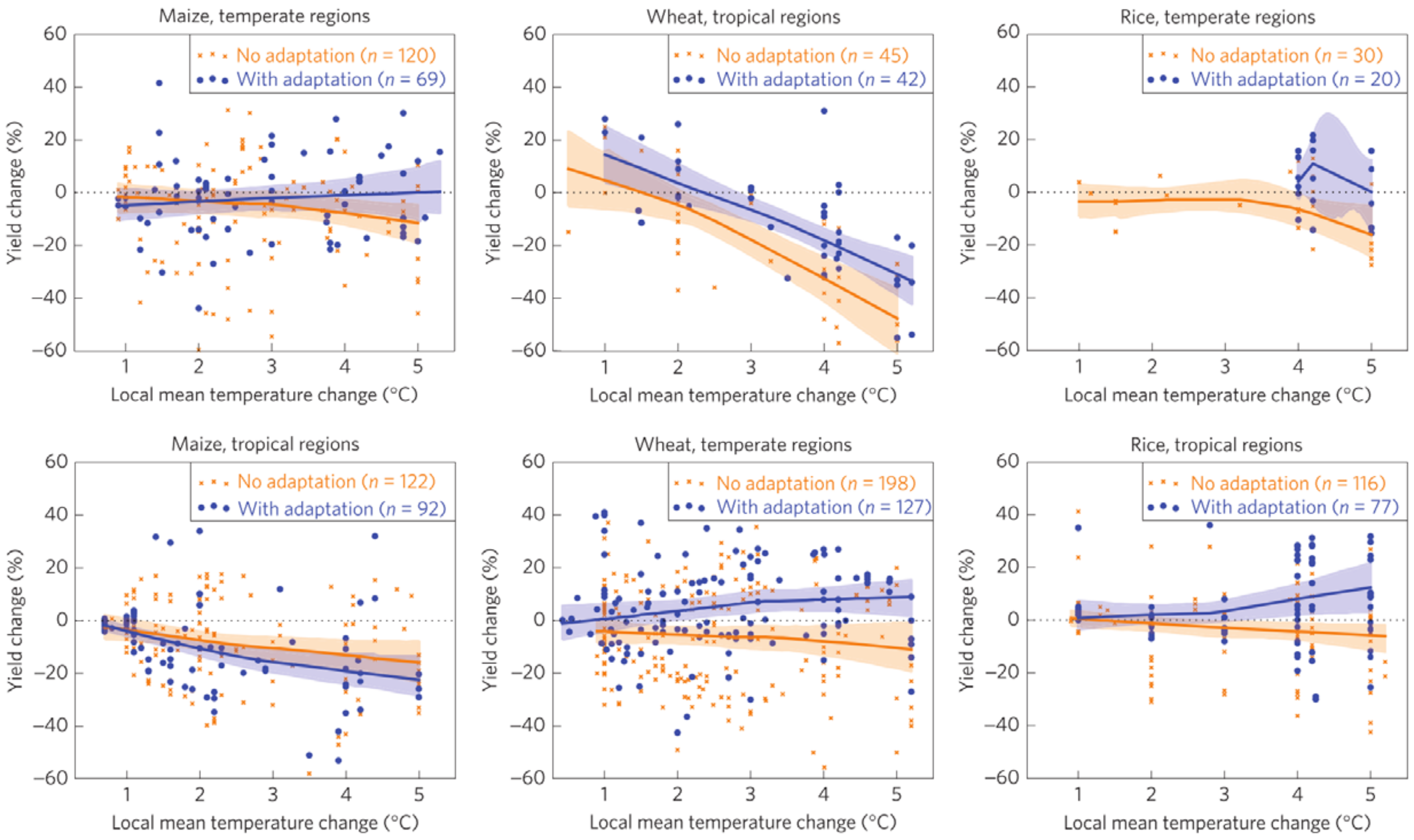
Individual Studies

Coordinated Model Inter-Comparisons

AgMIP Global Gridded Crop Model Inter-comparison (GGCMI)

1. Meta-Analysis

- Database of 1,010 point-estimates of yield change in response to temperature change compiled for IPCC AR5
- From 53 studies
- 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)

Ensemble Response Estimation

$$\Delta Y_{ijk} = \beta_{1j}\Delta T_{ijk} * Crop_j + \beta_{2j}\Delta T_{ijk}{}^2 * Crop_j$$

$$+ \beta_{3j}\Delta T_{ijk} * Crop_j * \bar{T}_{jk} + \beta_{4j}\Delta T_{ijk}{}^2 * Crop_j * \bar{T}_{jk}$$

$$+ \beta_5 f\left(\Delta CO_{2ijk}\right) + \beta_6 \Delta P_{ijk} + \beta_7 \Delta T_{ijk} * Adapt_{ijk} + \beta_8 Adapt_{ijk} + \varepsilon_{ijk}$$

Ensemble Response Estimation

Change in yield, data-point i, crop j, country k

$$\Delta Y_{ijk} = \beta_{1j}\Delta T_{ijk} * Crop_j + \beta_{2j}\Delta {T_{ijk}}^2 * Crop_j$$

$$+ \ \beta_{3j}\Delta T_{ijk} * Crop_j * \bar{T}_{jk} + \beta_{4j}\Delta {T_{ijk}}^2 * Crop_j * \bar{T}_{jk}$$

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Ensemble Response Estimation

Crop-specific quadratic warming response

$$\Delta Y_{ijk} = \beta_{1j}\Delta T_{ijk} * Crop_j + \beta_{2j}\Delta T_{ijk}{}^2 * Crop_j$$

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Ensemble Response Estimation

Impact of warming differs depending on baseline temperature

$$\Delta Y_{ijk} = \beta_{1j}\Delta T_{ijk} * Crop_j + \beta_{2j}\Delta T_{ijk}{}^2 * Crop_j$$

$$+ \beta_{3j}\Delta T_{ijk} * Crop_j * \bar{T}_{jk} + \beta_{4j}\Delta T_{ijk}{}^2 * Crop_j * \bar{T}_{jk}$$

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Ensemble Response Estimation

$$\Delta Y_{ijk} = \beta_{1j}\Delta T_{ijk} * Crop_j + \beta_{2j}\Delta T_{ijk}{}^2 * Crop_j$$

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$$+ \beta_5 f\left(\Delta CO_{2ijk}\right) + \beta_6\Delta P_{ijk} + \beta_7\Delta T_{ijk} * Adapt_{ijk} + \beta_8 Adapt_{ijk} + \varepsilon_{ijk}$$

Concave function of CO_2 allows for declining marginal effect

$$f\left(\Delta CO_{2ijk}\right) = \frac{\Delta CO_{2ijk}}{\Delta CO_{2ijk} + 100}$$

Ensemble Response Estimation

$$\Delta Y_{ijk} = \beta_{1j}\Delta T_{ijk} * Crop_j + \beta_{2j}\Delta T_{ijk}{}^2 * Crop_j$$

$$+ \beta_{3j}\Delta T_{ijk} * Crop_j * \bar{T}_{jk} + \beta_{4j}\Delta T_{ijk}{}^2 * Crop_j * \bar{T}_{jk}$$

$$+ \beta_5 f(\Delta CO_{2ijk}) + \beta_6 \Delta P_{ijk} + \beta_7 \Delta T_{ijk} * Adapt_{ijk} + \beta_8 Adapt_{ijk} + \varepsilon_{ijk}$$

Linear precip control

Ensemble Response Estimation

$$\Delta Y_{ijk} = \beta_{1j}\Delta T_{ijk} * Crop_j + \beta_{2j}\Delta T_{ijk}{}^2 * Crop_j$$

$$+ \beta_{3j}\Delta T_{ijk} * Crop_j * \bar{T}_{jk} + \beta_{4j}\Delta T_{ijk}{}^2 * Crop_j * \bar{T}_{jk}$$

$$+ \beta_5 f\left(\Delta CO_{2ijk}\right) + \beta_6 \Delta P_{ijk} + \beta_7 \Delta T_{ijk} * Adapt_{ijk} + \beta_8 Adapt_{ijk} + \varepsilon_{ijk}$$

True adaptation term – how does adaptation moderate the effects of warming

Ensemble Response Estimation

$$\Delta Y_{ijk} = \beta_{1j}\Delta T_{ijk} * Crop_j + \beta_{2j}\Delta T_{ijk}{}^2 * Crop_j$$

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$$+ \beta_5 f(\Delta CO_{2ijk}) + \beta_6\Delta P_{ijk} + \beta_7\Delta T_{ijk} * Adapt_{ijk} + \beta_8 Adapt_{ijk} + \varepsilon_{ijk}$$

"Adaptation Illusion" term – 'adaptations' that are beneficial today and in future climates

Ensemble Response Estimation

$$\Delta Y_{ijk} = \beta_{1j}\Delta T_{ijk} * Crop_j + \beta_{2j}\Delta T_{ijk}{}^2 * Crop_j$$

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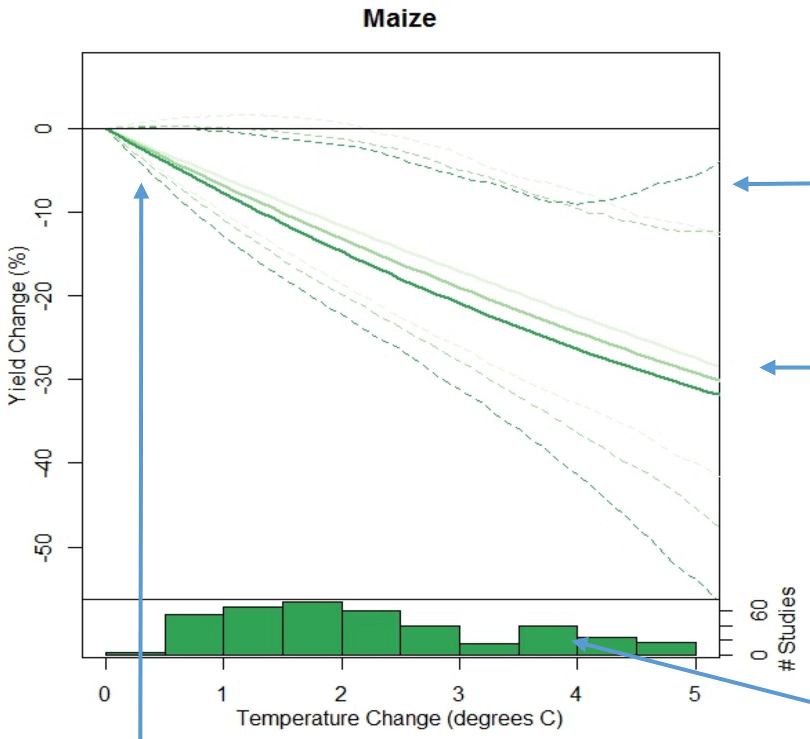
$$+ \beta_5 f(\Delta CO_{2ijk}) + \beta_6 \Delta P_{ijk} + \beta_7 \Delta T_{ijk} * Adapt_{ijk} + \beta_8 Adapt_{ijk} + \varepsilon_{ijk}$$

Errors estimated from 750 block-bootstraps, blocking at study level to allow for correlation between data-points from the same study

Ensemble Response Estimation

In summary, our approach allows for:

1. Non-linear, crop-specific impacts of warming
2. Variation in the impact of warming depending on baseline temperature
3. Declining marginal effect of increasing CO_2 concentrations
4. Inclusion of on-farm, agronomic adaptations

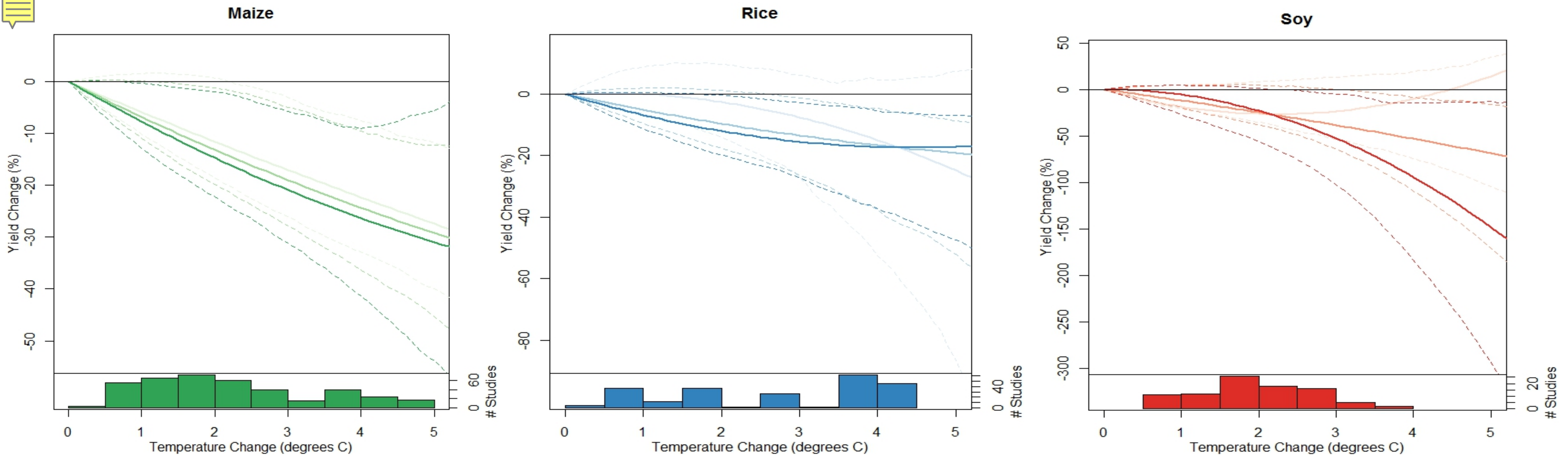


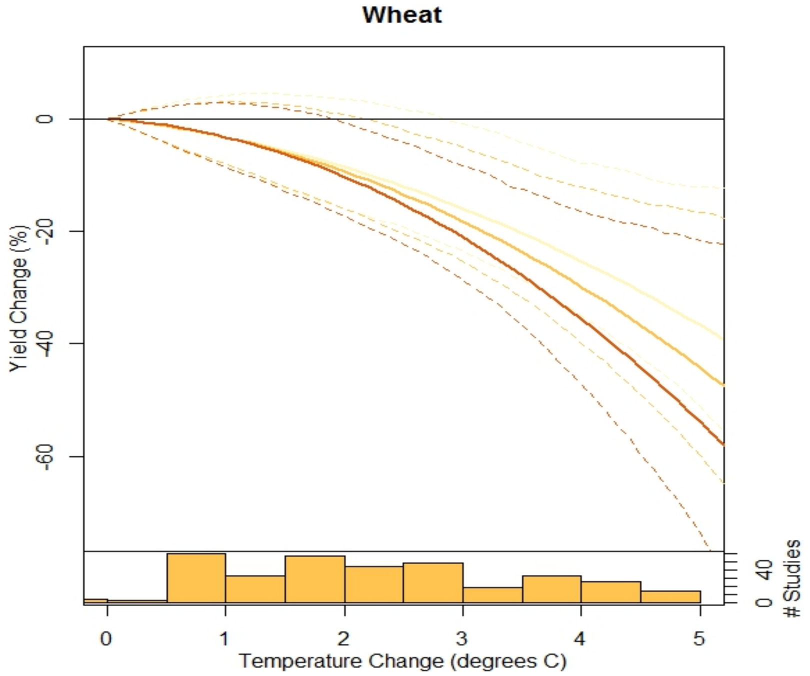
95% confidence intervals based on block-bootstrap

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

Number of data-points for estimation

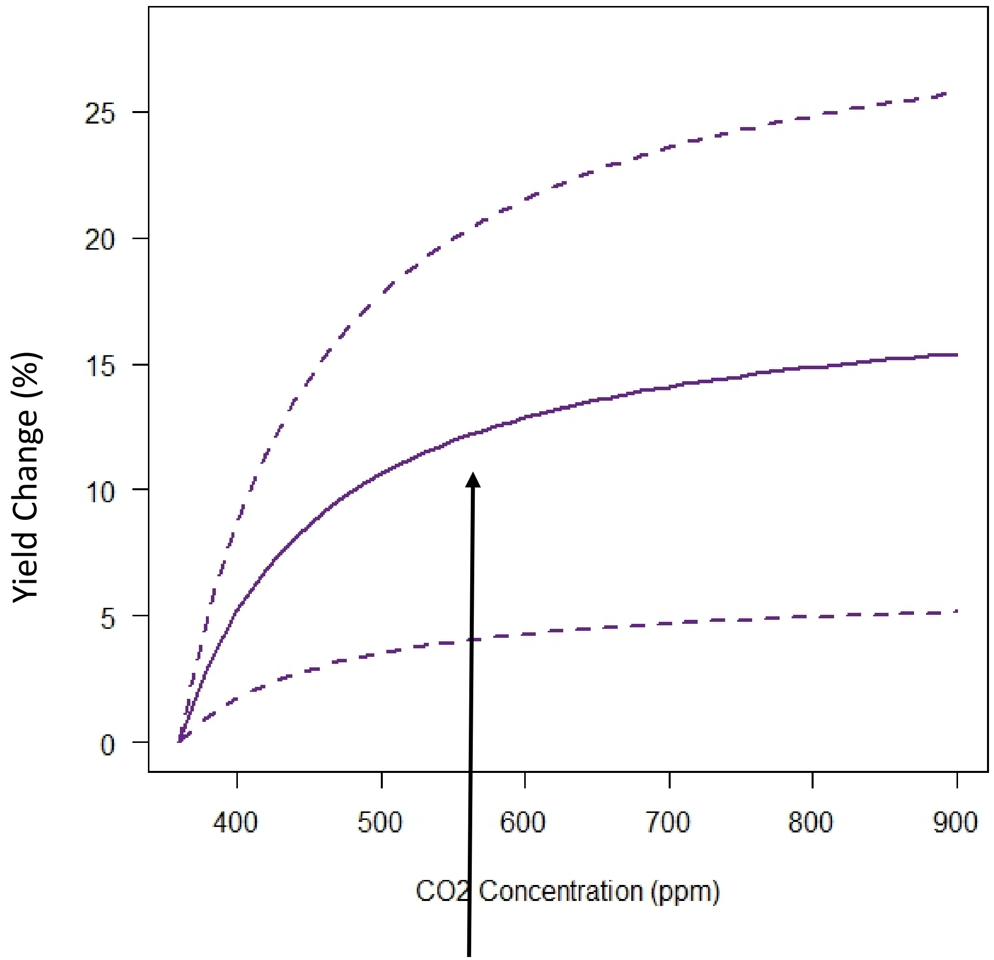
Temperature response, including adaptation (not CO_2)





- 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

CO_2 Response

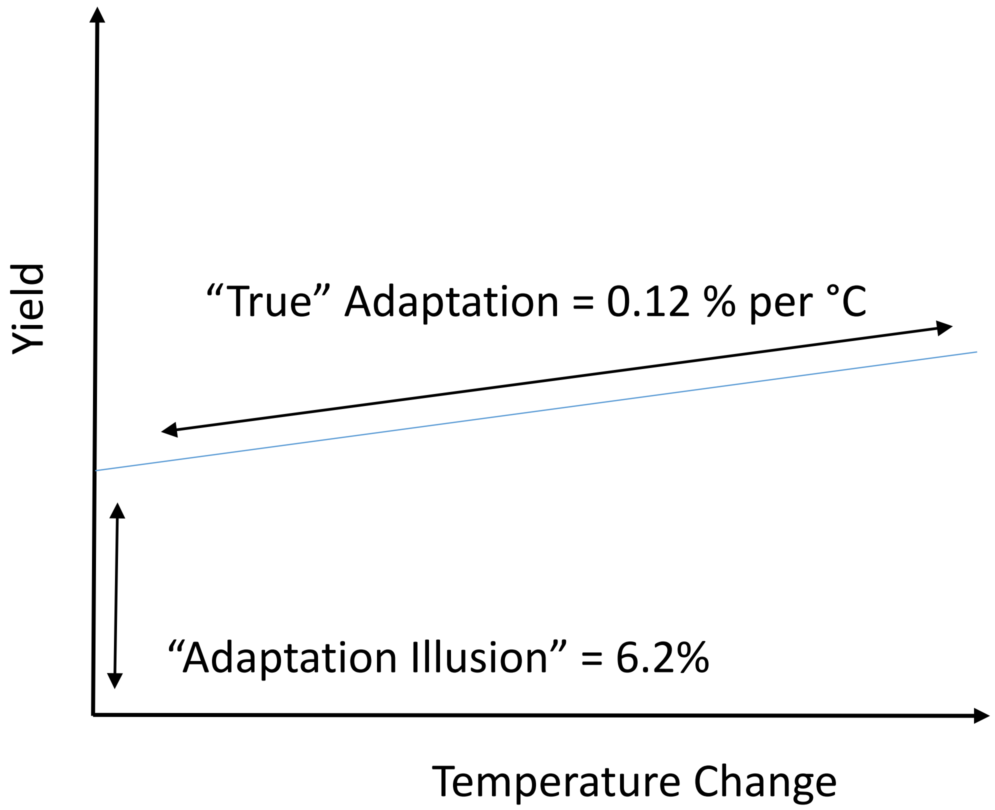


12% yield benefit from doubling of CO_2 from pre-industrial

Free Air Carbon Exchange (FACE) Experiments

- Good match for C_3 crops but high for C_4 crops
- Meta-analysis results that follow include CO_2 fertilization for C_3 but not for C_4 crops

Agronomic Adaptation



- Our results show evidence for the "adaptation illusion" described by Lobell (2014)
- Agronomic adaptations can be divided into:
    1. Increasing inputs that increase yields under present and future climates
    2. "True" adaptations that improve yields more in future climates than in the present
- Our results suggest most of what has been included in studies so far is the former rather than the latter

Statistical vs Process-Based Studies

- Distinction between process-based and empirical yield models much discussed but very few direct comparisons
- Conventional wisdom seems to be that process-based models tend to be more optimistic than statistical models
- Comparison is difficult because the former often include CO_2 fertilization whereas the latter do not
- We can use our database to test for differences between type of study, controlling for CO_2 fertilization

Statistical vs Process-Based Studies

$$\Delta Y_{ijk} = \beta_{1j}\Delta T_{ijk} * Crop_j + \beta_{2j}\Delta T_{ijk}{}^2 * Crop_j$$

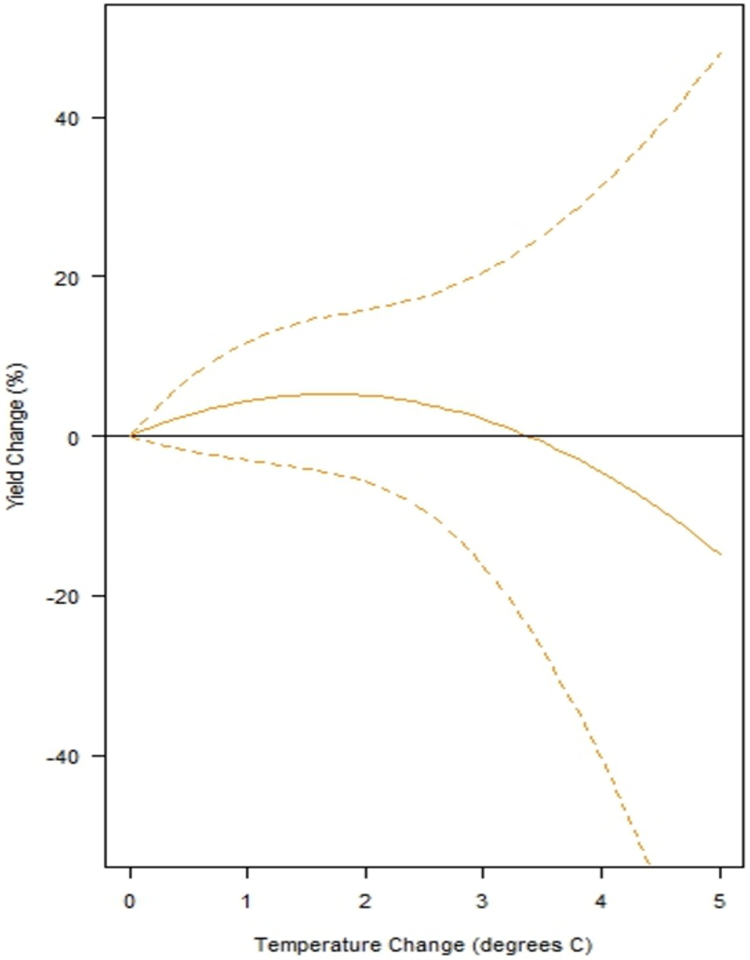
$$+ \beta_{3j}\Delta T_{ijk} * Crop_j * \bar{T}_{jk} + \beta_{4j}\Delta T_{ijk}{}^2 * Crop_j * \bar{T}_{jk}$$

$$+ \beta_5 f\left(\Delta CO_{2ijk}\right) + \beta_6 \Delta P_{ijk} + \beta_7 \Delta T_{ijk} * Adapt_{ijk} + \beta_8 Adapt_{ijk}$$

$$+ \underbrace{\beta_9 \Delta T_{ijk} * Stat_{ijk} + \beta_{10}\Delta T_{ijk}{}^2 * Stat_{ijk}} + \varepsilon_{ijk}$$

Allow effect of warming to vary between statistical and process-based studies

Statistical vs Process-Based Studies



Effect of Statistical Study Compared to Process-Based

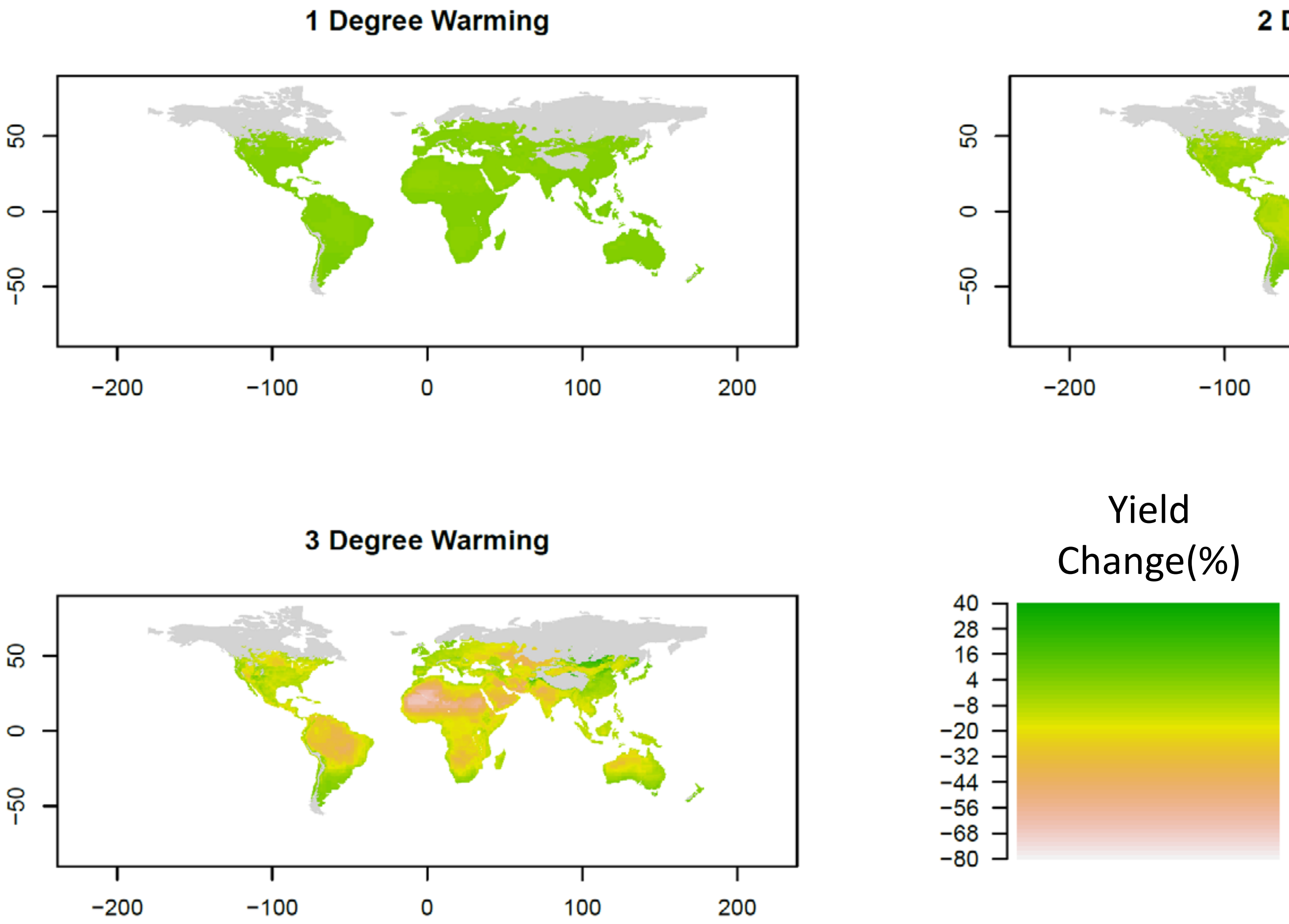
- Not strong evidence that results from statistical studies are different from process-based modeling studies
- Important to control for CO_2 fertilization when comparing across studies
- Limited number of empirical results in database, clustered around 1°C warming

Gridded Global Yield Change

- Our continuous response functions allow us to extrapolate yield response to warming

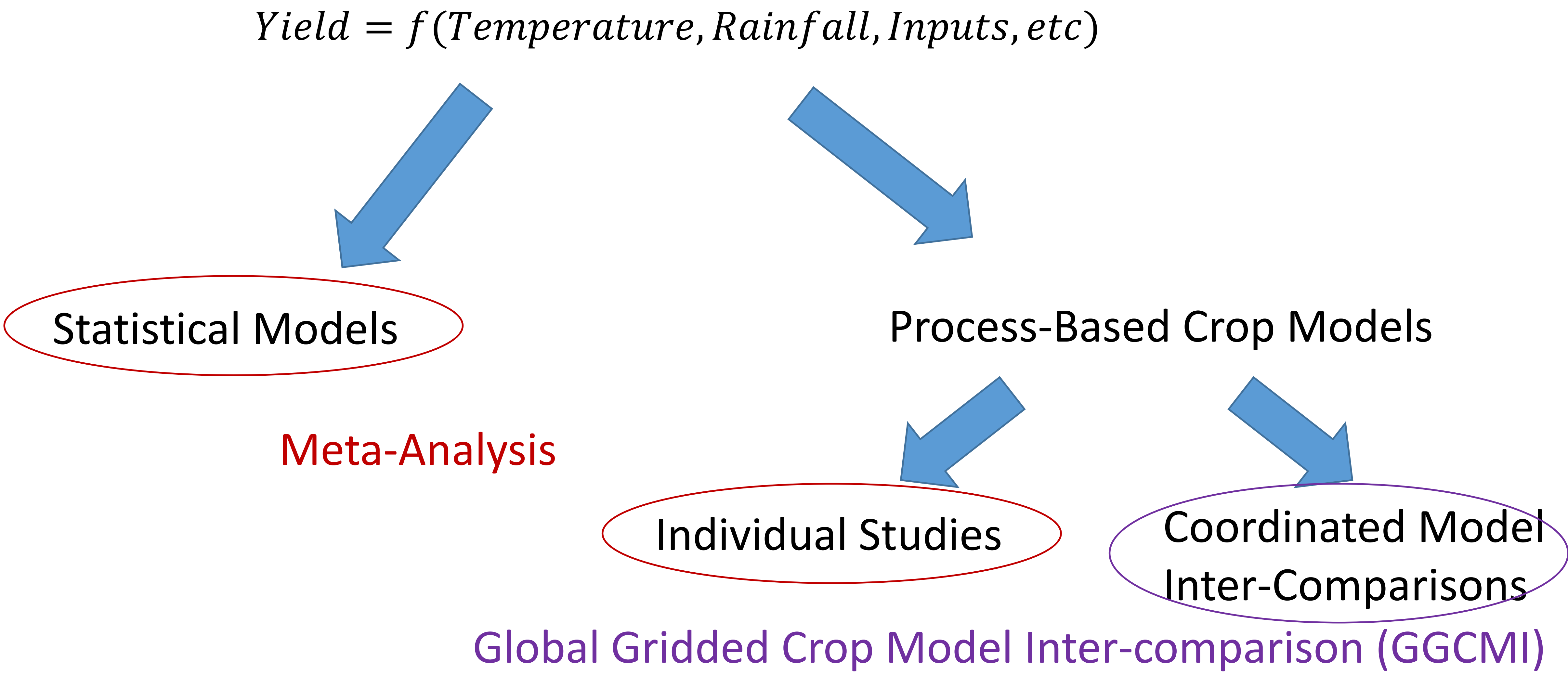
- Spatial variability in the yield response depends on:
  1. Baseline growing season temperature
  2. Scaling between local and global temperature change (CMIP5 Model Ensemble)

Gridded Global Yield Change



Gridded wheat yields, including adaptation and CO_2 fertilization

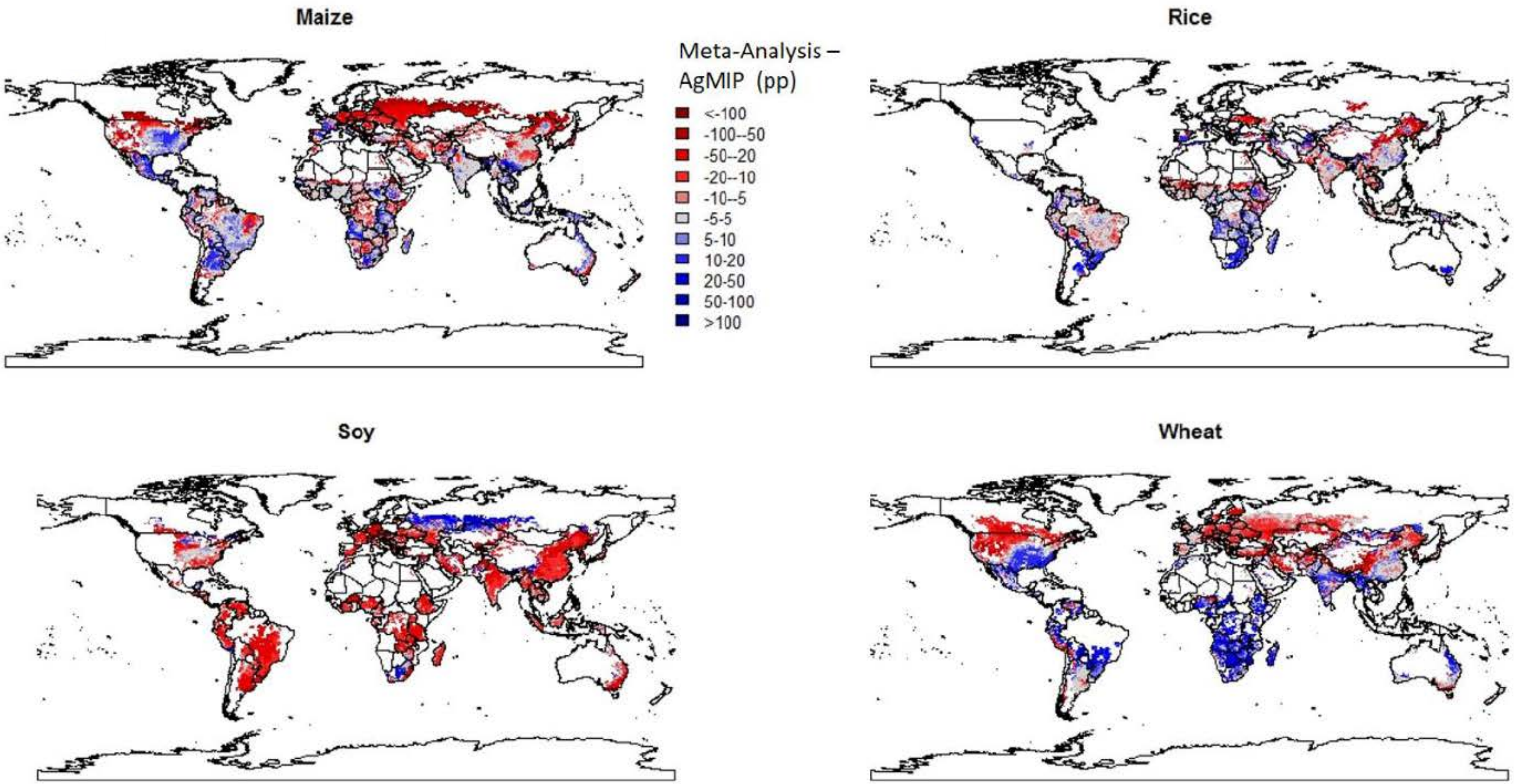
The Landscape of Crop-Response Modeling



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

Comparison of Meta-Analysis and AgMIP



Blue = Meta-analysis more positive than AgMIP
Red = Meta-analysis more negative than AgMIP

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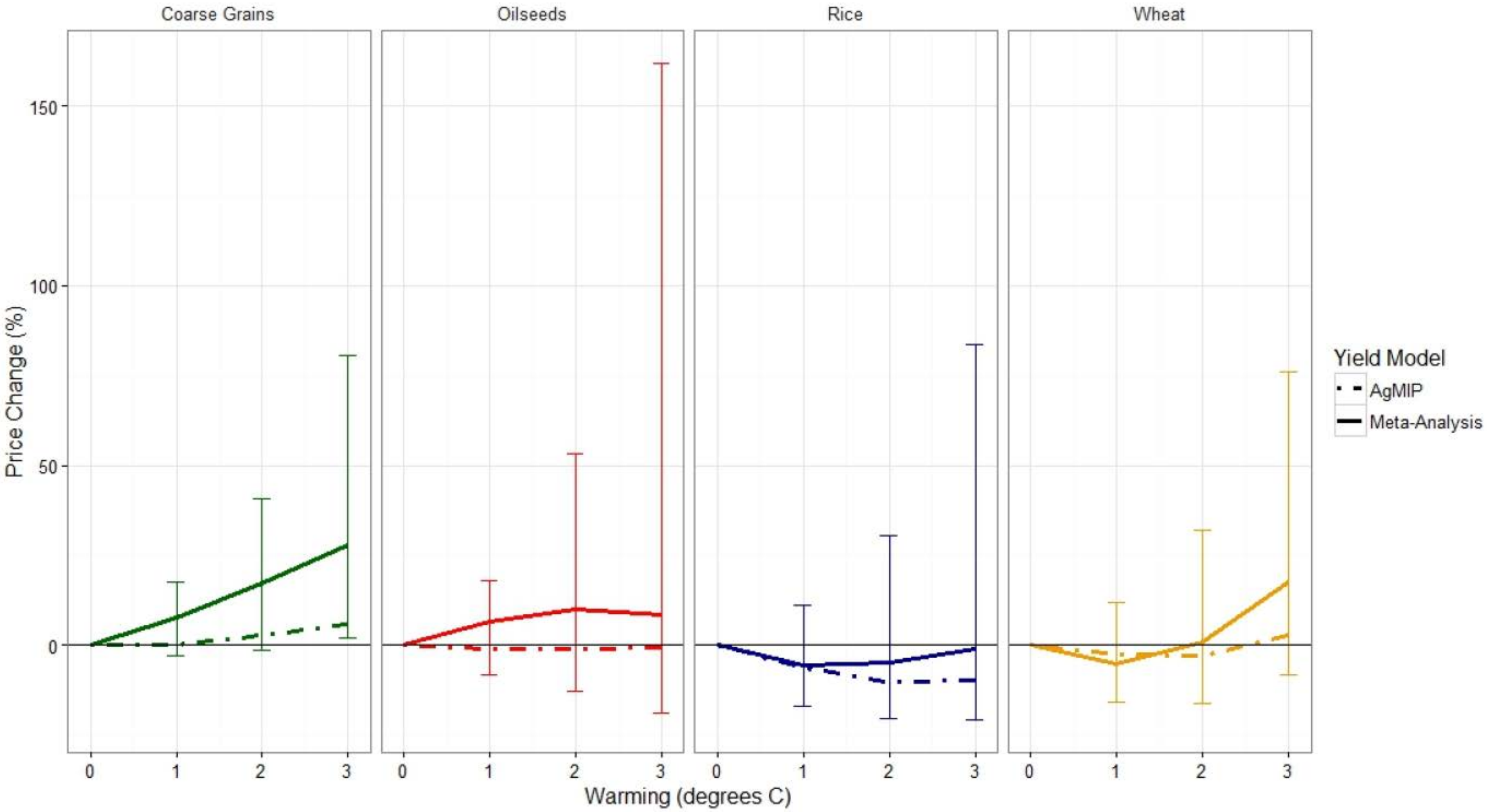
- **Welfare changes**
- Implications for the social cost of carbon

Welfare Consequences of Yield Changes

- GTAP run with 140 regions, 14 commodities (9 agricultural)
- Yield shocks aggregated to regional level (production-weighting) and introduced as Hicks-neutral technical change – both meta-analysis and AgMIP
- Report welfare changes as equivalent variation (EV)
- Economic adaptations (crop switching, intensification, trade adjustments, product substitution) are accounted for here

Welfare Consequences of Yield Changes



- Uncertainties from uncertain yield response are large
- Price increases in most sectors at 3°C warming (meta-analysis)
- Much more moderate price changes (AgMIP)

Welfare Consequences of Yield Changes

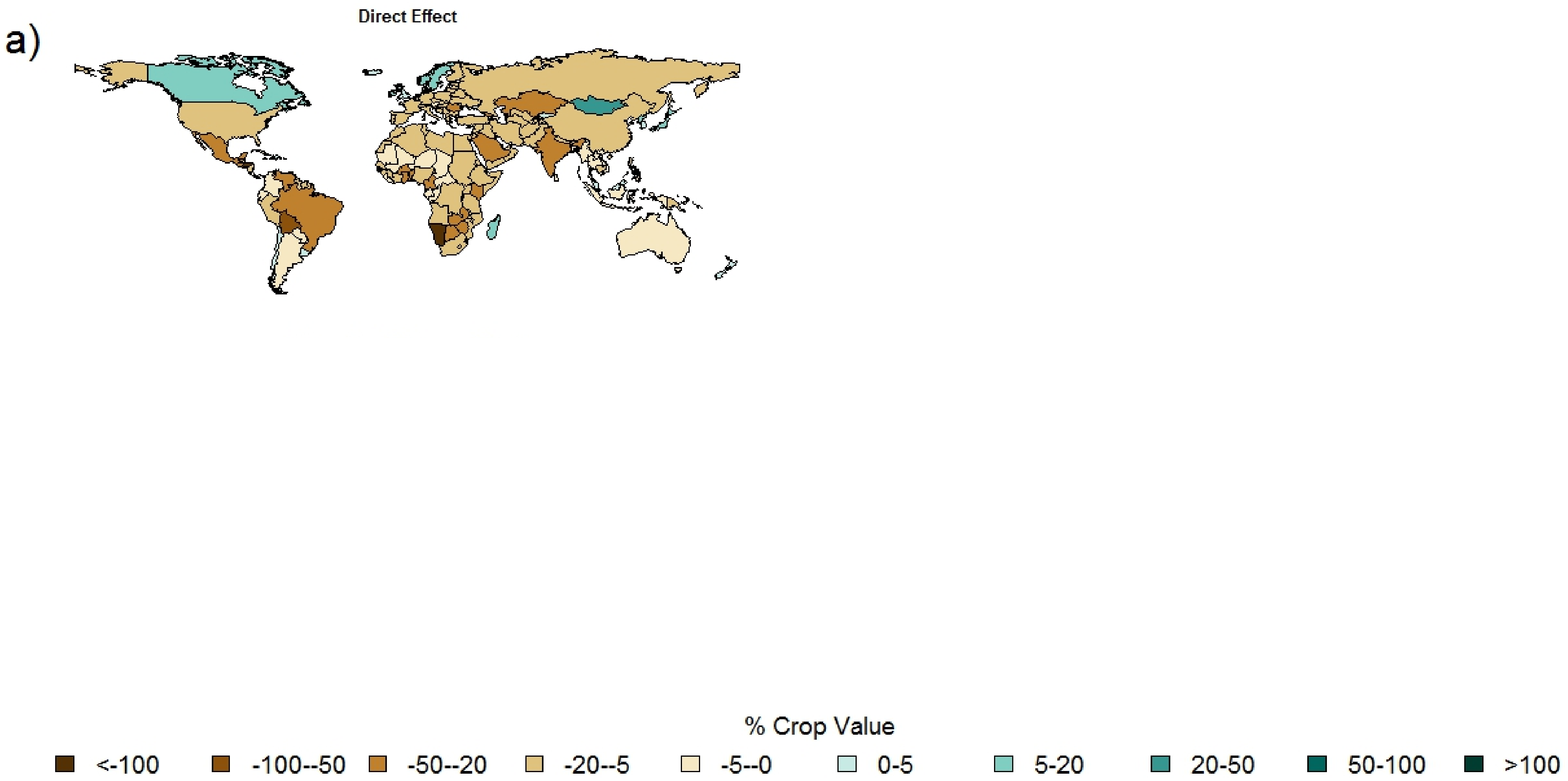
- We decompose welfare changes into three parts following Hertel and Randhir (2000):

   1. Direct productivity effect

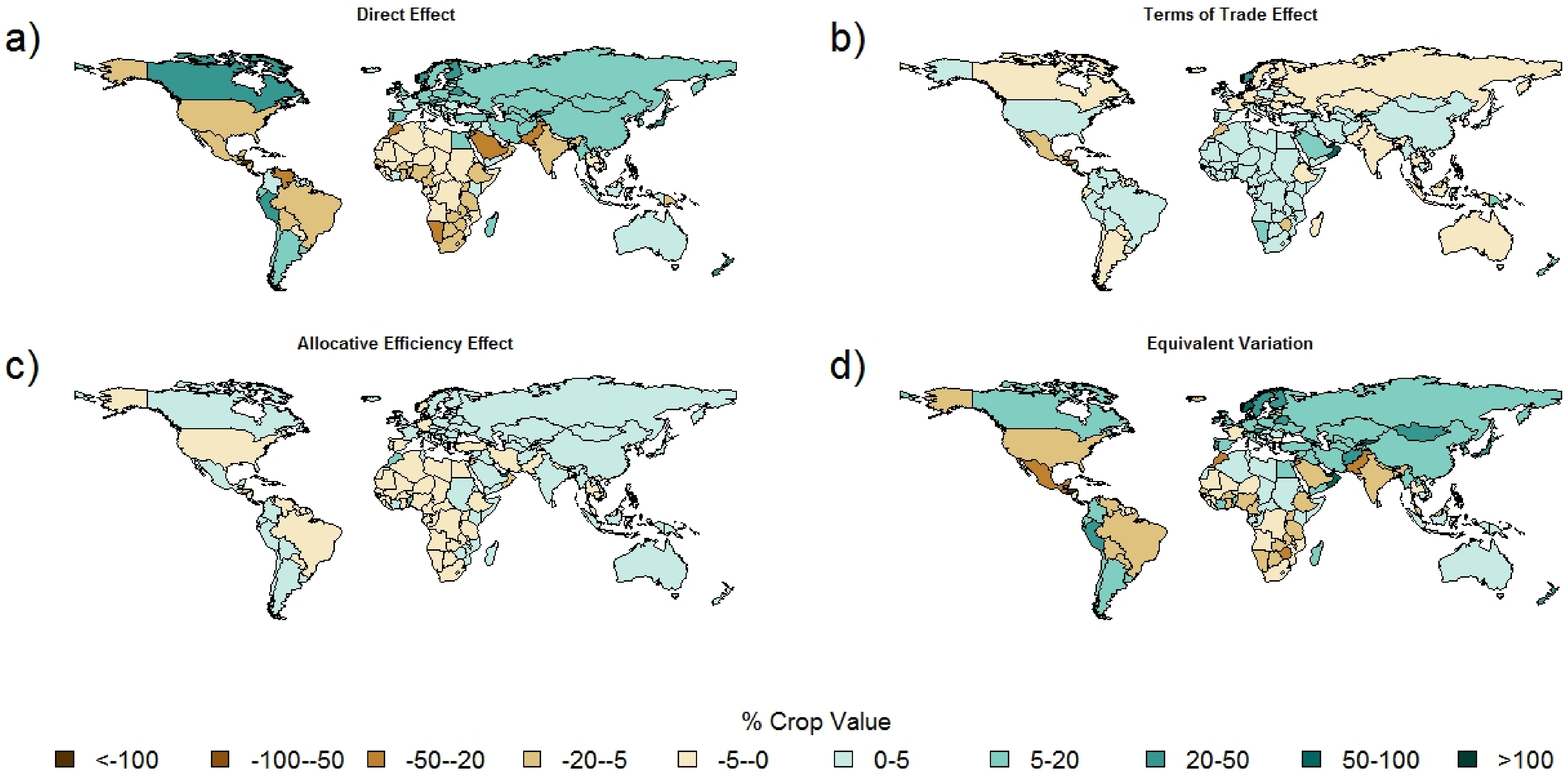
   2. Terms of trade effect

   3. Allocative efficiency

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



Welfare Change, 3° Warming (Meta-Analysis)



Welfare Change, 3° Warming (AgMIP)

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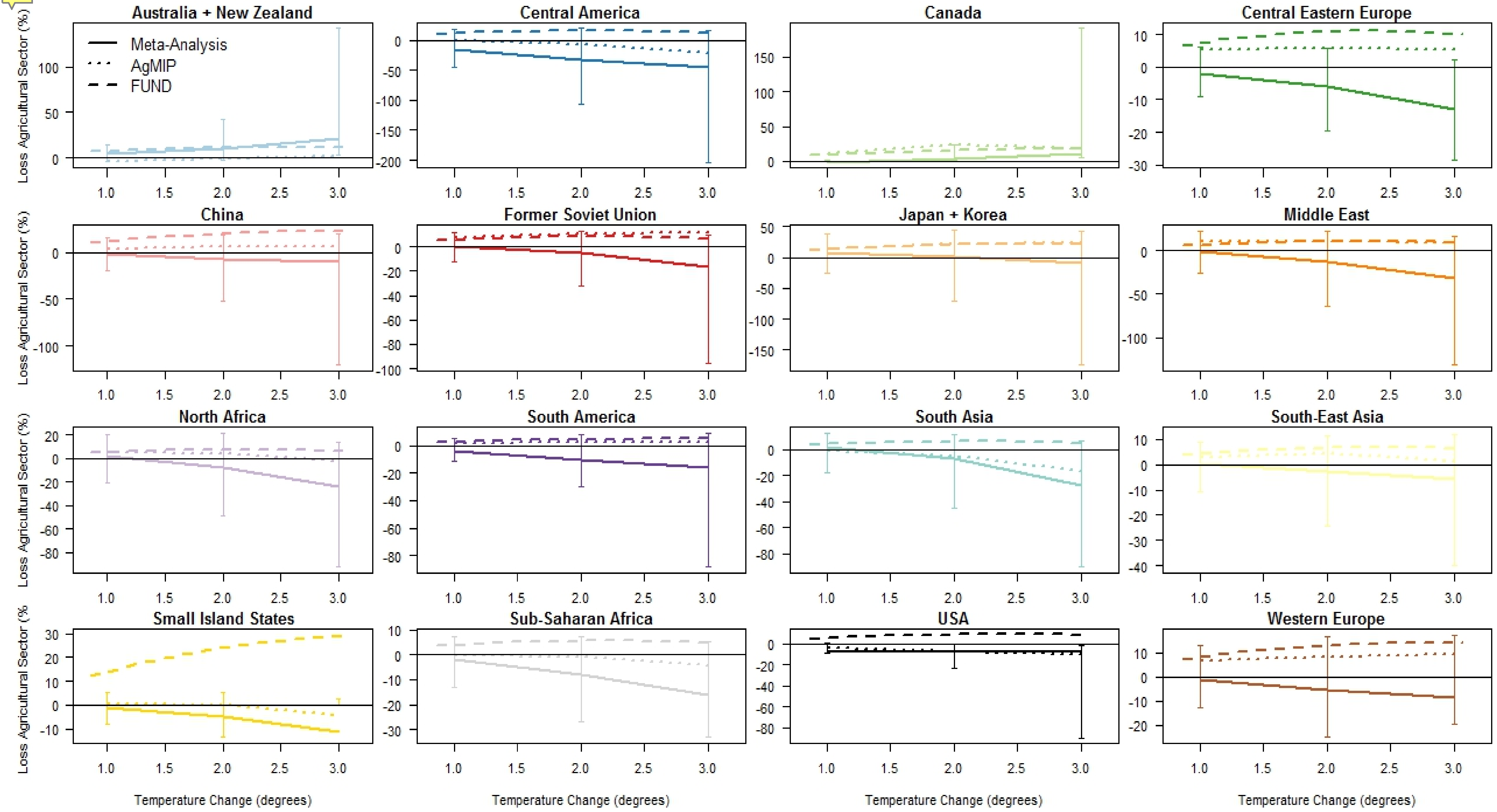
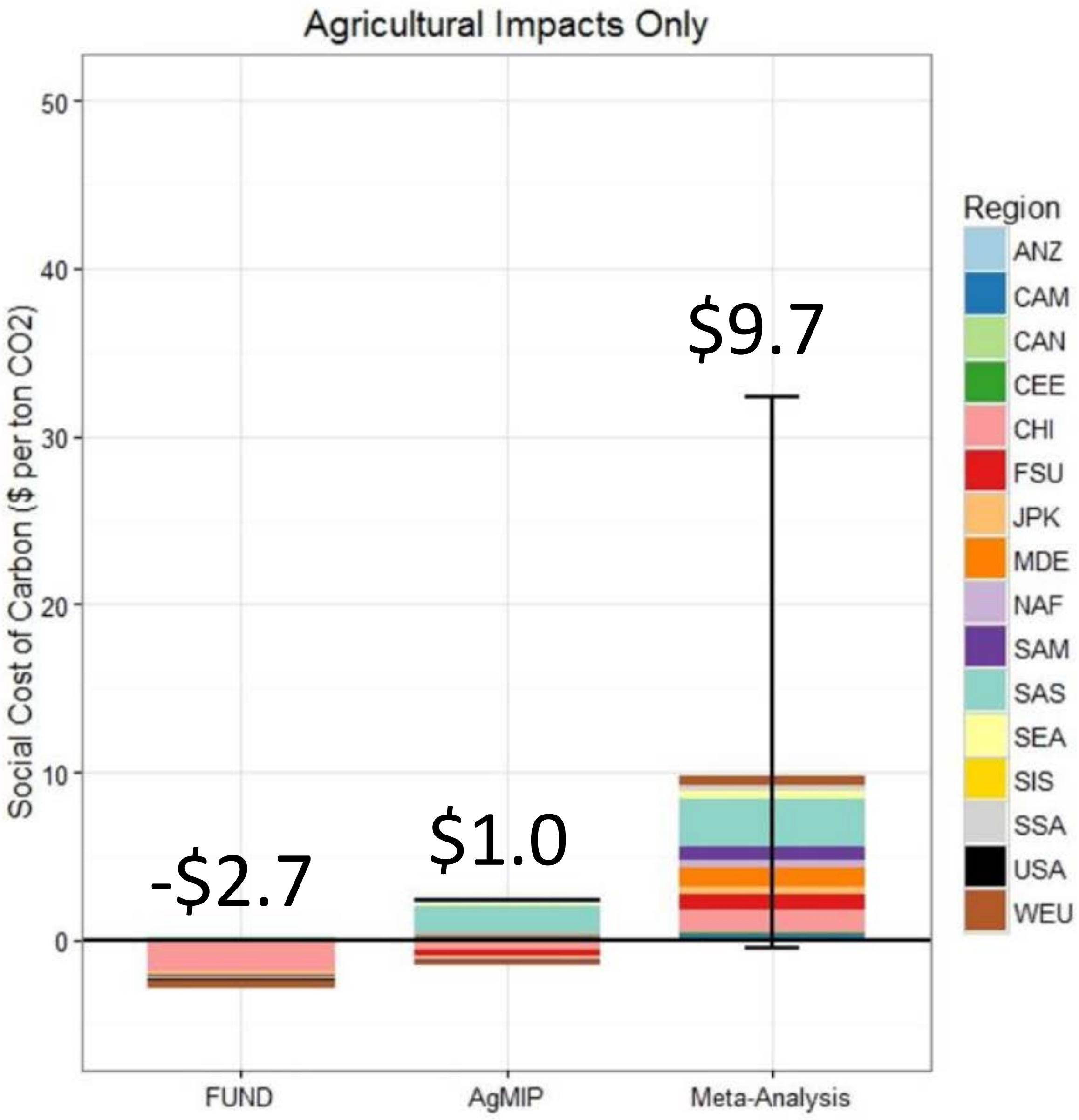
Implications for the SCC

- Given regional changes in welfare, we can create new damage functions for the agricultural sector to improve SCC estimates

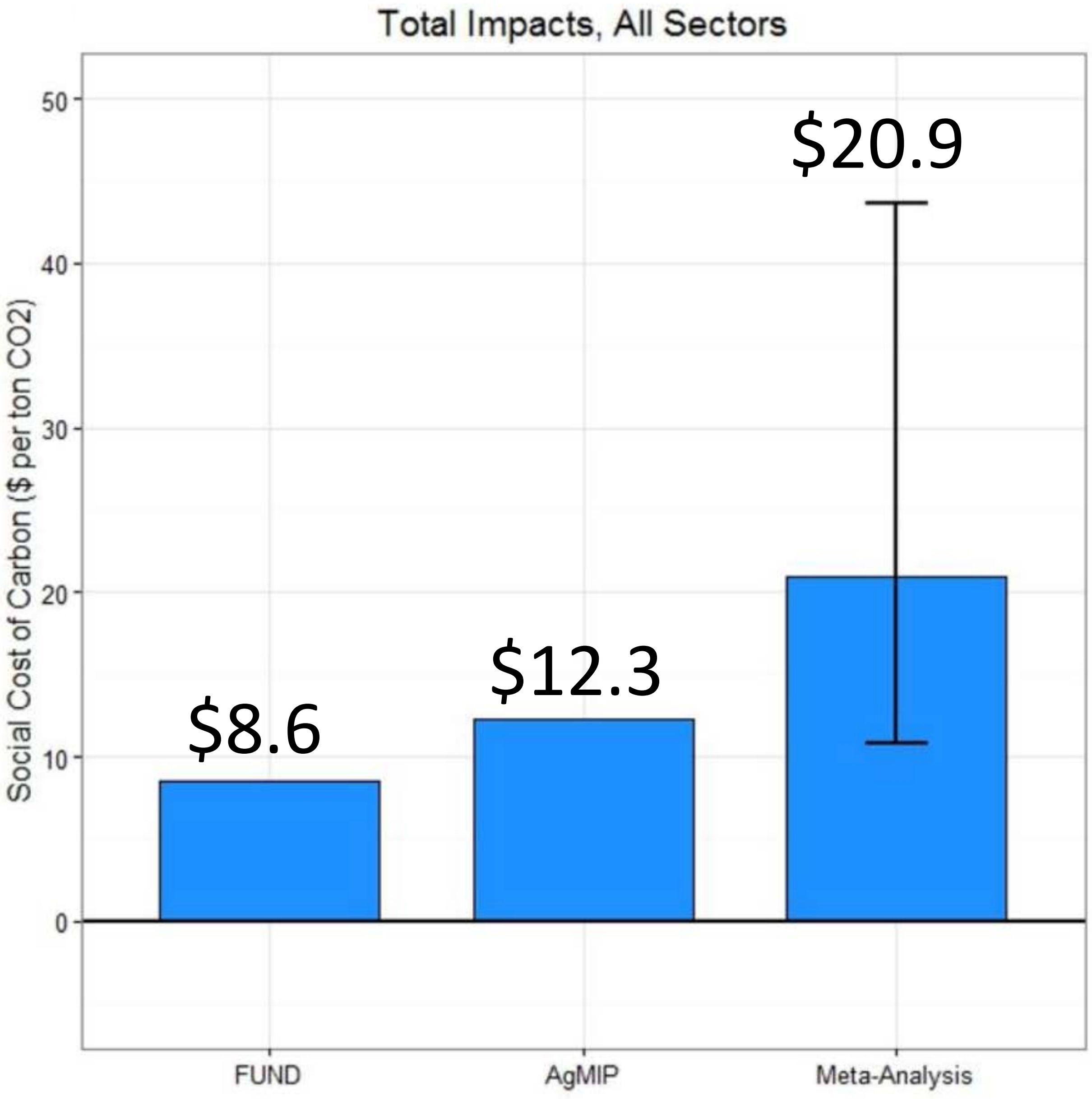

Australia + New Zealand
Central America
Canada
Central Eastern Europe
China
Former Soviet Union
Japan + Korea
Middle East
North Africa
South America
South Asia
South-East Asia
Small Island States
Sub-Saharan Africa
USA
Western Europe
Meta-Analysis
AgMIP
FUND
Loss Agricultural Sector (%)
Temperature Change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

Implications for the SCC

- Given regional changes in welfare, we can create new damage functions for the agricultural sector to improve SCC estimates
- Use a damage module that replicates FUND damages connected to a standardized climate model and BAU emissions scenario
- Calculate total SCC and decompose by region and sector



- Existing FUND damages show global net benefits from climate change impacts on agriculture
- Both updated damage functions show net costs



- This has a large effect on the total SCC
- Increases between 43% (AgMIP) and 143% (Meta-Analysis)
- Error bars include the AgMIP estimate but not the FUND result
- FUND consistently produces the lowest SCC – this change would bring it closer in line to other two models

Conclusion

1. New comprehensive meta-analysis of the scientific literature shows negative effects of warming for most regions and crops
2. Very small potential for agronomic adaptations to offset yield declines
3. Welfare consequences are negative in almost all regions. Smaller in net exporters and largest in importers
4. Direct effects and terms-of-trade effects both important components of welfare changes
5. Results differ from the AgMIP GGCMI ensemble, which shows larger potential for yield gains in temperate regions
6. Both new damage functions differ substantially from existing FUND damages that show benefits for all regions up to ~4-5 degrees of warming
7. Updating just the agriculture damage function increases the total SCC by between 43% and 143%
8. Demonstration of how scientific information can be incorporated into IAM damage functions in a timely and transparent manner