Sulfur: The 4th Major Nutrient and Why It's Time to Optimize Management Now

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CIRES

Environmental Biogeochemistry Group

CCA Indiana 2025

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CERTIFIED CROP ADVISER

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Key Points

- Sulfur is an intrinsic component of life at molecular to planetary scales
- Changes in human S use affect the need for optimized S applications in croplands
- There are environmental consequences of excess S in the environment (e.g., mercury methylation)
- We have an opportunity to manage S sustainably now
- There is a new project to compile S fertilizer data globally to create a publicly available resource through the FAO – email me to contribute – eve.hinckley@colorado.edu

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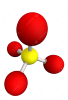

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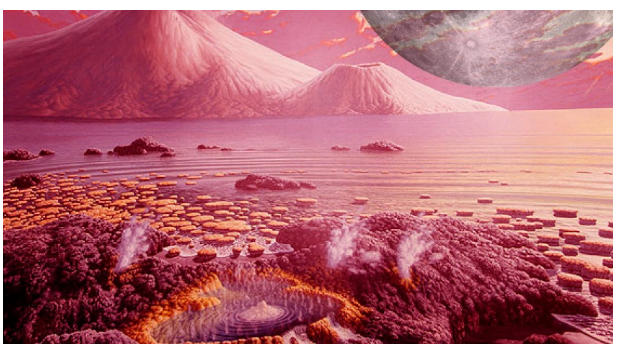
Sulfur is a central element of life on Earth

16
S
Sulfur
32.066

5



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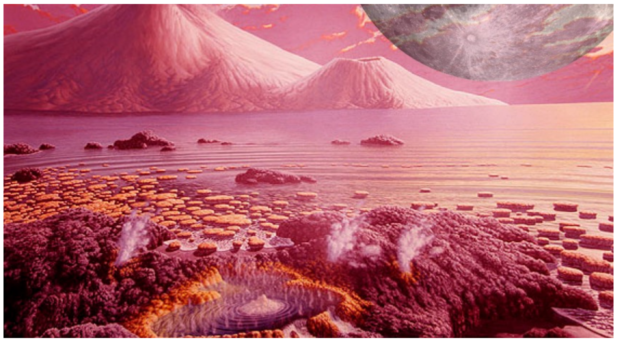

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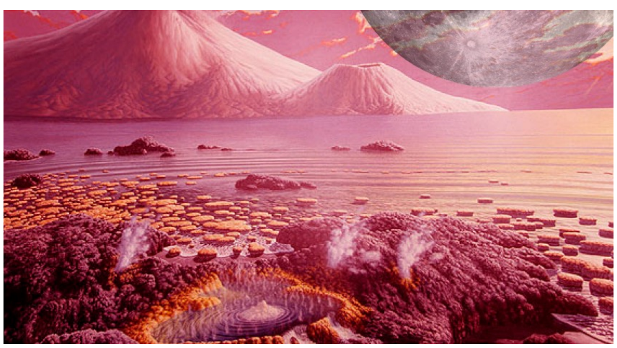

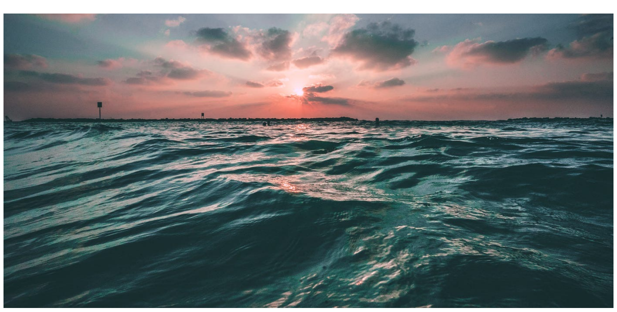

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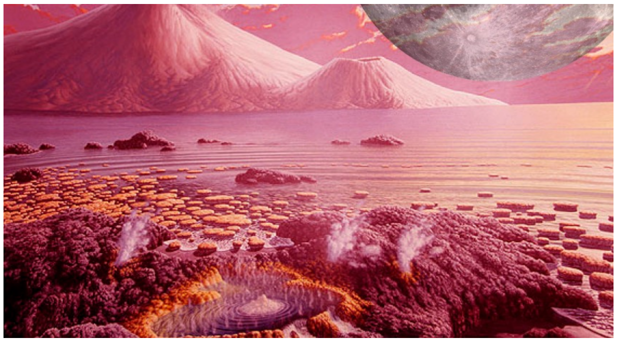

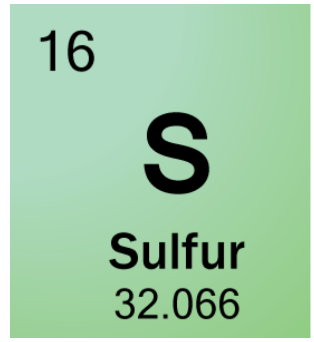

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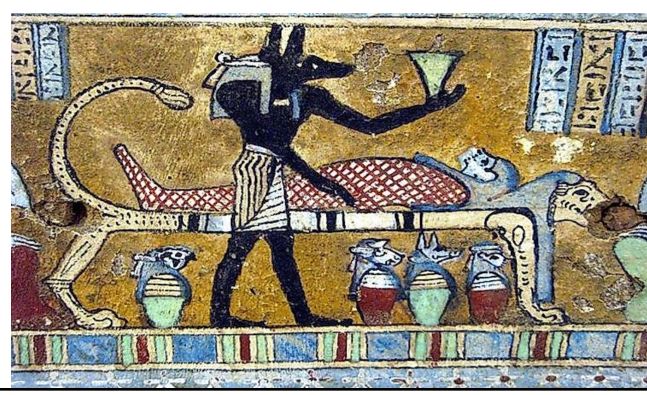

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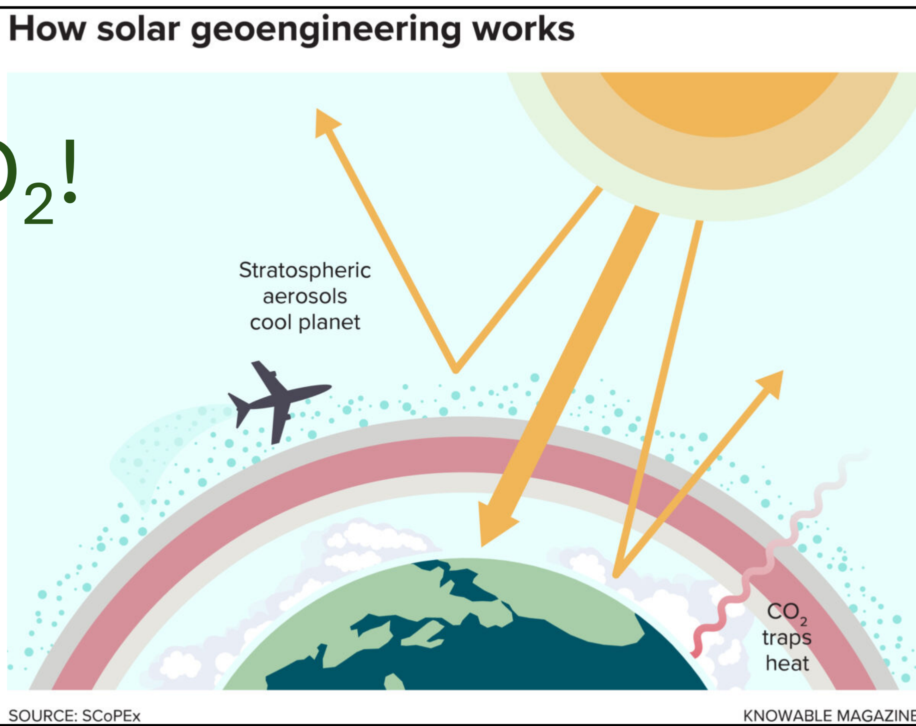
SO_2!


How solar geoengineering works
Stratospheric aerosols cool planet
CO_2 traps heat
SOURCE: SCoPEx
KNOWABLE MAGAZINE

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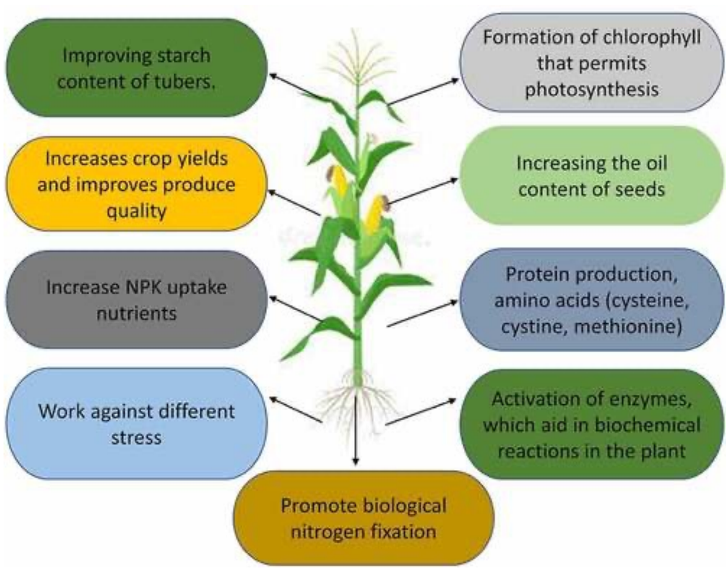
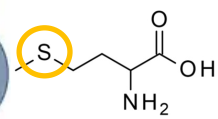
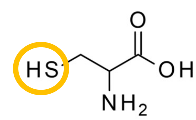
Sulfur in crop nutrition





Methionine



Cysteine

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This Talk

- Sulfur in croplands – a changing picture
- Motivation for optimization of S applications – data from my group and others
- Introduction to a new global-scale project – you can be involved!

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1. How is the picture of S use changing?

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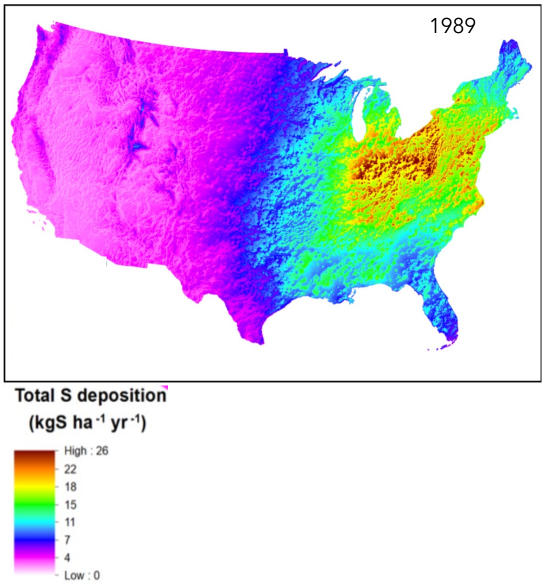
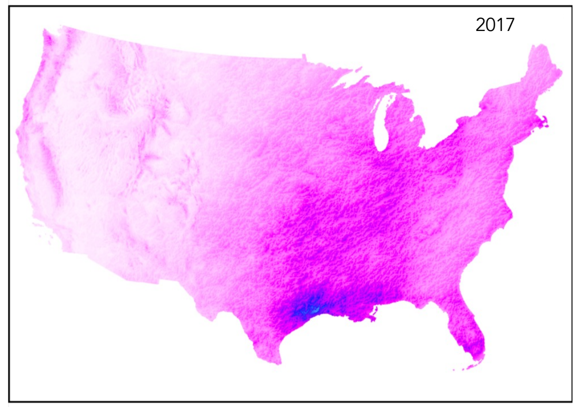
Trends in Atmospheric S Deposition





Hinckley et al. (2020) *Nature Geosci.*

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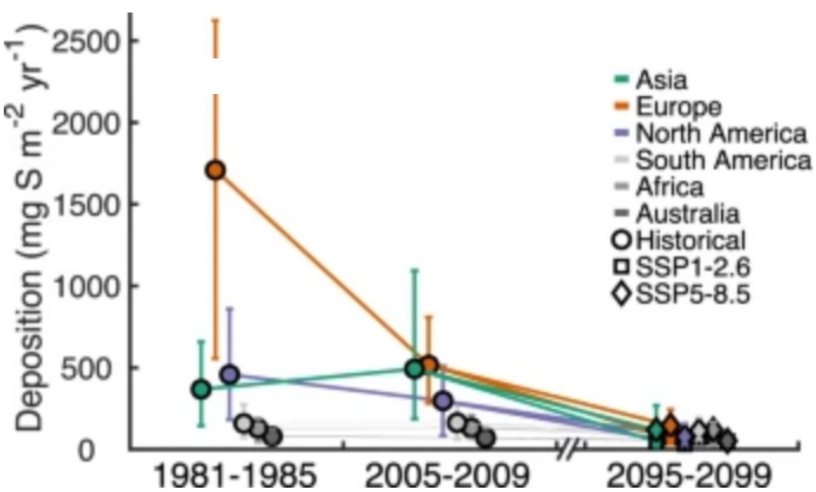
Atmospheric S deposition is declining around the world

Aerosol-chemistry-climate model, SOCOL-AER, simulations

Atmospheric S deposition to croplands declines 70-90%



Feinberg,…Hinckley, et al. (2021) *Nature Comm. Earth and Environ.*

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Climate-related pest pressures

Agriculture intensification

Sulfur-deficiency

Farmers are adding S

Hinckley et al. (2020) *Nature Geosci.*

21

Climate-related pest pressures

Agriculture intensification

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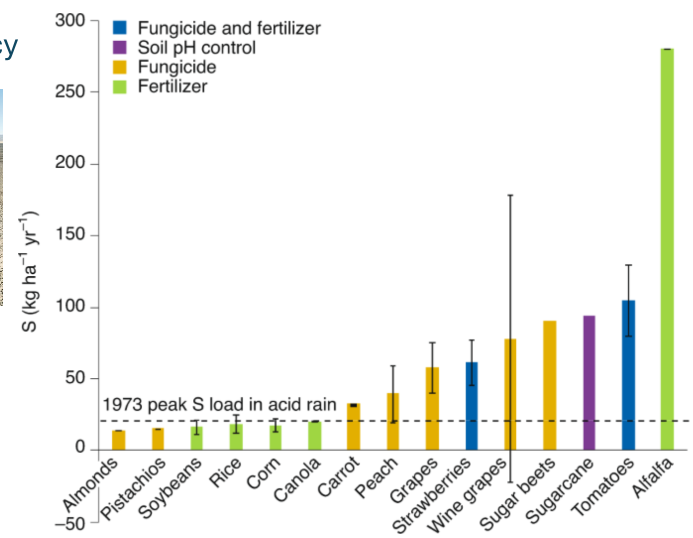
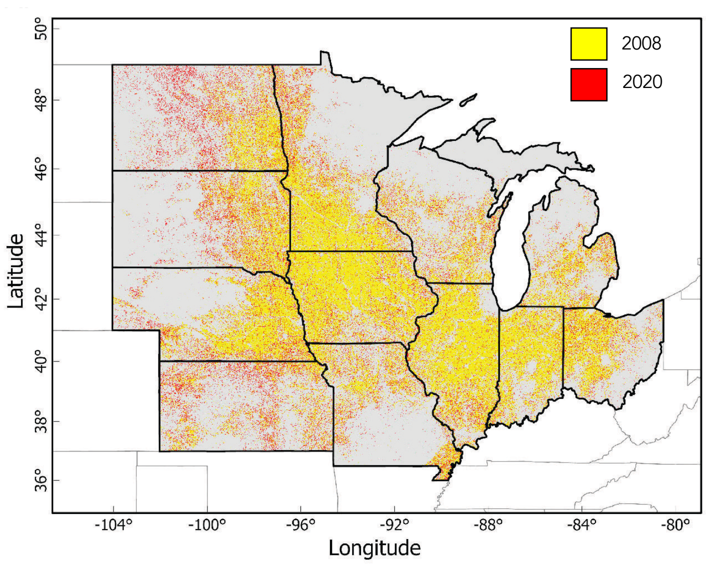


Hinckley et al. (2020) *Nature Geosci.*

22

Important implications for large ag regions, like the Midwestern US – corn and soybean



Source: Brittannica

Hinckley and Driscoll (2022) *Nature Comm Earth Environ*

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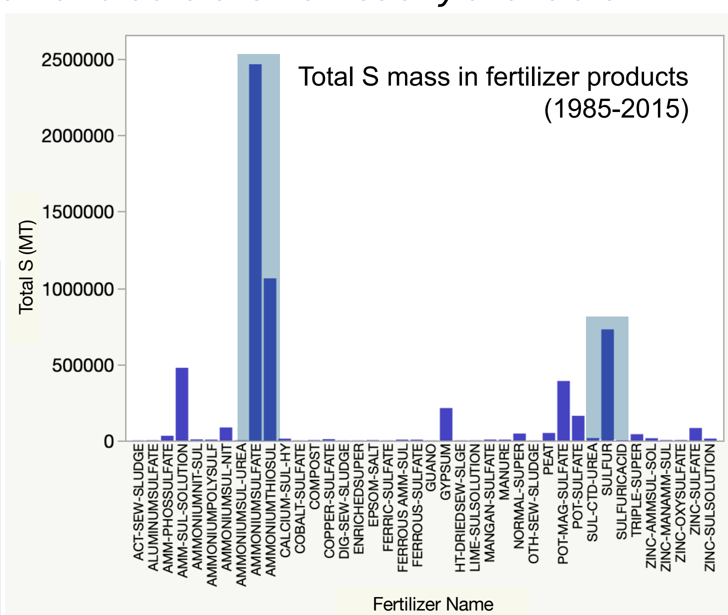
Investigating the available data…*and data are not readily available…*

Association of American Plant Food Control Officials (AAPFCO)

- Data reported in tons of product per county per year
- 40 S-containing products
- Determined chemical composition of products to calculate S mass
- Majority ammonium sulfate
- Aggregate to 12-state Midwest area



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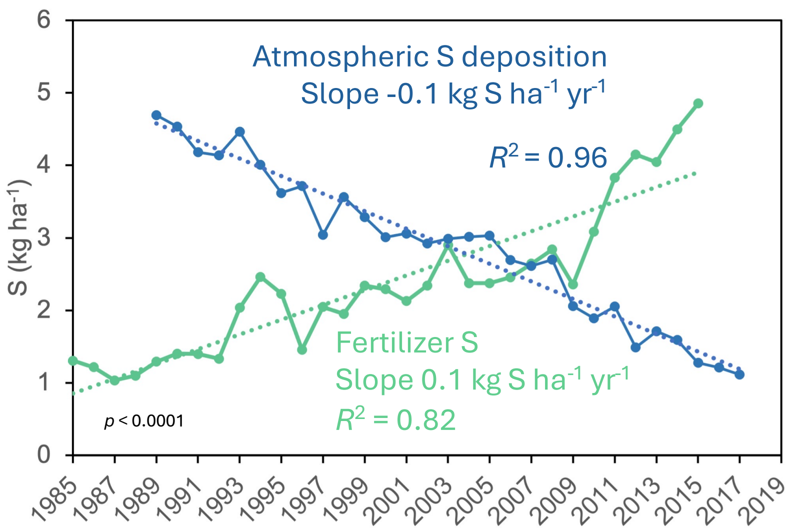
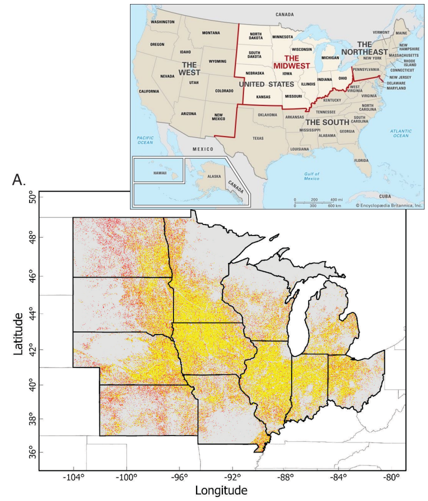
Evidence: atmospheric S deposition is decreasing and the need for fertilizer S is increasing





Increases in corn-soybean acreage between 2008 (yellow) and 2020 (red)

Hinckley and Driscoll (2022) *Nature Comm Earth Environ*

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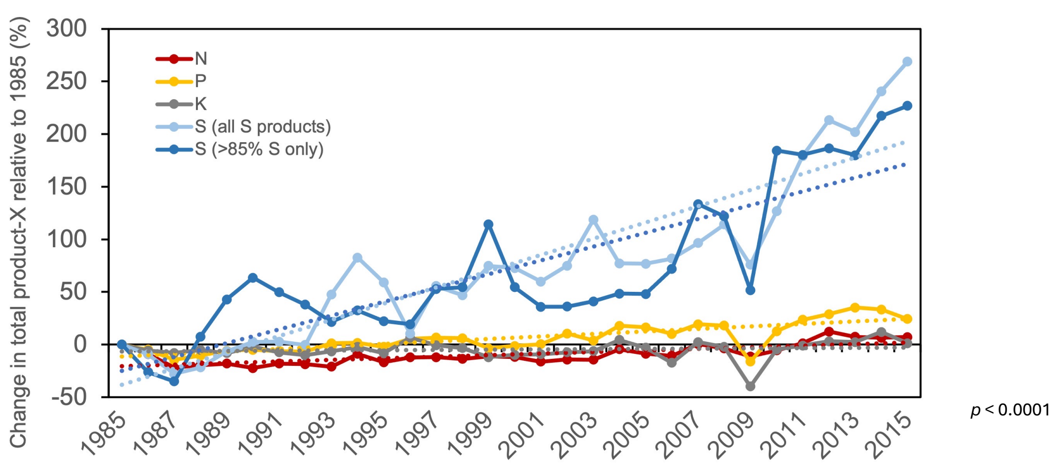
In Midwestern US: The rate of change in S fertilizers far outpaces N, P, and K



p < 0.0001

Hinckley and Driscoll (2022) *Nature Comm Earth Environ*

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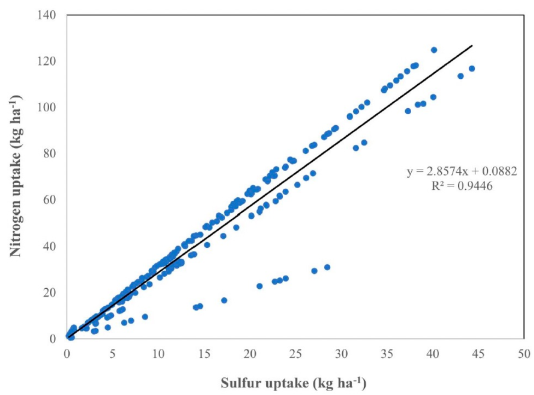
Interactions between S and N uptake; S minimizes N leaching



S fertilizer use increases crop N uptake

Agyin-Birikorang et al. (2024) *J. Plant Nutrition*

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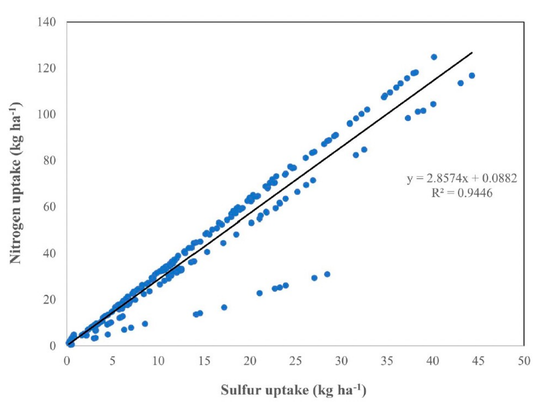

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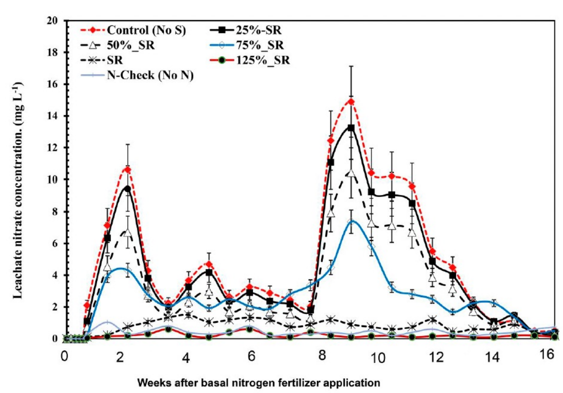

S fertilizer decreases N leaching losses

Agyin-Birikorang et al. (2024) *J. Plant Nutrition*

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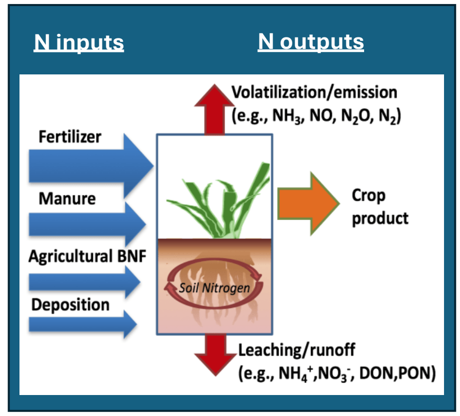
Interactions between S and N uptake; S minimizes N losses

- Sulfur addition increased NUE mainly by increasing the N recovery from the soil (Salvagiotti et al., 2009)
  - <<< N losses
- S increases shoot growth, causing NUE to go up (Carciochi et al., 2017)
  - >>> plant N uptake
- Suggest S-coated urea to reduce N losses (Mustafa et al., 2022)
  - <<< fertilizer N inputs (?)



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2. Why do we need to optimize S use?

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WELCOME to this world famous
wine growing region
NAPA VALLEY
napa valley vintners
...and the wine is bottled poetry...
Robert Louis Stevenson

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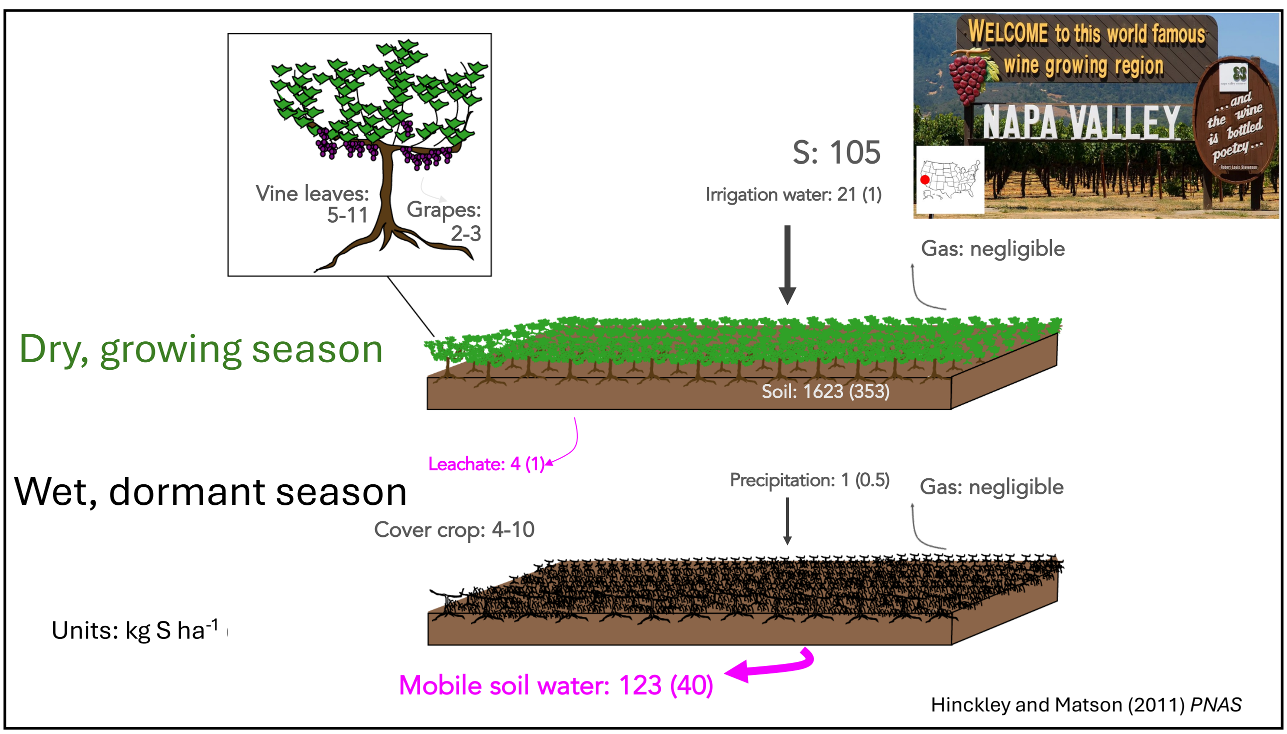
Vine leaves: 5-11
Grapes: 2-3
S: 105
Irrigation water: 21 (1)
Gas: negligible
Dry, growing season
Soil: 1623 (353)
Leachate: 4 (1)
Wet, dormant season
Precipitation: 1 (0.5)
Gas: negligible
Cover crop: 4-10
Units: kg S ha-1
Mobile soil water: 123 (40)
Hinckley and Matson (2011) PNAS

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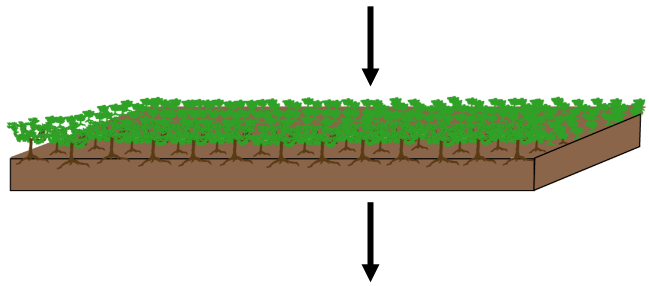
The Annual S Budget

IN: 127 (1)



OUT: 129 (40)

Units: kg S ha^{-1} (SD)

Hinckley and Matson (2011) *PNAS*

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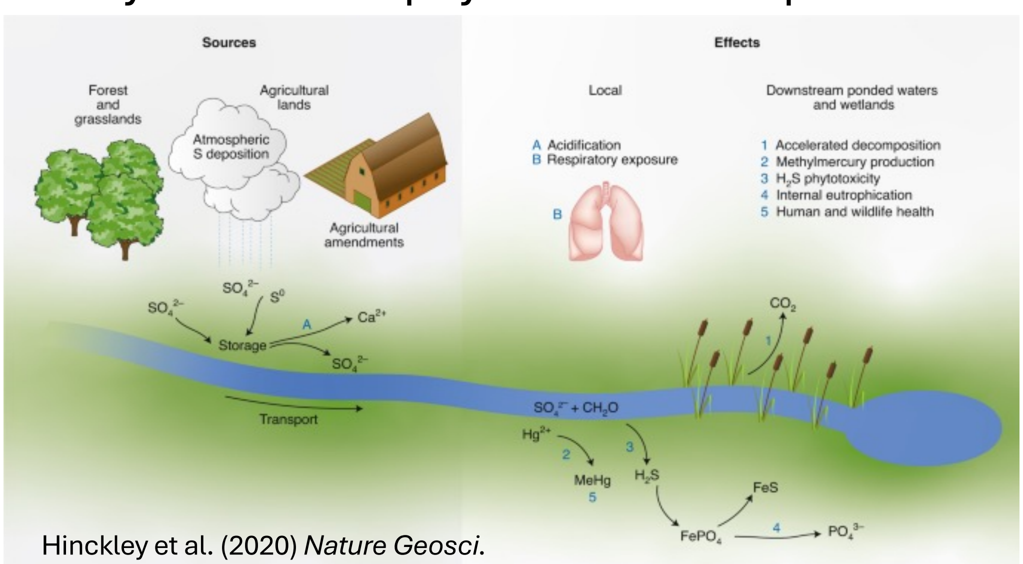
Implications of increasing S inputs…
…or why we need to pay attention to optimization



Hinckley et al. (2020) *Nature Geosci.*

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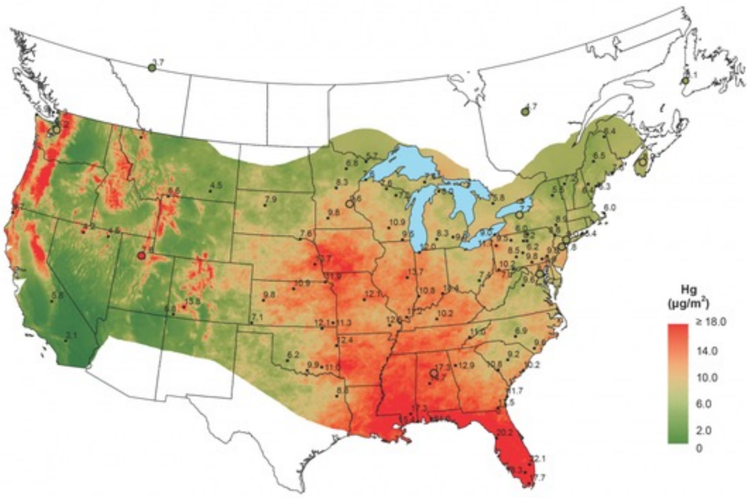
Sulfur interacts with mercury



- Mercury mobilized by industrial emissions
- The global mercury pool affects deposition amounts
- Weather and topography affect deposition amounts
- Deposited inorganic Hg can react and form methylmercury
- At least one Hg warning for fish consumption in every U.S. state

Source: Forbes

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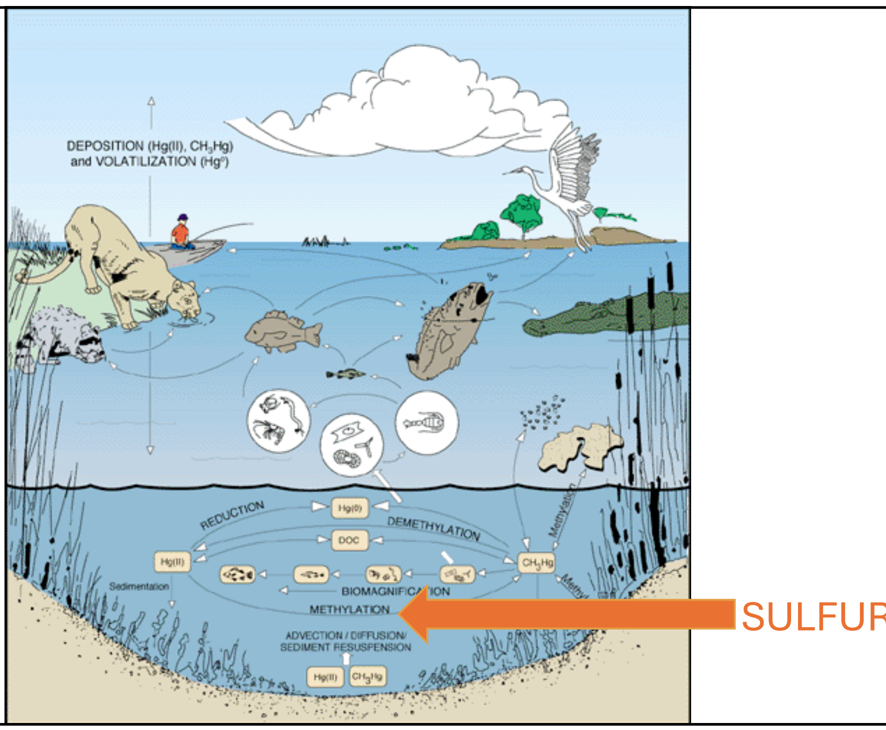
Formation of MeHg and bioaccumulation in the food web



Source: USGS

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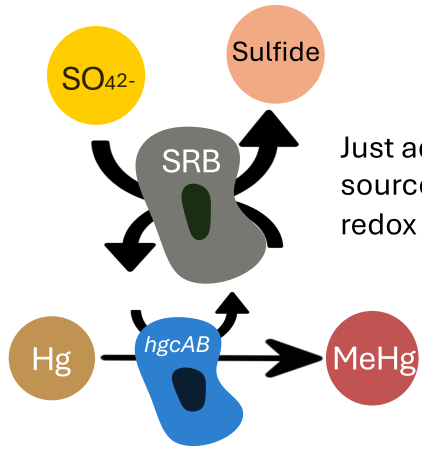
Environmental consequences of excess S in the environment

"Tomoko and Mother in the Bath," (1971) W. Eugene Smith



Just add a carbon source and fluctuating redox conditions...

Miller (2024)

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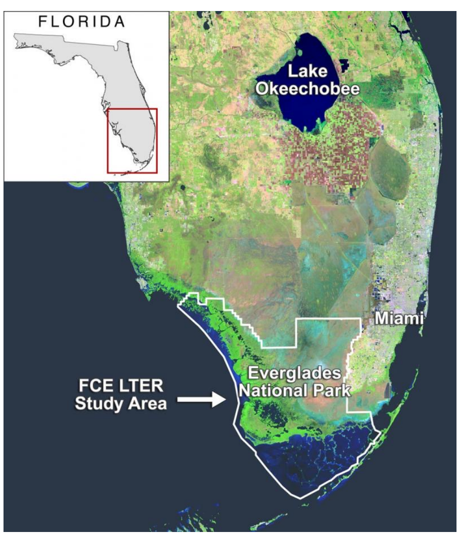
Environmental consequences of excess S in the environment



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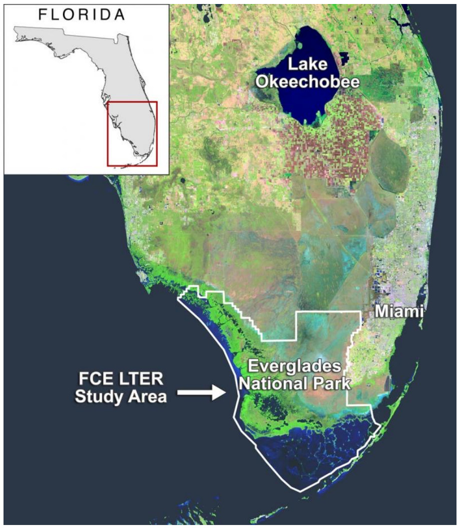

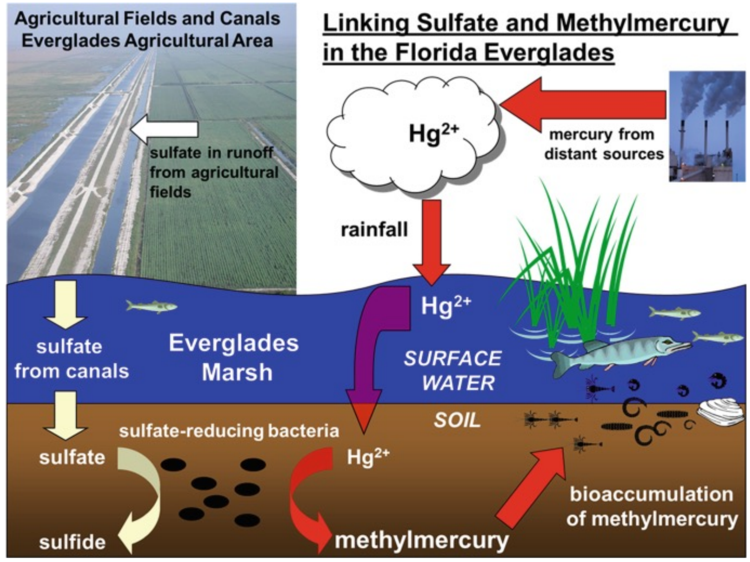

Orem et al. (2019) In: *Mercury and the Everglades*

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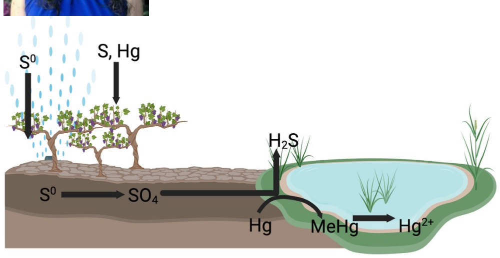
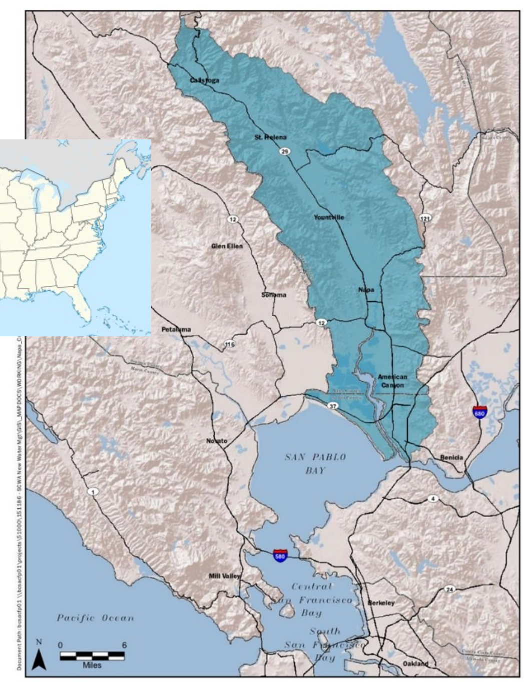
Environmental consequences of excess S in the environment

Asst Prof Jackie Gerson
Cornell University
Former postdoc





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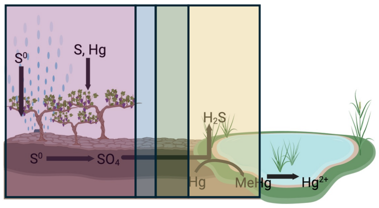
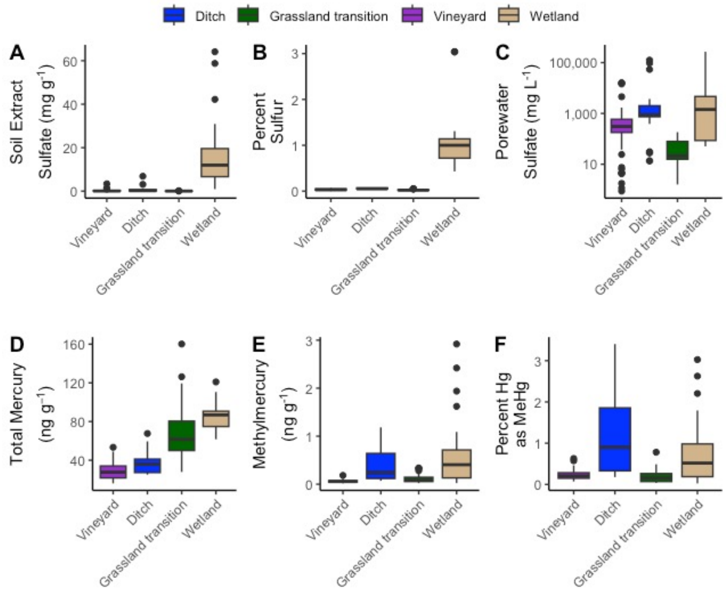
Environmental consequences of excess S in the environment





Wetlands receive sulfate from vineyards; ditches and wetlands have highest Hg as MeHg

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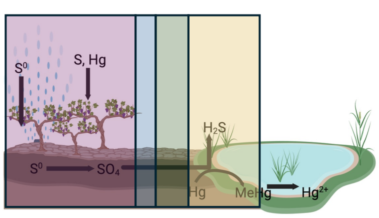
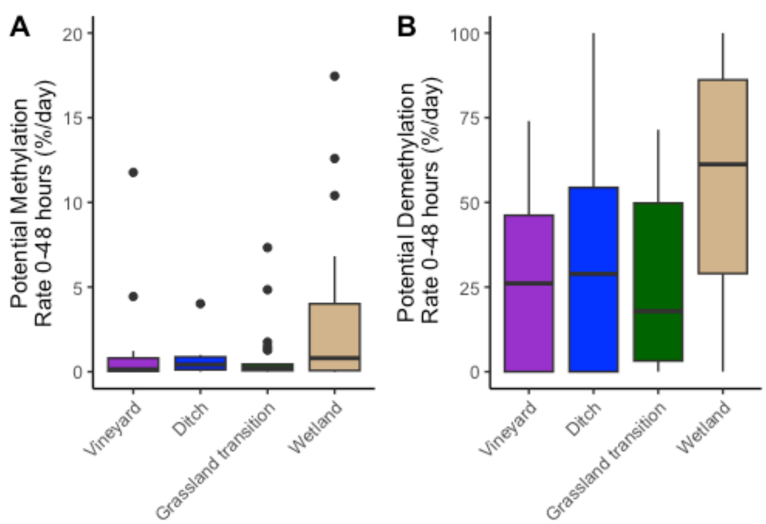
Environmental consequences of excess S in the environment





Wetlands have greatest potential for processing Hg (methylation and demethylation); S looks isotopically like vineyard and marine S.

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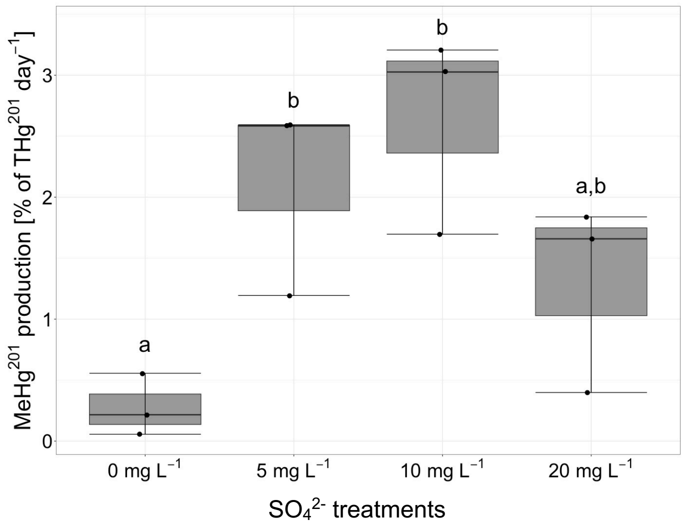
Environmental consequences of excess S in the environment

Dr. Hannah Miller,
Former Ph.D. student

Colorado Wetland Information Center



Miller et al. (2025) *Environ. Res. Letters*

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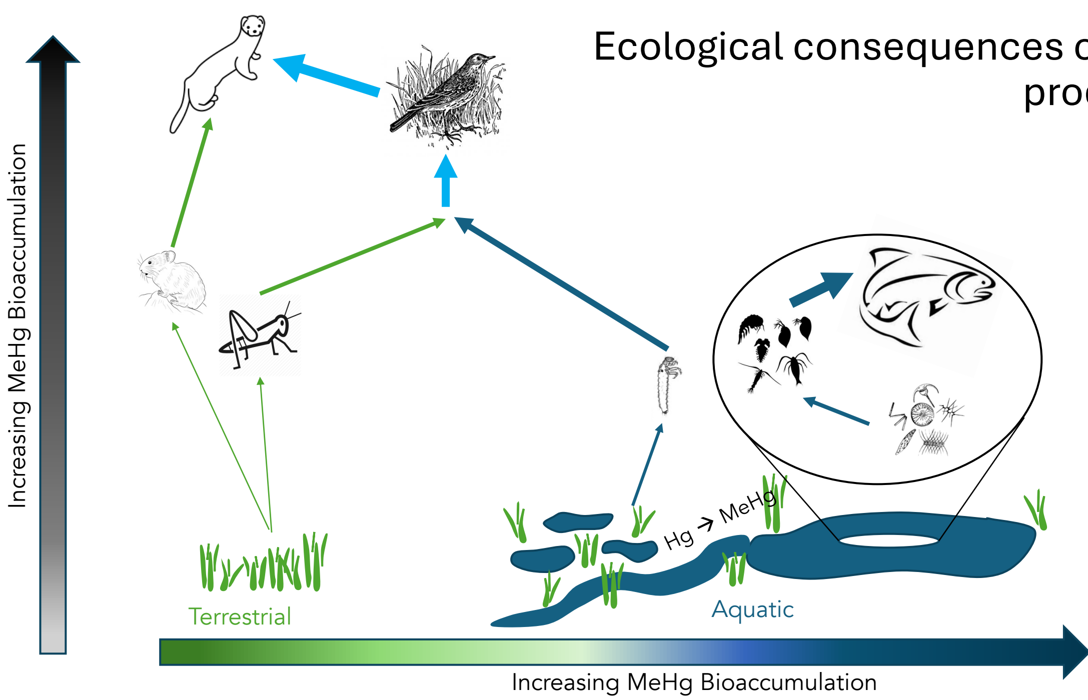
Ecological consequences of MeHg production



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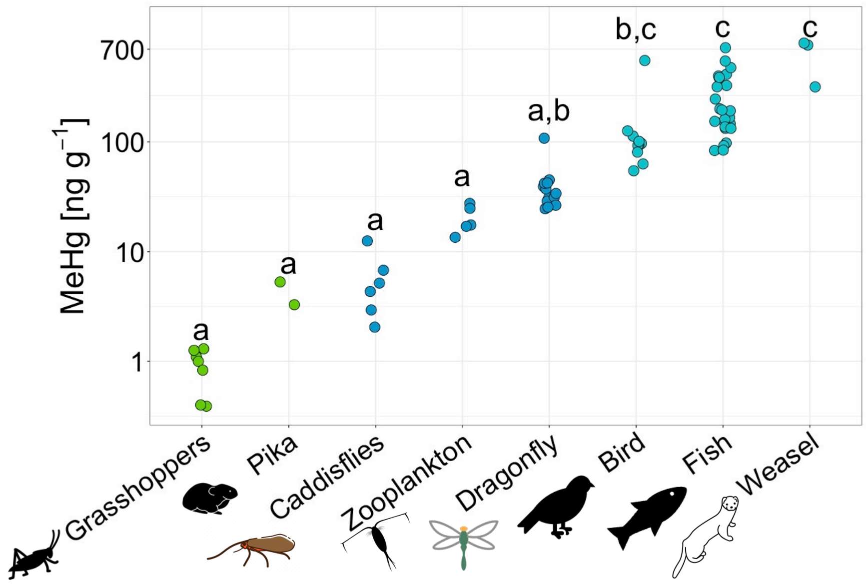
Ecological consequences of MeHg production



Miller et al., *in review*

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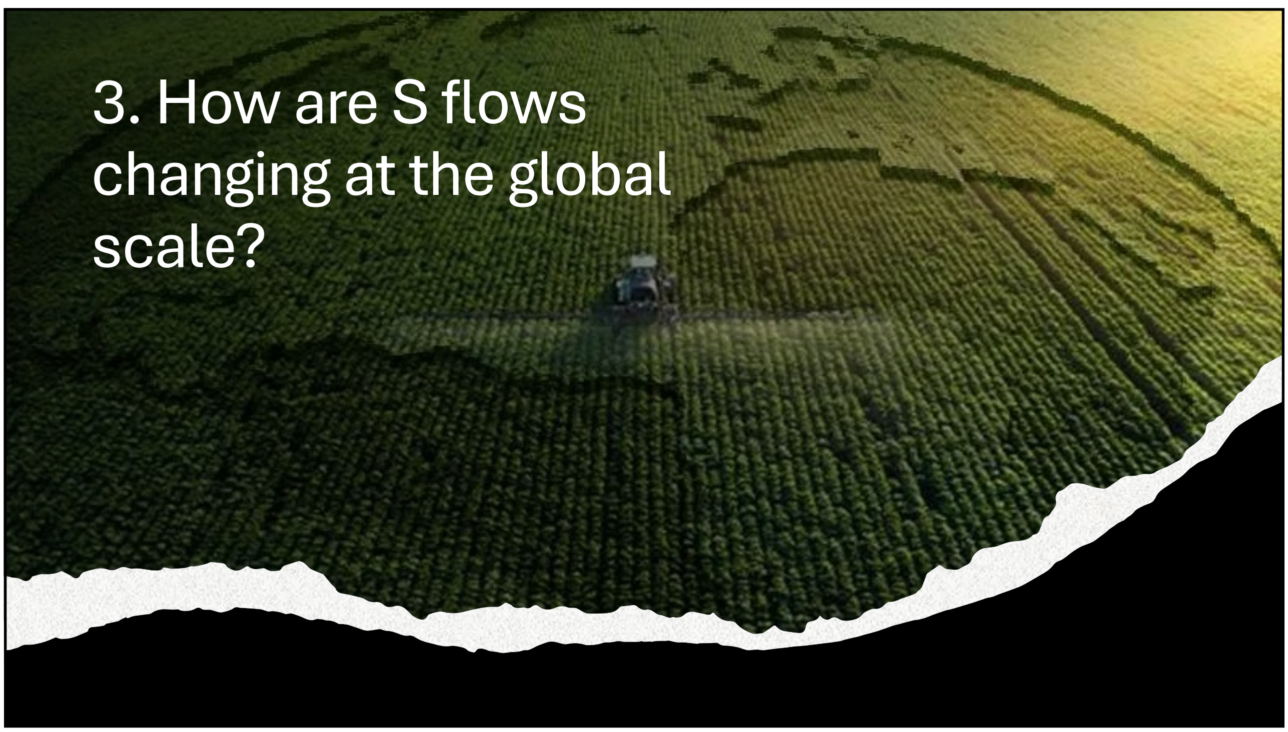

3. How are S flows changing at the global scale?

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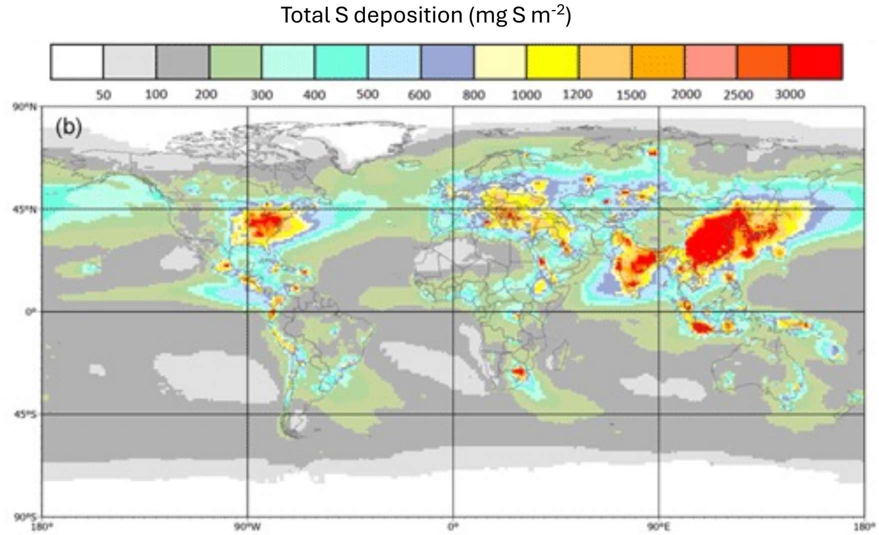
Global atmospheric S deposition



Rubin et al. 2023

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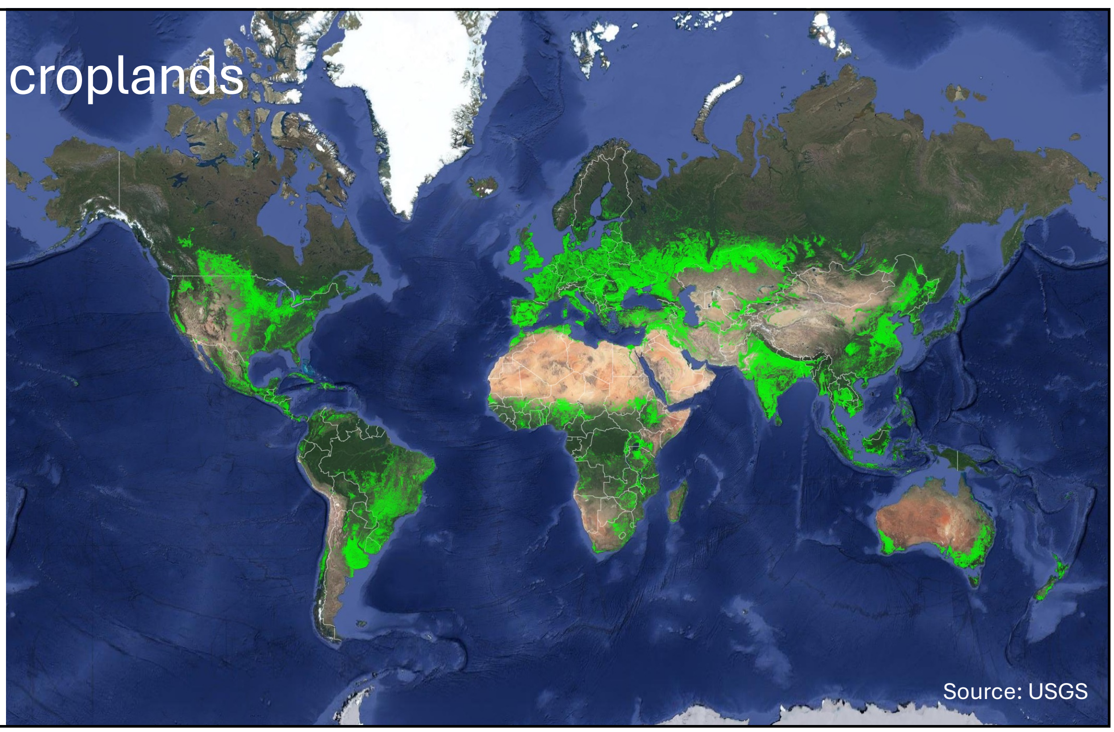
Global croplands



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Questions

- Where does S limitation to major crop systems occur and where is it likely to emerge?
- What is the balance between S inputs and outputs? (mass balance)
- How do historic trends in atmospheric S deposition compare with trends in agricultural S use?

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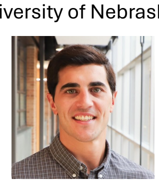
Global assessment of crop sulphur balance and limitation

University of Nebraska Lincoln

University of Colorado Boulder

Prof. Patricio Grassini
University of Nebraska

Assoc. Prof.
Eve-Lyn Hinckley
University of Colorado



Asst. Research Prof.
Walter Carciochi
University of Nebraska

Postdoctoral Scholar
Connor Olson
University of Colorado

TSI The Sulphur Institute

ifa International Fertilizer Association — Helping to feed the world sustainably

Koch Fertilizer · AdvanSix Good chemistry. · Shell · Nutrien · Mosaic · Maaden · IRM International Raw Materials Ltd · IFFCO · AngloAmerican · engro · Sulphur · ICL · Sulvaris · Yara

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But what about the country-to-global scale?

- Extent and degree of current on-farm S limitation to major crop systems in the world is unknown and likely to be underestimated
- There are no data on trends in atmospheric S deposition, fertilizer S inputs, and S balances over time
- This info is needed to optimize current S recommendations and manage crop systems sustainably; inform and forecast the global S fertilizer markets

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Objectives

1. Quantify emerging sulfur limitations to global crop yields in major cropping regions.
2. Develop time series of atmospheric S deposition and S fertilizer use by country.
3. Add S as the 4th nutrient to the global cropland nutrient balance database (https://cropnutrientdata.net) (i.e. national-scale S inputs and crop removal).

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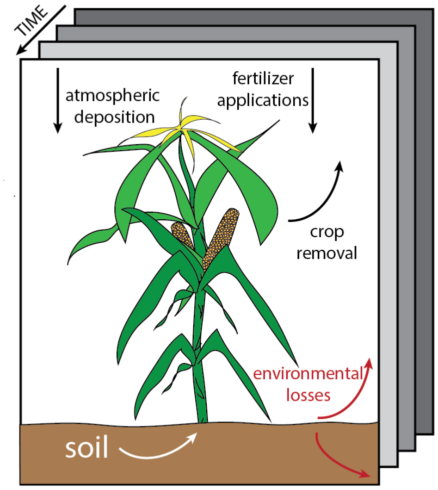
Activities

- ***Estimation of crop-system on-farm partial S balances***. Data: on-farm survey data, FAO-IFA crop nutrient budget database, sulfur deposition databases/maps.
  - ***Determination of plant S content / deficiency*** *via leaf/grain analysis*. Data: published and unpublished data from researchers in private and public sectors, collection of new data to confirm specific cases.
  - ***Estimation of soil S supply capacity*** *via soil tests (combination of SO_4^{-2}, organic matter, sand content, etc.) or S uptake in S-fertilizer omission plots*. Data: published and unpublished data from researchers in private and public sectors, soil labs.
  - ***Yield response to S fertilizer*** *based on short- and long-term on-farm experiments*. Data: published and unpublished data from researchers in private and public sectors.



Modified from: Hinckley and Driscoll (2022) *Nature Comm. Earth & Environ*

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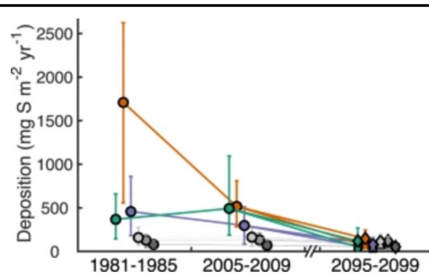
Activities (cont'd)

- ***Model time series of atmospheric S deposition.*** Estimate atmospheric S deposition rates over time using the global aerosol-chemistry-climate model. The modeling effort will be constrained by availability of data; we will aim to provide a time series starting before 2005, if possible.



Feinberg…Hinckley, et al. (2021) *Nature Comm. Earth & Environ.*

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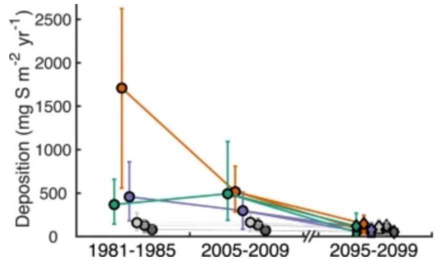
Activities (cont'd)



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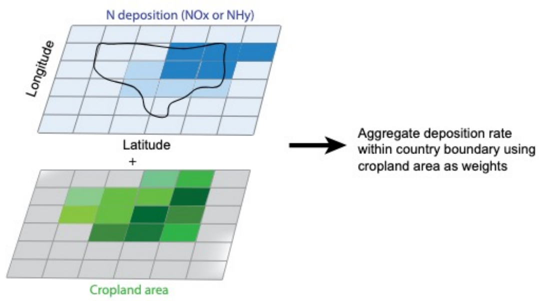

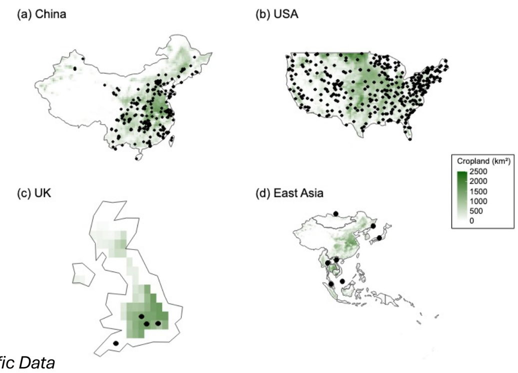

Vishwakarma et al. (2023) *Scientific Data*

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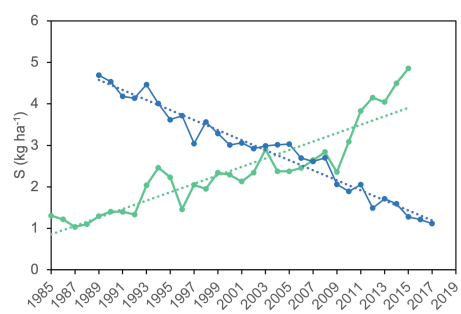
Activities (cont'd)

- ***Model time series of atmospheric S deposition.*** Estimate atmospheric S deposition rates over time using the global aerosol-chemistry-climate model. The modeling effort will be constrained by availability of data; we will aim to provide a time series starting before 2005, if possible.

Feinberg…Hinckley, et al. (2021) *Nature Comm. Earth & Environ.*

- ***Compile statistical time series of S fertilizer data.*** Following previous efforts made for N, P and K in the global Cropland Nutrient Balance database. Data: available statistics (e.g. fertilizer consumption byproducts, cropland area and production) published and unpublished datasets, surveys, and modeling assumptions to produce a time series of S fertilizer use by country, dating back to 1961 or the earliest year possible.



Hinckley and Driscoll (2022) *Nature Comm. Earth & Environ*

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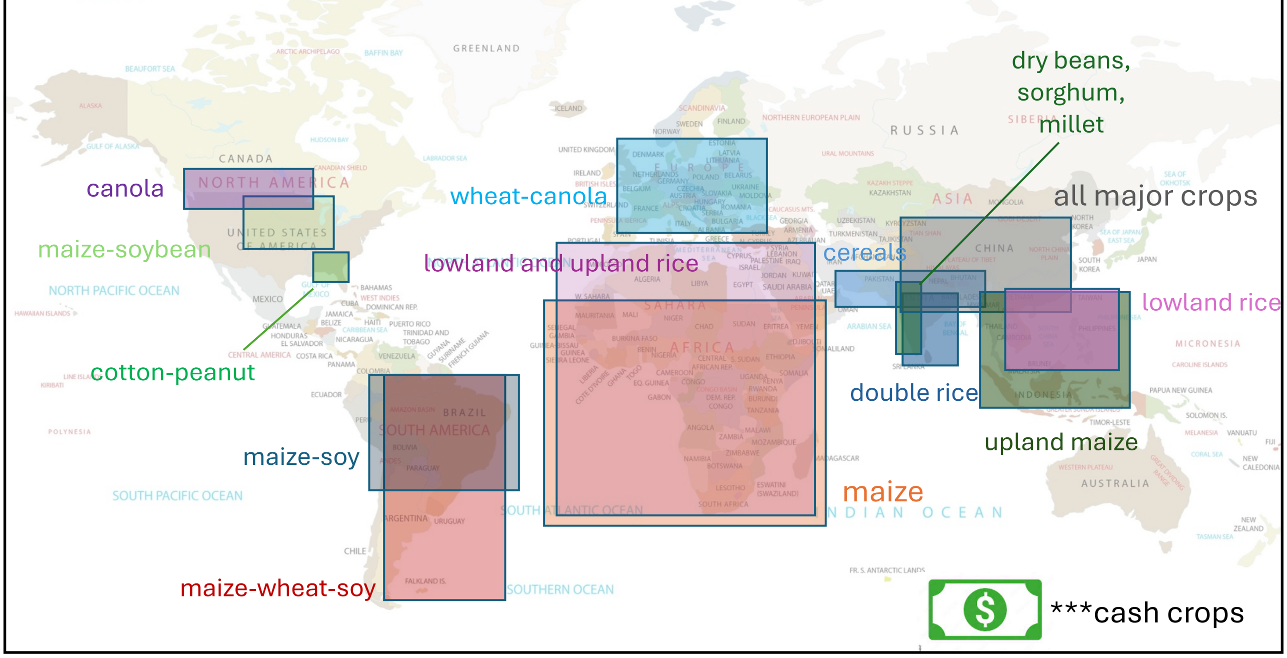
Target Cropping Systems



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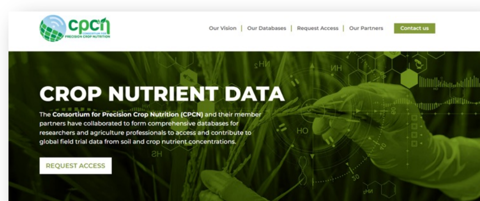
Expected Outcomes



- Thematic database on soil and plant S and yield response to S (e.g., Corporation for Precision Crop Nutrition)
- Global database on S, including S fertilizer use by country, for estimating national S balances
- Global time series of atmospheric S deposition and fertilizer use
- Identification of cropping systems where S is limiting
- Peer-reviewed publications in scientific literature
- Policy guidance publications/information materials
- A global network of researchers with a common interest in crop S research

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Now: Soliciting data contributions: Letter and concept note

Dear Colleague,

We trust that you are doing well. We are contacting you because we are now embarking on a global project on sulfur (S) led by the University of Nebraska-Lincoln, University of Colorado Boulder, The Sulphur Institute, and the International Fertilizer Association. The attached concept note summarizes the project goal and methodology.

The project aims to quantify emerging S limitations to global crop yields in major cropping regions and develop national-scale time series of sulfur inputs, outputs, balance and use efficiency. The latter will be integrated in the Global Cropland Nutrient Balance database published annually of FAO, https://www.fao.org/faostat/en/#data/ESB.

We are reaching out to you because we need your help to collect existing data on sulfur in crop production for the project. As indicated in the attached document, we are looking for data needed to:

(i) compute on-farm S balances (e.g., yield, S concentrations in produce and residue, S inputs)
(ii) diagnose plant S deficiencies (e.g., leaf/grain analysis)
(iii) estimate soil S supply (e.g., soil S-sulfate concentration, total plant S uptake in omission plots)
(iv) quantify the yield response to S fertilizer addition (e.g., yield measured in short- or long-term fertility trials that include S treatments, as well as interactions with N or other nutrients)

We are very interested in collecting both on-farm data as well as data from trials conducted at research stations. Please don't hesitate to contact us with any specific questions or suggestions you may have.

We believe that having a publicly available global database on S would be a unique good that can serve many users and applications around the world. We also believe that it will add value and recognition to your own work. Some additional benefits for your collaboration include co-authorship of the database publication in a citable repository (with CrossRef DOI), open use of the dataset for your own research, and free access to our virtual S workshop.

We plan to create a thematic database on S in crop production to store all the information collected throughout our project and make it available via the crop nutrient data platform (https://cropnutrientdata.net/). Although we encourage you to make your data open access, if you prefer us to keep it confidential, we will not make them publicly available.

We look forward to hearing back from you and learning about the extent and significance of S limitation to crop yields around the world! In the meantime, we send you our warmest regards.

Scientific committee
Patricio Grassini & Walter Carciochi (UNL)
Eve-Lyn Hinckley & Connor Olson (CU Boulder)
Achim Dobermann (IFA)
Ron Olson & Craig Jorgenson (TSI)

For questions and suggestions, please contact Dr. Walter Carciochi (wcarciochi2@unl.edu)

Please, feel free to share this invitation with colleagues who can potentially contribute to this exciting project.

Global Assessment of Crop Sulphur Balance and Limitation

I. Introduction

Sulphur (S) limitation occurs when crop demand is not met by S supply from soil, fertilizers, and other sources. Historically, research and management of S have been overshadowed by macronutrients such as nitrogen (N), phosphorus (P), and potassium (K) (Gerendás et al., 2013; Zenda et al., 2021). Indeed, there is neither a global database on S inputs and outputs nor a global time series of S fertilizer use that can serve as the basis for understanding past and current use, estimate nutrient balances, or forecast fertilizer market demand. However, the importance of S in crop management has gained attention in recent decades due to a higher frequency of S deficiencies in some agricultural regions of the world (Feinberg et al., 2021; Sharma et al. 2024; Lu et al., 2025). Higher frequency of S deficiencies in recent years has been attributed to several factors, including reduced atmospheric S deposition (Hinckley et al., 2020; Hinckley and Driscoll, 2022), higher purity of current fertilizers, higher crop yields with associated larger S demand, and loss of soil organic matter (Hinckley et al., 2020), which accounts for most of the soil S pool (Jez et al. 2008).

Previous analyses of S limitations in major agro-ecosystems were limited to a few regions globally (e.g., Hinckley and Driscoll, 2022; Weil and Mughogho, 2000; Dobermann et al. 1998, Aulakh and Chhibba, 1992; Khurana et al., 2008; Pias et al. 2019; Lu et al. 2025 and references therein). Moreover, most of these studies were conducted many decades ago. Another limitation of many prior studies is that much of the data originates from experimental station trials, which often lack direct applicability to farmers' fields due to differences in soil properties, management practices, and crop productivity levels. With global cropland expanding rapidly, there are likely also newly cultivated areas where S limitations to crop yields may be present but remain unknown due to a lack of prior research. In addition, recent research has demonstrated that S applications affect other major nutrients, such as influencing N use efficiency (Agyin-Birikorang et al., 2024). Therefore, it is now important to conduct global assessments of (1) the most recent data on existing and emerging S limitations across major global cropping systems and (2) atmospheric S deposition and fertilizer S inputs over time to quantify S fertilizer needs, inform markets, and improve S recommendations for managing cropping systems sustainably (Gerson and Hinckley, 2023).

II. Objectives

1. Quantify emerging S limitations to global crop yields in major cropping regions.
2. Develop time series of atmospheric S deposition and S fertilizer use by country.
3. Calculate national-scale S inputs, crop removal, and balance.

III. Activities

Activity #1. To determine the degree of S limitation, we will follow the approach summarized by Grassini et al (2022), which was previously applied to diagnose potassium deficiencies for rice, maize, and oil palm in Indonesia (Sugianto et al., 2023; Rizzo et al., 2024). This approach is also used in an ongoing IFA-sponsored project that quantifies global K limitations to crop yields (Carciochi et al., 2024), which is supported by seven IFA members and led by Drs. Grassini and Carciochi. The proposed new project on S consists of an integrated assessment of S limitations to crops based on four different approaches:

#1. Estimation of crop-system on-farm S balances. Possible data sources: on-farm survey data, FAO-IFA crop nutrient budget database, S deposition databases/maps.

#2. Determination of plant S deficiency via leaf/grain analysis. Possible data sources: published and unpublished data from researchers in private and public sectors

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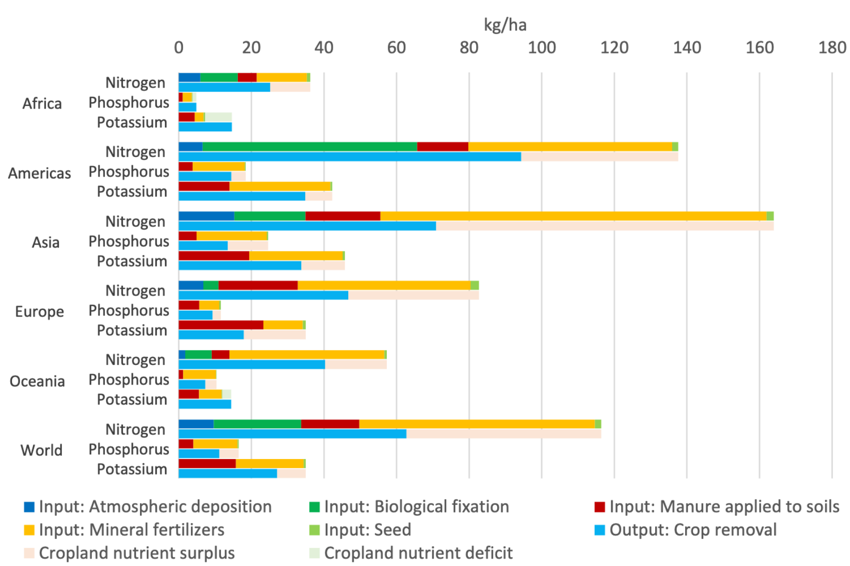
Figure 7: Cropland nutrient balances by region and nutrient, 2013–2022 average



Source: FAO. 2024. FAOSTAT: Cropland nutrient balance. [Accessed November 2024]. https://www.fao.org/faostat/en/#data/ESB. Licence: CC-BY-4.0.

FAO just released the latest compilation of N data. We expect to be able to get similar insights from this S project!

Major input: Mineral fertilizers

Americas: Most biological N fixation

Europe: Uses the most manure

Asia: Greatest mineral fertilizer use and cropland nutrient surplus

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The global S project is underway!

If you or your colleagues have datasets that you can contribute, please talk to me or send an email: eve.hinckley@colorado.edu

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Key Points

- Sulfur is an intrinsic component of life at molecular to planetary scales
- Changes in human S use affect the need for optimized S applications in croplands
- There are environmental consequences of excess S in the environment (e.g., mercury methylation)
- We have an opportunity to manage S sustainably now
- There is a new project to compile S fertilizer data globally to create a publicly available database through the FAO – email me to contribute – eve.hinckley@colorado.edu

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Acknowledgements
Contact:
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www.ebgscience.org
Environmental Biogeochemistry Group
NSF
USDA
TSI THE SULPHUR INSTITUTE
ifa INTERNATIONAL FERTILIZER ASSOCIATION
Helping to feed the world sustainably

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