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Multi-step attribution – the bridge to enable climate security

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OVERVIEW

The Climate Impact Determining Etiology Through Pathways (CLDERA) project is enabling multi-step attribution in the climate by developing quantitative relationships between a climate forcing and its downstream impacts aiming to improve climate risk assessments and decision-making.

NEED

Climate impacts (like drought, flooding, or crop yield) are driving national security, legislative and legal foci.

Complex coupling between processes obscure the relationships between sources and downstream impacts.

Traditional attribution connects a source to a primary climate variable in a single step.

Modified from: http://www.thesourgrapevine.com/2019/11/the-ball-of-string-theory-for-learning.html

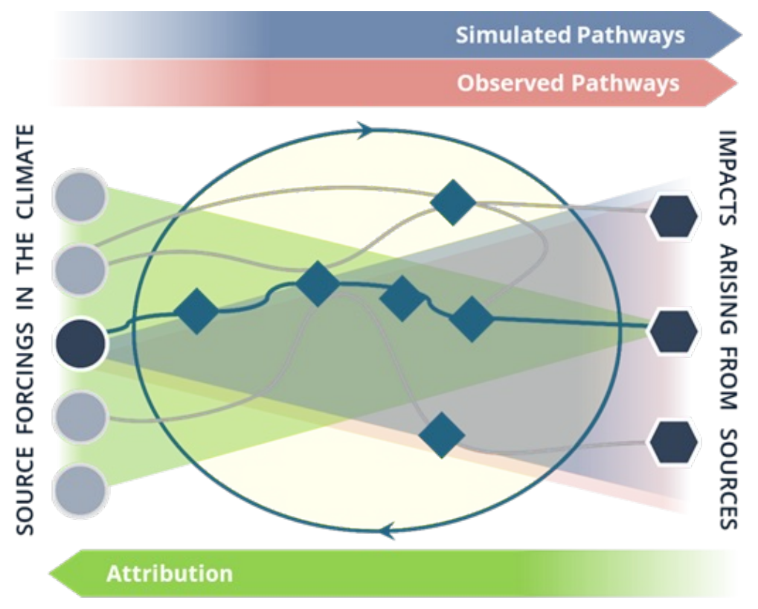
The technical challenge is to draw quantitative relationships in a multi-step attribution framework.

APPROACH

Develop quantitative representations of the pathway, e.g. the spatio-temporally evolving chain of physical processes, between a source and its downstream impacts.

Pathways combine multiple variables to strengthen the connection between source and impact and enable new methods to

- address variability
- rank source importance
- constrain attribution approaches

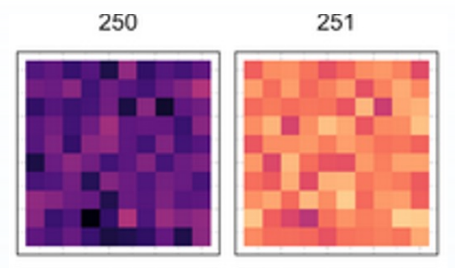


Demonstrate computational approaches on simulations and observations of the 1991 eruption of Mt. Pinatubo in the Philippines

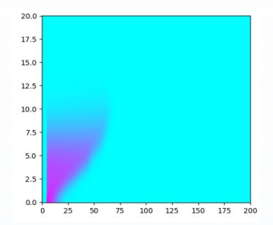
TIERED VERIFICATION

Developed data sets of increasing complexity with key characteristics of the multi-step attribution problem to explore sensitivities, establish viability, and prove usefulness of advanced methods/tools.

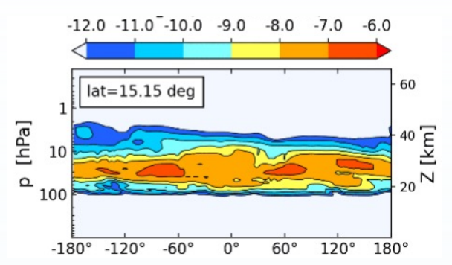
Data & Model complexity



Synthetic Relationships



Gaussian Plume with prescribed winds



Idealized atm. + embedded pathways

Mt. Pinatubo in fully coupled climate model

Moving towards attributing and assessing impacts related to agricultural productivity and relevant for national security.

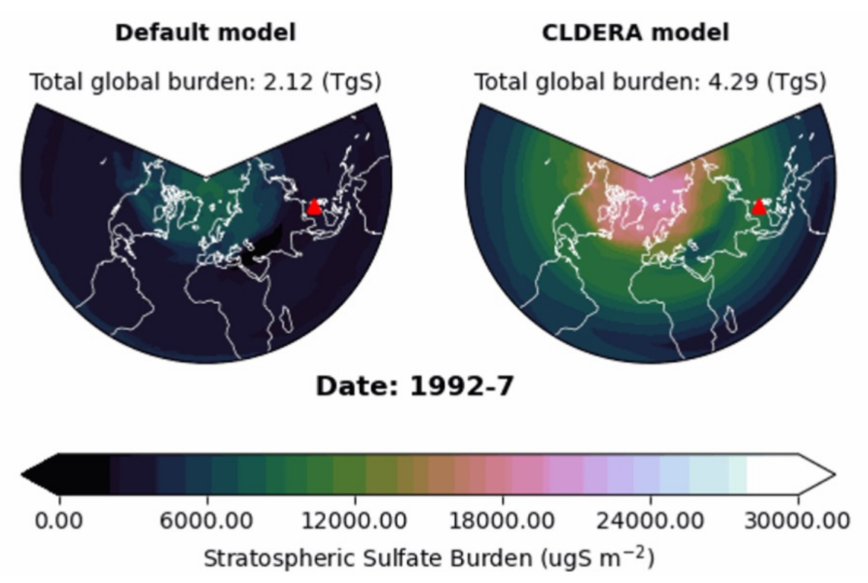
REFERENCES

[1] Golaz, J.-C., et al., The DOE E3SM Coupled Model Version 2: Overview of the Physical Model and Initial Model Evaluation. Journal of Advances in Modeling Earth Systems, 14(12) e2022MS003156 (2022).
[2] Brown, et al., Simulating the Mount Pinatubo eruption with E3SMv2 – a microphysical prognostic stratospheric aerosol approach. In prep.
[3] Kompanizare, et al., Assessment of effective LAI and water use efficiency using Eddy Covariance data, Science of The Total Environment, 802 (2022).
[4] Proctor, et al., Estimating global agricultural effects of geoengineering using volcanic eruptions, Nature, 560, pages 480–483 (2018).
[5] USDA Crop Production Historical Track Records, April 2019, ISSN: 2157-8990.

MODELING MT. PINATUBO

Implemented volcanic prognostic aerosols in the Energy Exascale Earth System Model (E3SMv2-PA) [1,2]

Generated simulation ensembles of Pinatubo, counterfactual, and varying eruption mass.



TECHNICAL THRUSTS

Method development under three technical thrusts designed to detect changes, model pathways, and attribute impacts.

Simulated Pathways

Random Forest Regression (RFR): Generate feature pathway networks using multi-variate RFR.

Tracing: Add active and passive tracers to E3SM to enable model evaluation and pathway identification.

Signature-Based Clustering: Find & track time-evolving variable clusters for use as features in pathway identification.

Profiling: Dynamically trace pathways in E3SM as the software executes (in-situ).

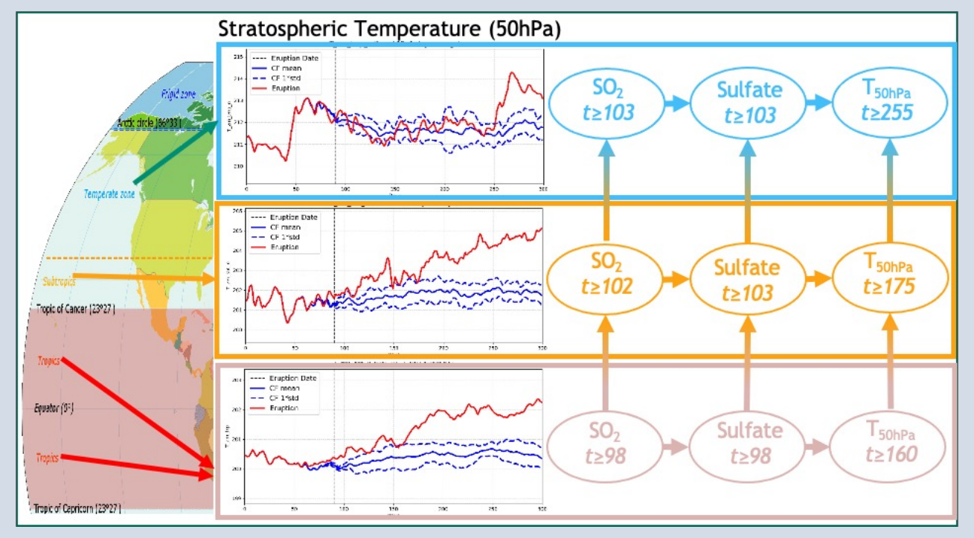


Figure. Tracing the progression of anomalies in SO_2, sulfate, and stratospheric temperature due to an idealized eruption.

Observed Pathways

Data Fusion: Fuse observational datasets to obtain near-real time global measurements.

Dynamic space-time models: Establish correlations between multiple variable nodes.

Changepoint methods: Detect significant climate shifts regionally and globally.

Echo State Networks (ESNs): Develop interpretable methods to quantify relationships between pathway nodes.

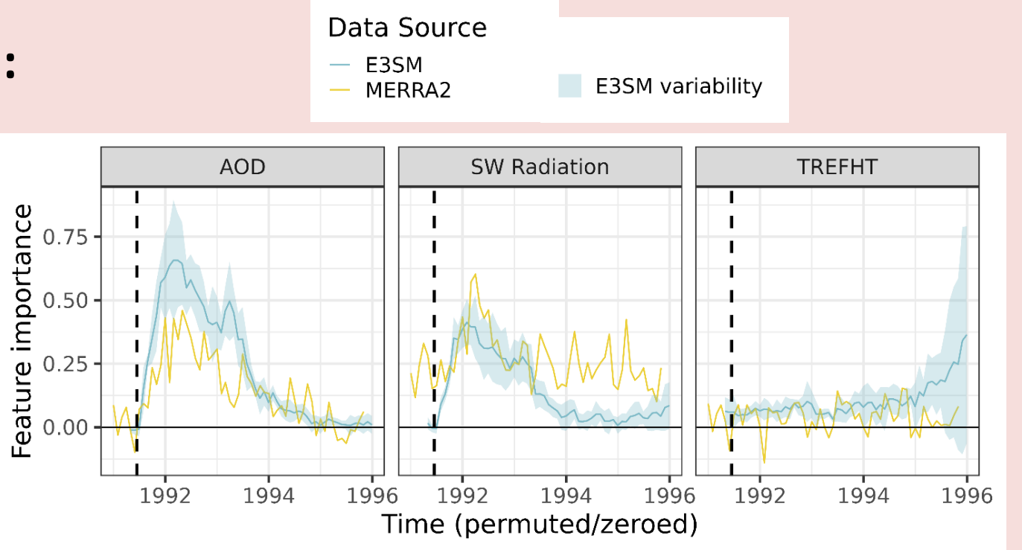


Figure. Feature importance of aerosol optical depth, shortwave radiation and surface temperature for E3SM and MDERRA-2 reanalysis.

Attribution

Inverse Optimization: Identify source characteristics by developing deep operator neural networks (DONNs) for PDE-constrained optimization.

Causal Modeling: Develop causal discovery method to represent causal networks.

Enhanced Fingerprinting: Investigate advanced principal component analyses to enable downstream impact attribution.

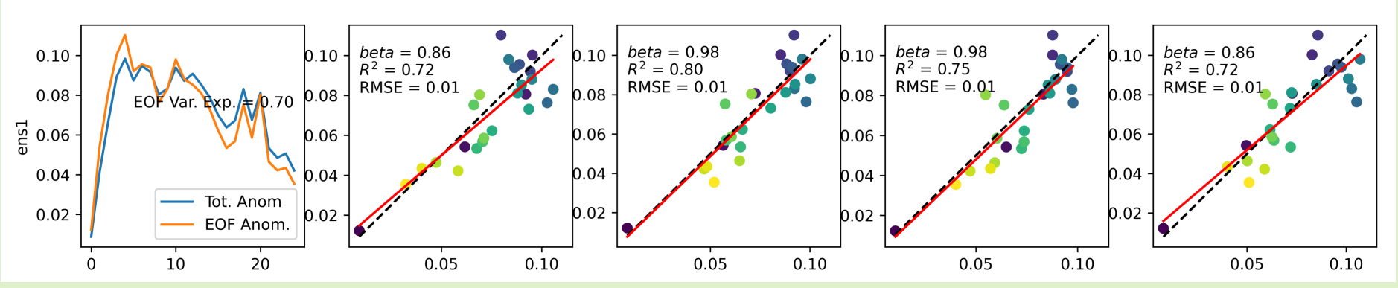
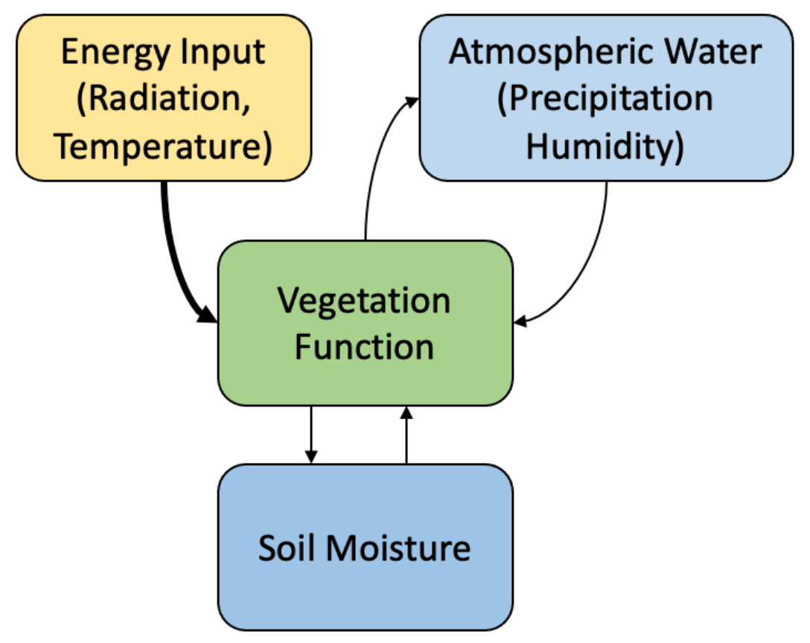


Figure. Perfect model attribution for aerosol optical depth using fingerprinting. Regress four ensemble members against ensemble 1.

AGRICULTURAL PRODUCTIVITY PATHWAY

Approach:

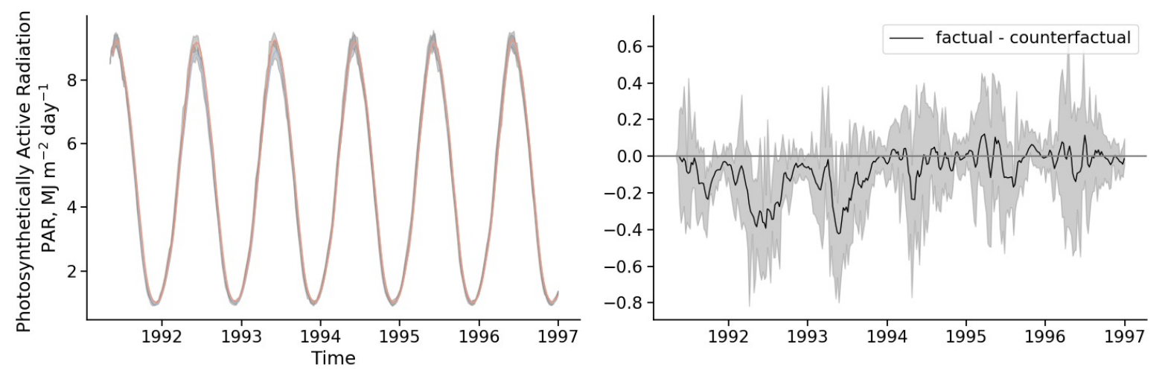
- Identify the drivers of changes in agricultural productivity.
- Use E3SMv2-PA to model a generalized plant response to these changes in the temperate north.
- Model crop-specific impacts due to changes in the light environment by incorporating crop-specific extinction coefficients.



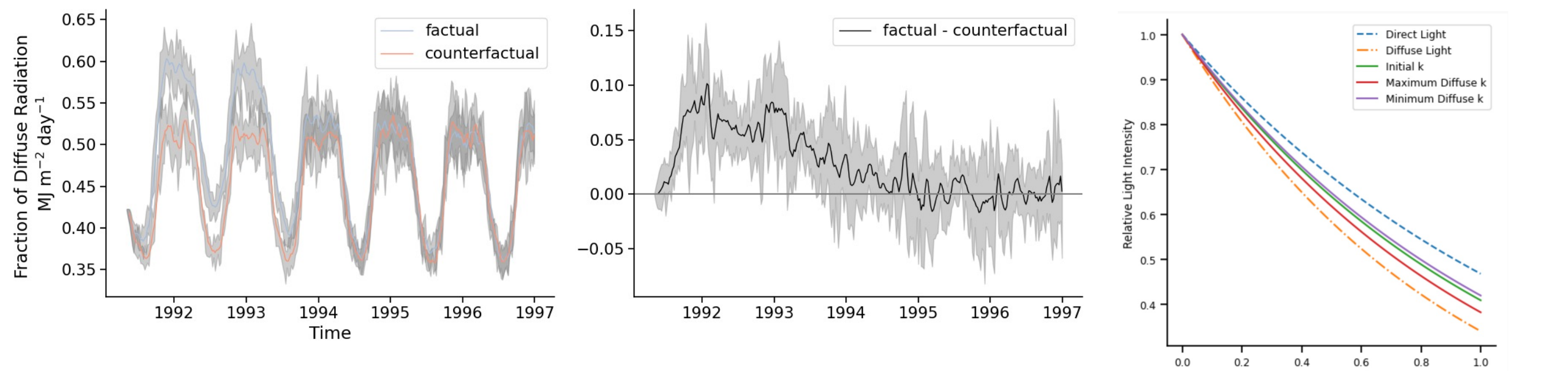
Mt Pinatubo affected two main drivers of plant productivity: water and energy.

RADIATIVE IMPACTS

Changes in light environment due to Mt Pinatubo decreased the photosynthetically active radiation (PAR) reaching plants through aerosol scattering of incident radiation and increased the amount of diffuse light.



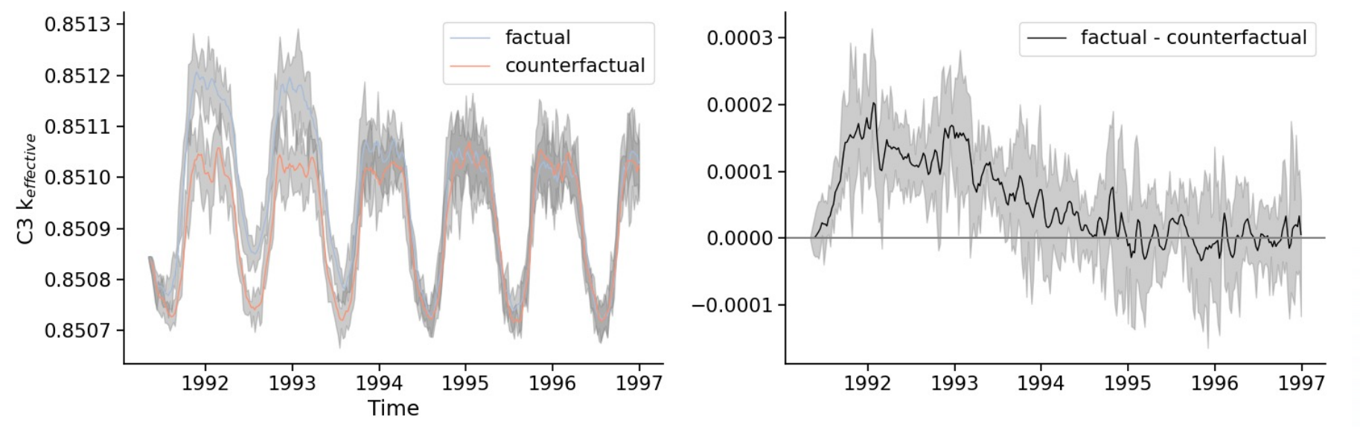
Develop models of Beers law that captures how C3/C4 plants respond differently, through extinction coefficients, to increases in diffuse light.



$$k_{\text{eff}} = k_{\text{direct}} \cdot (1 - f_{\text{Diffuse}}) + k_{\text{diffuse adjusted}} \cdot f_{\text{Diffuse}}$$

C3 plants (e.g., alfalfa, soybean)

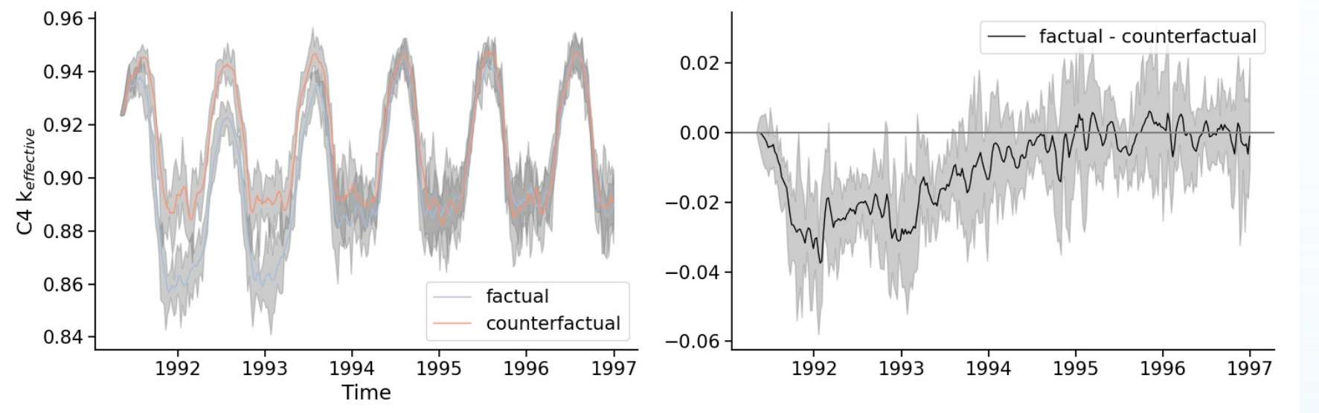
- Often have a canopy structure that is more adapted to diffuse light.
- Under direct light conditions, C3 plants might not be as efficient as C4 plants in light utilization.



$k_{\text{direct,alfalfa}} = 0.84$ [3]
$k_{\text{diffuse adjusted}} = 1.2 k_{\text{diffuse}}$

C4 plants (e.g., corn)

- Are generally more adapted to high light conditions.
- Leaf structure and orientation allow for more effective penetration and utilization of direct sunlight throughout the canopy.



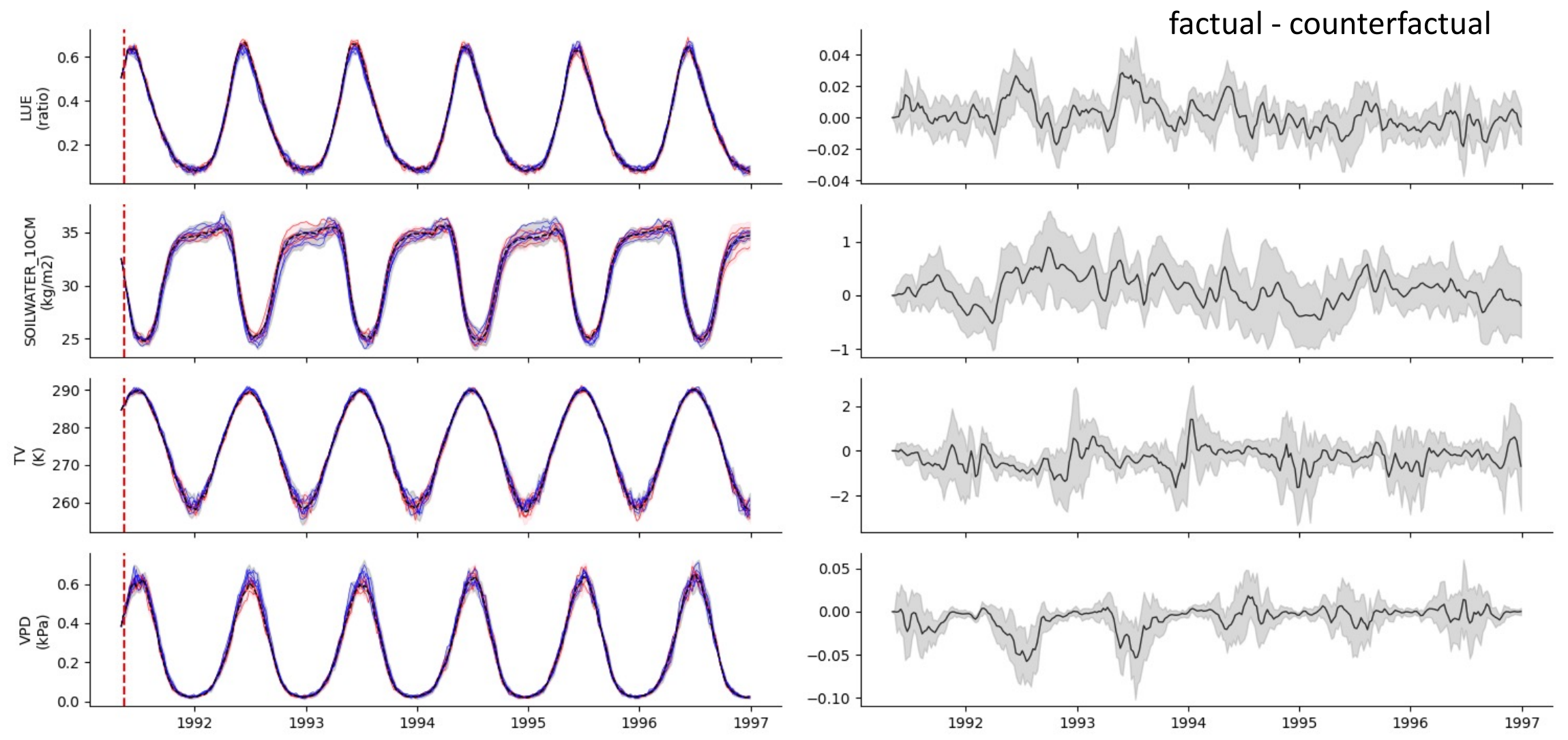
$k_{\text{direct,corn}} = 1.08$ [3]
$k_{\text{diffuse adjusted}} = k_{\text{diffuse}}$

Use these crop-specific extinction coefficients to calculate the fraction of Absorbed Photosynthetically Active Radiation (fAPAR) specific to C3/C4. This is a measure of how much of the available sunlight (PAR) is absorbed by the plants for photosynthesis.

$$fAPAR = \int_0^{LAI} (1 - \exp(-k \cdot \text{depth}))\, d(\text{depth})$$

LIGHT USE EFFICIENCY (LUE)

Light use efficiency (LUE) is a measure of the combined vegetative response of the plant functional types in E3SMv2-PA computed as photosynthesis/absorbed photosynthetically active radiation. It incorporates the environmental drivers changing in response to Pinatubo that effect photosynthesis including changes in temperature (TV), soil moisture, and vapor pressure deficit (VPD).

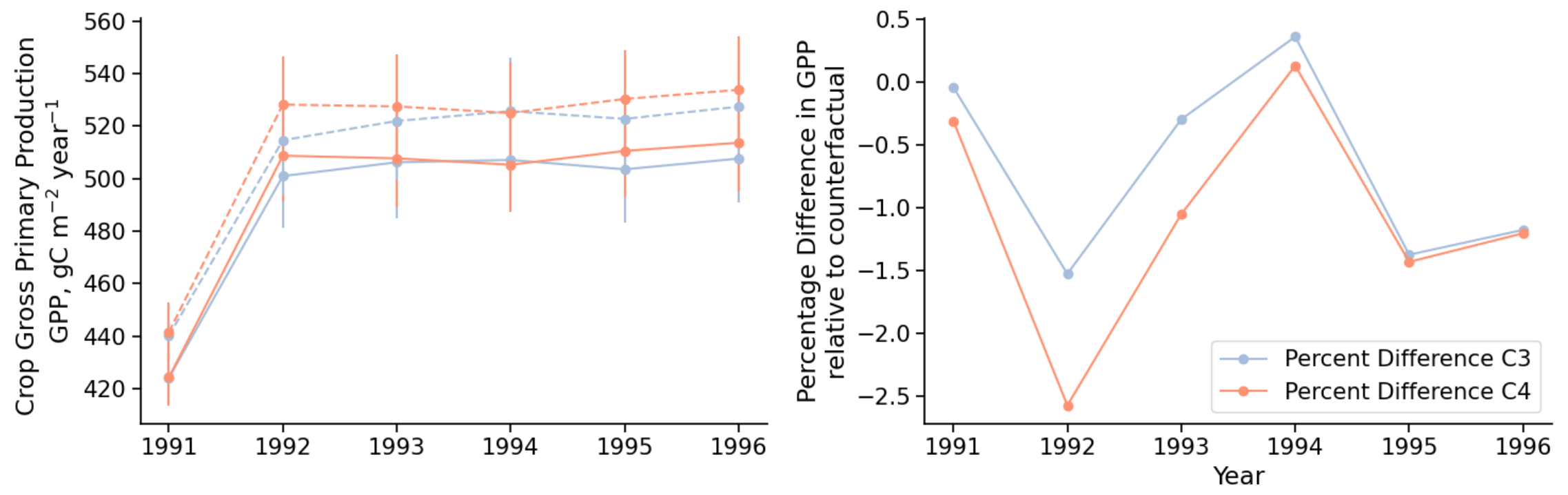


- After Pinatubo, LUE increased, and VPD decreased
- These impacts were seasonal, and persisted for ~2 or 3 years

GROSS PRIMARY PRODUCTIVITY

Gross Primary Productivity (GPP) incorporates effects from radiative changes and LUE.

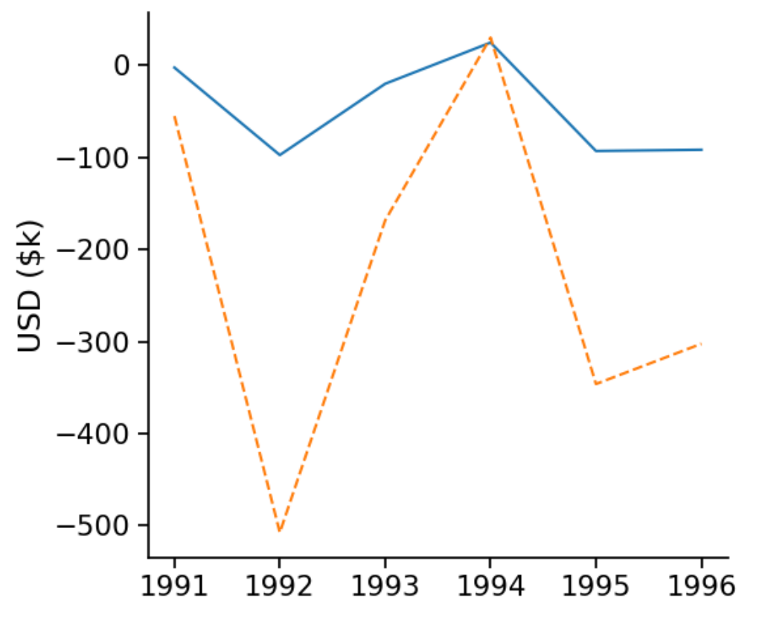
$$GPP = PAR \cdot fAPAR \cdot LUE$$



Using a purely empirical model, Proctor *et al.* 2018 [4] showed Pinatubo reduced C4 yields by 9.3% and C3 yields by 4.8%.

Here we find lower yield reductions of only 2.6% for corn (C4) & 1.5% for alfalfa (C3). Given our models employ a non-agriculture specific response to other environmental changes from Pinatubo (soil-water, VPD, and temperature) this difference seems reasonable.

ECONOMIC ANALYSIS



Cumulative lost economic impact (1991-1996) [5]

- $1.35M for corn (C4) in US
- $0.28M for alfalfa (C3) in US

Assumptions:

- Increased yield would not alter sale price of crop.
- Model emphasizes yield change due to radiation. Future work could include other drivers.

NEXT STEPS

- Employ CLDERA methods under the three technical thrusts to analyze the agricultural pathway.
- Use simulation ensembles with varying volcanic eruption mass to evaluate how agricultural productivity changes with eruption size.

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