The Financial Toll of Climate-Induced Crop Losses

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STEP 1

Fit statistical model

Panel regression model with T_{max} and SPEI as independent predictors

$$Y_{ct} = \beta_T f_T(T_{ctg}) + \beta_S f_S(S_{ctg}) + \lambda_c + \alpha_c t + \epsilon_{ct}$$

STEP 2

Calculate yield impact

Grid-level yield impact calculated as the difference between the estimated and baseline yield

STEP 3

Get production & economic impact

Convert yield impact to production and economic impact using FAO producer price data

STEP 4

Get warming due to emitters

Get local growing season temperature increase due to Emitters' CO_2 using rTCRE framework

$$dT_{ie} = E_e \Phi_i rTCRE$$

STEP 5

Attribute impacts to emitters

Apply fitted coefficient to estimate yield impact due to emitter-attributable warming; convert to economic impact

$$dy_{ite} = \beta_T f_T(T_{ig,base} + dT_{iet}) - \beta_T f_T(T_{ig,base})$$

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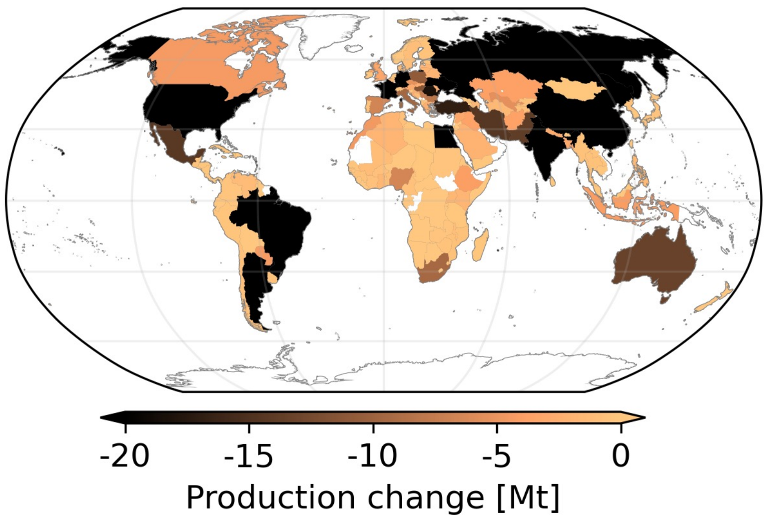
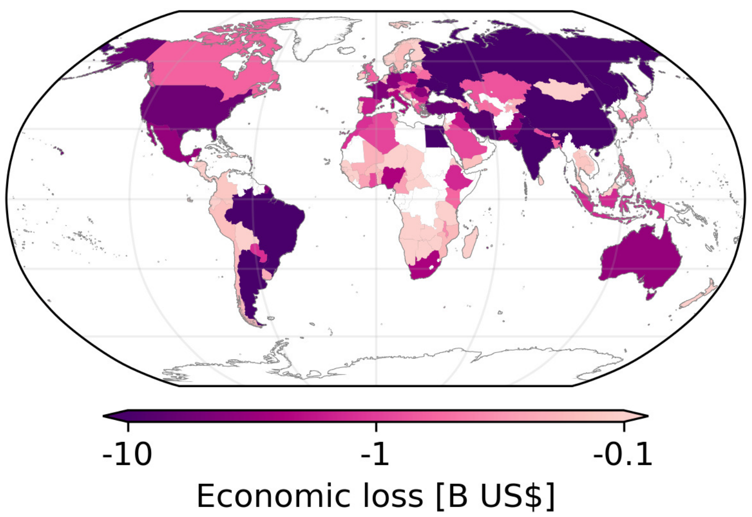
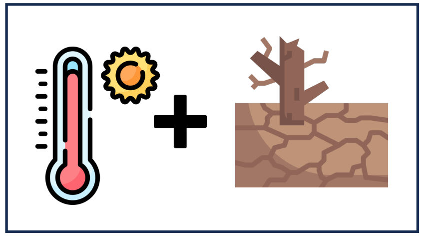
Production impact [Mt]

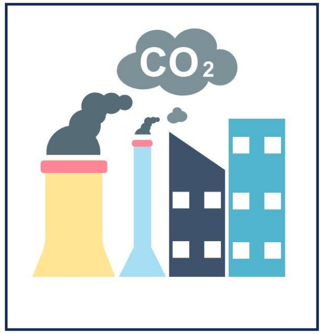


Economic impact [US$]





- 855 Mt of global crop losses
- $251 billion in aggregated economic loss



Carbon Majors

- 427 Mt global crop losses
- $119 billion in heat-induced crop losses

Top 10% richest people

- 277 Mt global crop losses
- $78 billion in heat-induced crop losses

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7 May 2026

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Background

- Detrimental impacts of heat and drought on global agriculture are well documented, but their economic consequences are underexplored.

Research Objectives

- Provide an estimate of future climate driven financial impacts from global agricultural losses using a statistical model based on heat and water stress.
- Attribute heat-induced losses to top emitting individuals and Carbon Majors.

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Data

Source	Variable	Resolution
ISIMIP3a, 3b	T_{max}, SPEI-3	0.5° × 0.5° grid-point cubic expansion, averaged over growing season, aggregated to national scales using national harvested-area weights
FAO	Crop yield, production, harvested-area for maize, wheat, and soybeans	National
	Producer prices [US$/tonne]	National
	Irrigation fraction	5 arc-minute, coarsened to 0.5° × 0.5°
World Bank	GDP (historical)	National
Koch & Leimbach (2023)	GDP (SSP projection)	National

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Time periods

- Model fitting and study period: 2007-2019
- SPEI-3 calibration reference period: 1974-2004
- Historical and SSP impact baseline period: 1974-2004

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Statistical Model

- Statistical model (panel regression) with climate variables (T_{max} and SPEI-3) as independent predictors, controlling for country-specific fixed effect and long-term time trend (Proctor et al., 2022)

$$Y_{ct} = \beta_T f_T T_{ctg} + \beta_S f_S S_{ctg} + \lambda_c + \alpha_c t + \epsilon_{ct} \tag{1}$$

Y_{ct}	Crop yield for country *c* and year *t*
T_{ctg}, S_{ctg}	mean growing season T_{max} and SPEI-3 for country *c* and year *t*
β_T, β_S	Regression coefficients
$f_T(\cdot), f_S(\cdot)$	Cubic expansions of grid-point values, spatially averaged to country-level using HA weighting
λ_c	Fixed effect for time-invariant differences between countries (e.g., soil type)
$\alpha_c t$	Within-country linear time trend (e.g., technological adoption)

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Complementary Statistical Models

- Panel regression model including irrigation terms (I_c)

$$Y_{ct} = \beta_T f_T T_{ctg} + \beta_S f_S S_{ctg} + \beta_{TI} f_T\left(T_{ctg} I_c\right) + \beta_{SI} f_S\left(S_{ctg} I_c\right) + \lambda_c + \alpha_c t + \epsilon_{ct} \quad (2)$$

- Panel regression model including interaction terms between T_{max} & SPEI-3

$$Y_{ct} = \beta_T f_T\left(T_{ctg}\right) + \beta_S f_S\left(S_{ctg}\right) + \beta_{TS} f_{TS}\left(T_{ctg} \cdot S_{ctg}\right) + \lambda_c + \alpha_c t + \epsilon_{ct} \quad (3)$$

$f_T(\cdot), f_S(\cdot)$	Quadratic expansions of grid-point values
$f_{TS}(\cdot)$	Quadratic polynomial TS, T^2S, TS^2, T^2S^2

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Model Evaluation

- Model evaluation: out-of-sample (OOS) cross-validation within-R^2
  - within-R^2: share of yield variation explained solely by climate variables after removing fixed effects and time trends

- Two methods to estimate within-R^2:
  - Random 10-fold CV
  - Blocked leave-one-year-out (LOYO) CV

Crop	Model	Overall adjusted R^2	Random CV R^2	Blocked CV R^2
Maize	t3s3	0.96	0.030	0.019
	t3s3_irr	0.96	0.021	0.018
	t2s2_int	0.96	0.018	0.003
Wheat	t3s3	0.93	0.064	0.059
	t3s3_irr	0.93	0.063	0.062
	t2s2_int	0.93	0.068	0.062
Soybeans	t3s3	0.89	0.077	0.053
	t3s3_irr	0.89	0.077	0.033
	t2s2_int	0.89	0.072	0.052
All	t3s3	0.70	0.057	0.047
	t3s3_irr	0.70	0.058	0.048
	t2s2_int	0.70	0.052	0.042

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Impact Calculations (1)

- Yearly grid-level yield impact (dy_{it}) [%]: change in yield relative to baseline yield, using the β coefficients from the fitted model

$$dy_{it} = \left[\beta_T f_T T_{itg} + \beta_S f_S S_{itg}\right] - \left[\beta_T f_T T_{ig,base} + \beta_S f_S S_{ig,base}\right] \qquad (4)$$

- Aggregated to country level using harvested-area (HA) weighting:

$$dy_{ct} = \sum_{i \in c} dy_{it} \frac{HA_i}{\sum_{i \in c} HA_i} \qquad (5)$$

- National production impact (dp_{ct}) [ton]:

$$dp_{ct} = dy_{ct} y_{ct} HA_{ct} \qquad (6)$$

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Impact Calculations (2)

- Production losses (*dp*) are converted to economic impacts (*de*) [US$] using crop-specific producer prices *PP* [US$/ton] from FAO:

$$de_{ct} = dp_{ct}PP_{ct} \tag{7}$$

- Economic losses relative to national economies (*degdp*)[%]:

$$degdp_{ct} = \frac{de_{ct}}{GDP_{ct}} \tag{8}$$

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Impact Attribution to Emitters

- Use nonlinear β_T coefficients of temperature from the fitted model to estimate yield impacts of warming induced by emissions from groups of emitters:

$$dT_{ie} = E_e \cdot \Phi_i \cdot rTCRE \qquad (9)$$

$$\Phi_i = \frac{dT_{ig}}{dT_i} \qquad (10)$$

- Grid-point yield impact due to emitter-attributable warming (dT_{ie}):

$$dy_{ite} = \beta_T f_T(T_{ig,base} + dT_{iet}) - \beta_T f_T(T_{ig,base}) \qquad (11)$$

- Corresponding country-level, emitter-attributable yield, production and economic impact calculated using equations 5-8

For country c, what are the yield, production and economic losses of a given crop, attributable to the warming caused by emissions from emitter E_e?

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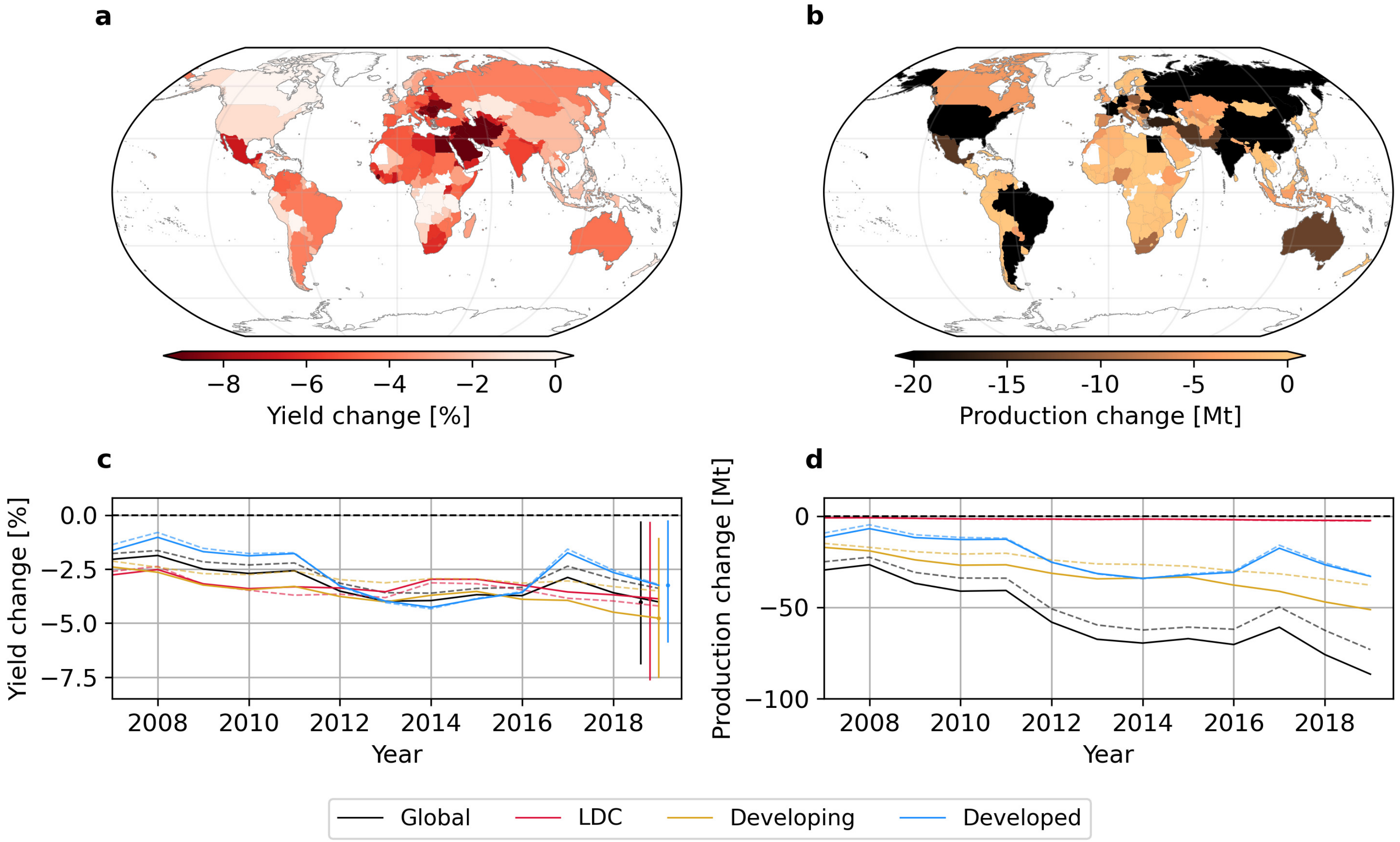
Results

Historical Crop Yield and Production Impact



- Global losses from extreme heat and drought:
  - 3.48% of baseline
  - 855 Mt

- LDCs comparable yield losses ([%]) with developed nations, despite smaller production losses

Solid lines = main model; dashed lines = model with irrigation terms

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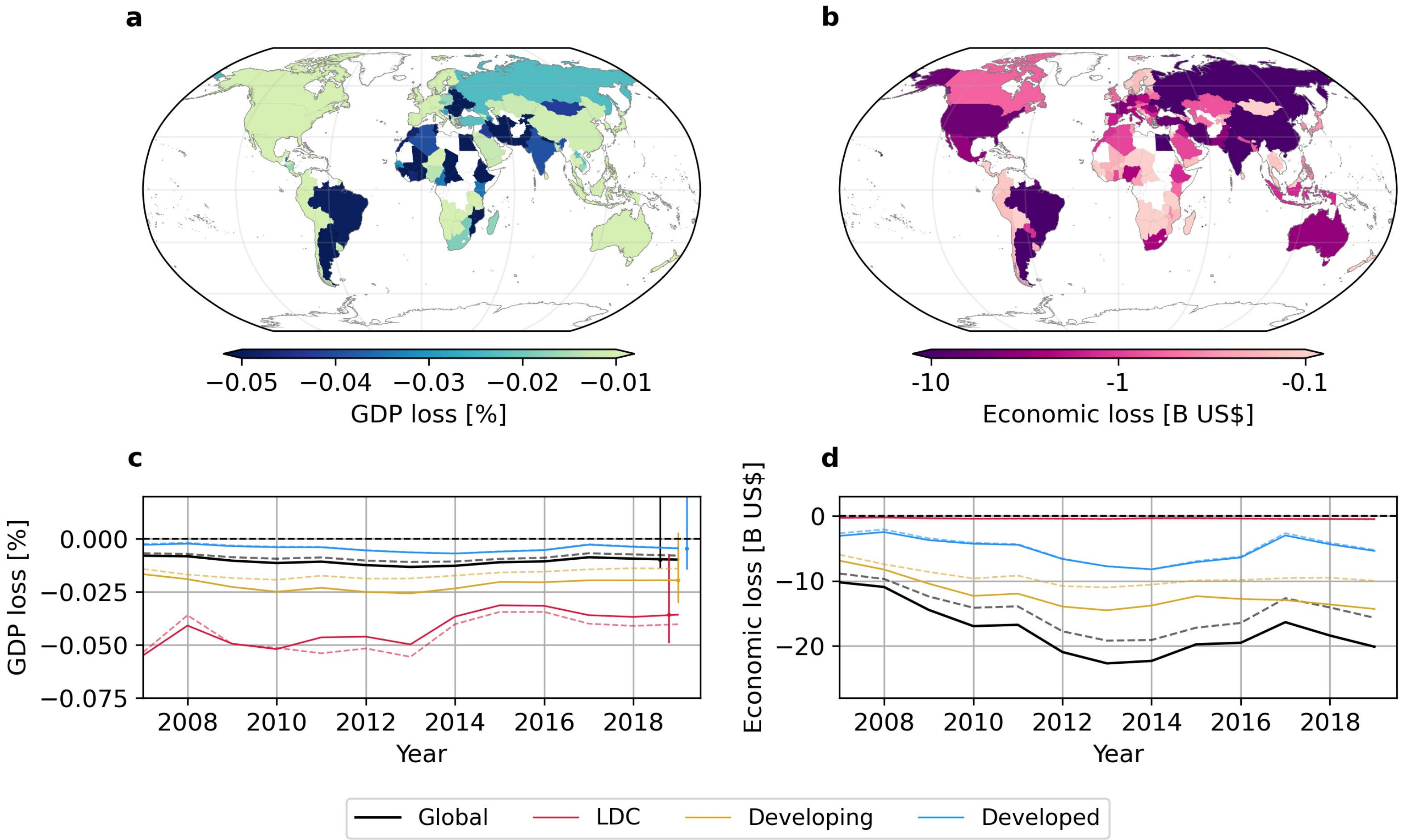
Historical Economic Impact



- Global economic losses
    - 0.04% of GDP
    - $251 billion

- Much more severe relative consequences for LDCs

	USA	Malawi
de	$6 billion	$0.2 billion
degdp	0.001 %	0.34 %
pop in agri.	2 %	65 %

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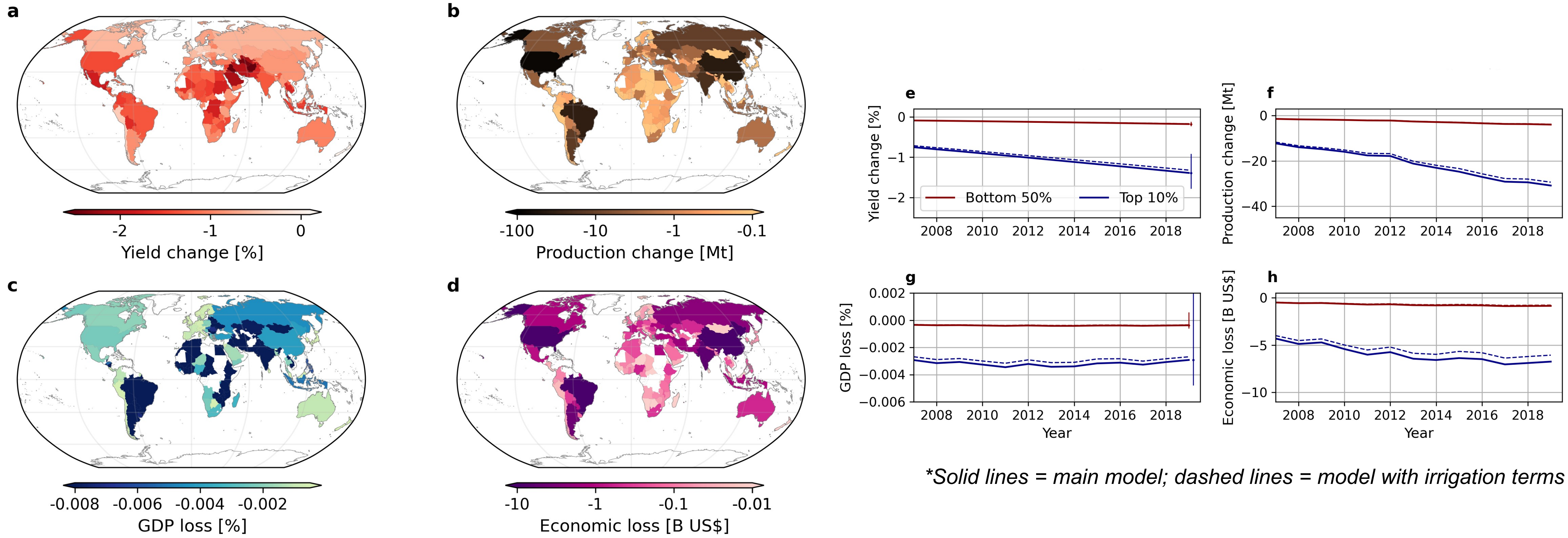
Losses Attributable to Richest Individuals



**Solid lines = main model; dashed lines = model with irrigation terms*

- CO_2 emissions from the richest 10% (232.6 $GtCO_2$) accounted for over eight times more of the global production and economic losses (54.2% vs. 6.6% of total) than those from the poorest 50% (32.6 $GtCO_2$).

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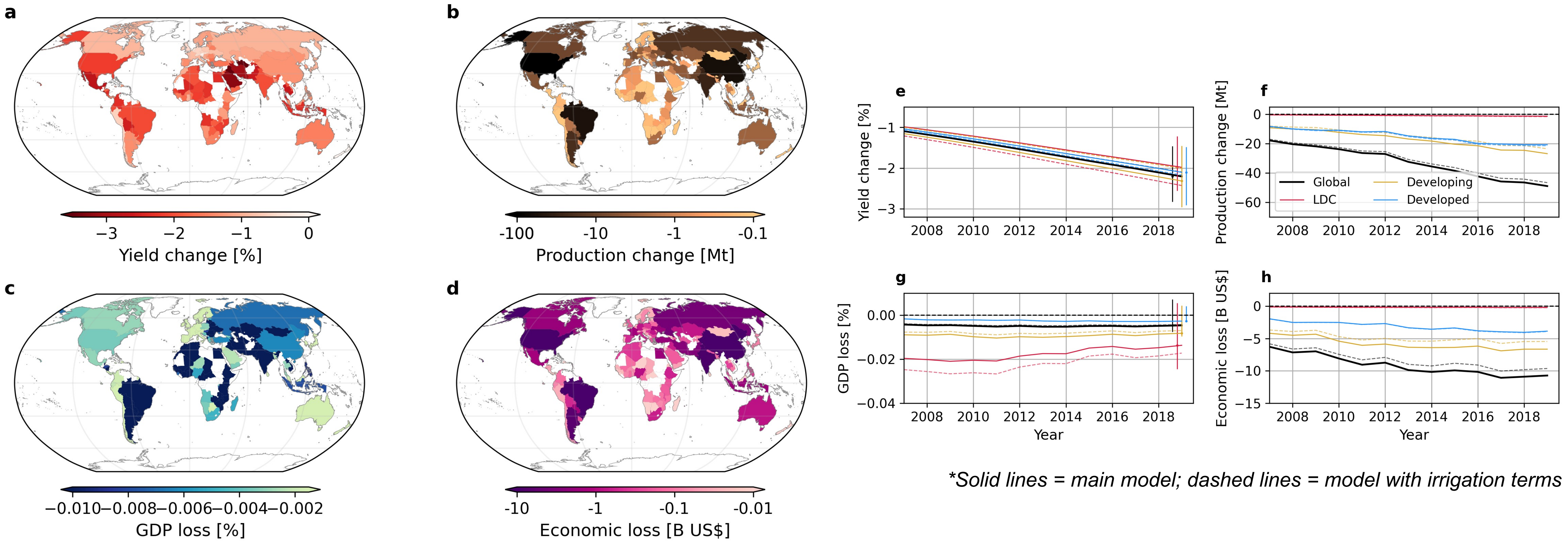
Losses Attributable to Carbon Majors



**Solid lines = main model; dashed lines = model with irrigation terms*

- CO_2 emissions from the Carbon Majors (322.9 $GtCO_2$) linked to 427 Mt ($119 billion) in crop losses

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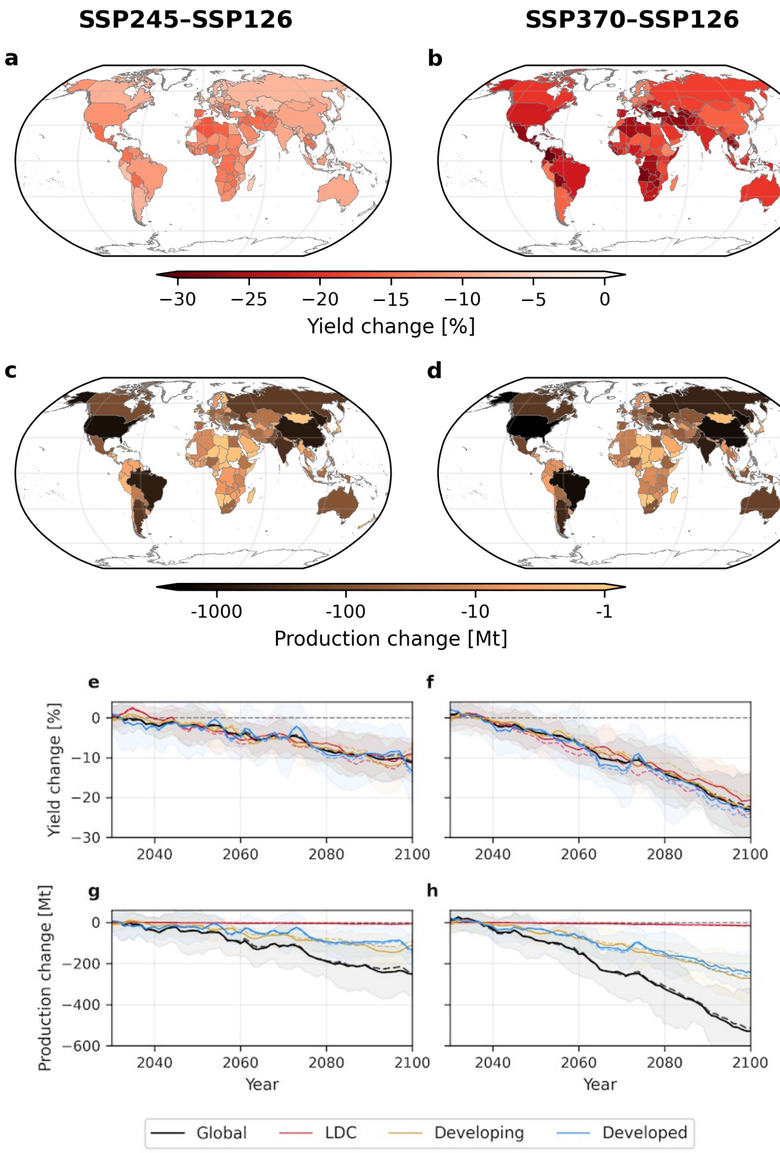
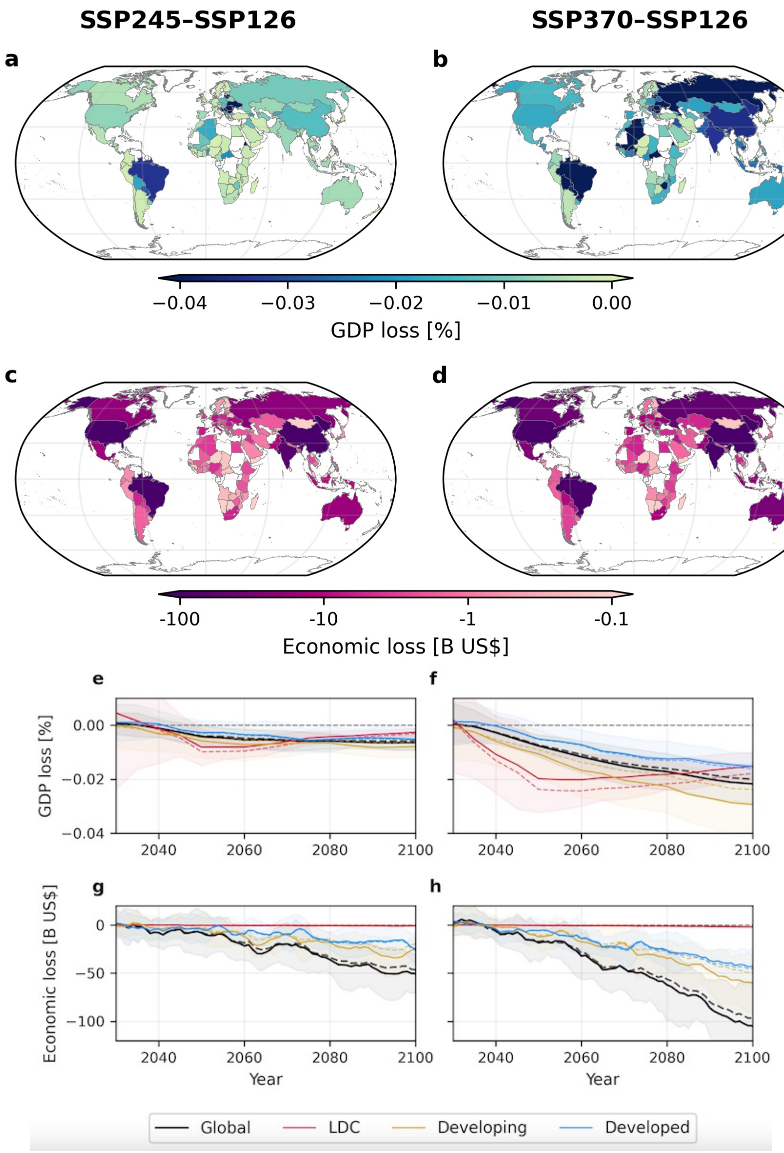
Projected Crop Losses from Heat and Drought





- Global economic losses could increase from $20 billion (2019) to $161 billion (2100) under SSP3-7.0
- Following SSP1-2.6 could avoid $105 billion of these damages

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Summary

- We develop a statistical model to assess the impact of extreme heat and drought on crop yield, and estimate the resulting economic losses

- As a percent of GDP, less-developed countries experience the highest economic losses, despite their absolute losses in US dollars being much smaller than those of developed countries.

- The richest 10% caused over 8x the economic damage of the poorest 50%, while Carbon Majors' emissions are linked to $119 billion in economic losses

- The world stands to save approximately $105 billion annually by 2100 when following SSP1-2.6 compared to SSP3-7.0

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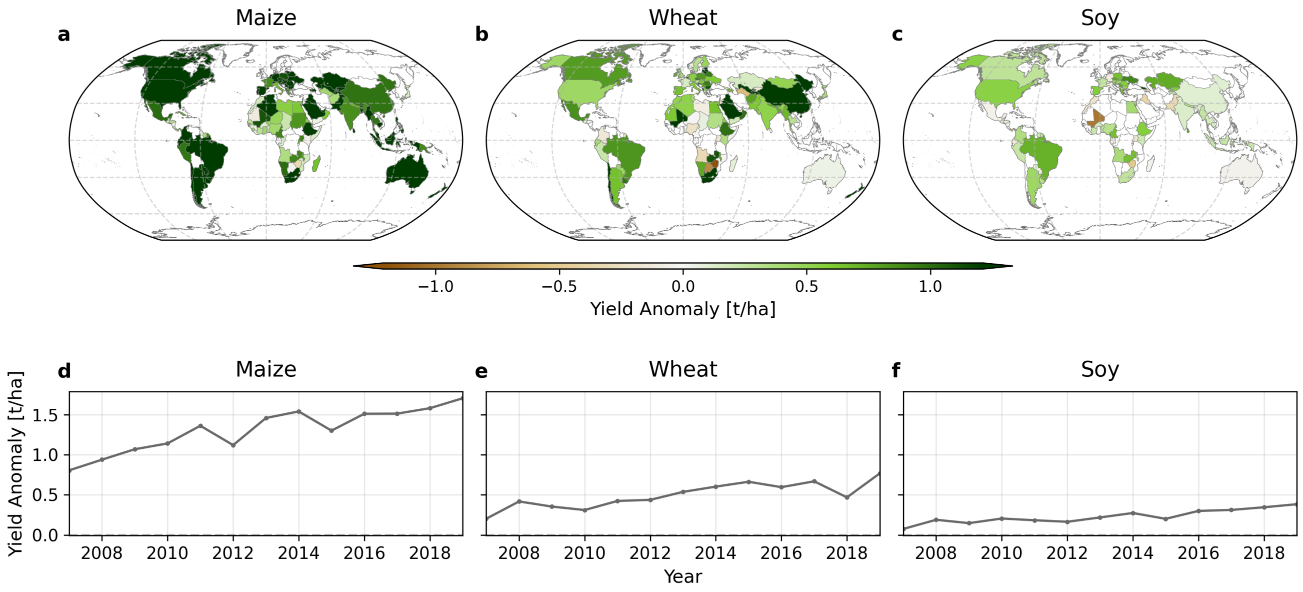
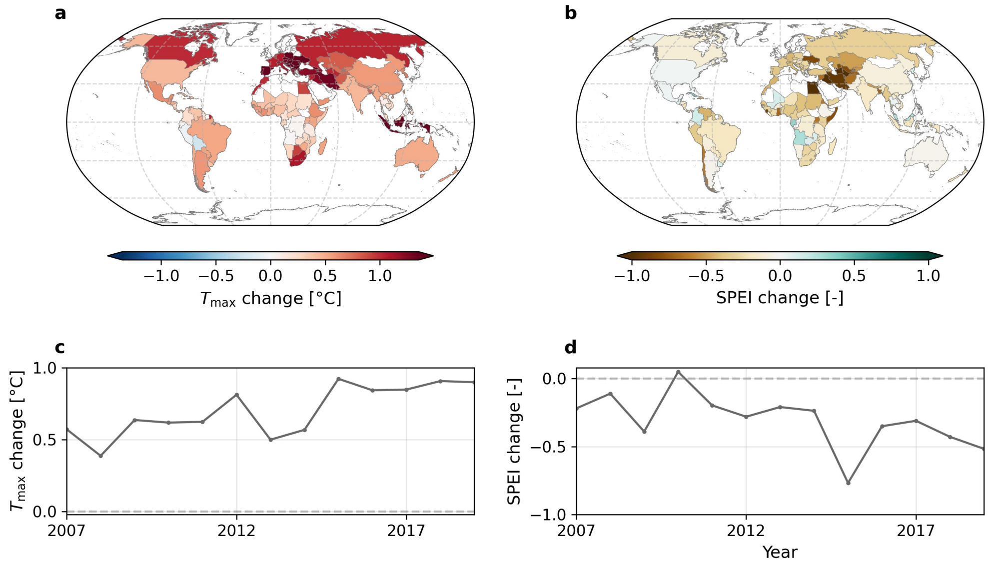
Additional Results

Historical Crop Yield and Climate





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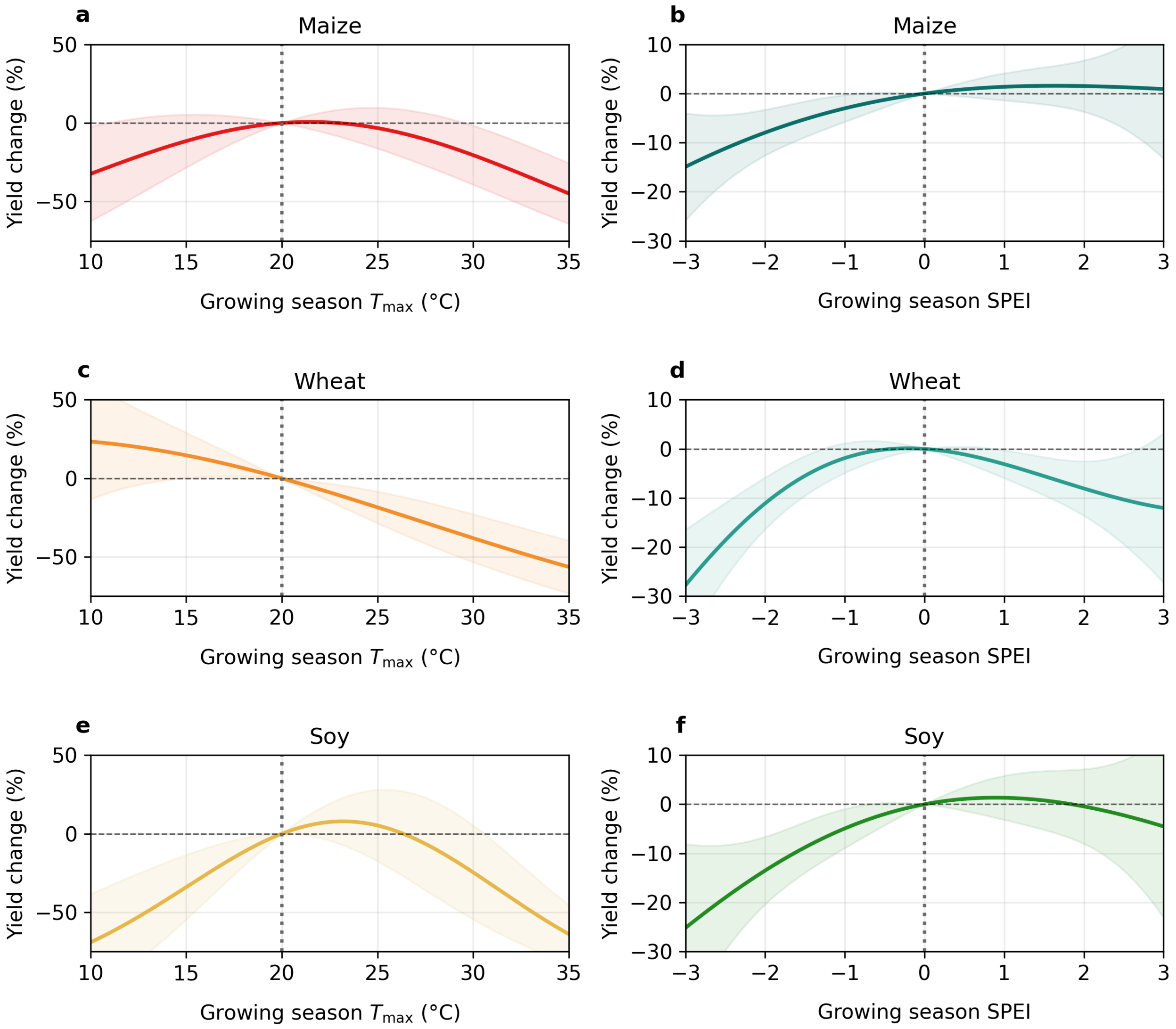
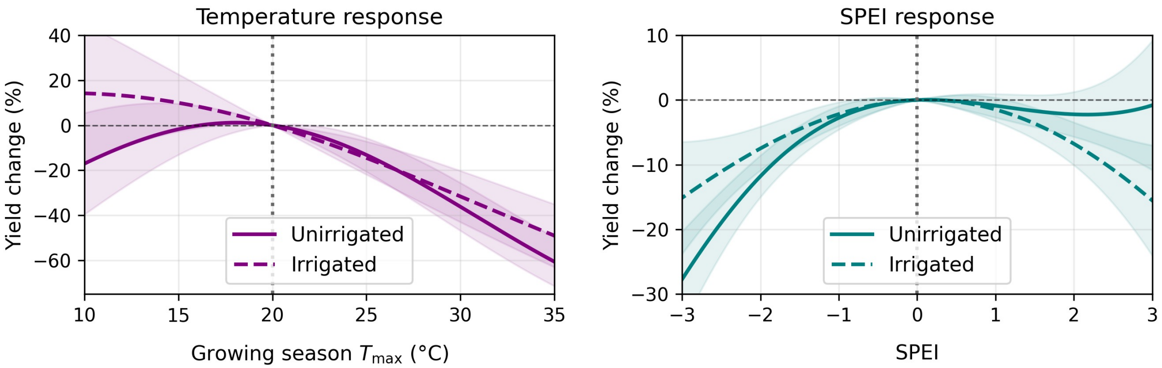
Response Curves of Fitted Model



Irrigated vs. un-irrigated



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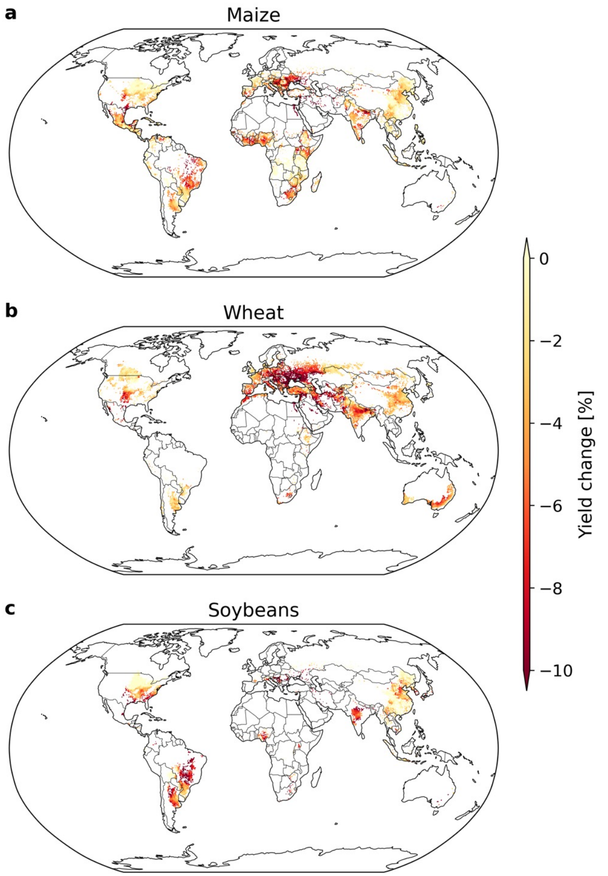
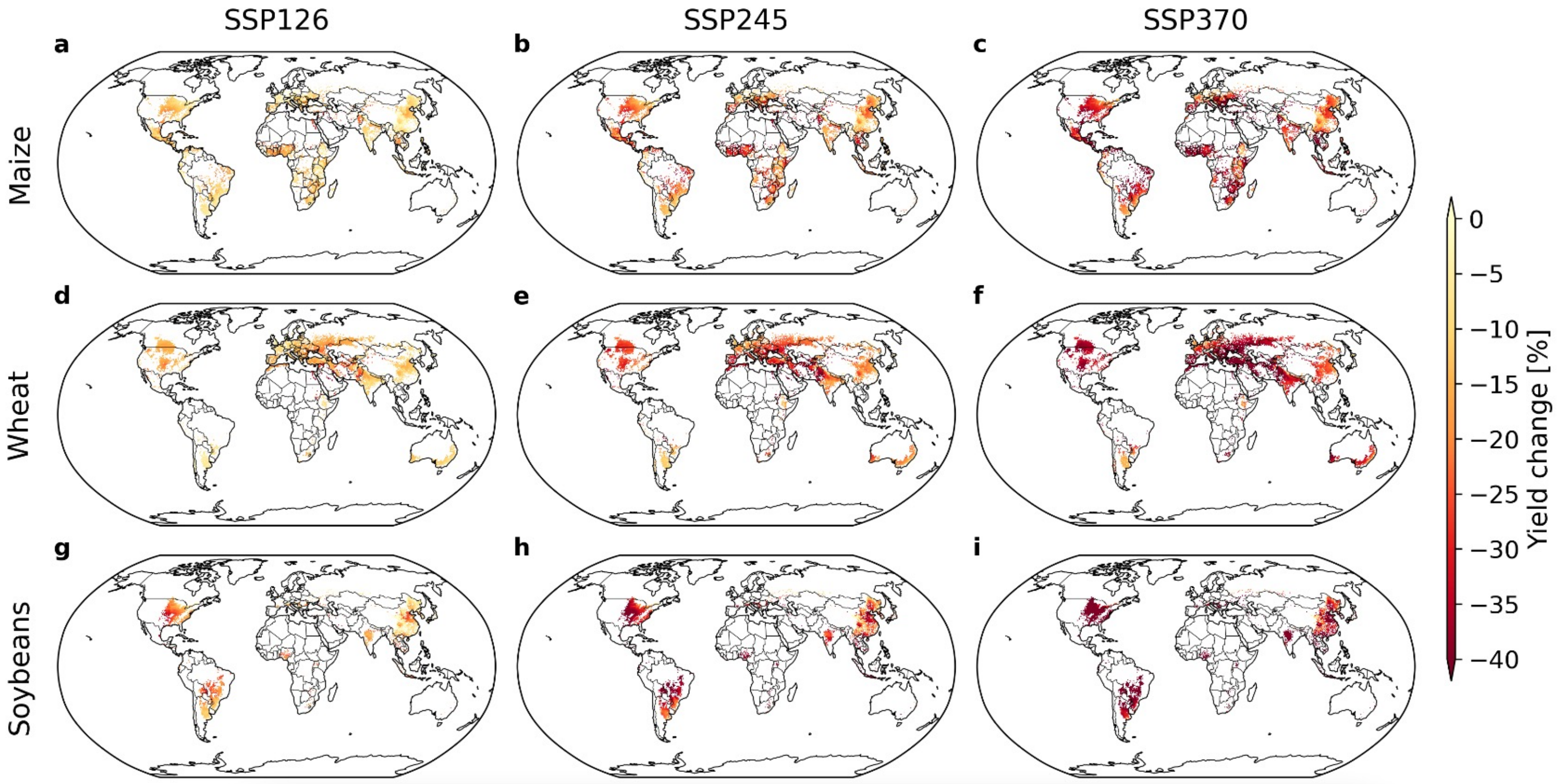
Gridded Yield Loss

Historical



Future SSPs



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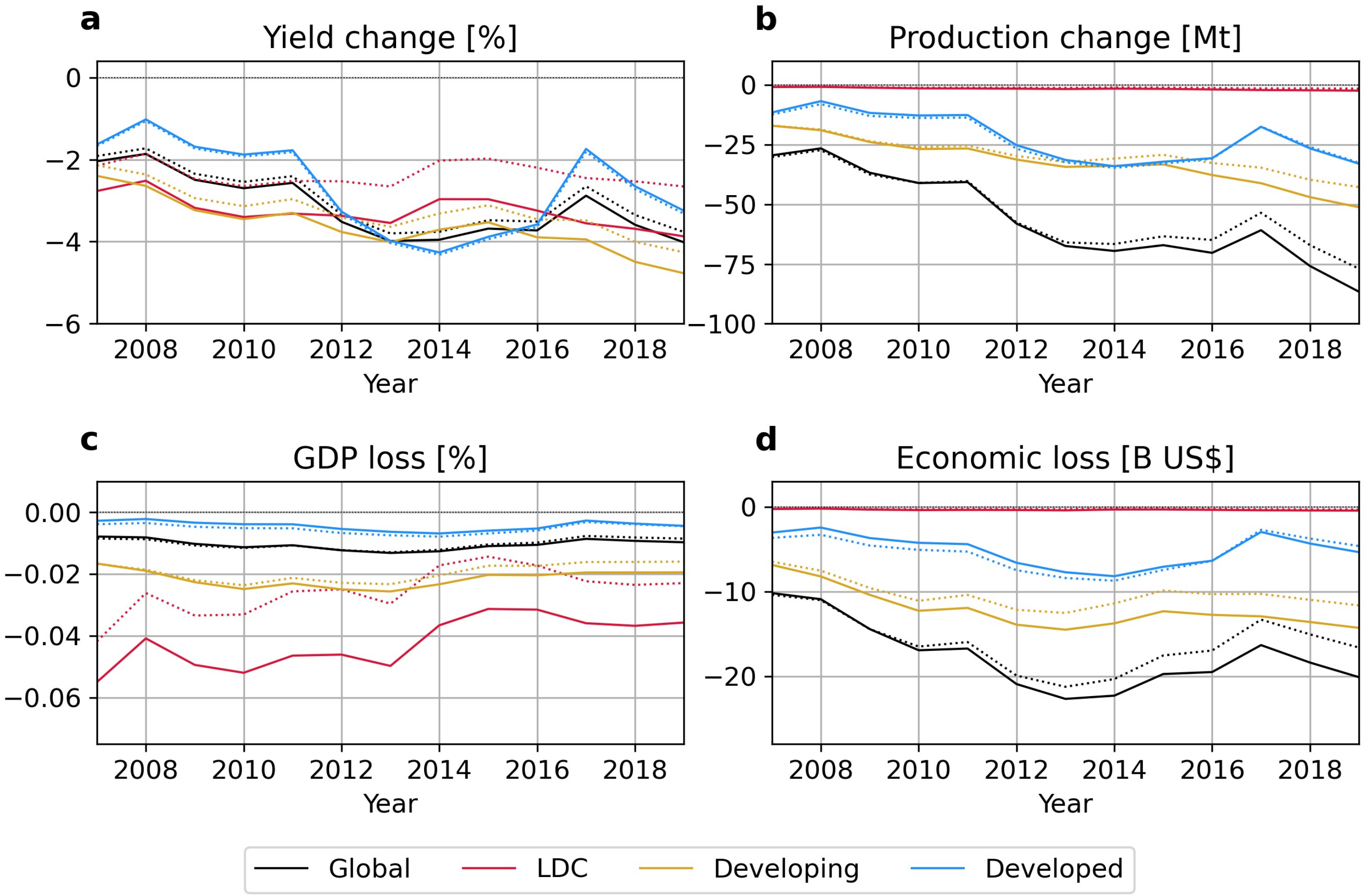
CO_2 Fertilization Effect



- Post-hoc adjustment for CO_2 effect using CO_2 fertilization meta-regression analysis coefficients from Zhu et al. (2023)

**Solid lines = main model; dotted lines = with post-hoc CO2 effect correction*

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