Sulphur: The 4th Major Nutrient

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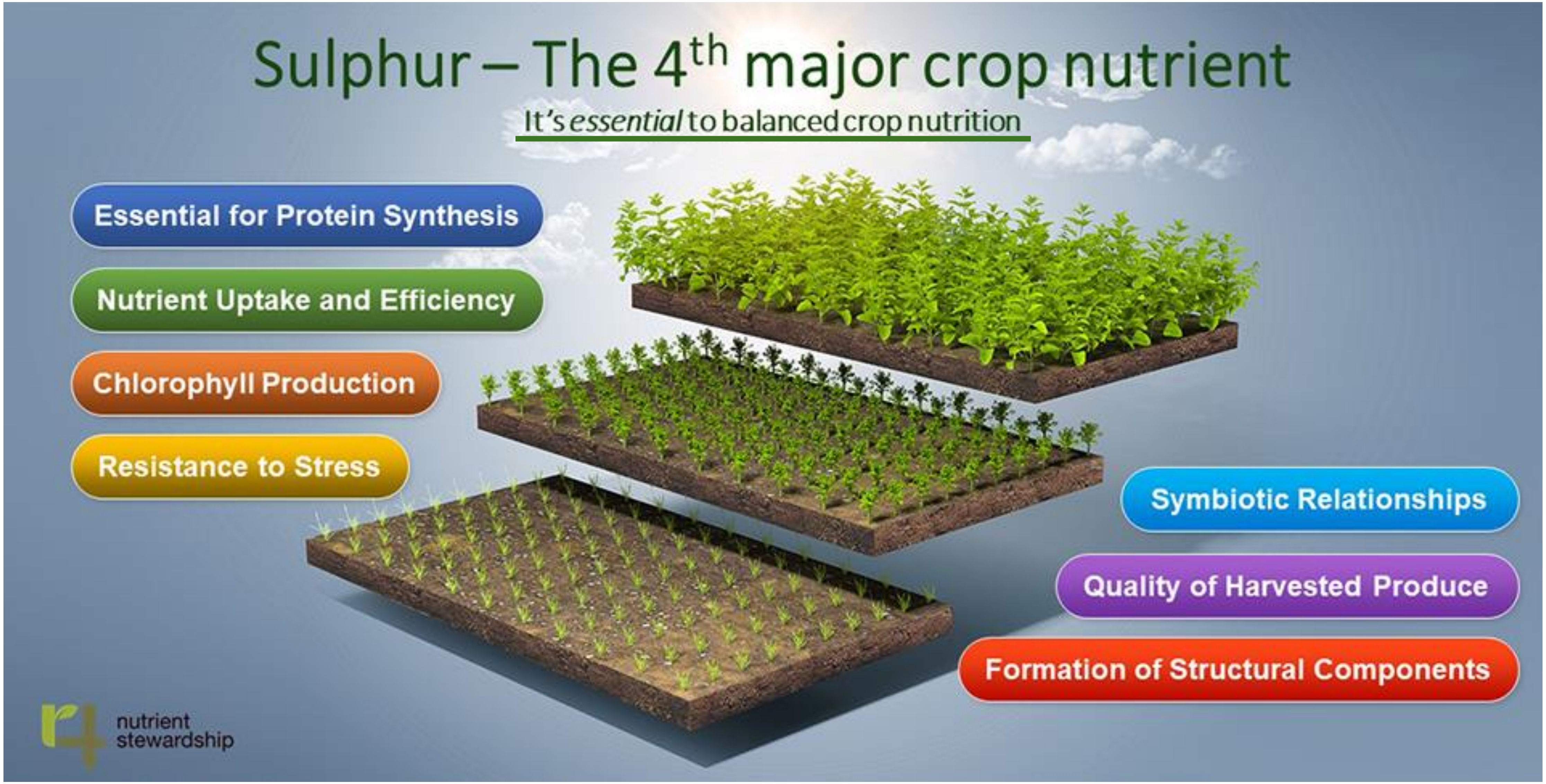
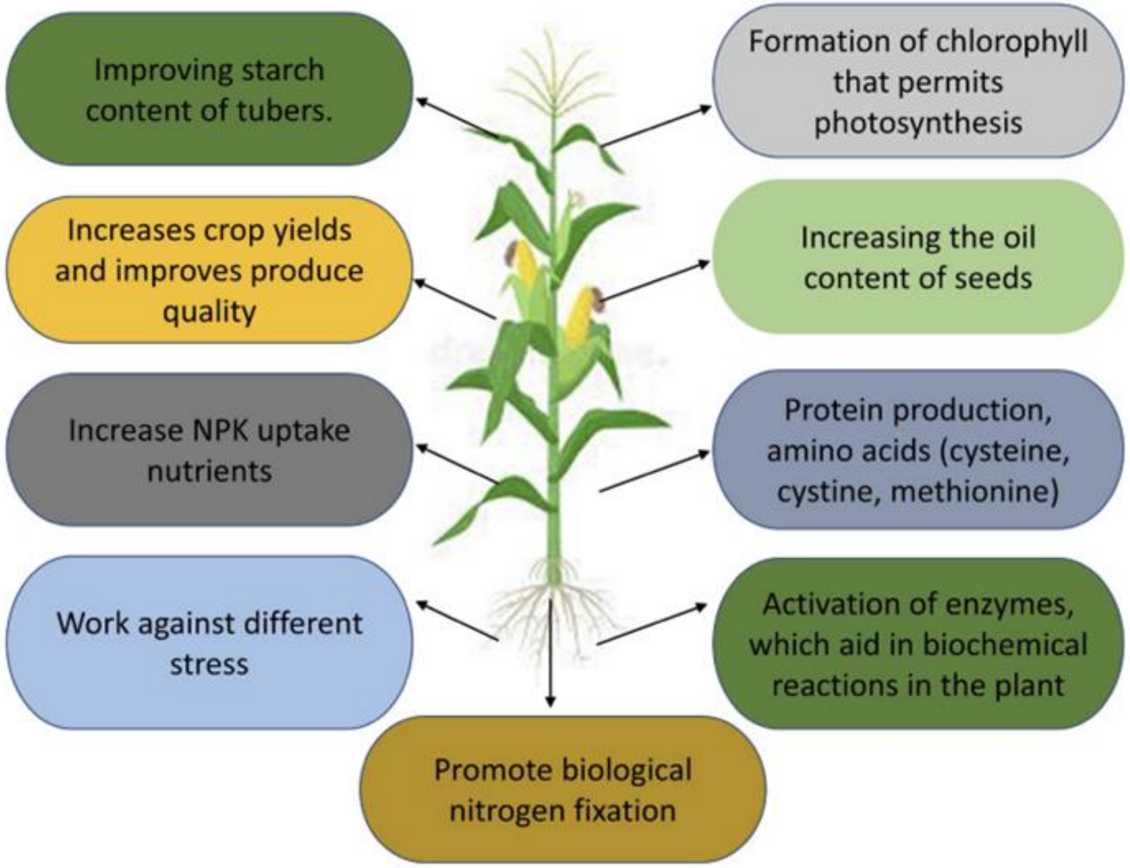
Recognize Sulphur's Critical Roles in Crop Yields and Quality



Sulphur Plays Many Important Roles in Plant Nutrition

Role of Sulphur in Plant Growth and Development

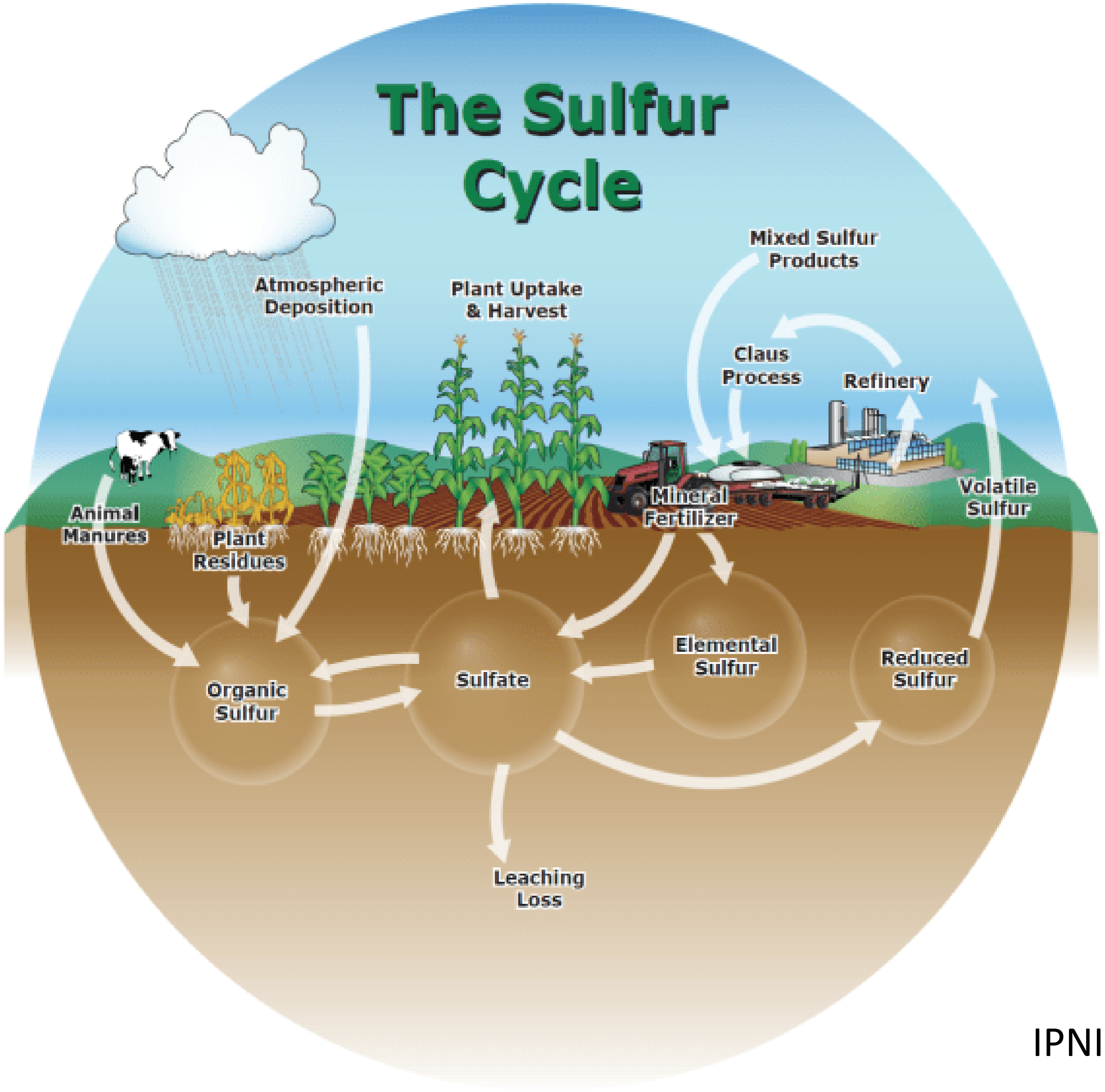


https://www.tandfonline.com/doi/full/10.1080/15592324.2022.2030082

The Behavior of Sulphur is Complex…

…in many ways, similar to nitrogen

- Sulphate is mobile in soil
- Sulphur is readily transformed among forms
- Organic fraction is key soil reserve
- Key element in proteins



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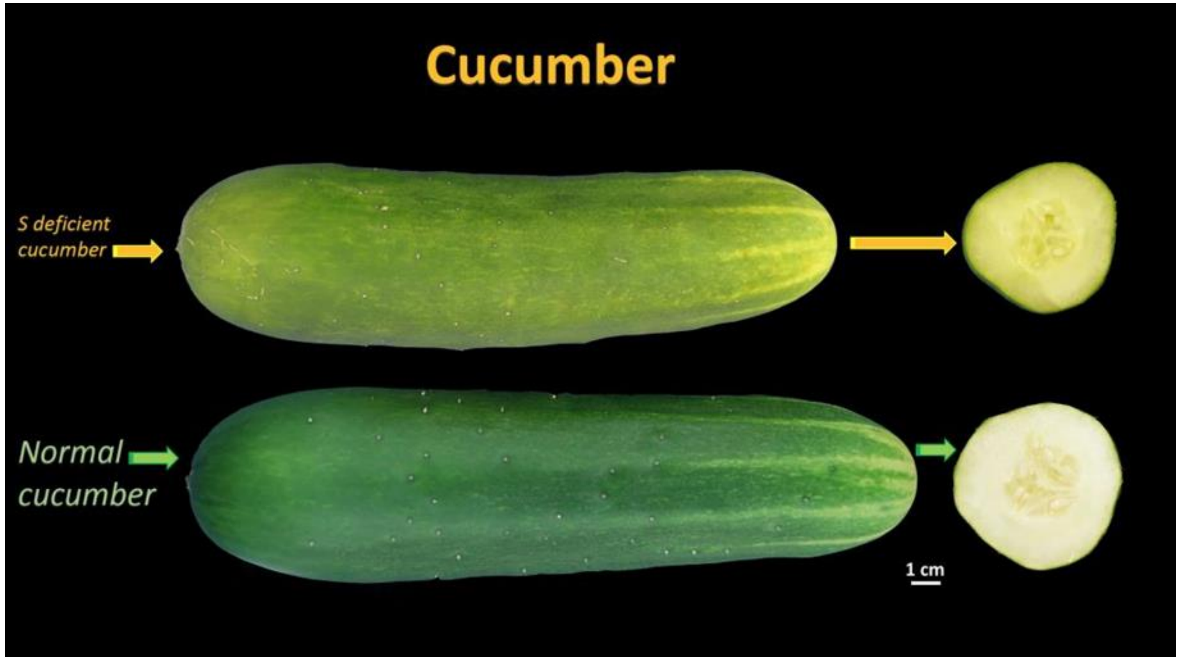
Sulphur Deficiencies Becoming More Common in Crops

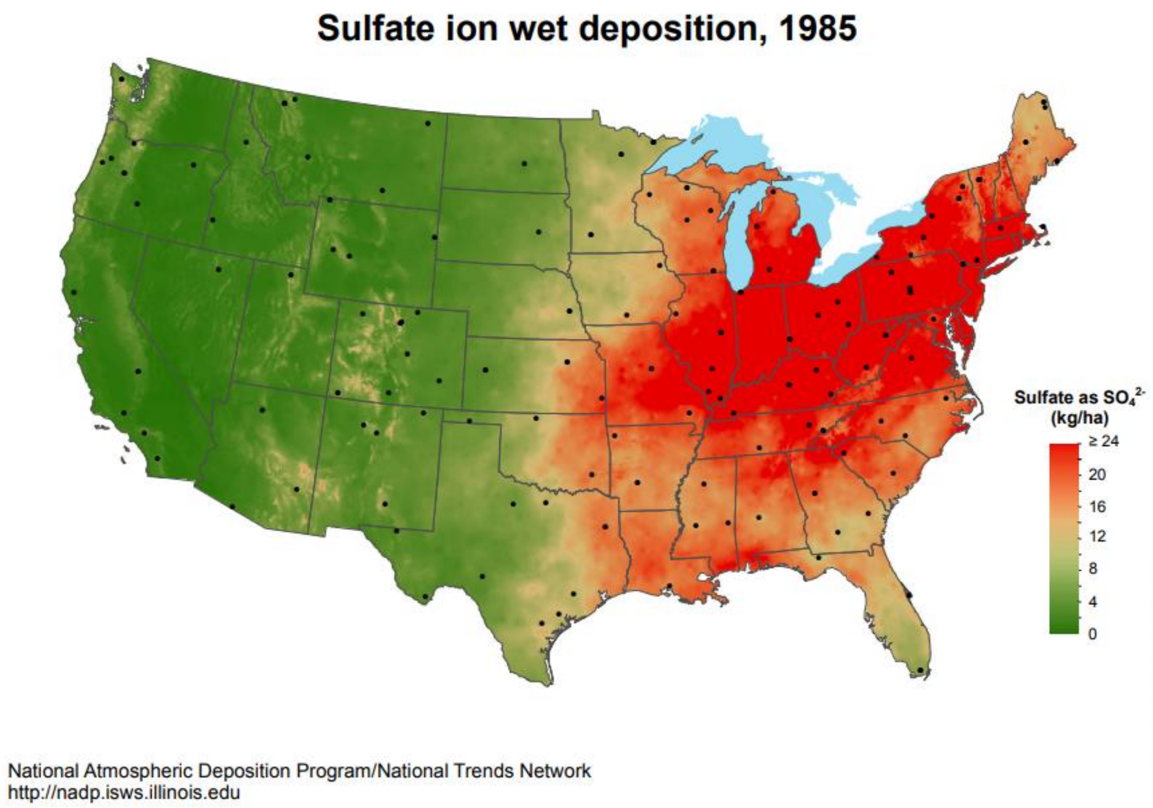
Leading to losses of yield and nutritional quality and increasing stress susceptibility

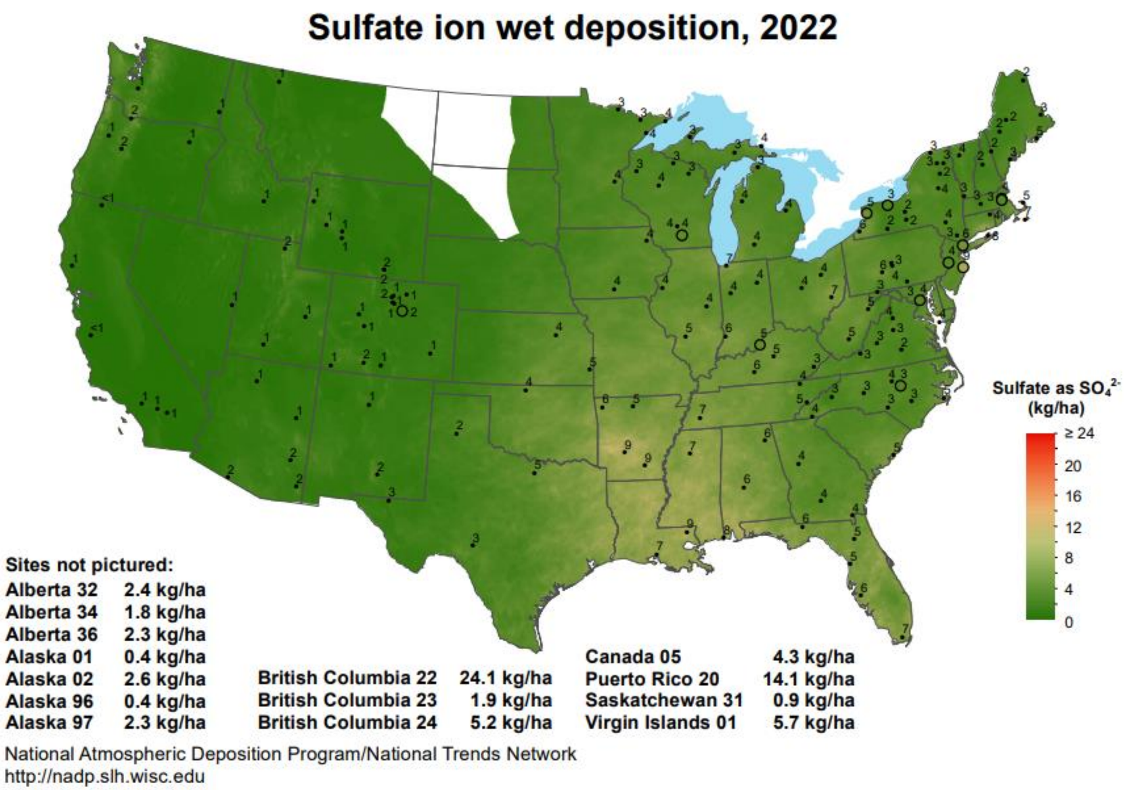
Main reasons behind increasing prevalence of S-deficiency:

- Large reductions in atmospheric S deposition
- Greater S removal with increasing crop yields
- Common use of purer (lower S content) N and P fertilizers
- Less S in other fertilizers and pesticides
- Soil organic matter loss from erosion and soil degradation



Changes to the Sulfur Cycle – Some History



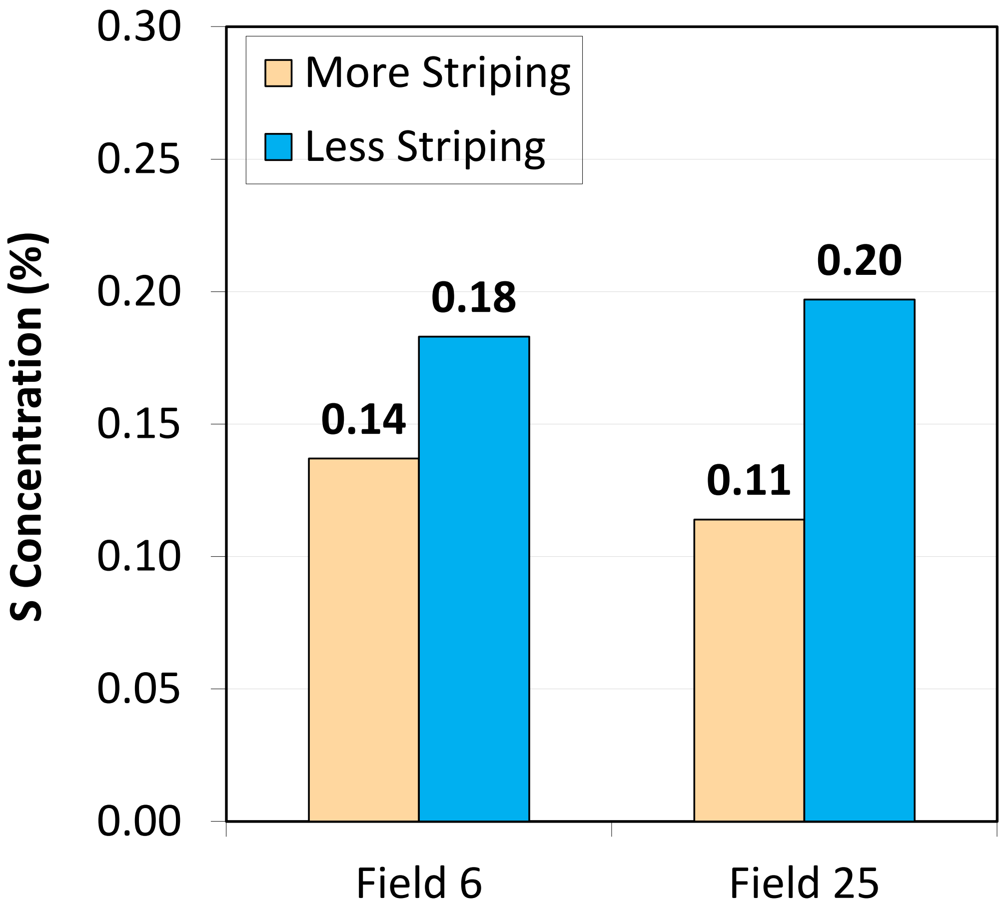


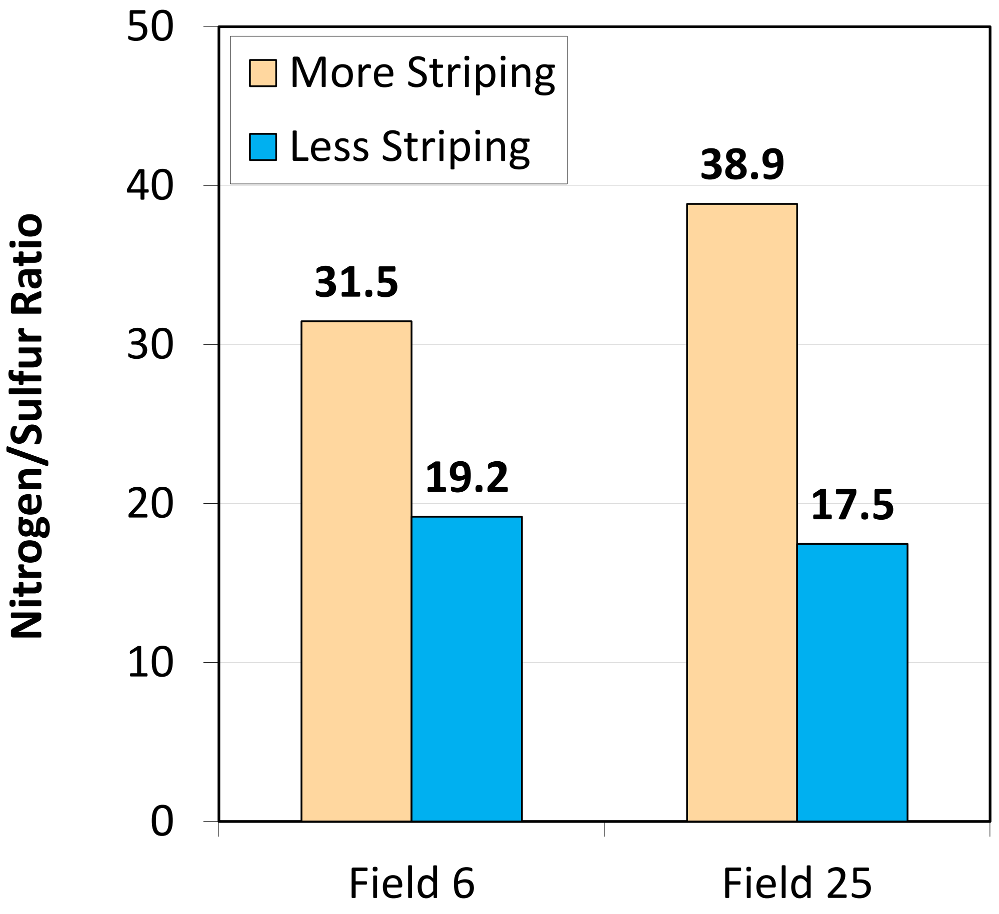
Sulfate ion deposition has declined sharply in the Eastern US since 1985 from amounts exceeding crop need to almost nil.

Sulfur Deficiency in A Nitrogen Study

- Delaware 2005
- Sandy, low organic-matter soils
- Irrigated corn
- N rates and sources

Leaf Nutrient Comparison – Youngest Collared Leaf





Source: Dr. G. Binford, formerly Univ of Delaware

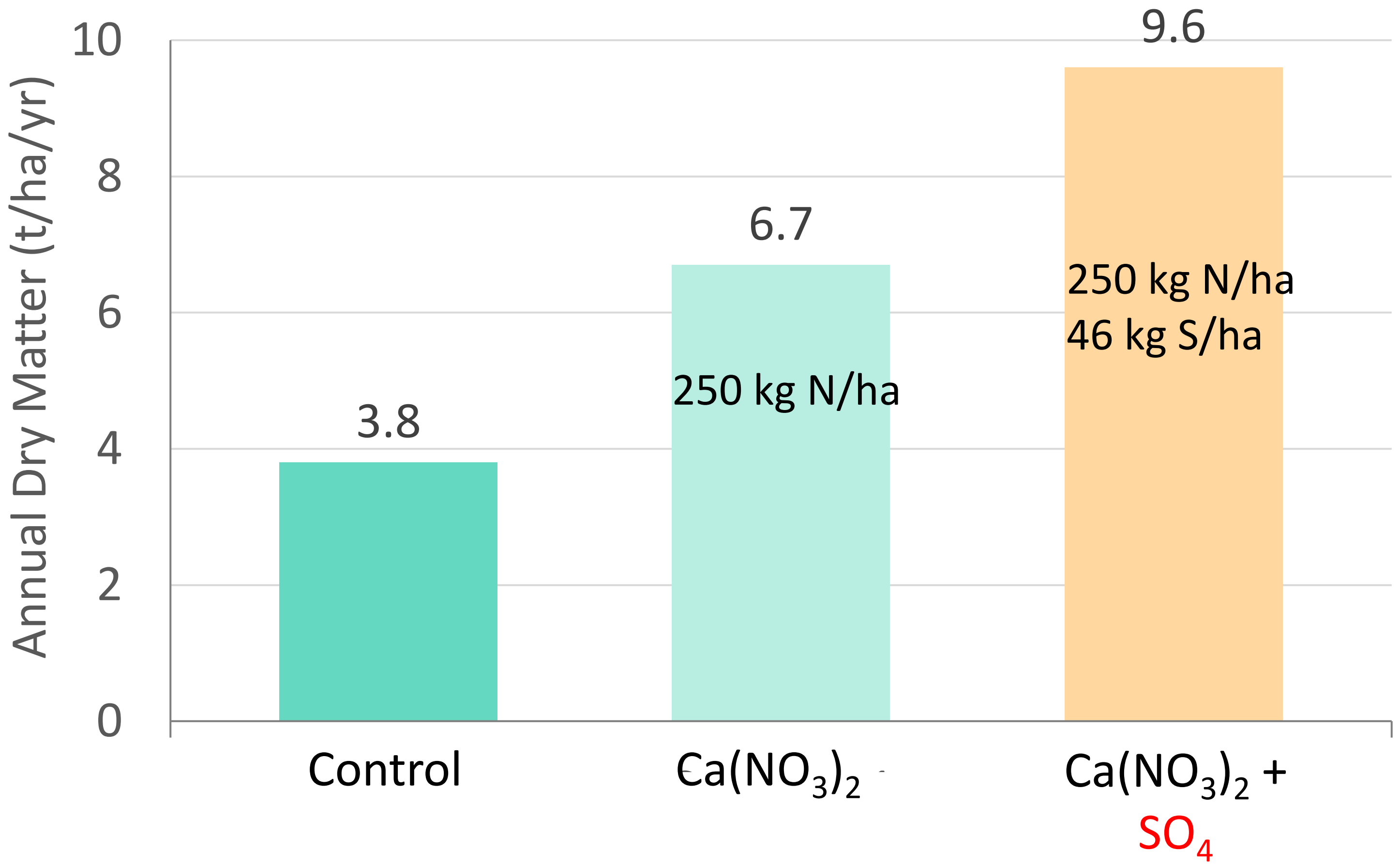
Nitrogen and Sulphur Cannot Be Decoupled in Plant Nutrition

Sulphur deficiency:

- Reduces N-use efficiency
- Reduces nitrate uptake and metabolism
- Reduces protein formation and increases amino acid accumulation
- Increases nitrate and non-protein N accumulation in plant tissue
- Impairs nitrate reductase formation and activity
- Reduces N-fixation by legumes

Strong Synergism Between Nitrogen and Sulphur

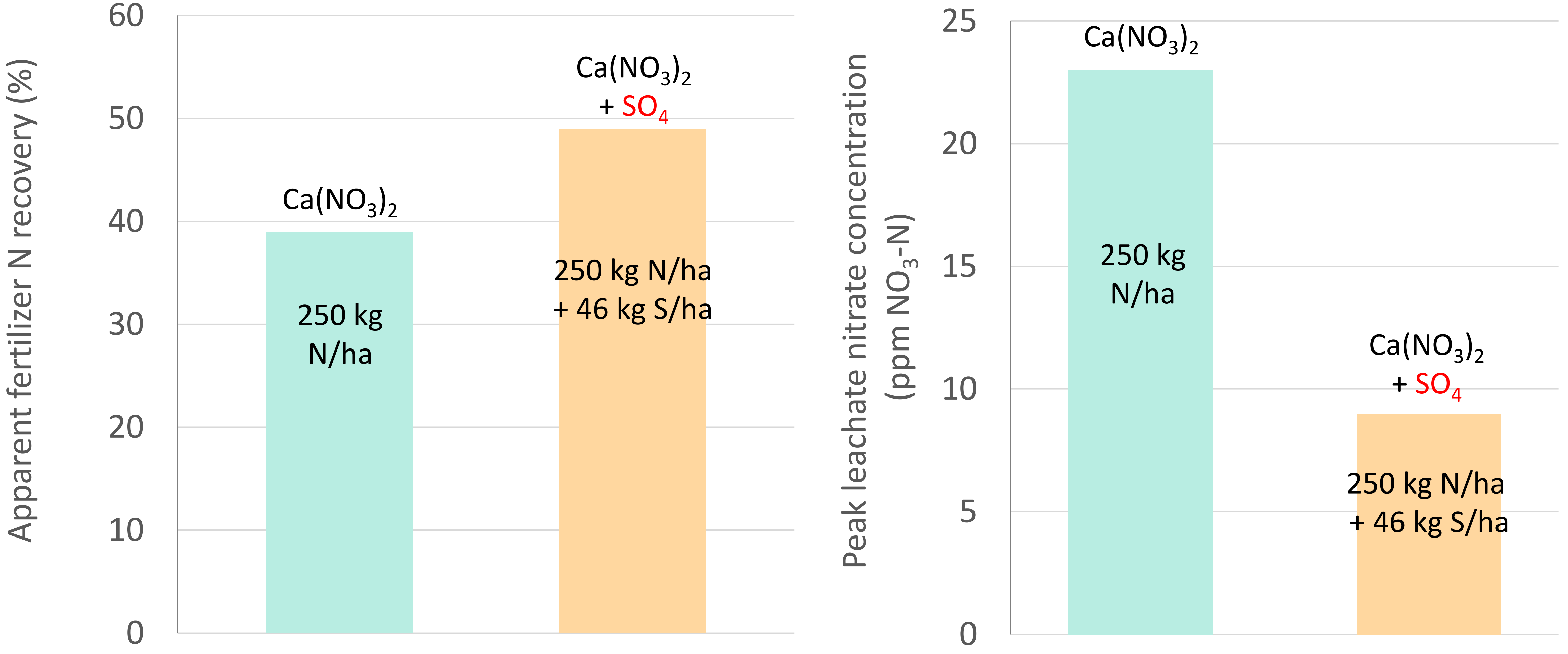
Many examples in the literature - for example, this study on grass production



N:S ratio of ~ 12:1 to 15:1

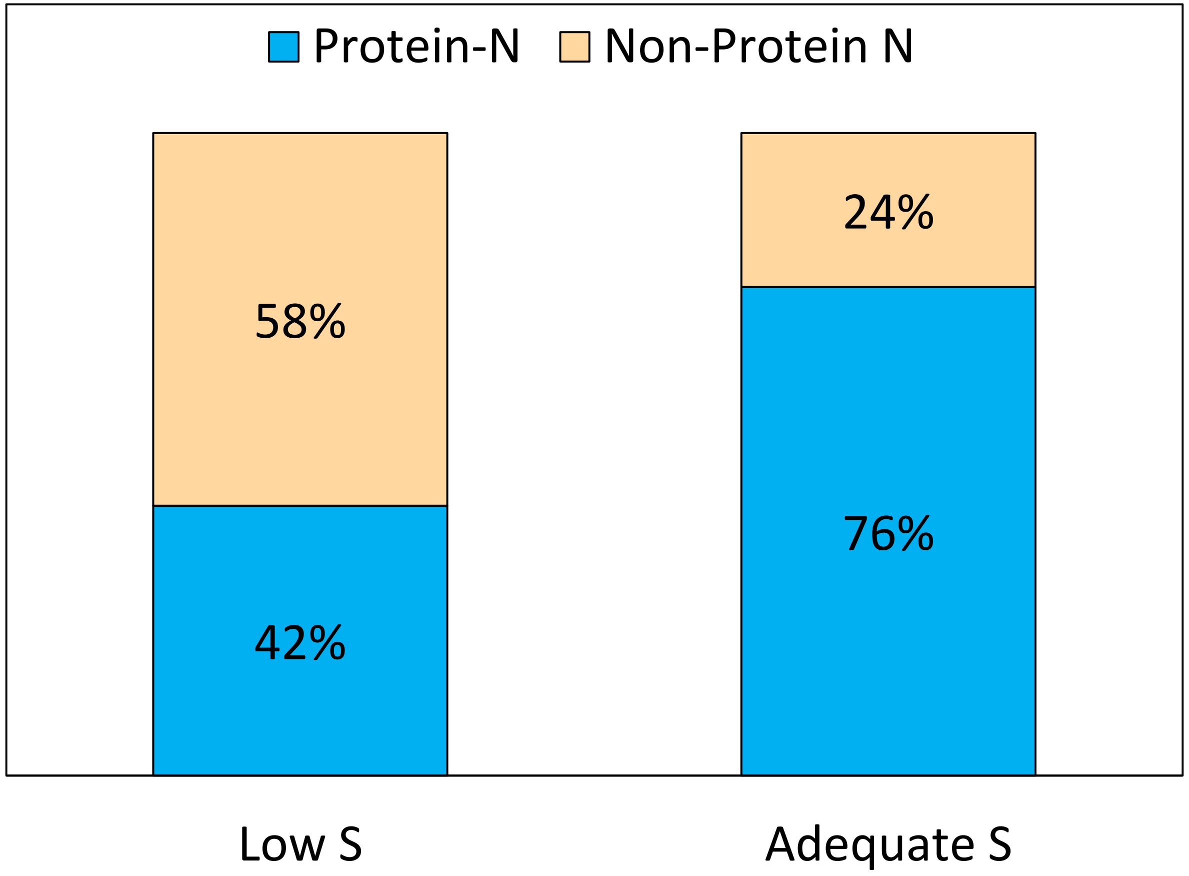
Aspel et al., 2021; adapted from Dr. R. Mikkelsen, Yara, TSI World Symp, 2023

Strong Synergism Between Nitrogen and Sulphur on N-Use Efficiency



Aspel et al., 2021; adapted from Dr. R. Mikkelsen, Yara, TSI World Symp, 2023

Protein Development And Non-Protein-N Influenced By S

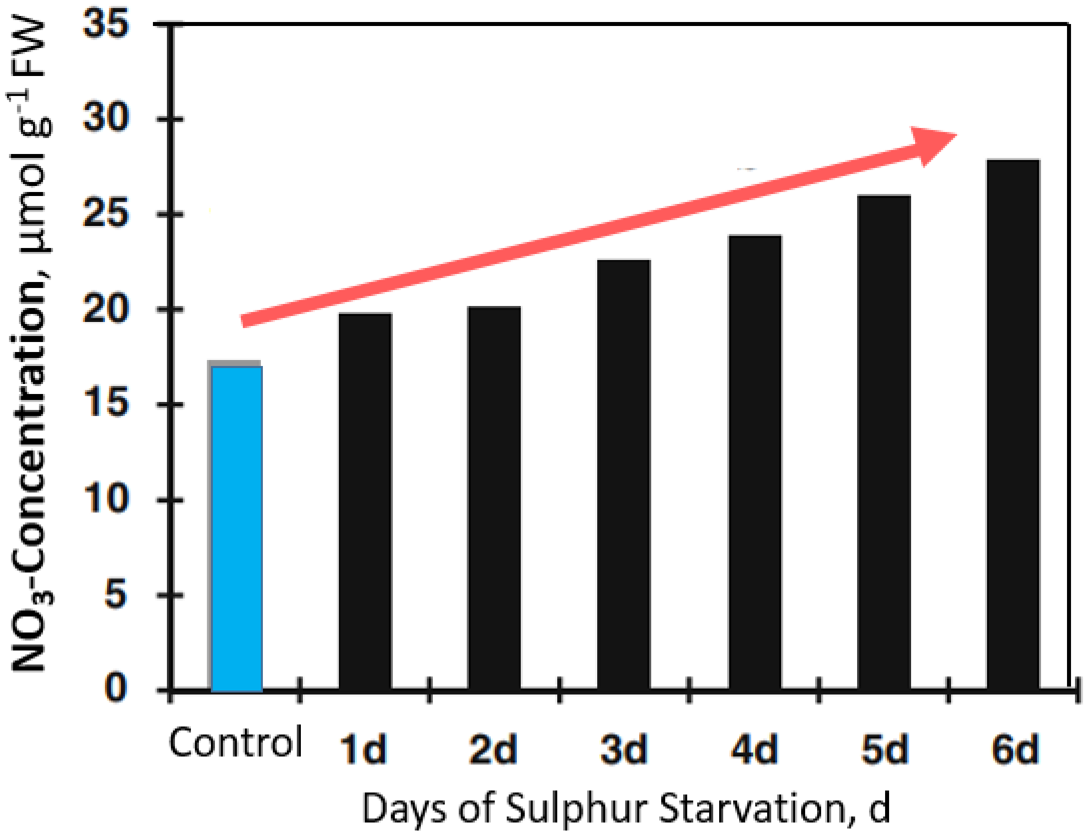


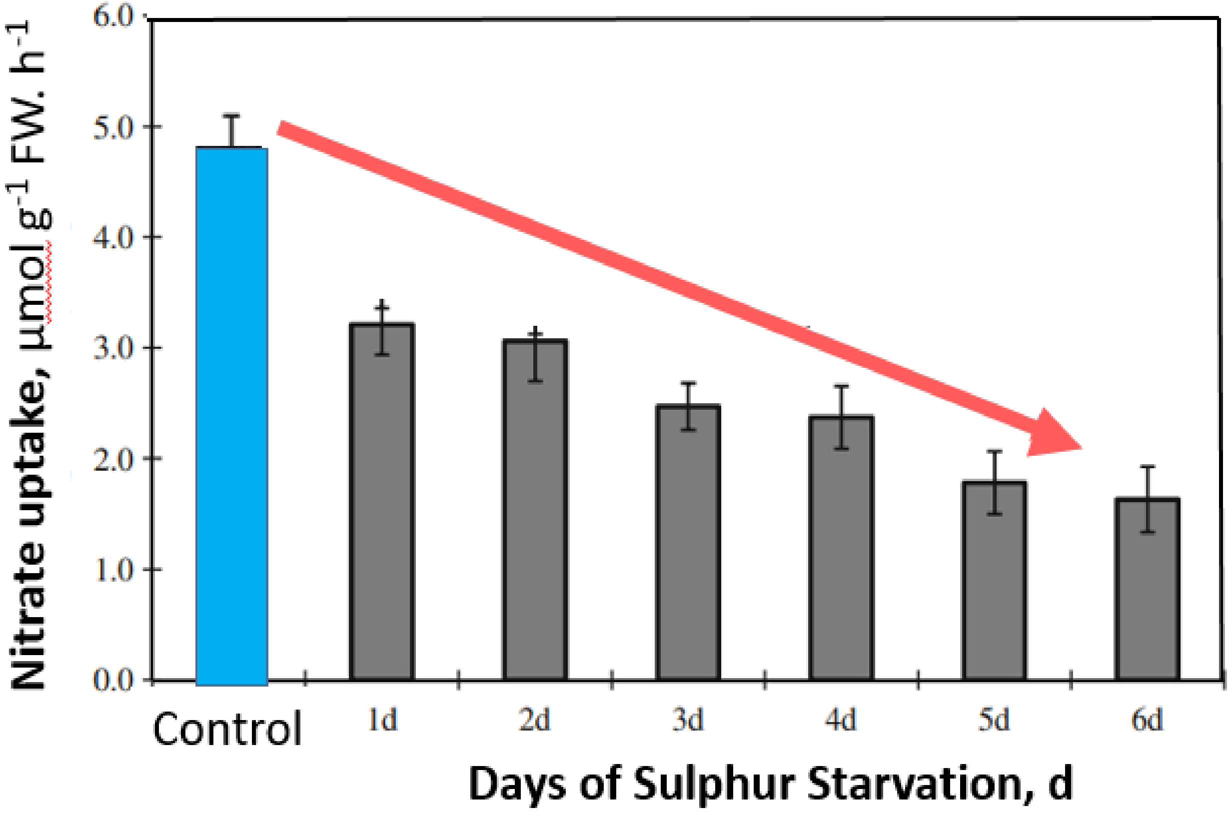
Variety of health effects from consumption of excess nitrate in food

Rending et al. 1976, Plant and Soil 44, 423-437; Adapted from Dr. I. Cakmak, Sabanci Univ., TSI World Symp, 2023

Changes in Leaf NO_3 Concentration and Root NO_3 Uptake During S Starvation

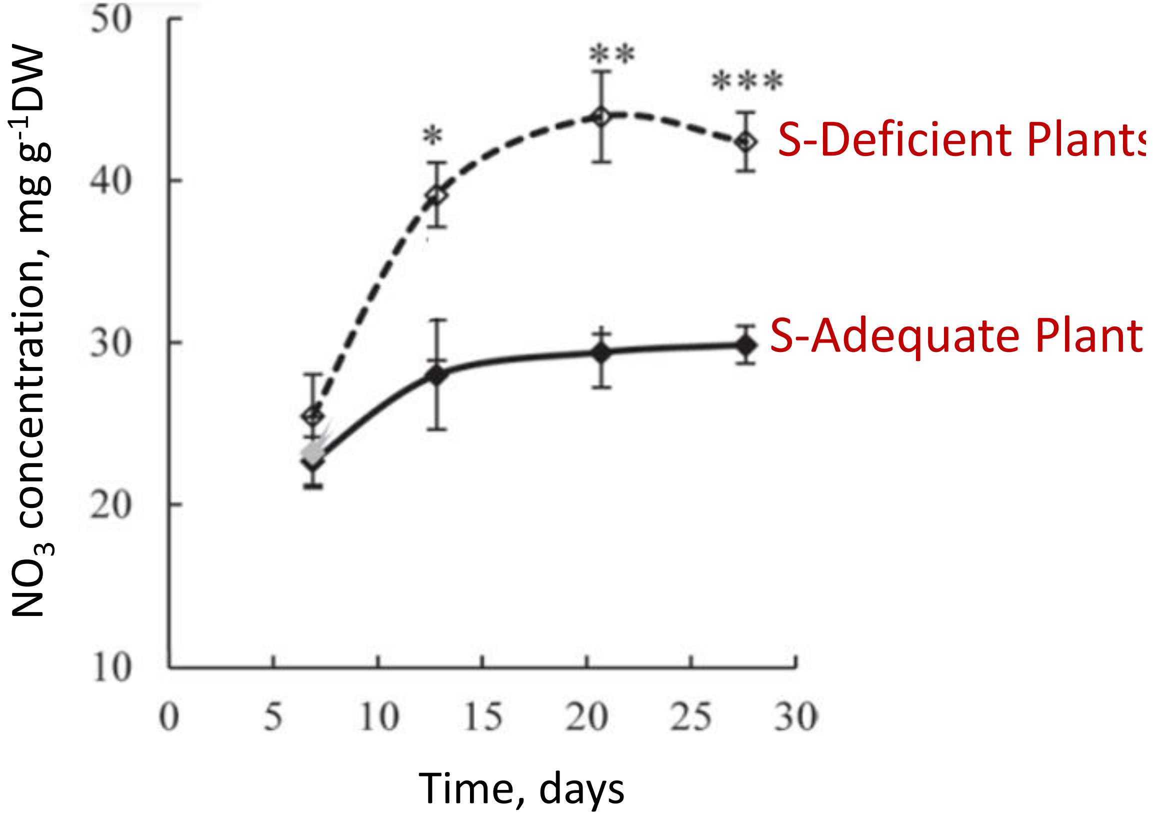
Rapeseed plants were first grown under adequate S and then transferred to growth medium without S for 6 days.

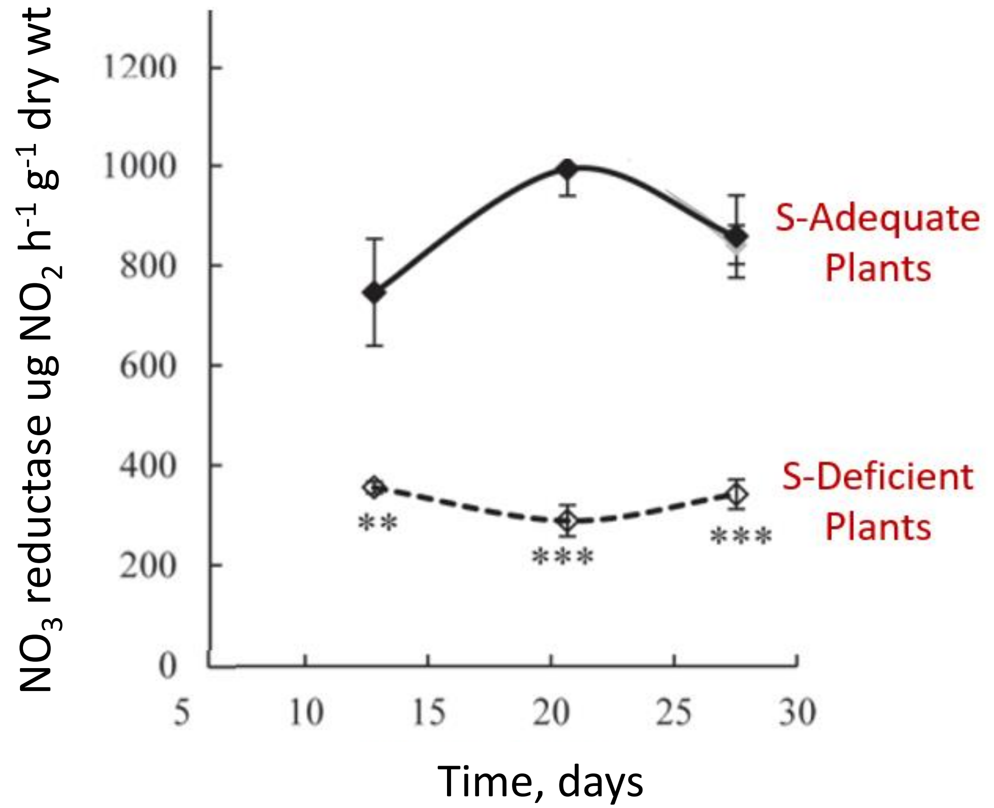




Kaur et al. 2011, Protoplasma, 48:299-311; adapted from Dr. I. Cakmak, Sabanci Univ., TSI World Symp, 2023

Sulfur deficiency has detrimental effects on nitrate uptake, nitrate transport, and nitrate reductase activity, due to signaling mechanisms from high accumulation of free amino acids as a consequence of impaired protein synthesis.





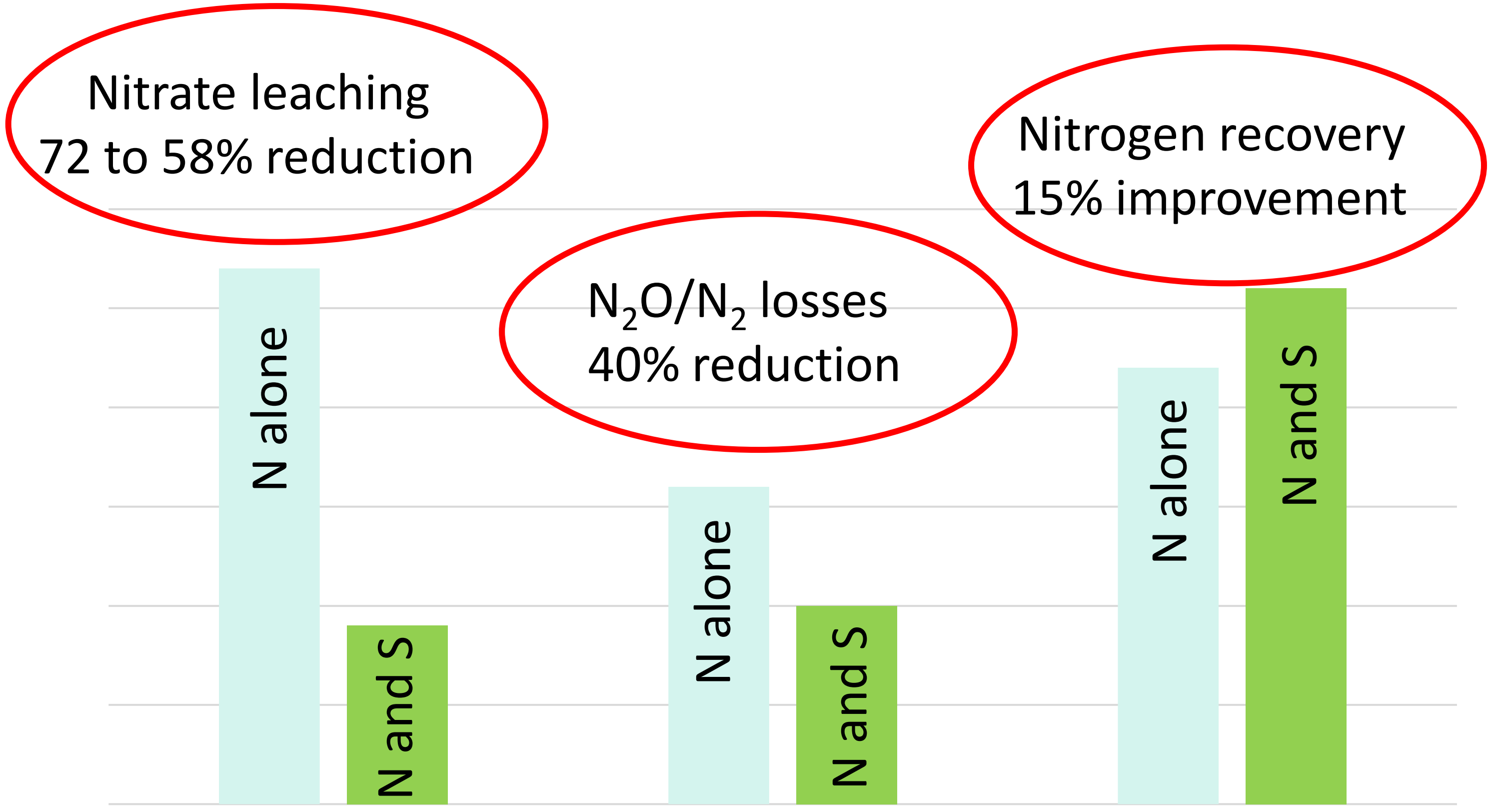
Adequate Sulphur Reduces N Losses and Enhances N-Use Efficiency

N-Use Efficiency – A Global Goal

- Nitrate leaching
- N_2O emissions
- NUE gains

Low N-Use Efficiency

- Economic loss of key crop input
- Air and water quality degradation
- Lost productivity
- Reduced food quality

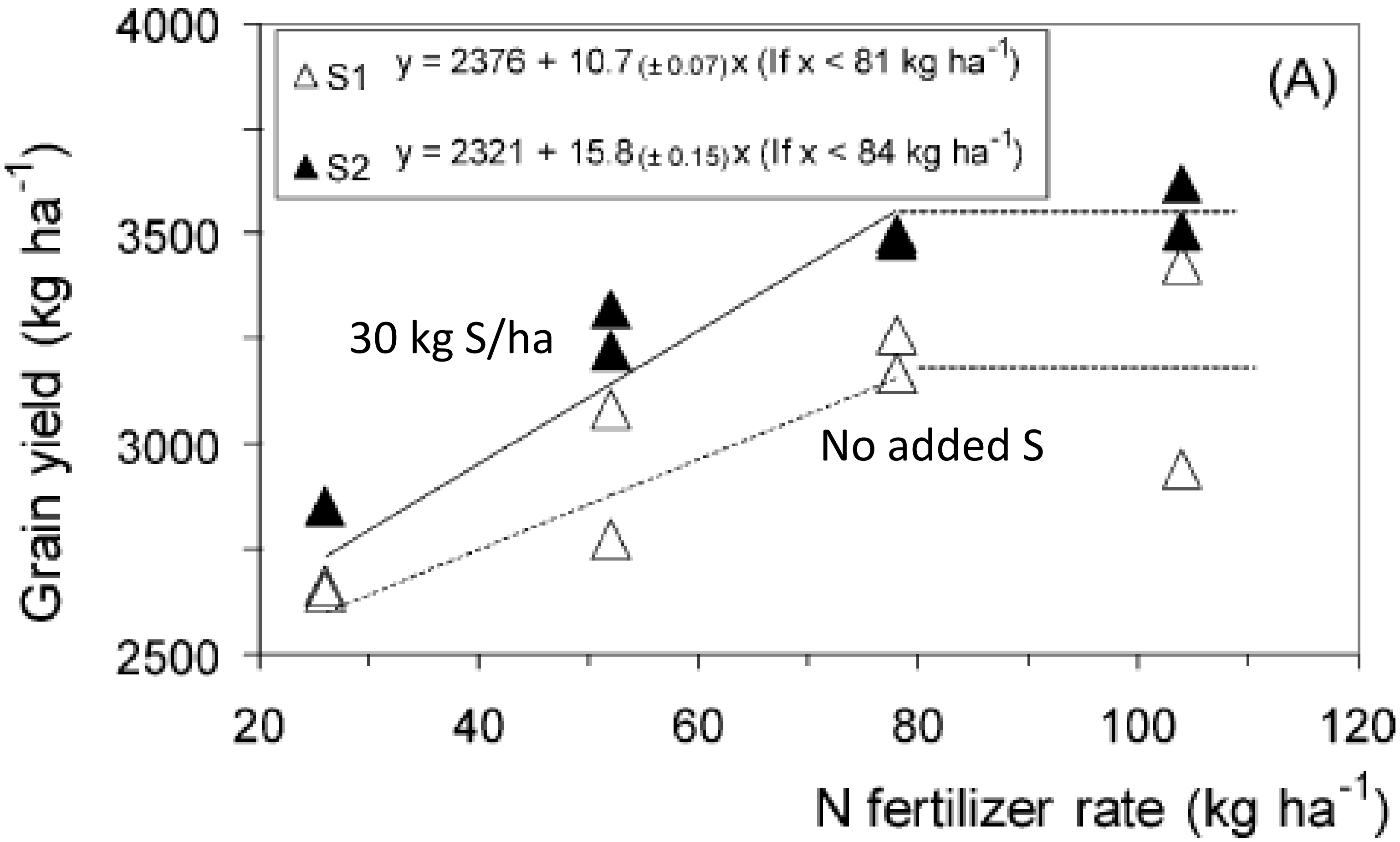


The effect of sulphur application on the efficiency of nitrogen use in two contrasting grassland soils

L. BROWN*, D. SCHOLEFIELD, E. C. JEWKES, N. PREEDY, K. WADGE AND M. BUTLER

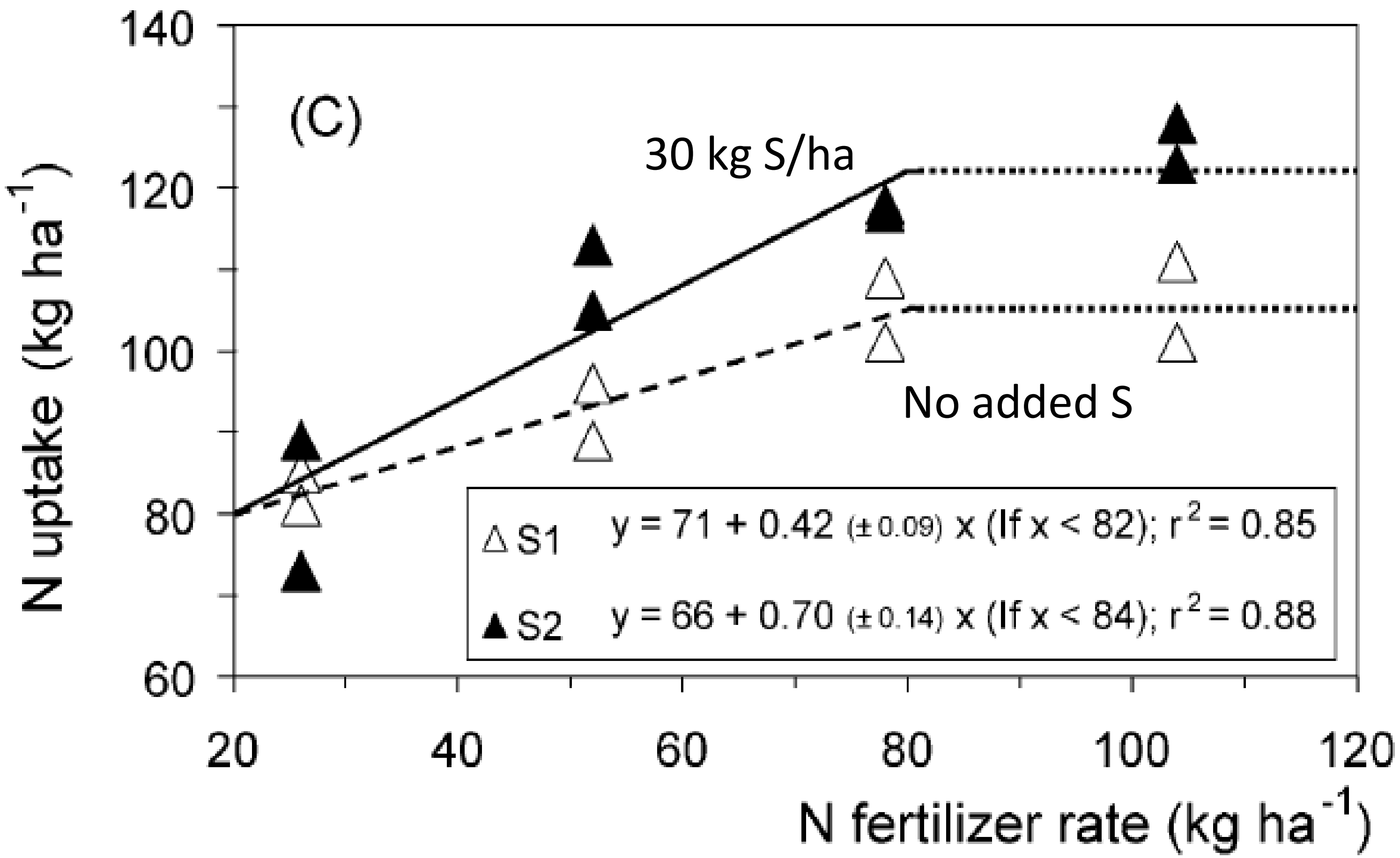
Nitrogen and Sulphur Cannot Be Decoupled in Plant Nutrition

Greater wheat yield and N-use efficiency with adequate S



Nitrogen and Sulphur Cannot Be Decoupled in Plant Nutrition

Adequate S drives greater N uptake



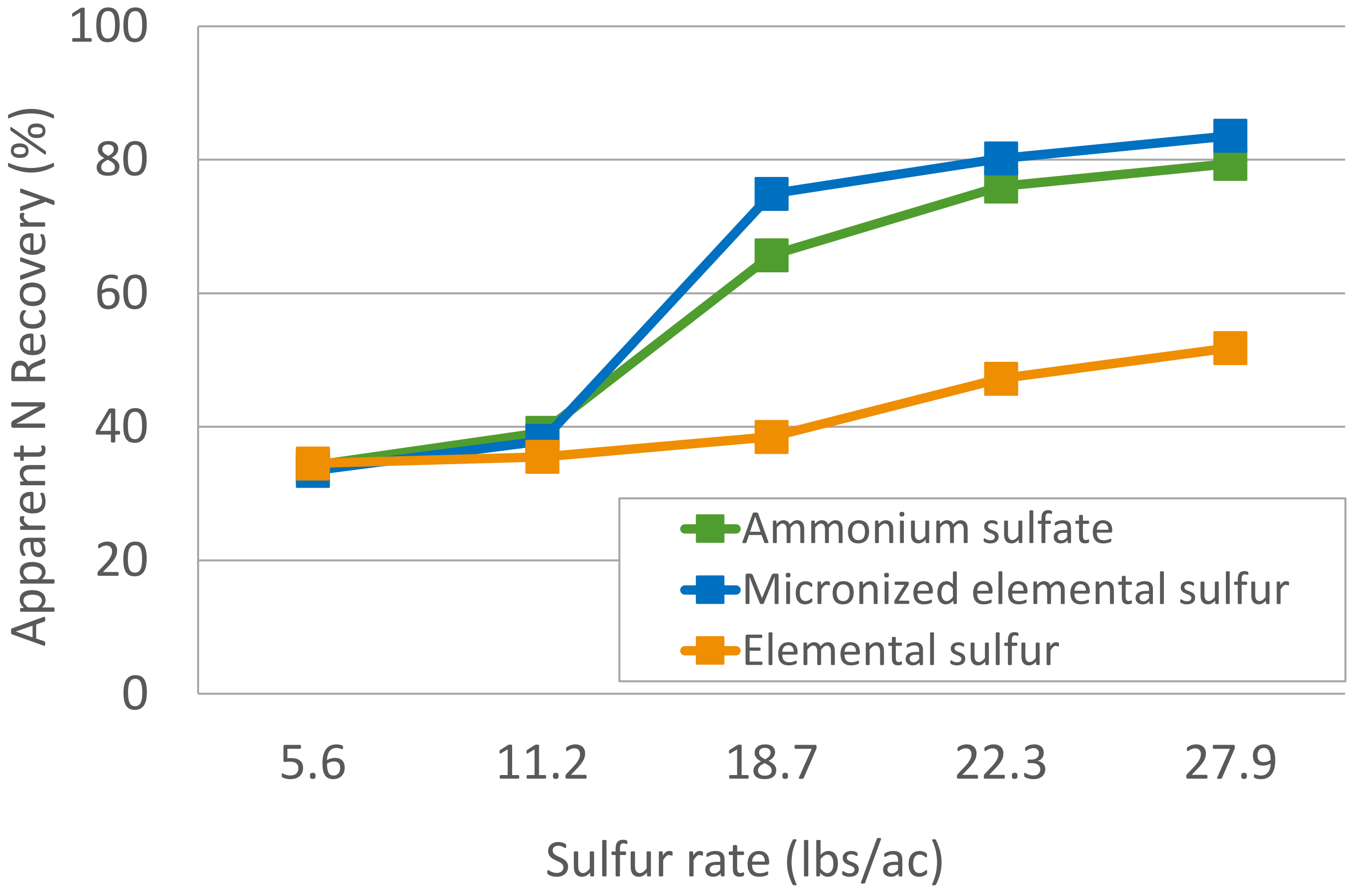
Source: Salvagiotti et al. 2009. Field Crops Res. 113 (2009) 170–177

Sulfur Availability Increases Nitrogen Recovery Efficiency

Increasing sulfur availability increased N uptake and recovery efficiency.

Ammonium sulfate and micronized elemental sulfur produced greater response.

Data represent average of US sites from 2020 to 2022.



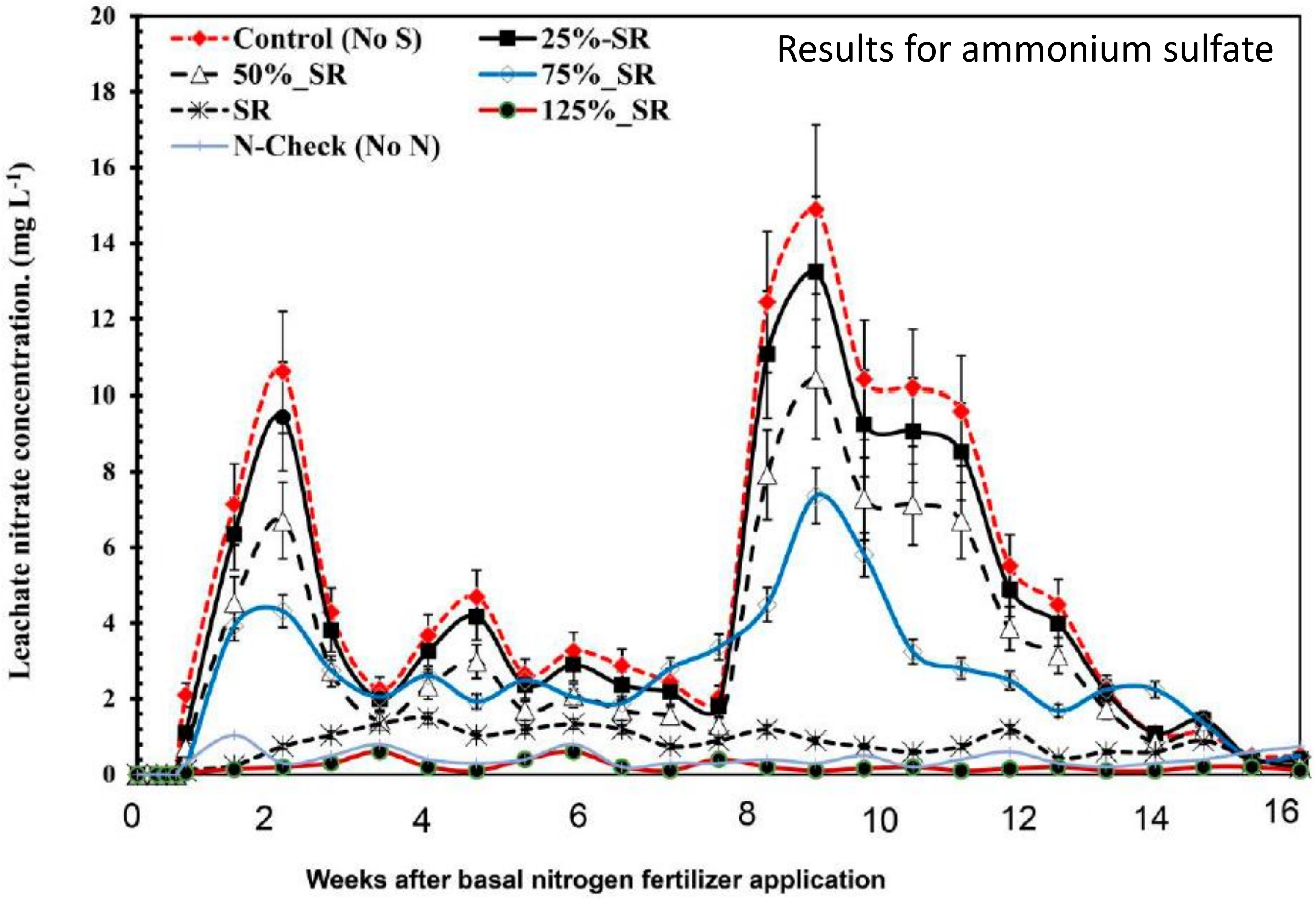
Source: Agyin-Birikorang et al 2024, J Plant Nutr 47:15, 2389-2405.

…And Minimizes Nitrate Losses

"Sulfur Availability Minimizes Nitrate Leaching Losses In Vulnerable Agricultural Soils"

From these studies we can conclude:

- Sulfur is a key regulating element in plant N use
- Sulfur can be a key element in optimizing N-use efficiency
- Balancing sulfur with nitrogen could be a tool to help reduce N losses



Source: Agyin-Birikorang et al 2024, J Plant Nutr 47:15, 2389-2405. Average of six sites and three years (2020-2022).

Nitrogen and Sulphur Interactions – Induced S Deficiency

How Is Sulfur Affecting Our Assessments of Nitrogen-Use Efficiency?

How much is sulfur deficiency confounding…

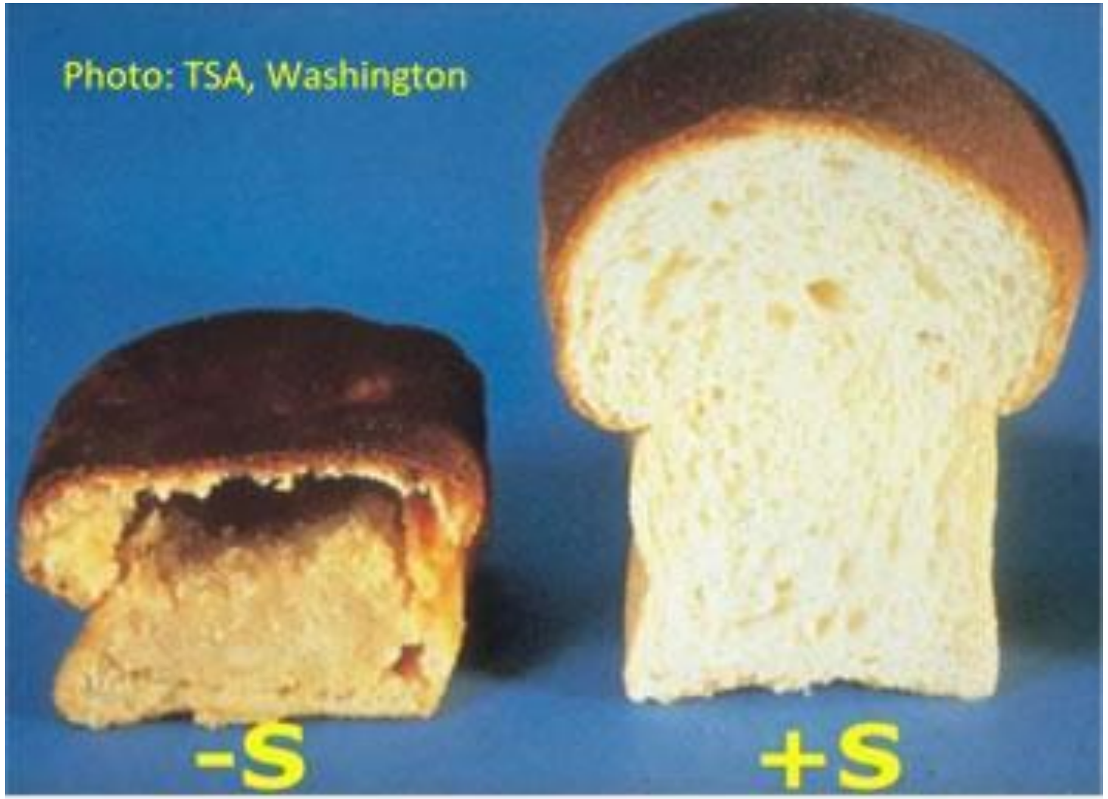
- nitrogen response observations?
- understanding of N-use efficiency?
- sensor measurements and calibration?

Sulphur Enhances Food Quality

Nitrogen and sulphur impact biomass and grain **yield** (esp. grain size)

Insufficient S produces poor baking **quality** occurs before yield is impacted [N:S ~16:1 suggested]

Insufficient formation of S-rich proteins and change in dough properties



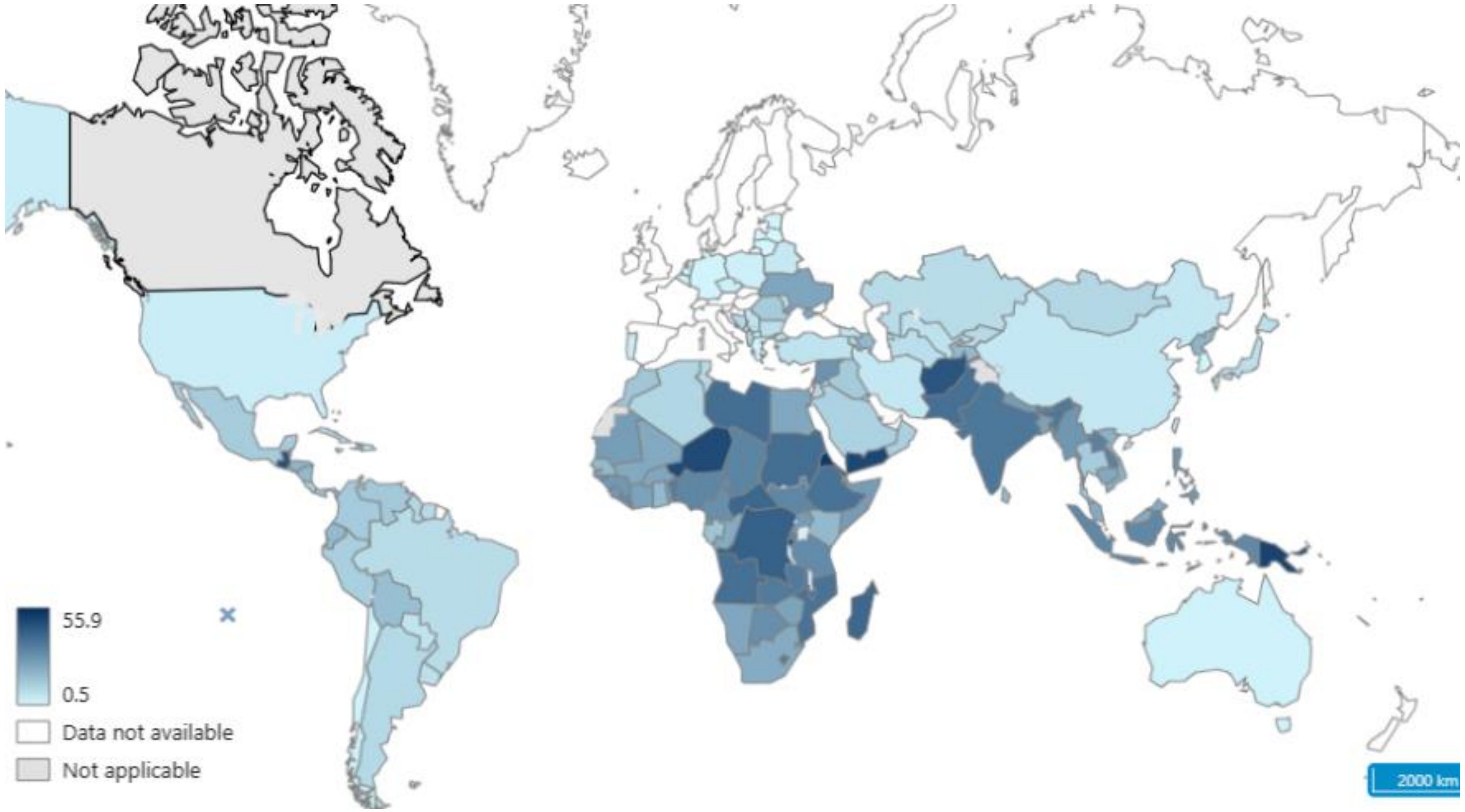
Micronutrient Deficiencies a Global Health Concern

Stunting in children linked to micronutrient nutrition, particularly zinc, during early childhood.

Micronutrient deficiencies affect >2 billion people with serious health complications and economic burden (Bouis and Saltzman, 2013; Global Food Sec.; Byerlee and Fanzo, 2019: Global Food Sec)

Published research shows sulfur nutrition is highly beneficial for better root uptake, root-to-shoot transport, and translocation of Zn and Fe into grain.

Stunting prevalence in children under age 5 – percentage.



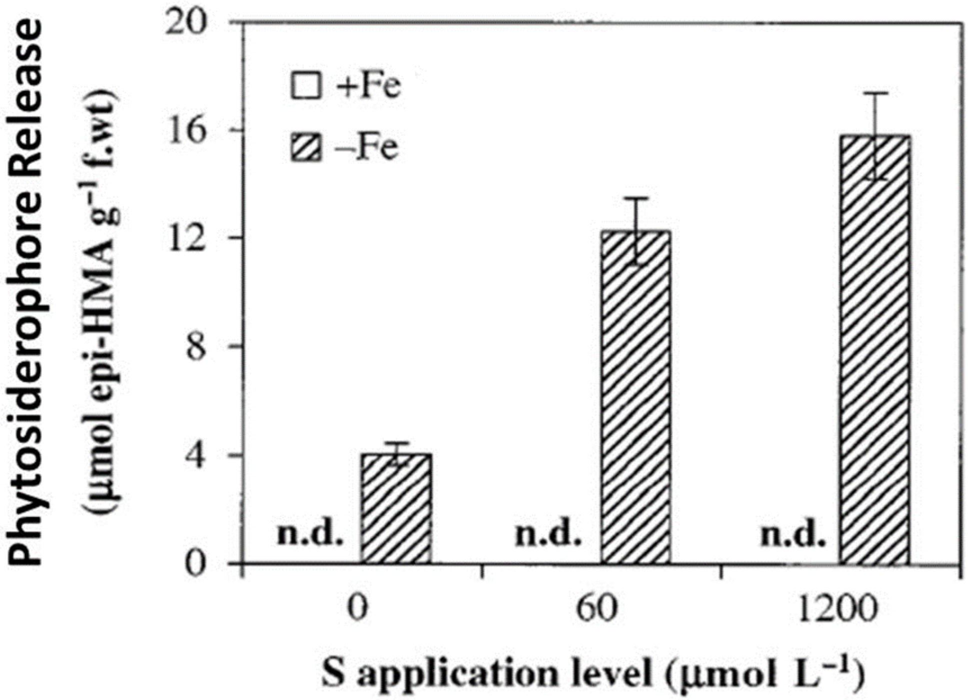
Source: WHO: https://www.who.int/data/gho/data/indicators/indicator-details/GHO/gho-jme-country-children-aged-5-years-stunted-(-height-for-age--2-sd)

Sulphur Promotes Uptake of Iron (Fe) and Zinc (Zn) – Two Examples

Phytosiderophores

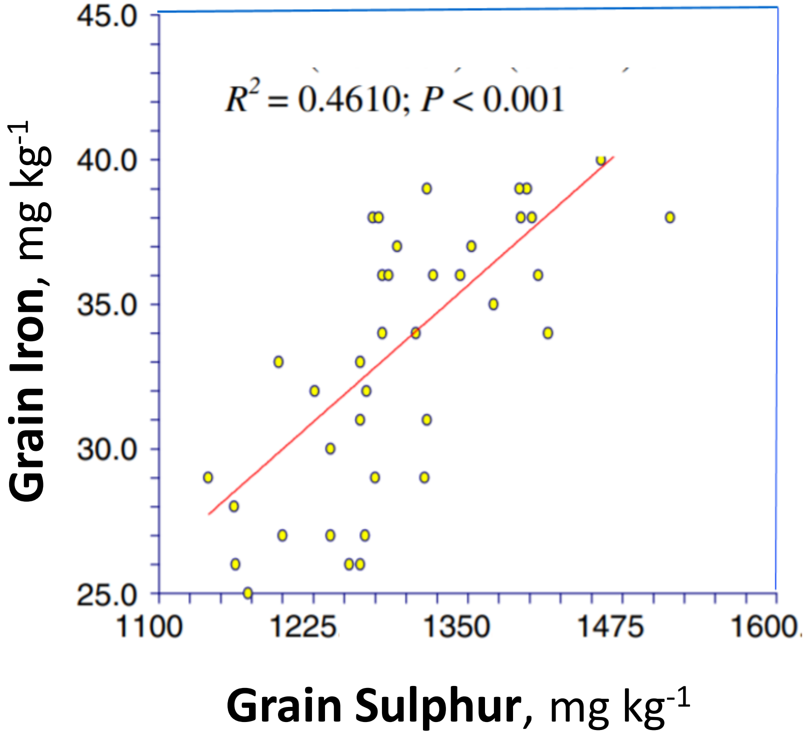
Cereals respond to iron deficiency by root exudation of iron and zinc chelating substances called **phytosiderophores** highly effective in solubilizing sparingly soluble inorganic Fe(III) compounds. Phytosiderophores are also important for iron and zinc translocation.

Biosynthesis and root release of phytosiderophores depends on adequate S nutrition of plants



Phytosiderophore release enhanced with added S. *Astolfi et al. 2006, Soil Sci. Plant Nutr.*

Sulphur Promotes Uptake of Iron (Fe) and Zinc (Zn) – Two Examples



Reduced dietary intake of micronutrients in low-income, cereal-based diets is a key global health problem.

Improving S nutrition of crops could contribute to better mineral nutritional value of cereal diets (biofortification).

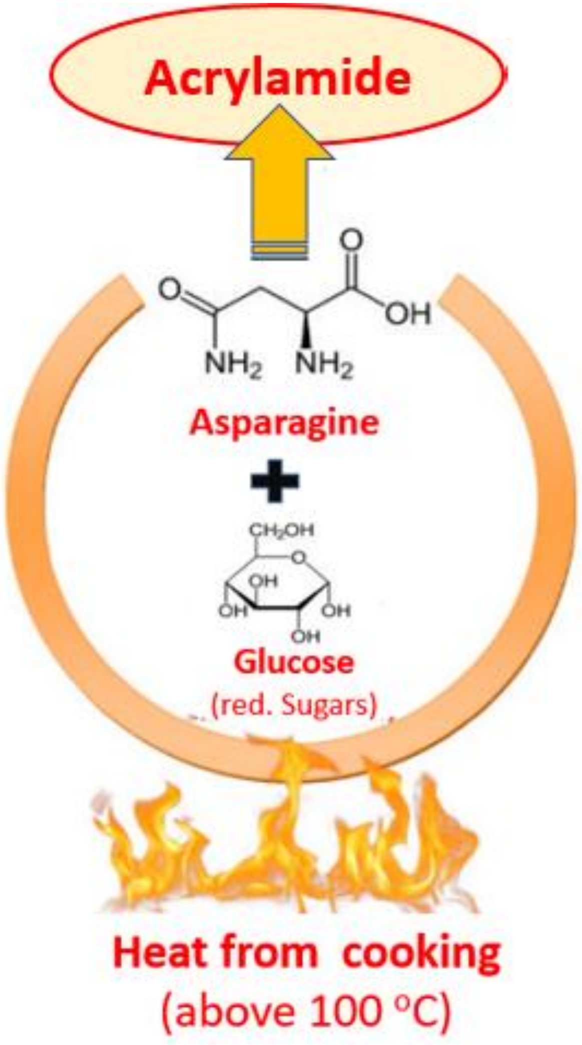
Nicotianamine

Nicotianamine (NA) occurs in all plants, is a well-known Zn and Fe chelator, and is involved in Fe and Zn translocation within plants, especially in seeds.

Synthesis of nicotianamine depends on sufficient S nutritional status of plants. S-containing methionine is a precursor for biosynthesis of nicotianamine.

Adapted from Dr. I. Cakmak, Sabanci Univ., TSI World Symp. 2023

Presence of Acrylamide in Foods Cooked at High Temperatures



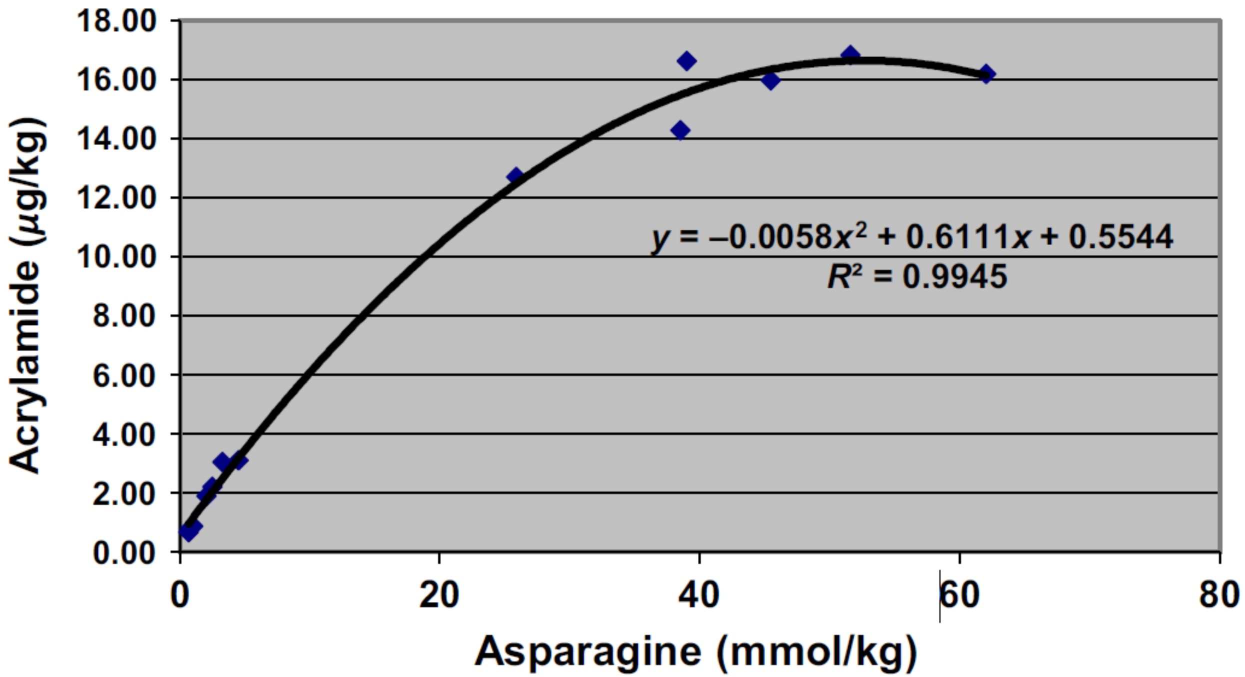
Adapted from International J. Pharmacology, *2014, 10: 182-199.*

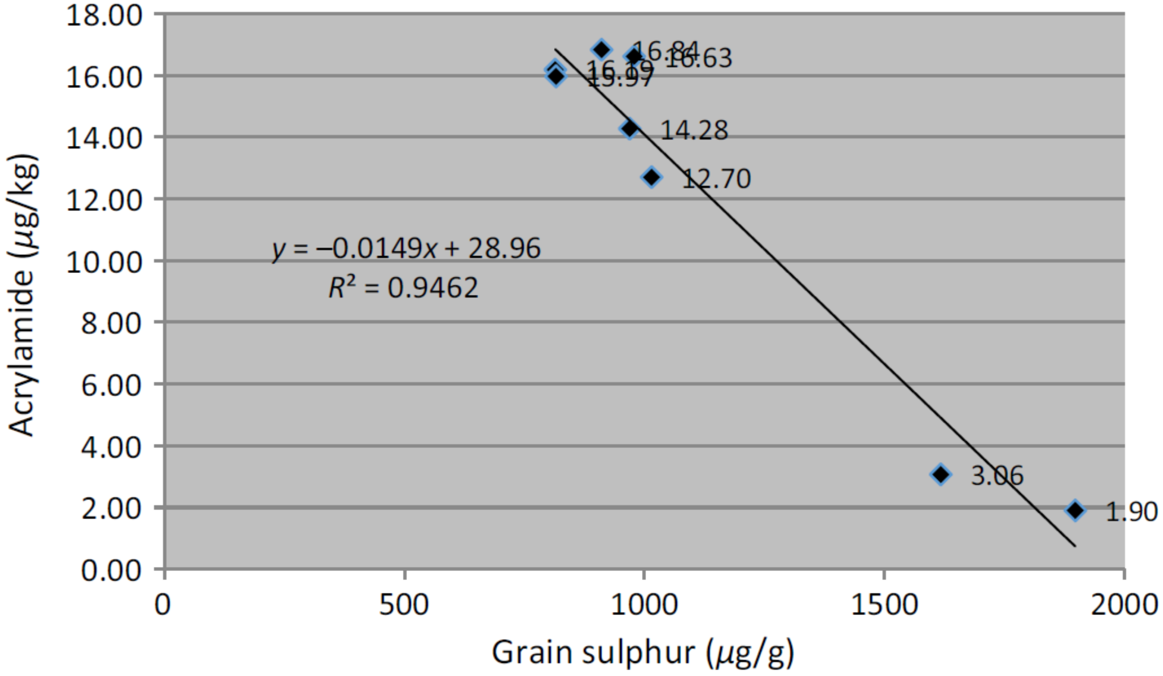
- Acrylamide is generated during food processing at high temperatures – involves reducing sugars and <u>free asparagine</u>.
- Acrylamide present in a range of fried and oven-cooked foods is worldwide concern – classified as probable carcinogen
- Asparagine is major amino acid in potatoes and cereals.
- High nitrogen rates increase asparagine and acrylamide.
- *Mottram et al. 2002, Nature 419, 448–449*

Better Sulfur Nutrition Decreases Flour Acrylamide Content

Acrylamide concentrations in heated wheat flour decrease with increasing grain S.

- “Sulfur deficiency in particular causes a massive accumulation of free asparagine in wheat grain which should be avoided: an application rate of [20 lbs/ac] is recommended, more if the soil is already sulfur deficient.”
- “Nitrogen fertilizer is required to maintain the yield and quality of the crop, but excessive application should be avoided.”



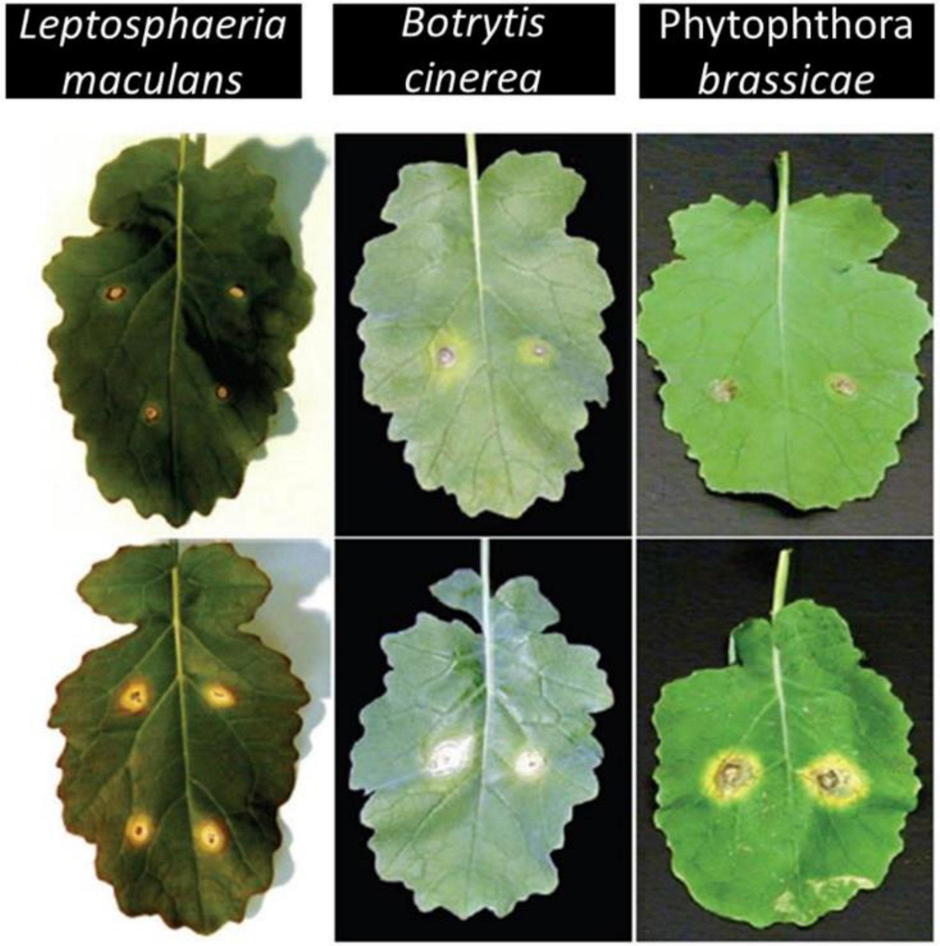


Sulphur, Crop Stress, and Disease

Nutritional and physiological changes in low-S crops increase susceptibility to stress and disease.

Adequate S is required for production of sulfur-containing compounds such as antifungal proteins (e.g., defensins), allicins, phytoalexins, glutathione, and glucosinolates which play an important role in defense against pathogens.

Field observations show positive correlation between S-fertilization and enhanced disease resistance.
Dubuis et al 2005: J. Phytopathol.153, 27–36 Weinmann et al., 2023 in Marschner's Mineral Nutrition of Plants



Adequate Sulfur

Low Sulfur

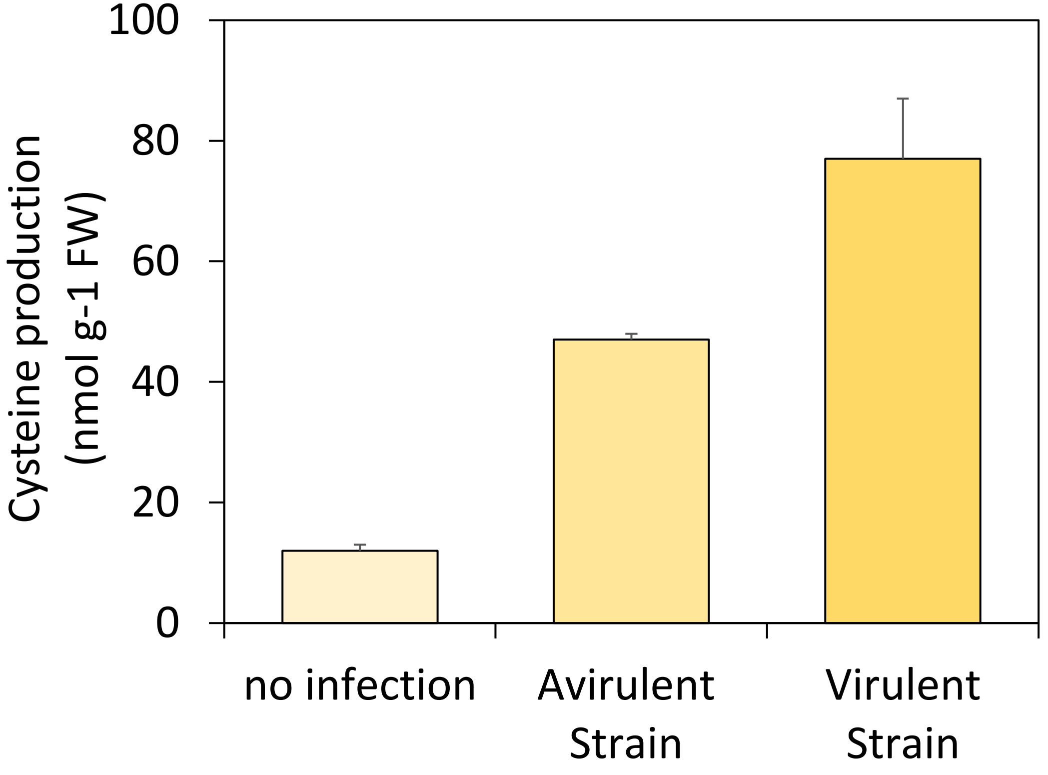
Cysteine, a Sulfur Amino Acid, Helps Control Fungal Diseases

Research indicates cysteine has properties of controlling fungal diseases

- May act as an early signal directing plant host reaction or
- Act directly on fungal development
- Cysteine inhibits mycelial growth and spore germination of fungal pathogens Phaeomoniella chlamydospora and Phaeoacremonium minimum

Roblin et al., 2018, Plant Physiol. Biochem. 129 :77–89

Cysteine increases after inoculation of Arabidopsis with the bacterial pathogen P. *Syringae*



Kruse et al 2007, Plant Biol. 9: 608 – 619

Glutathione, a Sulfur Compound, is An Antioxidant

Glutathione plays a key role in tolerance to biotic and abiotic plant stress conditions

Leaf concentrations of sulfur and **glutathione (GSH)** of canola plants grown with adequate or low S fertilization.

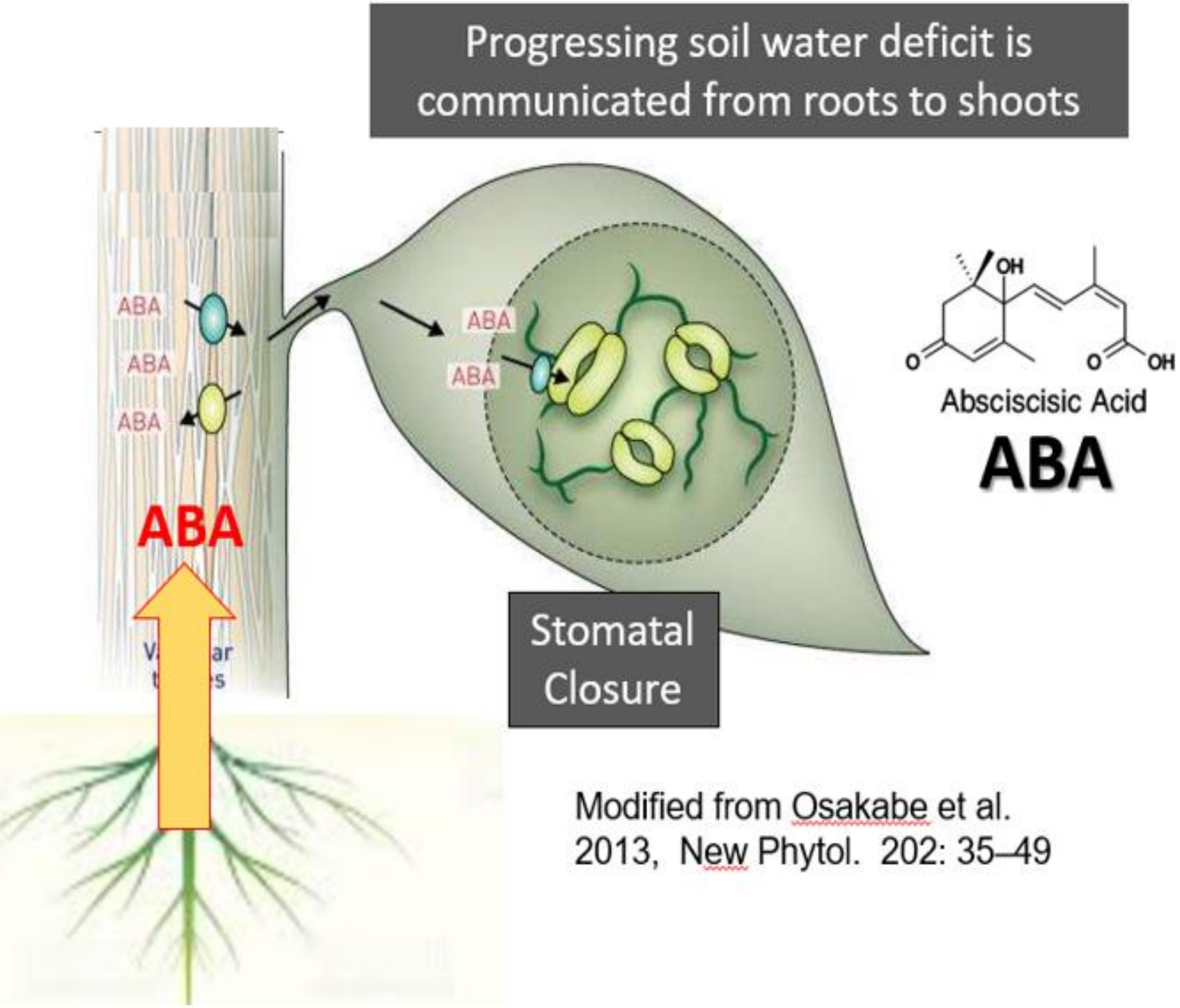
Sulphur Treatment	**Total S** (%)	**Total GSH** (nmol/g FW)
Adequate S	**1.02**	**59.1** ±7.5
Low S	**0.10**	**3.7** ±1.0

Dubuis et al 2005. J. Phytopathol.153, 27–36; Adapted from Dr. I. Cakmak, Sabanci Univ., TSI World Symp. 2023

Sulphur and Moisture Stress

Upon drought stress, xylem-derived sulfate seems to be key signaling molecule that induces stomatal closure. *Malcheska et al., 2017 Plant Physiol.; Batool et al., 2018, Plant Cell.*

Results indicate a specific role of S nutrition in drought stress tolerance of plants. *Batool et al., 2018, Plant Cell, 30: 2894–2895*



Modified from Osakabe et al. 2013, New Phytol. 202: 35–49

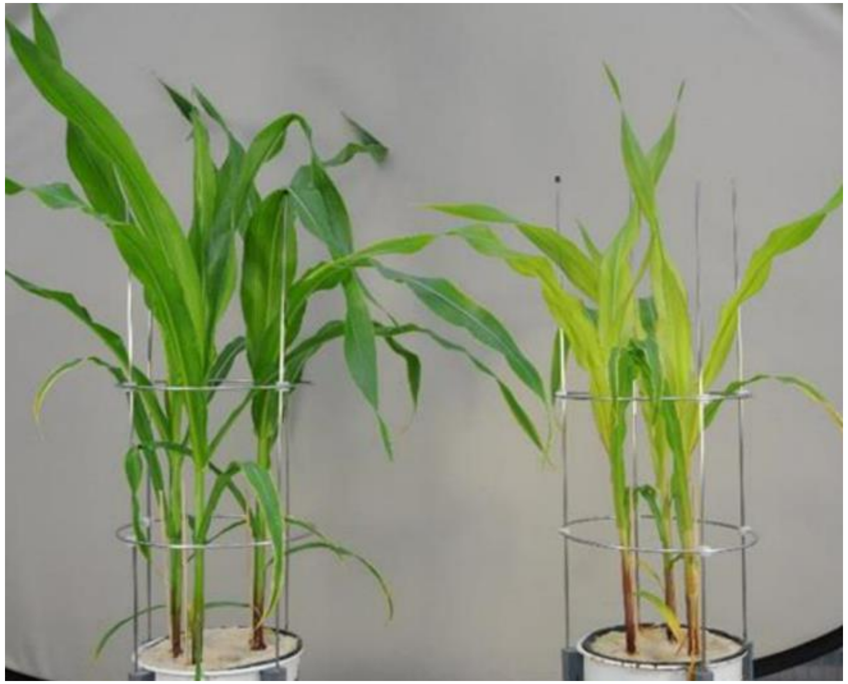
Sulphur is the 4th Major Nutrient – Summary and Closing Thoughts

An overlooked key to greater nitrogen-use efficiency, productivity, and crop quality

Sulphur regulates and enhances many important plant processes that:

- Promote productivity
- Production efficiency
- Nutrient-use efficiency
- Plant stress tolerance
- Disease resistance
- Food quality and nutrition

https://www.sulphurinstitute.org



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