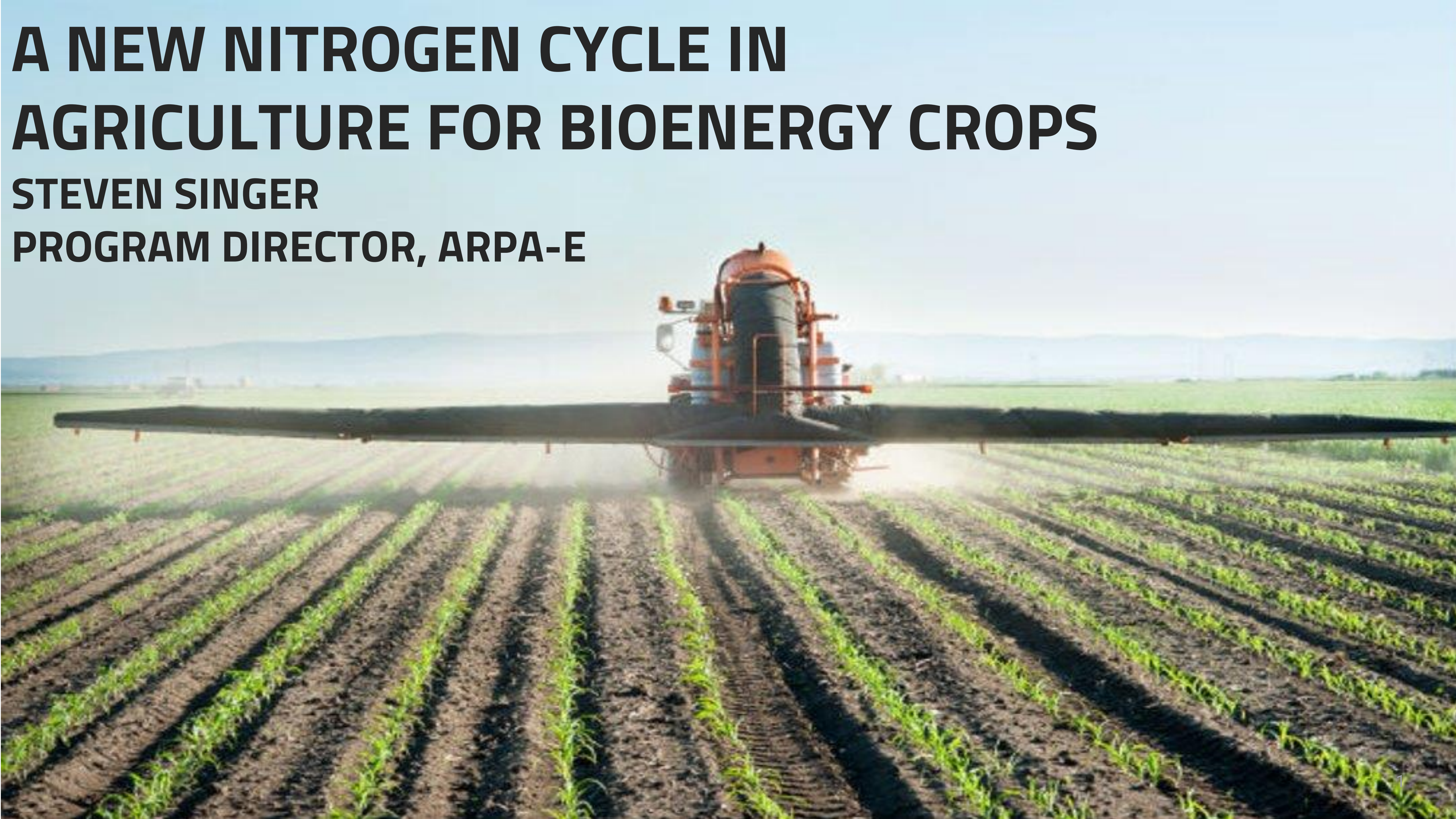
A NEW NITROGEN CYCLE IN AGRICULTURE FOR BIOENERGY CROPS

STEVEN SINGER
PROGRAM DIRECTOR, ARPA-E



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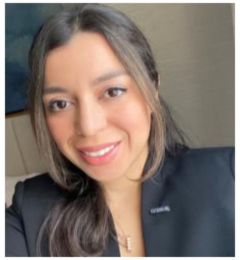
Liu


Leonela
Carriedo


Truong
Nguyen


Mikaela
Algren


Calden
Stimpson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Joldersma


Ben
Weiner


Elise
Goldfine


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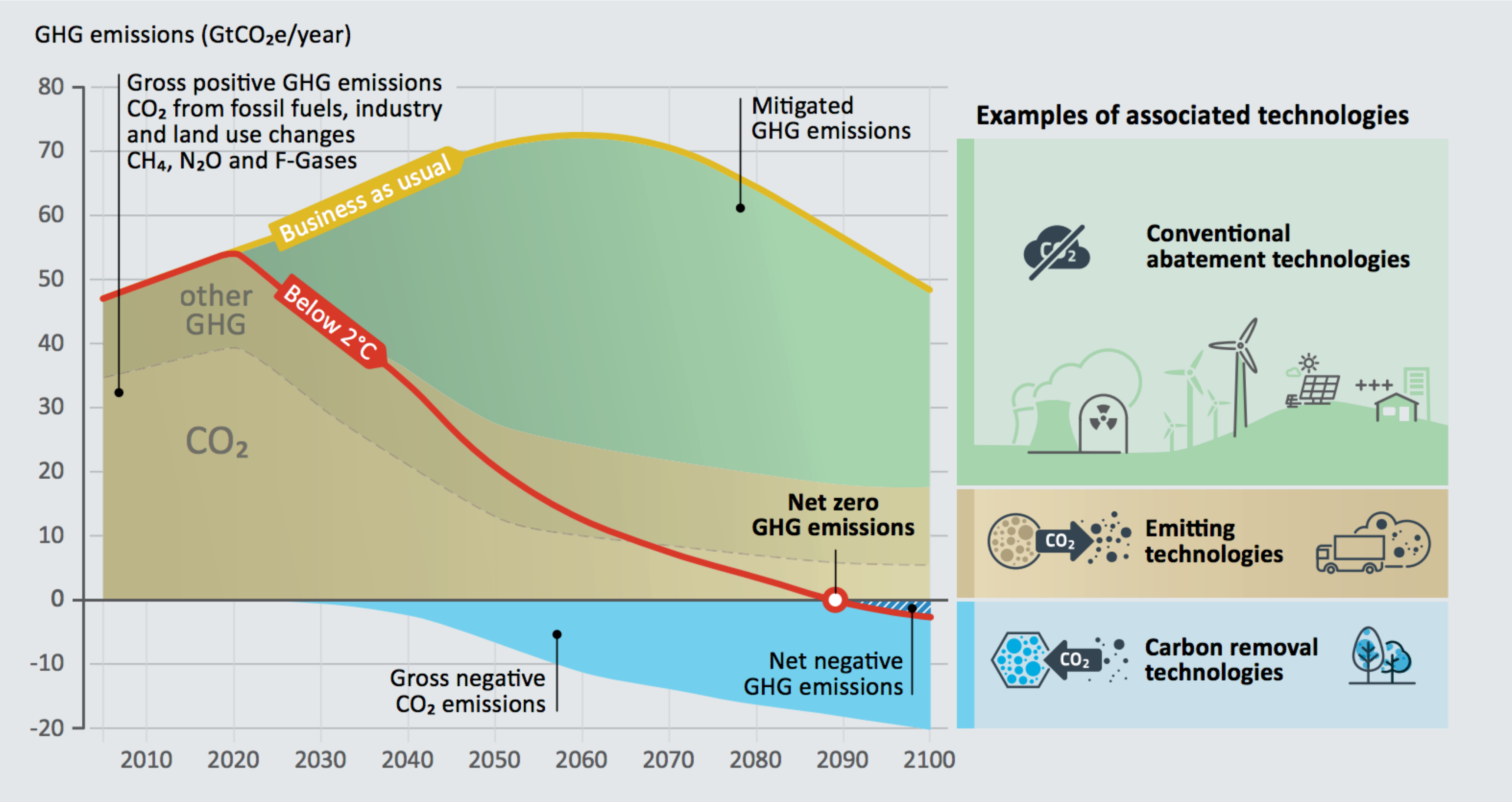
Cadle


Sade
Ruffin


Miriam
Greenberg


David
Lee

All paths to <2^0 C warming require GHG mitigation and negative emissions



National Academy of Sciences. *Negative Emissions Technologies and Reliable Sequestration: A Research Agenda.* 2019. p. 3

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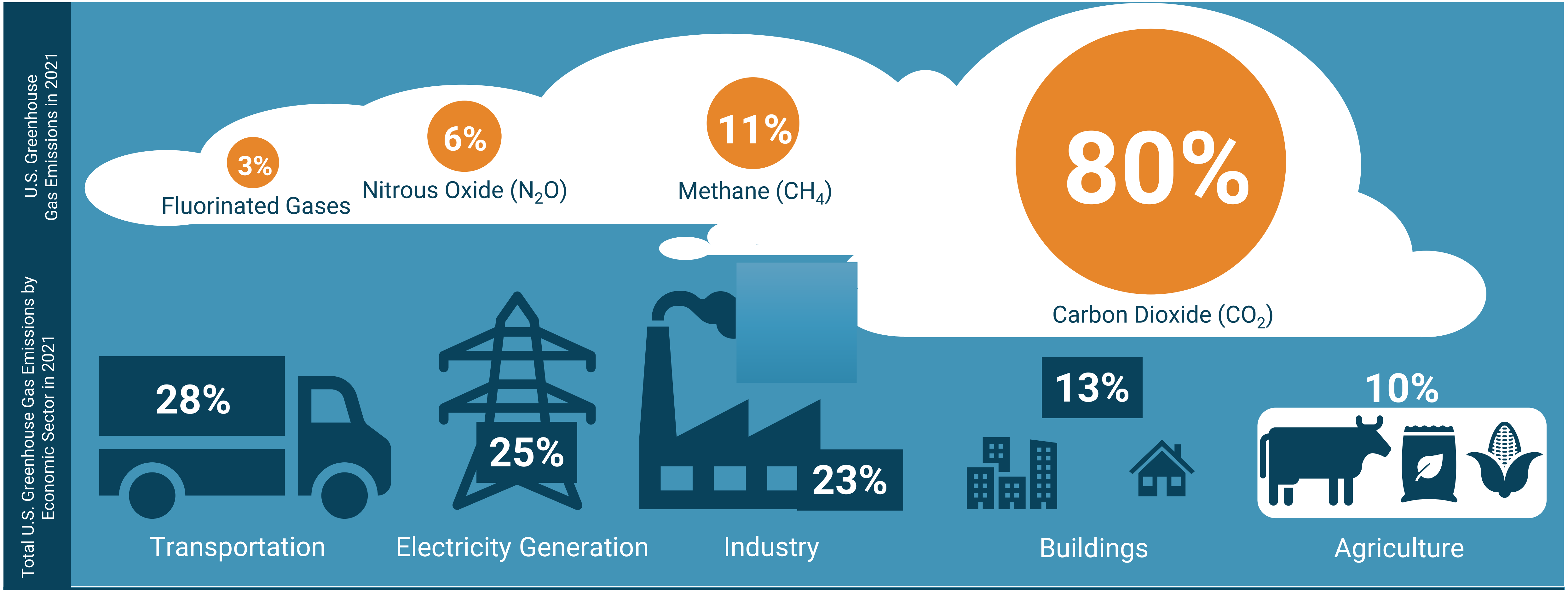
CHANGING WHAT'S POSSIBLE

GHG emissions from agriculture are difficult to decarbonize



U.S. Greenhouse Gas Emissions in 2021

3% Fluorinated Gases

6% Nitrous Oxide (N_2O)

11% Methane (CH_4)

80% Carbon Dioxide (CO_2)

Total U.S. Greenhouse Gas Emissions by Economic Sector in 2021

28% Transportation

25% Electricity Generation

23% Industry

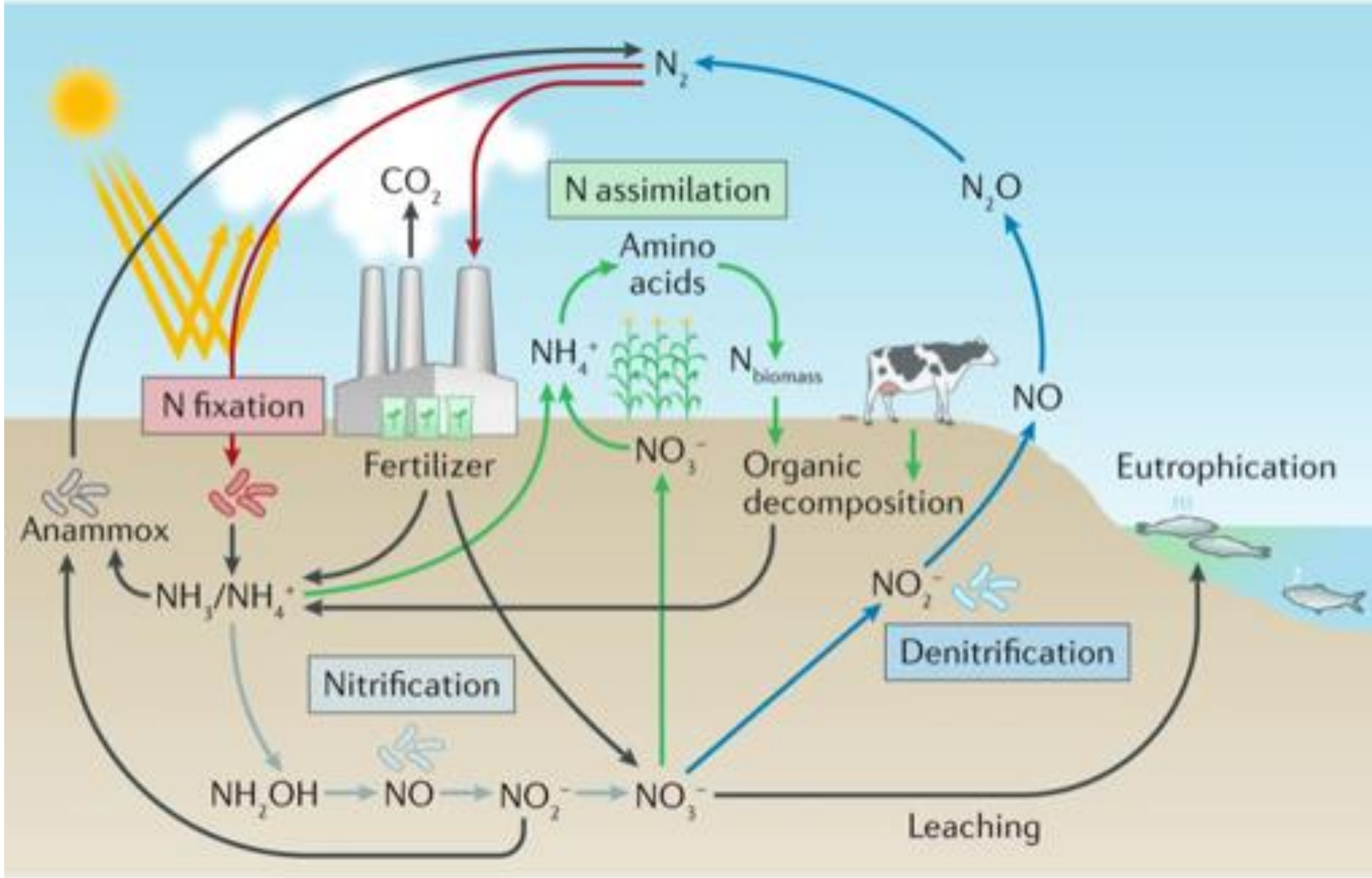
13% Buildings

10% Agriculture

Electrification has less impact on agriculture GHGs compared to other sectors

Figure 1: Greenhouse Gas Contribution in the US.
Graphic adapted from University of Nebraska-Lincoln Institute of Agriculture and Natural Resources
Data from Environmental Protection Agency, Inventory of U.S. Greenhouse Gas Emissions and Sinks (2021)

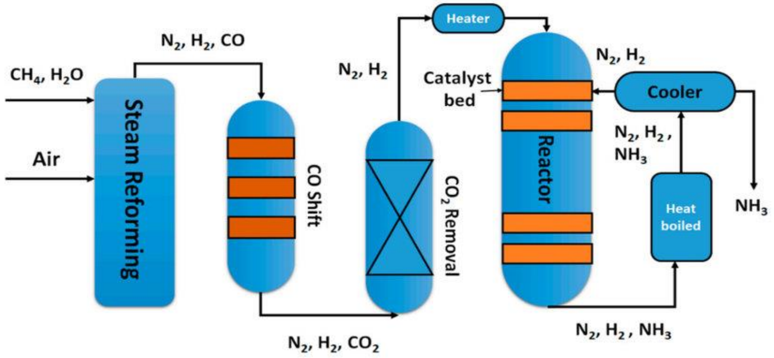
The agricultural nitrogen cycle emits CO_2 and N_2O (6% total GHGs)



The challenges of the current agricultural N cycle

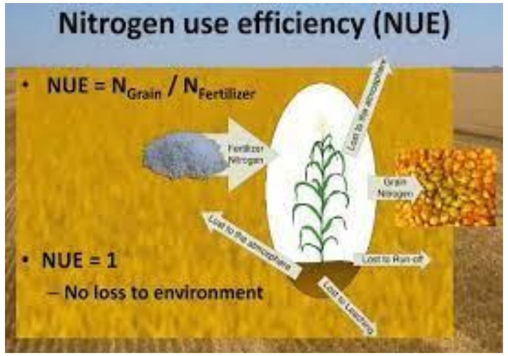
- Synthetic NH_3 production is a high energy process & generates significant CO_2
- A significant fraction of N input to cropland is lost to the environment
- Excess N inputs to soil lead to N_2O emissions and eutrophication in waterbodies

Haber-Bosch Process



- 1% of global energy (0.5% US)
- 1-2% global emissions

Nitrogen Use Efficiency (NUE)

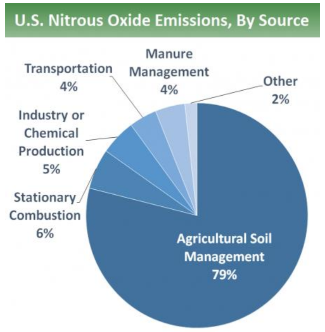


Nitrogen use efficiency (NUE)

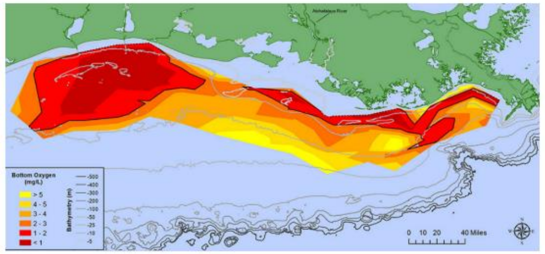
- NUE = $N_{Grain} / N_{Fertilizer}$
- NUE = 1
  - No loss to environment

- Corn <50%
- $4.2B lost

N_2O emissions and eutrophication



- N_2O GWP is 273x CO_2 at 100-year time horizon
- Ag N_2O emission 4% of total GHGs as CO_2e



Map showing the hypoxia area on the Louisiana Gulf of Mexico shelf in 2021

Credit: N. Rabalais, LSU/LUMCON (NOAA 2021)

https://oceanservice.noaa.gov/facts/deadzone.html

- ~27% of N input to soils is lost to waterbodies
- Creates coastal dead zones

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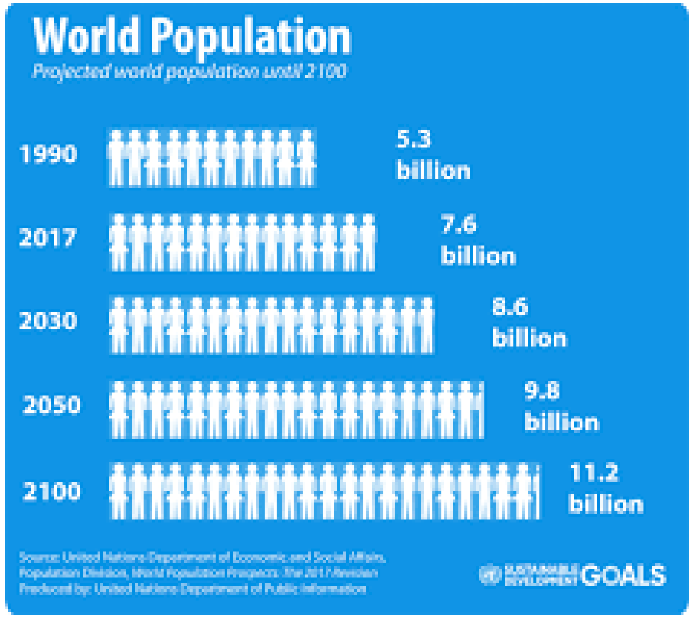
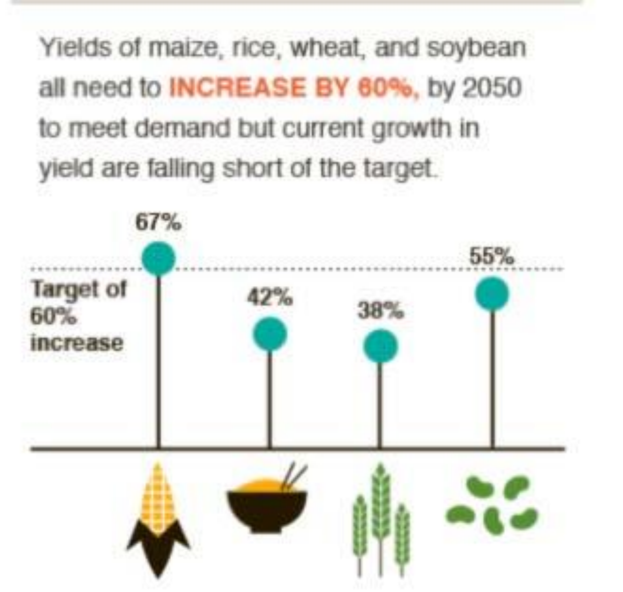
CHANGING WHAT'S POSSIBLE

These challenges will only get more difficult!

Food



Source: United Nations Department of Economic and Social Affairs, Population Division, World Population Prospects: The 2017 Revision
Produced by: United Nations Department of Public Information



Yields of maize, rice, wheat, and soybean all need to **INCREASE BY 60%**, by 2050 to meet demand but current growth in yield are falling short of the target.

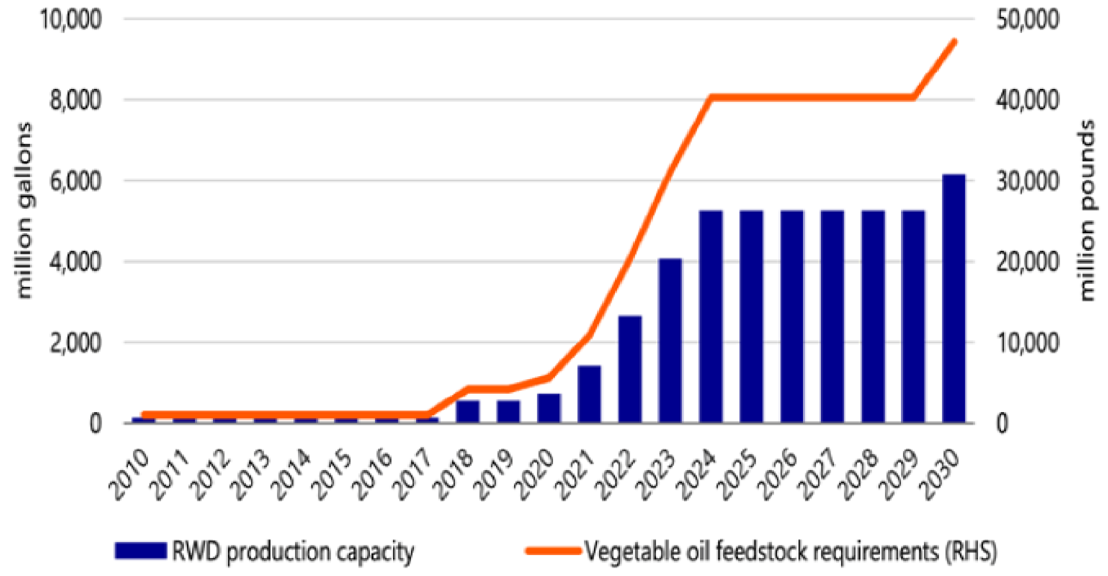
Source: Ray et al., 2013

Big Facts
ccafs.cgiar.org/bigfacts

CGIAR Climate Change, Agriculture and Food Security CCAFS

Fuel

Figure 3: Rapid ramp-up in US renewable diesel production capacity, 2010–2030



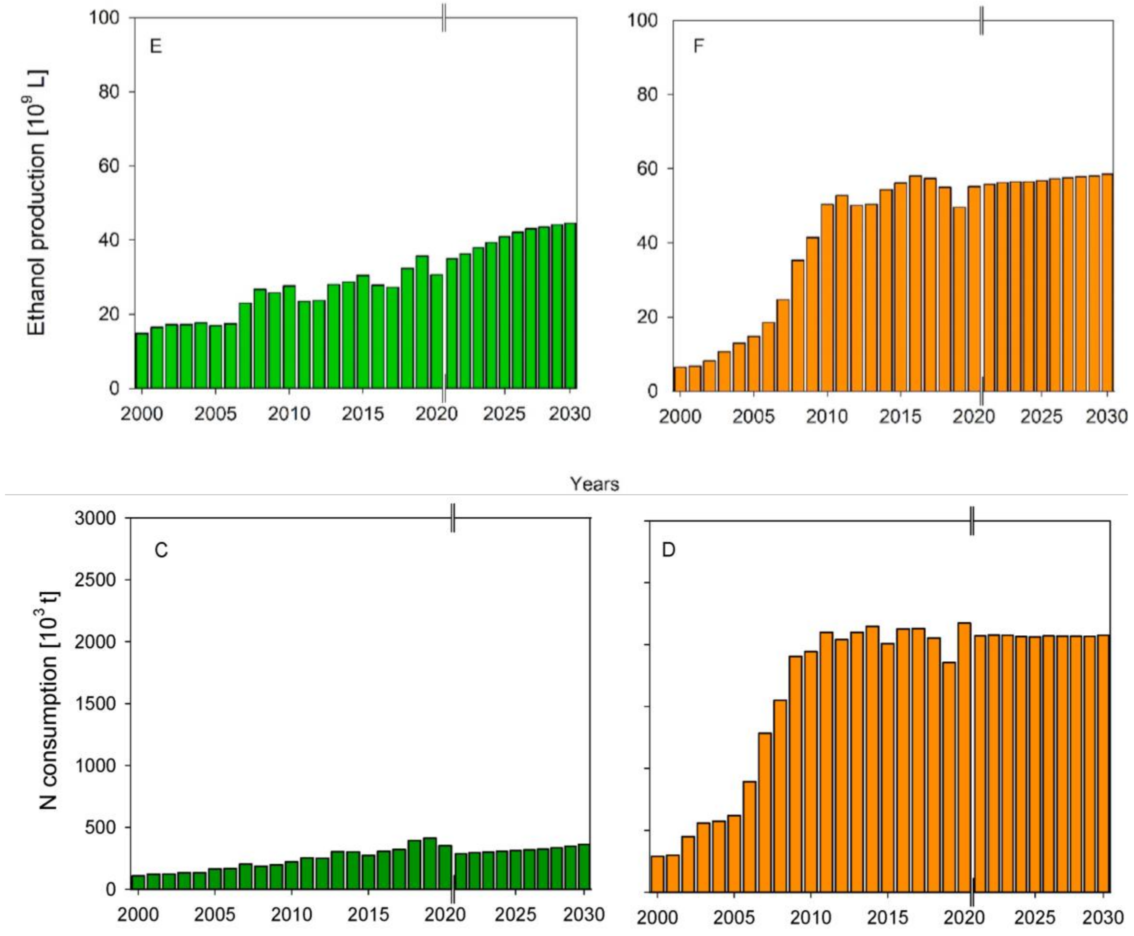
Source: Biodiesel Magazine, Rabobank 2021

Biofuel production and increased N fertilizer use are correlated

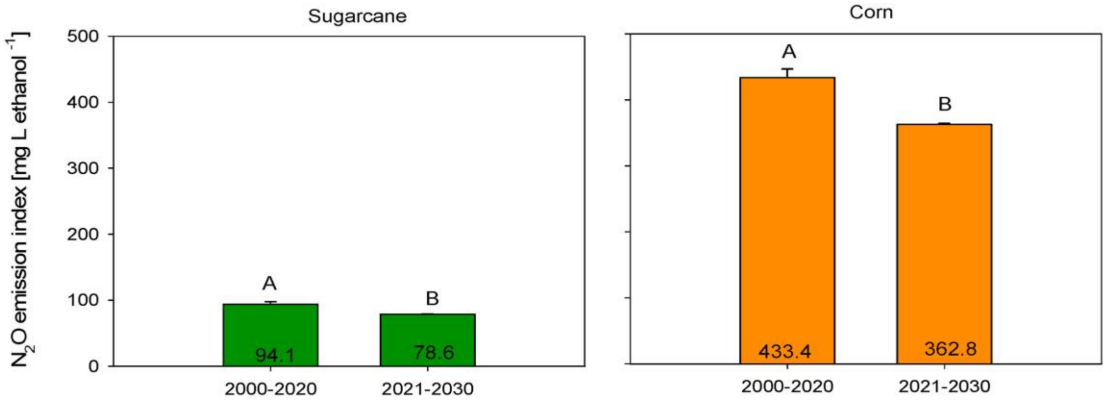
Ethanol production

Brazilian sugarcane

US corn



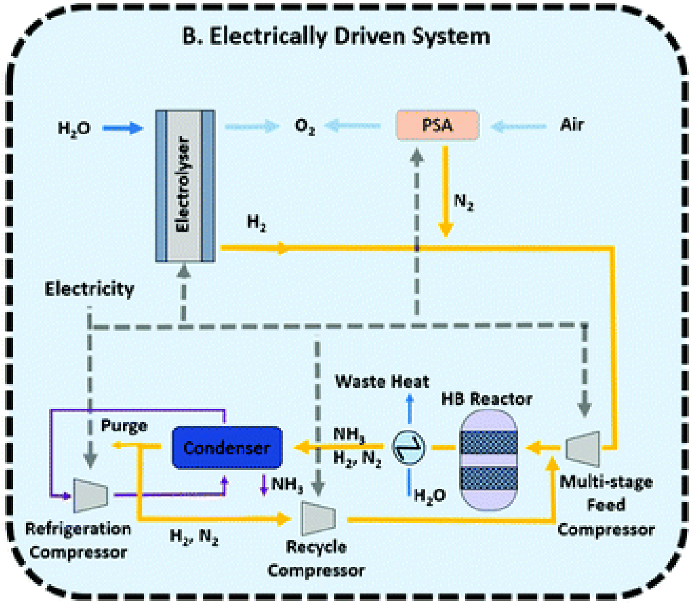
N_2O emissions



FUELING THE FUTURE FOR CLEANER SKIES

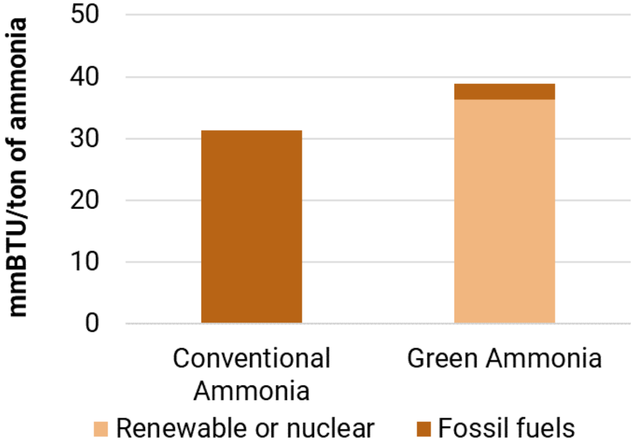
Take off with UOP's ethanol to jet (ETJ) process technology. The next generation of renewable fuels.

Green NH_3 reduces CO_2 emissions in agriculture but not N_2O



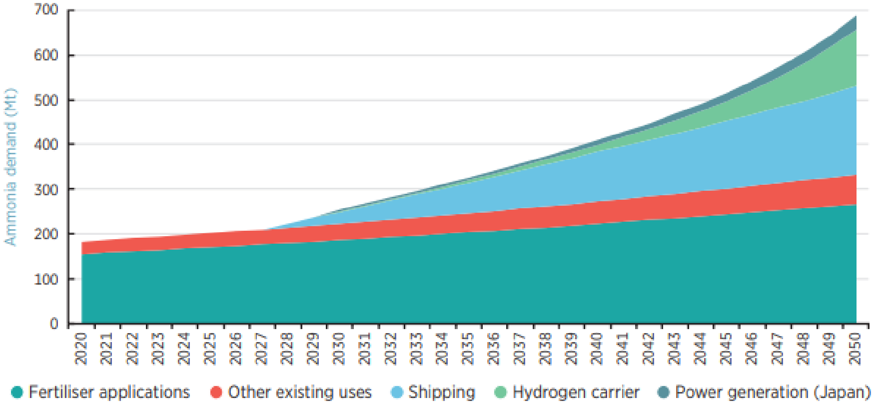
Adapted from: *Energy Environmental Science*, **2020**, *13*, 331

Energy for NH_3 synthesis



GREET 1 2022, Ag Inputs, Table 3

NH_3 in 2050 (1.5°C scenario)



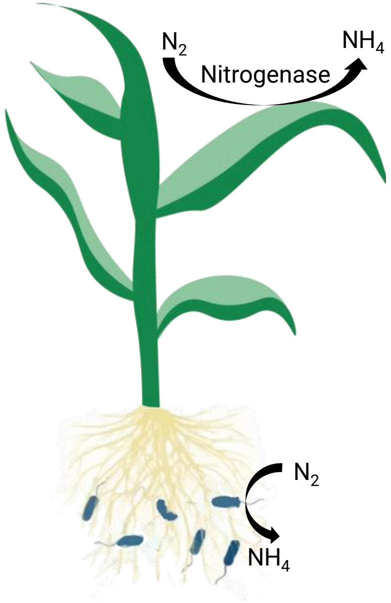
Data from: IRENA 2022

94 milion MT of green H_2 needed to produce 80% of projected ammonia demand in 2050 (566 Mt ammonia)

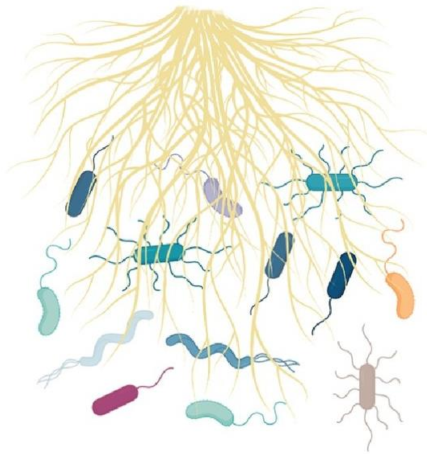
- 44% of projected global H_2 in 2050 (Wood MacKenzie)

Biology can address the challenges of the N cycle: N inputs

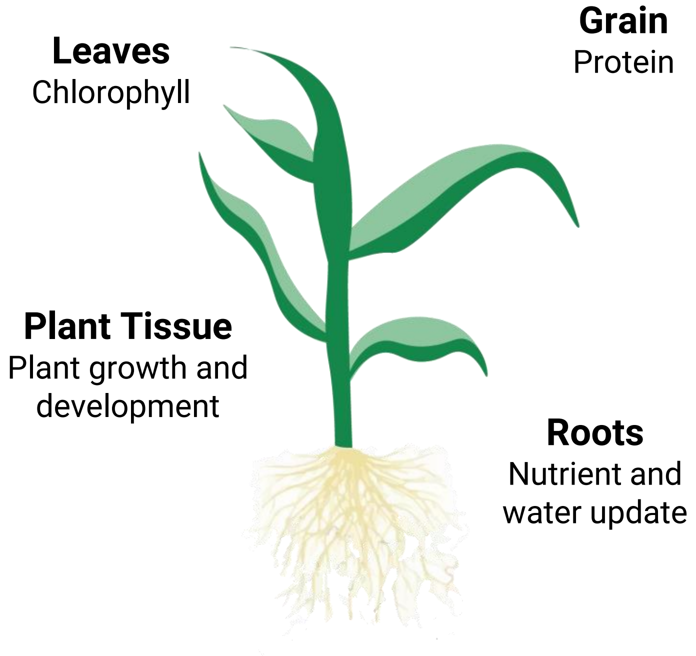
Engineer nitrogen fixing crops, and diazotrophs



Engineer associative fixation and designed microbiomes



Plant N uptake and metabolism



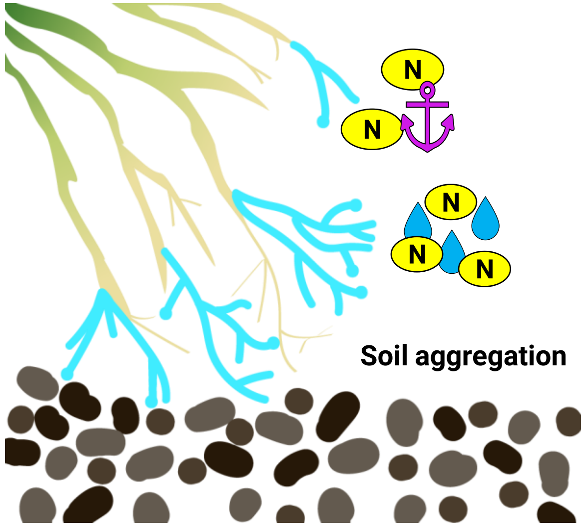
Leaves
Chlorophyll

Grain
Protein

Plant Tissue
Plant growth and development

Roots
Nutrient and water update

Soil N mineralization



Adapted from Chakraborty et al. (2023) *Trends in Microbiology*

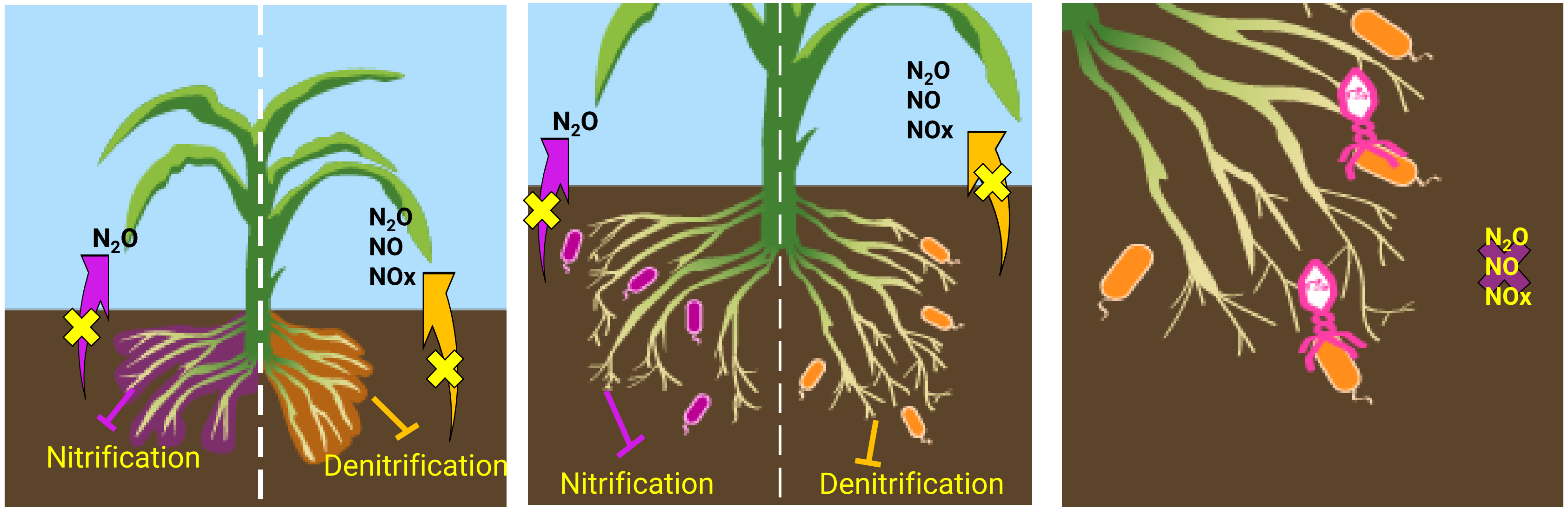
Biology can address the challenges of the N cycle: N_2O emissions

Inhibit N_2O emissions from nitrification or denitrification

Engineer crops

Engineer microorganisms or design microbiomes

In field gene editing of native soil microbiome



CHANGING WHAT'S POSSIBLE

Why ARPA-E: building on established ARPA-E programs

Trait development

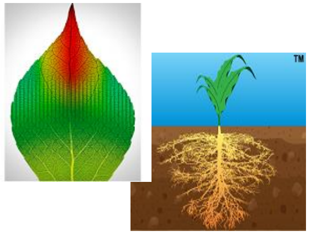
PETRO

Plant metabolic engineering and synthetic biology

Identify improvements

TERRA

/ ROOTS



Focus on breeding and high throughput phenotyping of energy sorghum

Enable measurement of GHG outcomes

SMARTFARM

Measuring N_2O emissions from corn and soybeans and developing scalable GHG monitoring technologies

CHANGING WHAT'S POSSIBLE

Biofuel crops are exemplary targets for creating a new N cycle

Corn

- 16.1 tons of N/km^2/y
- 40% of total US fertilizer; **6 Tg/y N input**
- 94 million acres in US
- 15 billion gallons EtOH production
- EtOH to jet major SAF pathway

Soybeans

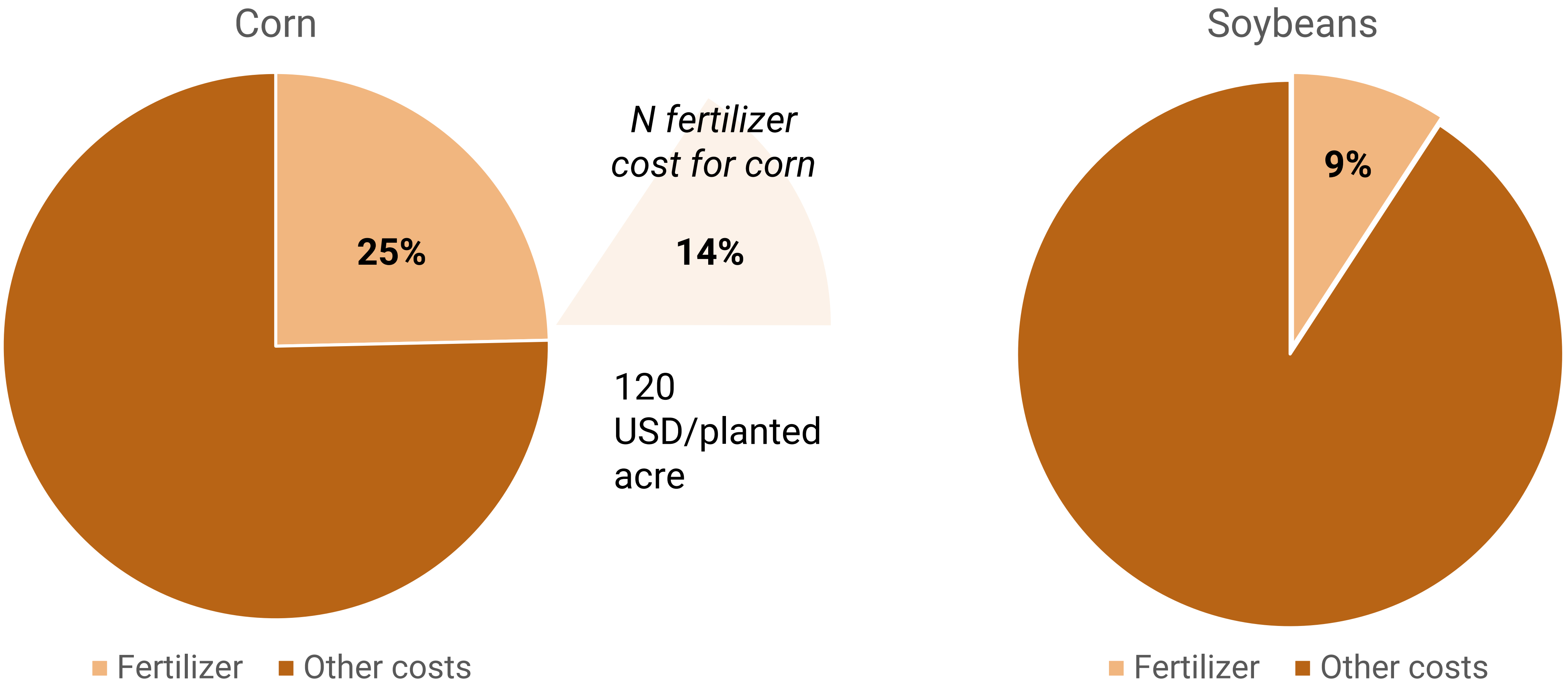
- 0.6 tons of N/km^2/y
- N_2-fixing symbiosis with bacteria; **9 Tg/y N input**
- 80 millions acres in US
- 1.5 billion gallons per year biodiesel and renewable diesel
- Hydrotreated oil for SAF

Sorghum

- 7.4 tons of N/km^2/y
- Lignocellulosic SAF production: BER focus
- 6.4 million acres
- Potential for carbon storage
- Abiotic stress tolerance

CHANGING WHAT'S POSSIBLE

Cost of N fertilizer is significant for corn



N fertilizer cost for corn

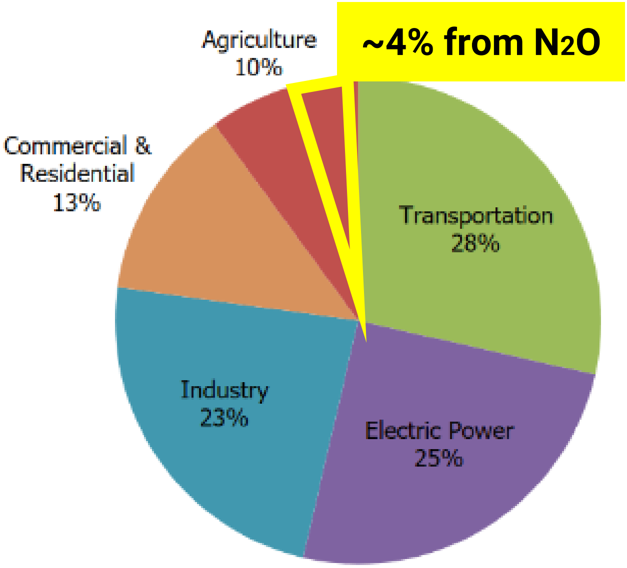
14%

120 USD/planted acre

Sources: USDA Cost-of-production forecasts for major U.S. field crops, 2022F-2023F, University of Illinois' farmdocDAILY (N fertilizer costs)

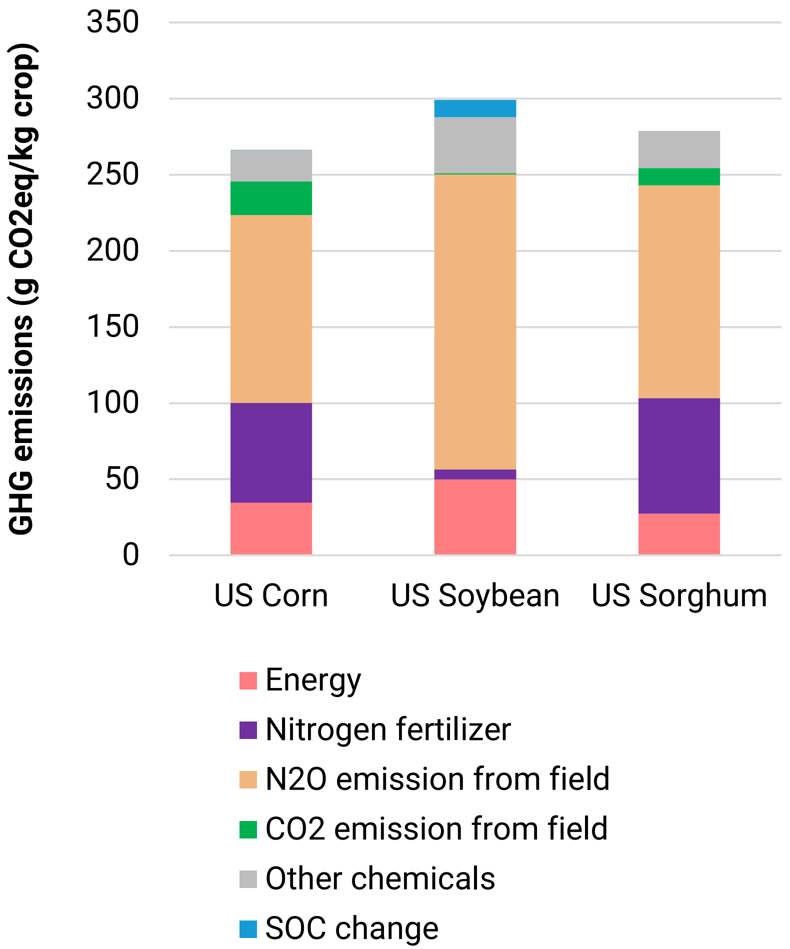
N_2O emissions result from both chemical and biological N inputs

GHG emissions by economic sector (2021)

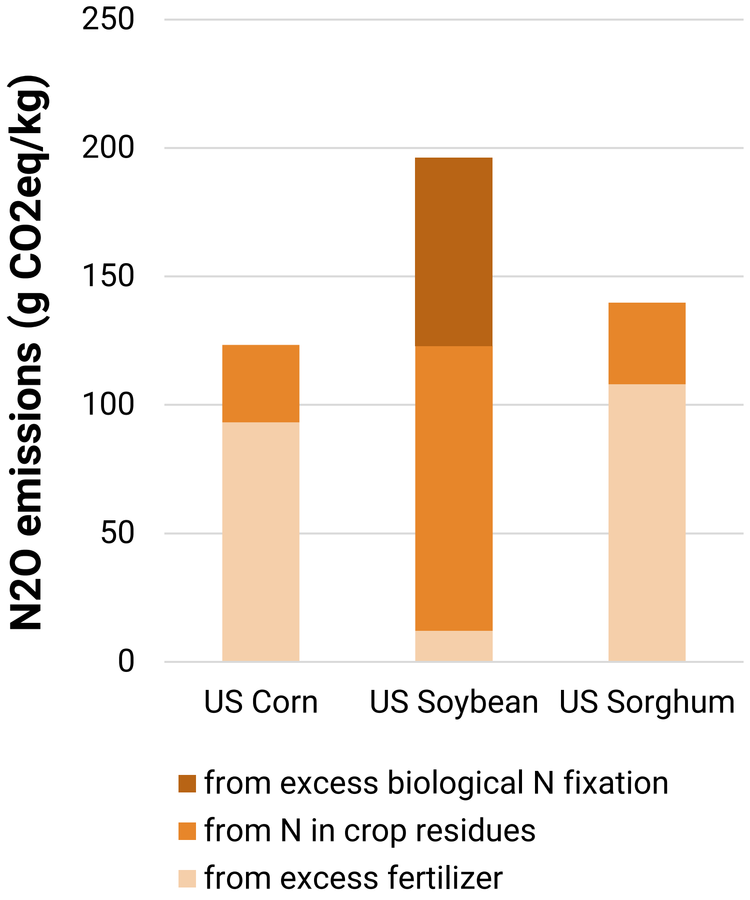


Sources of Greenhouse Gas Emissions | US EPA

Lifecycle GHG emissions

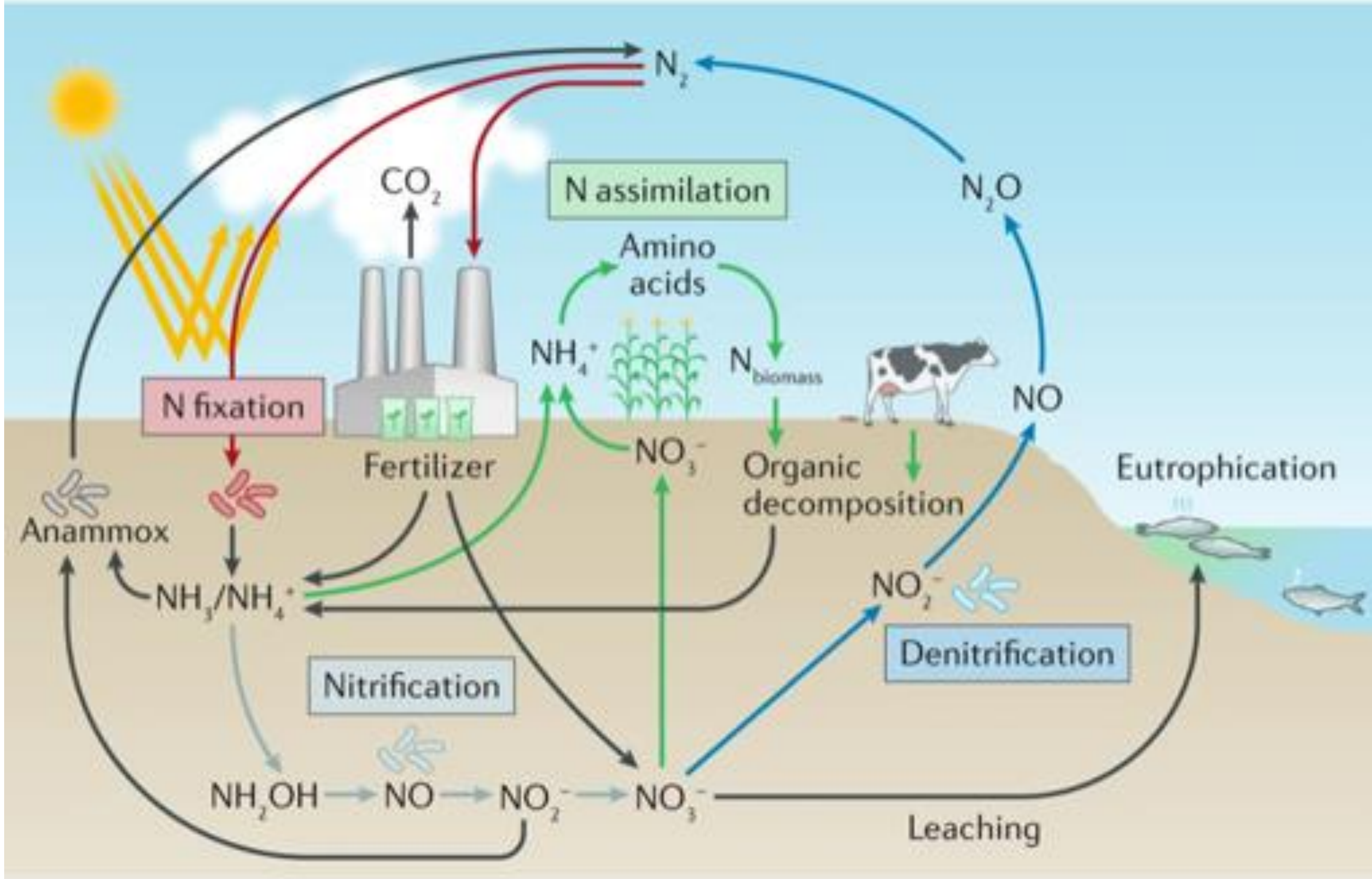


Nitrous oxide emission from field



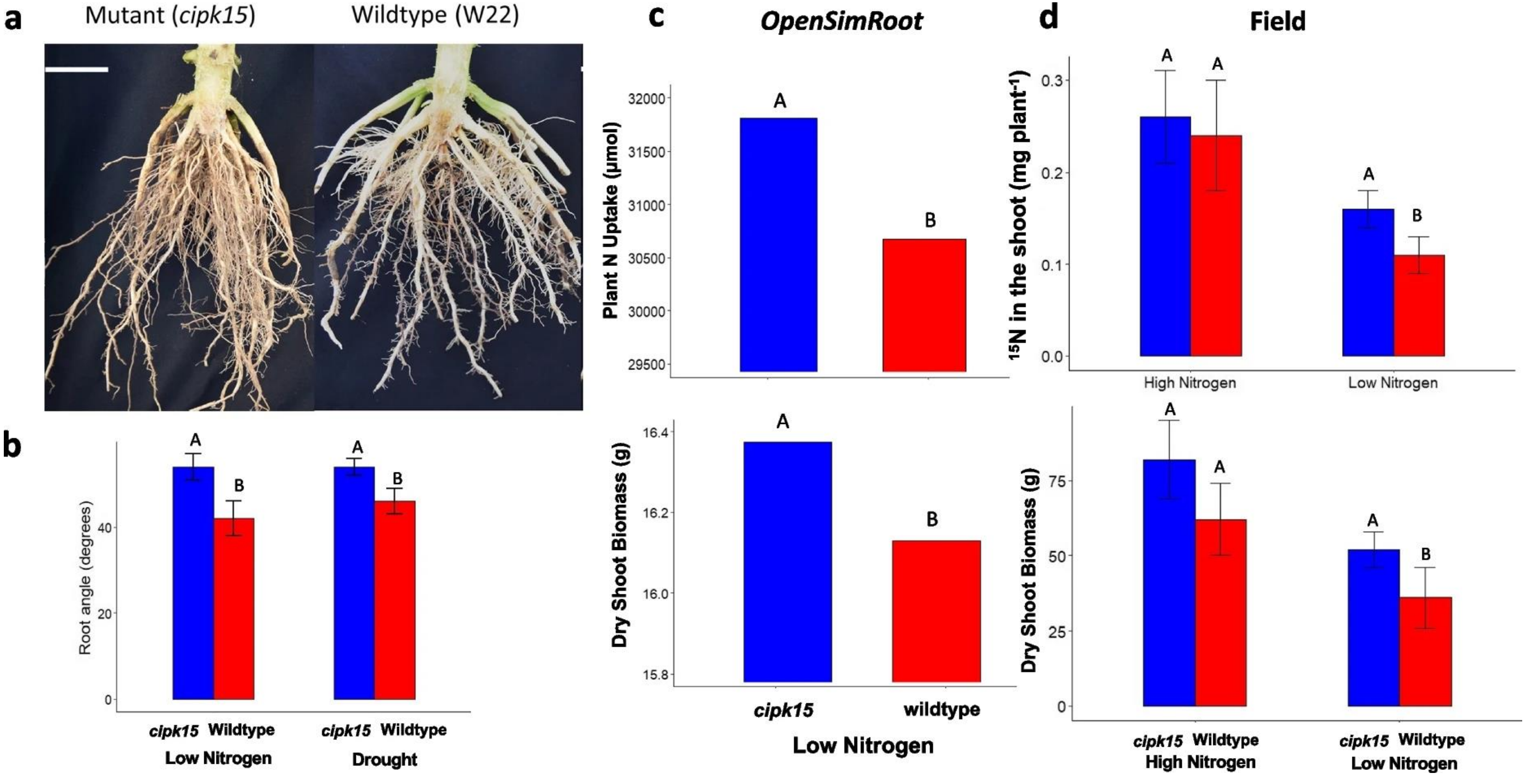
Data from GREET 2022, FD-CIC

Program technical areas



1. Plant NUE
2. Biological nitrogen fixation
3. Soil N mineralization
4. Direct N_2O mitigation

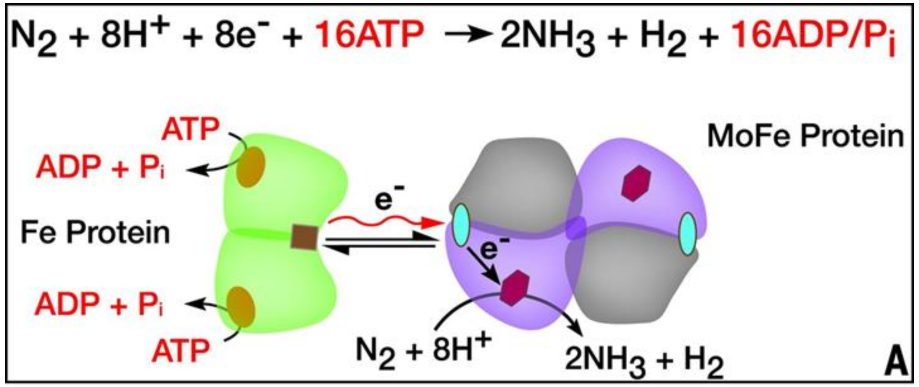
Plant nitrogen use efficiency- can we maintain yield with less N?

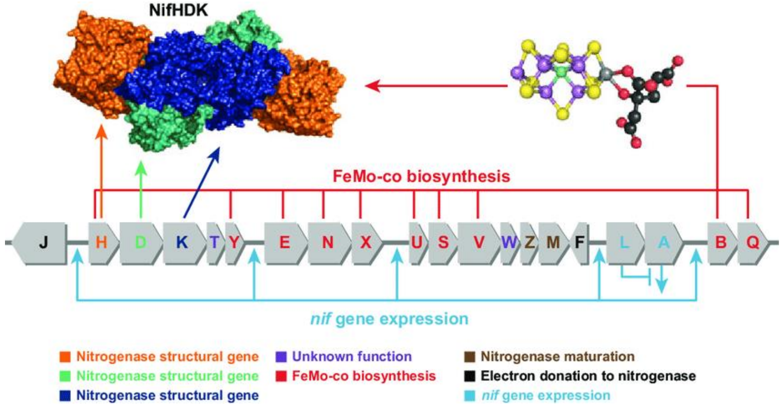


Lynch et al. *Plant and Soil* (2023): 1-55.

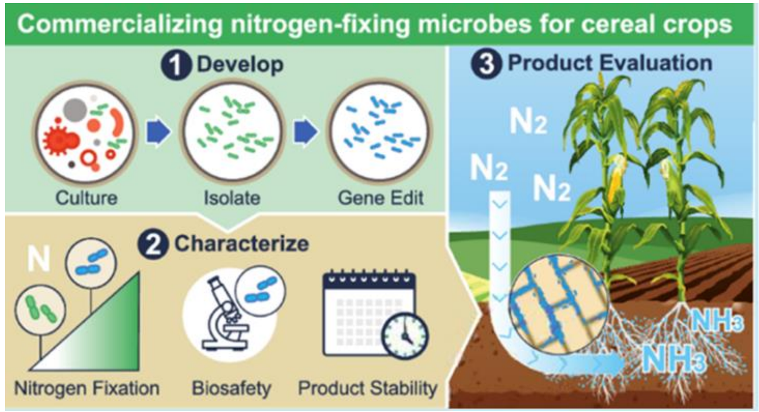
Nitrogen fixation- on roots and in plants

Nitrogenase: a complex enzyme for a complex process





Engineered N_2-fixing isolates

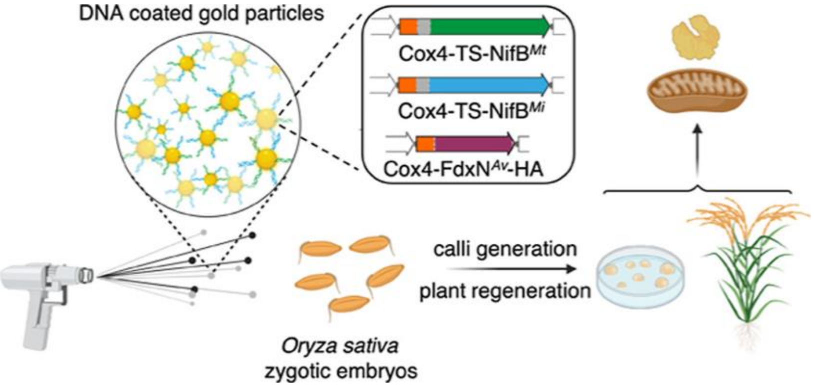


Wen et al. *ACS Synthetic Biology* 10:(2021): 3264–3277

Root-associated microbiomes

Van Dezyne et al. *PLoS Biology* 16 (2018): e2006352
Venado et al. *biorxiv* 2023.08. 05.552127

Expression *in planta*



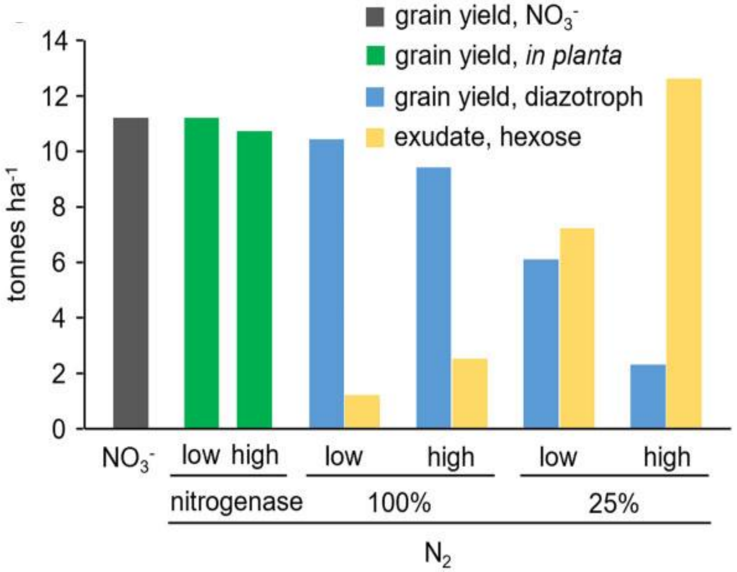
He et al. *ACS Synthetic Biology* 11 (2022): 3028-3036

CHANGING WHAT'S POSSIBLE

Is nitrogen fixation enough?

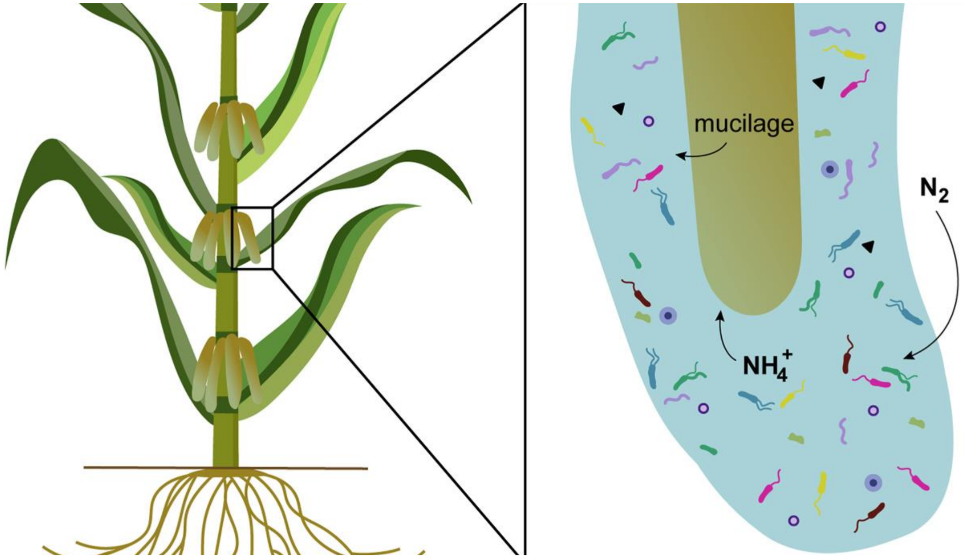
Limited by energy (sugar) from the plant → a BNF/yield trade-off

***In planta* and free-living:** what if you replaced 100% of fertilizer with BNF?
→ Yield loss ~0-80%, depending on scenario



ARPA-E targets: C/N transfer efficiency, respiratory protection

Aerial roots: how much N is fixed by natural aerial root mucilage communities?
→15 kg N/ha



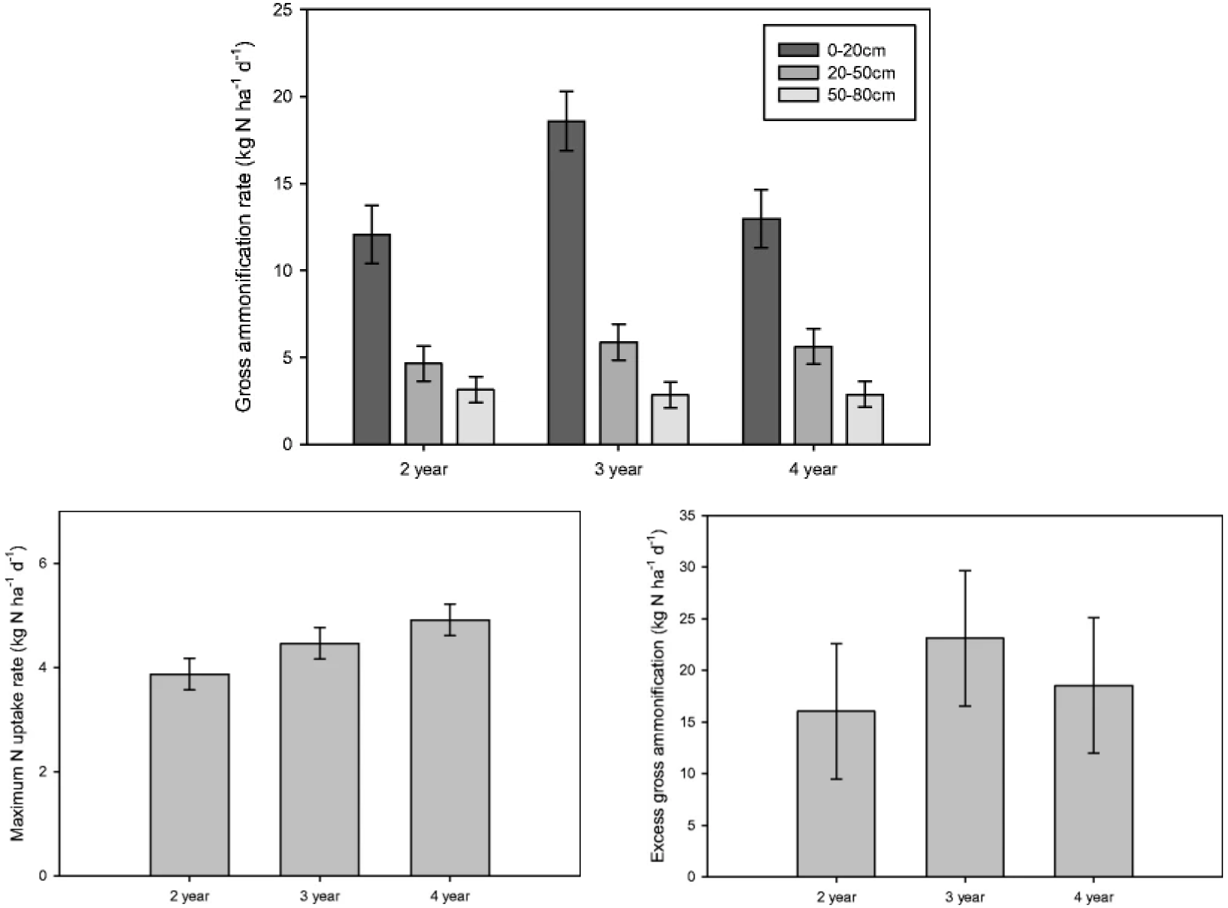
ARPA-E targets: mucilage production, microbial NF regulation

Bathe, et al. *Plant Physiology* 191.4 (2023): 2093-2103.
Van Gelder et al. *Plant Science* (2023): 111815.

CHANGING WHAT'S POSSIBLE

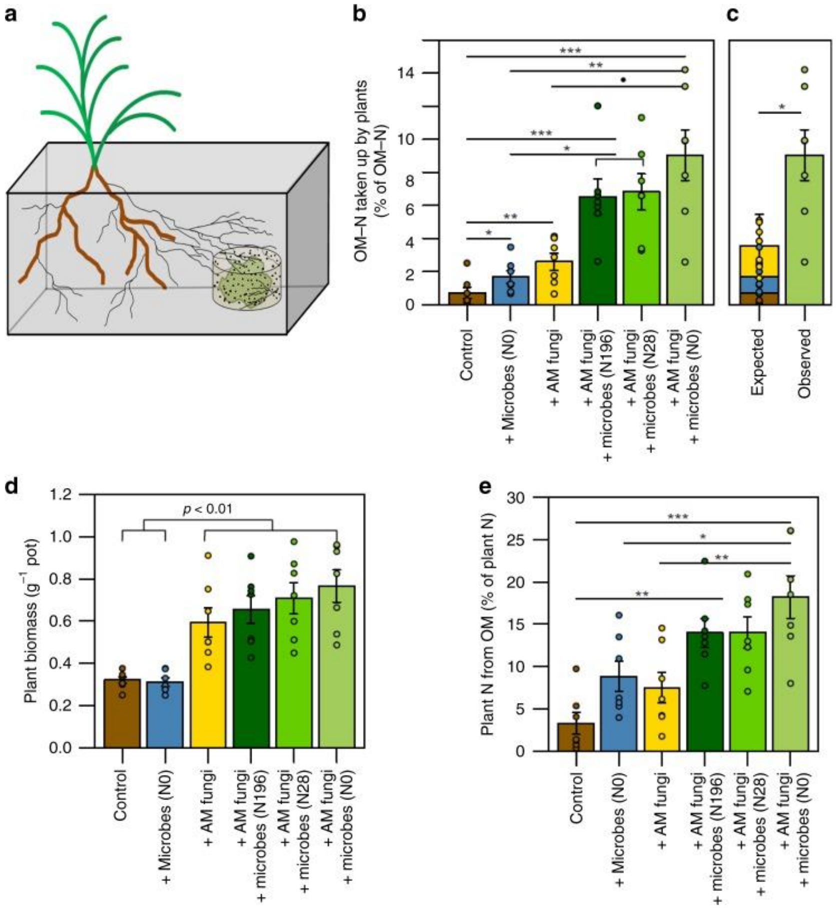
Can soil N mineralization replace synthetic fertilizer?

Gross soil ammonification is greater than plant N uptake



Osterholz et al. *Plant and Soil* 415 (2017): 73-84

Arbuscular mycorrhizal fungi double N delivered to plant

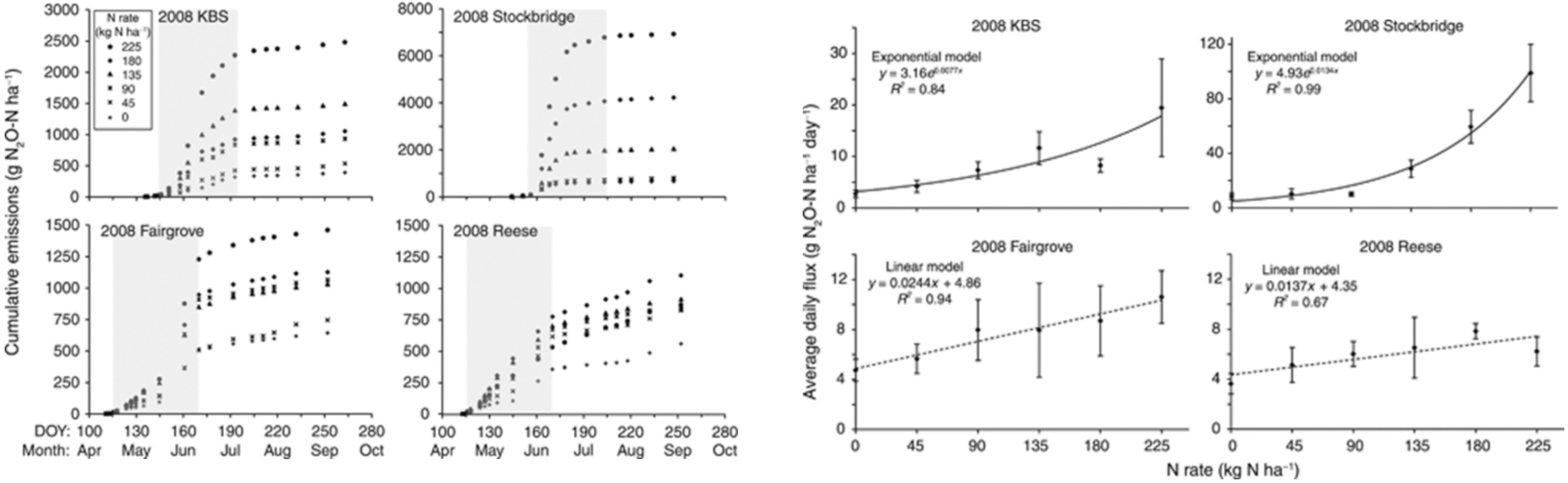


Hestrin et al. *Communications Biology* 2.1 (2019): 233.

CHANGING WHAT'S POSSIBLE

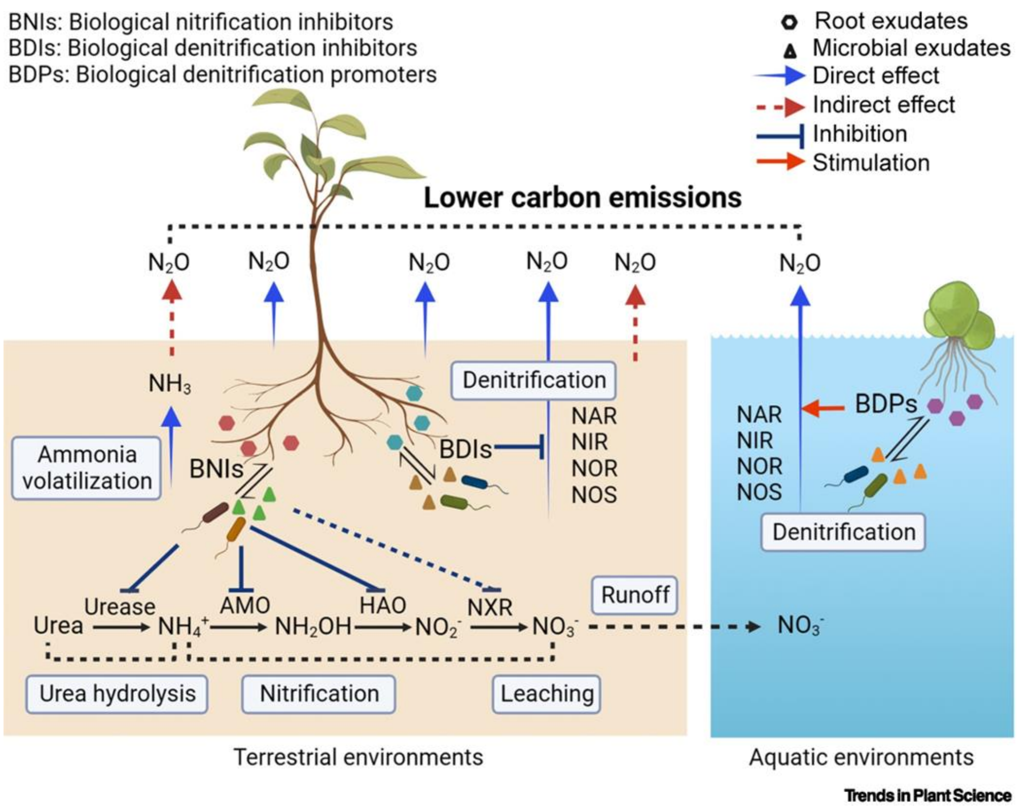
Can reduction in N inputs reduce N_2O emissions?

Positive correlation between applied N and N_2O emissions in corn fields

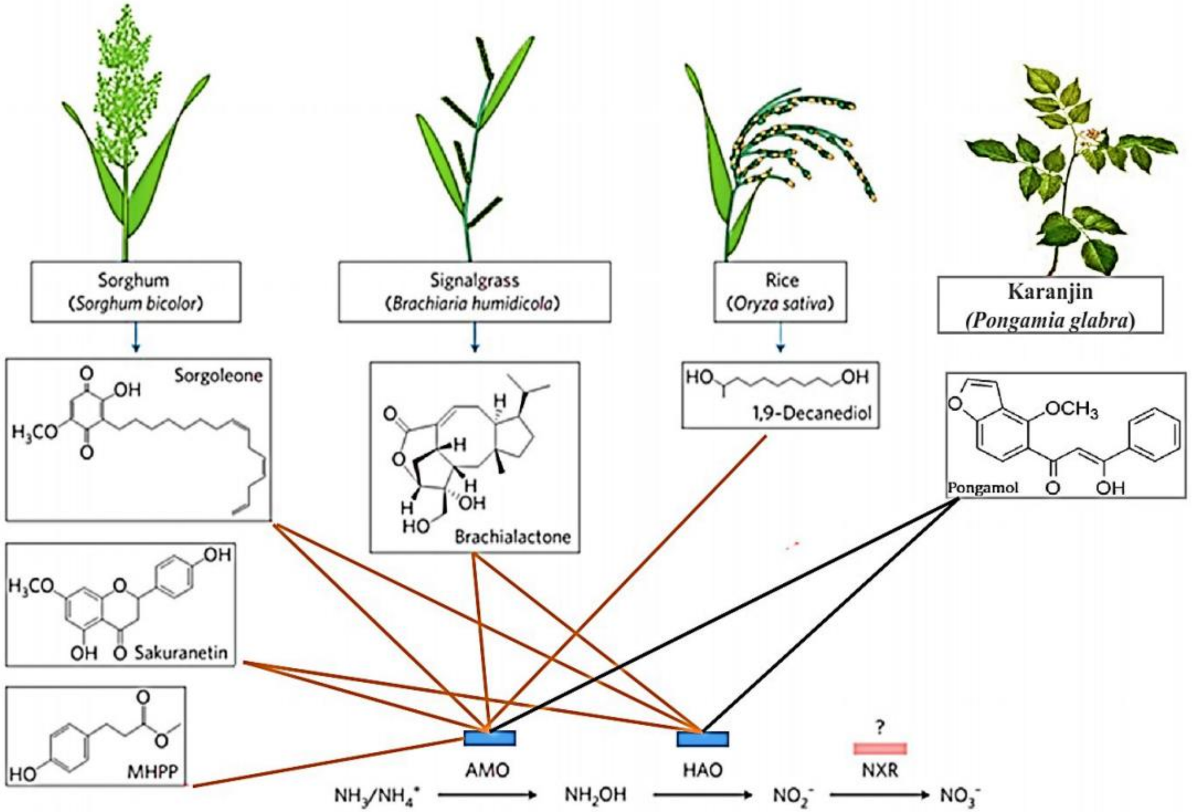


Hoben et al" *Global Change Biology* 17.2 (2011): 1140-1152.

Biological nitrification and denitrification inhibition

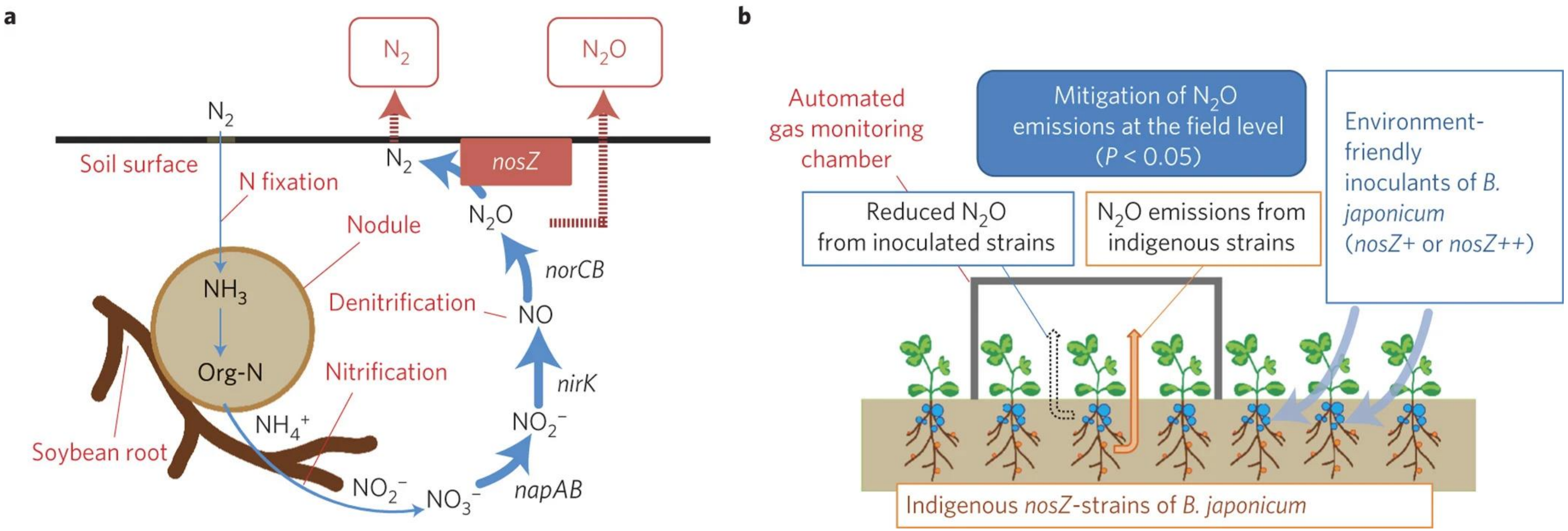


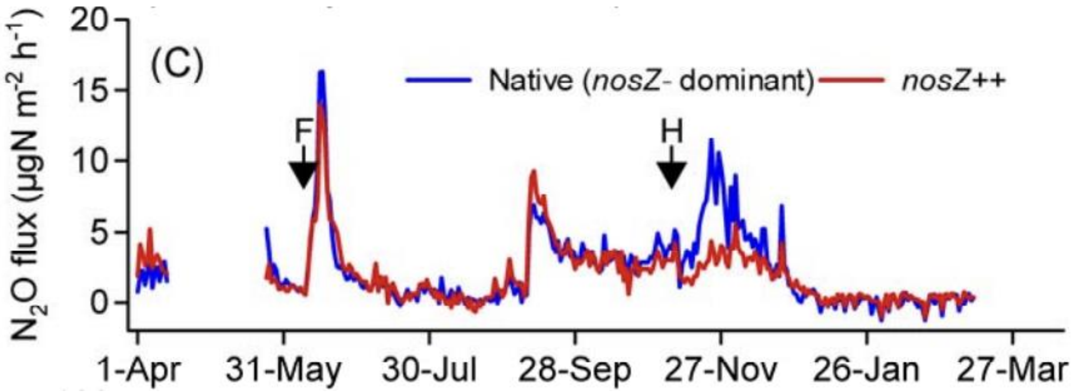
Lu et al. *Trends in Plant Science* (2023).



Saud, Shah, Depeng Wang, and Shah Fahad. " *Frontiers in Plant Science* 13 (2022): 854195.

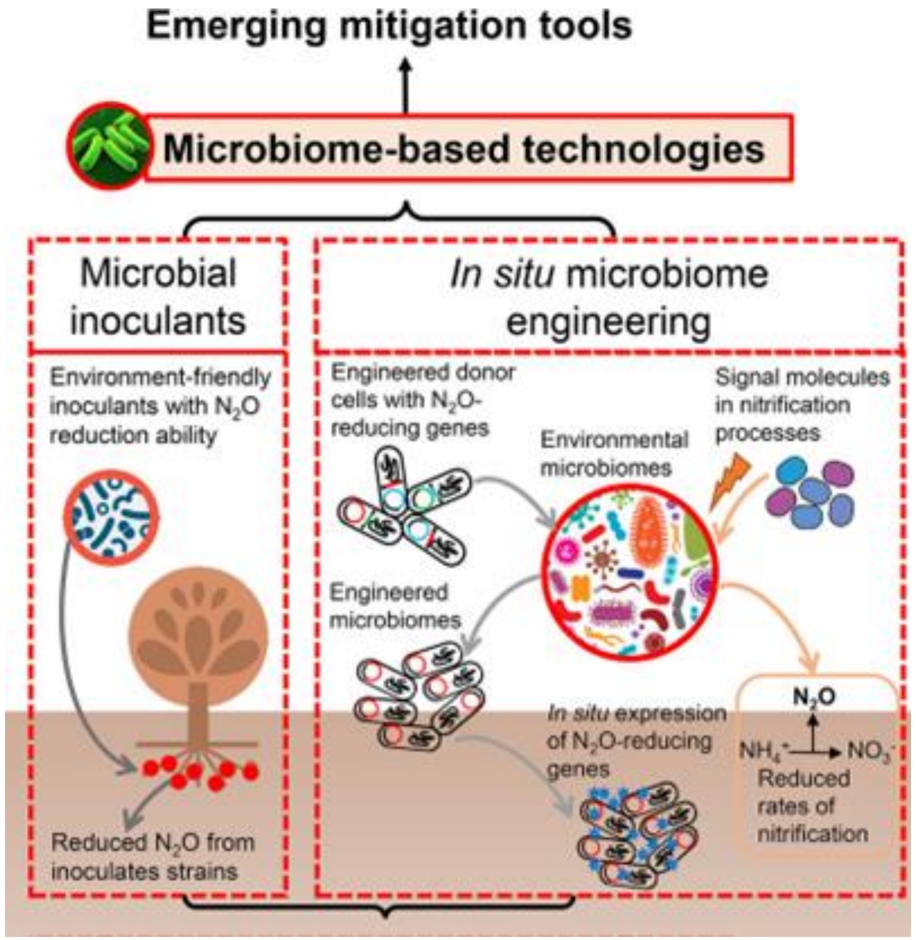
Altering N_2O emission directly in the soil in soybeans





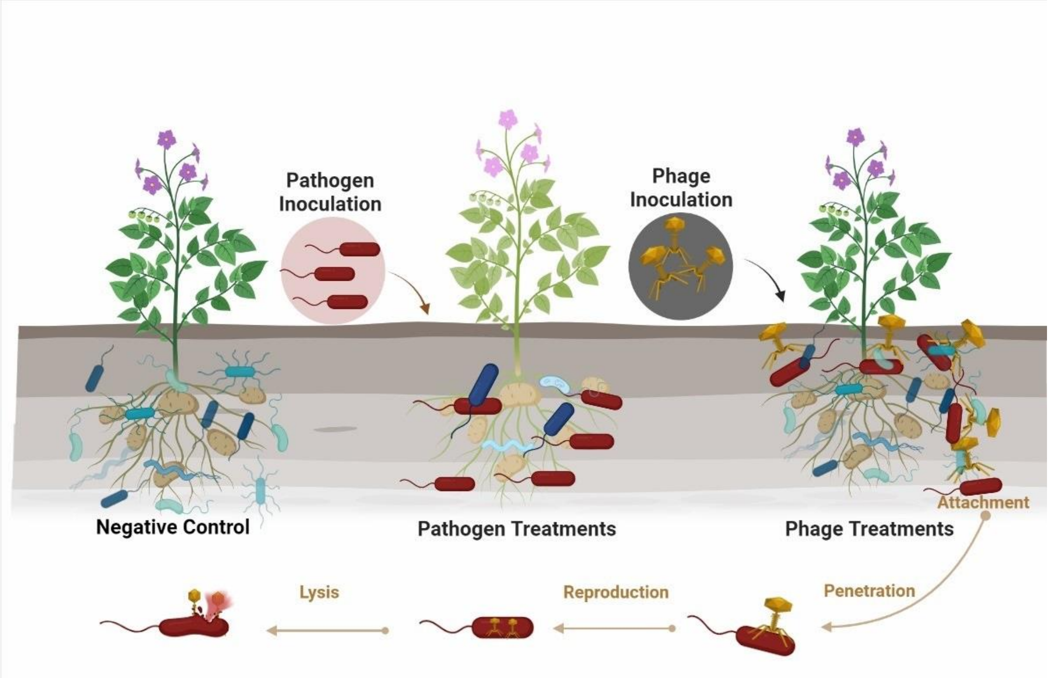
Itakura et al. *Nature Climate Change* 3.3 (2013): 208-212

Engineering the soil microbiome to mitigate N_2O



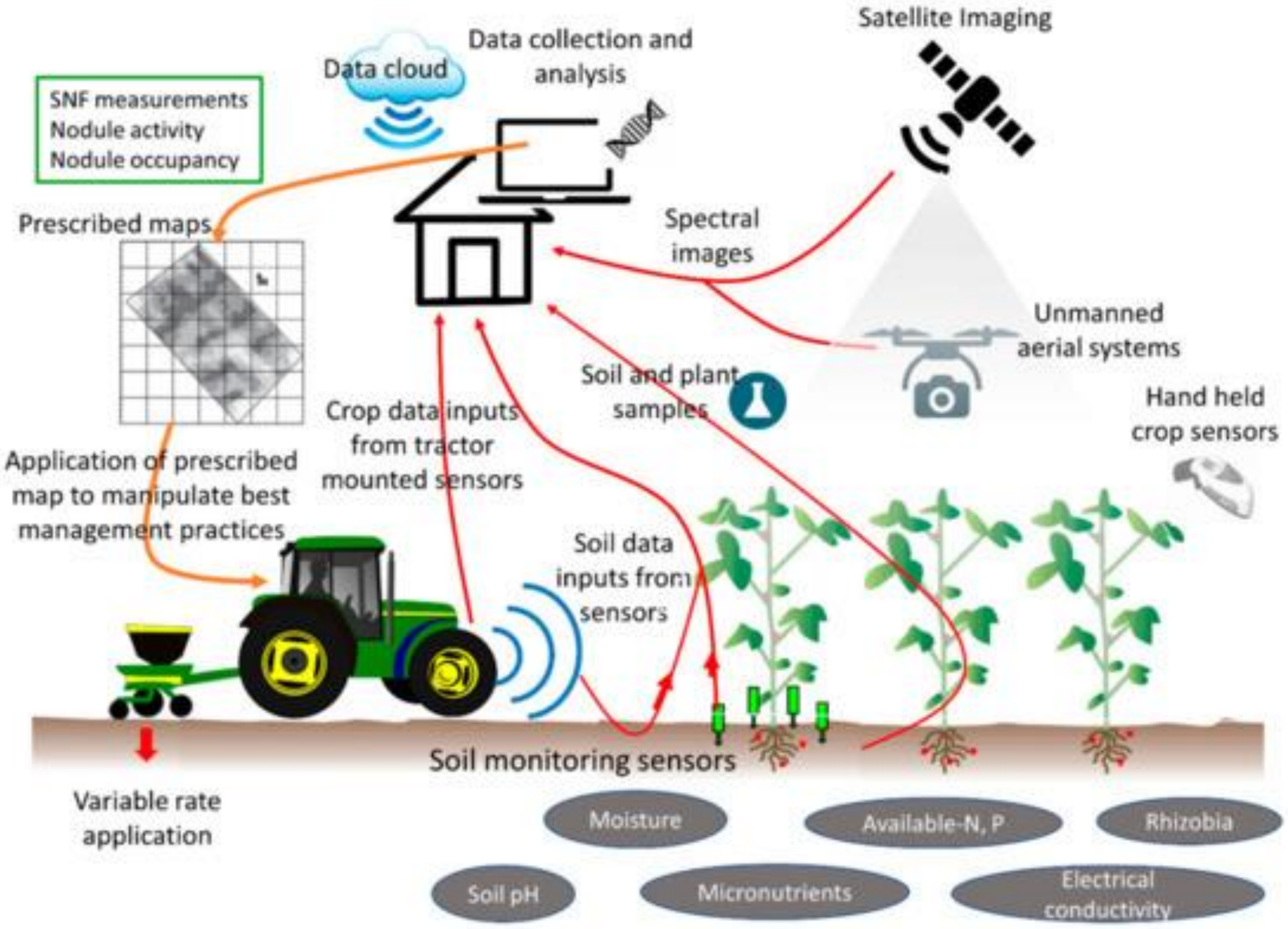
Hu, Hang-Wei, Ji-Zheng He, and Brajesh K. Singh. *Microbial Biotechnology* 10.5 (2017): 1226-1231.

Phage therapy for the N cycling microbiome



Mousa et al. *Antibiotics* 11.8 (2022): 1117.

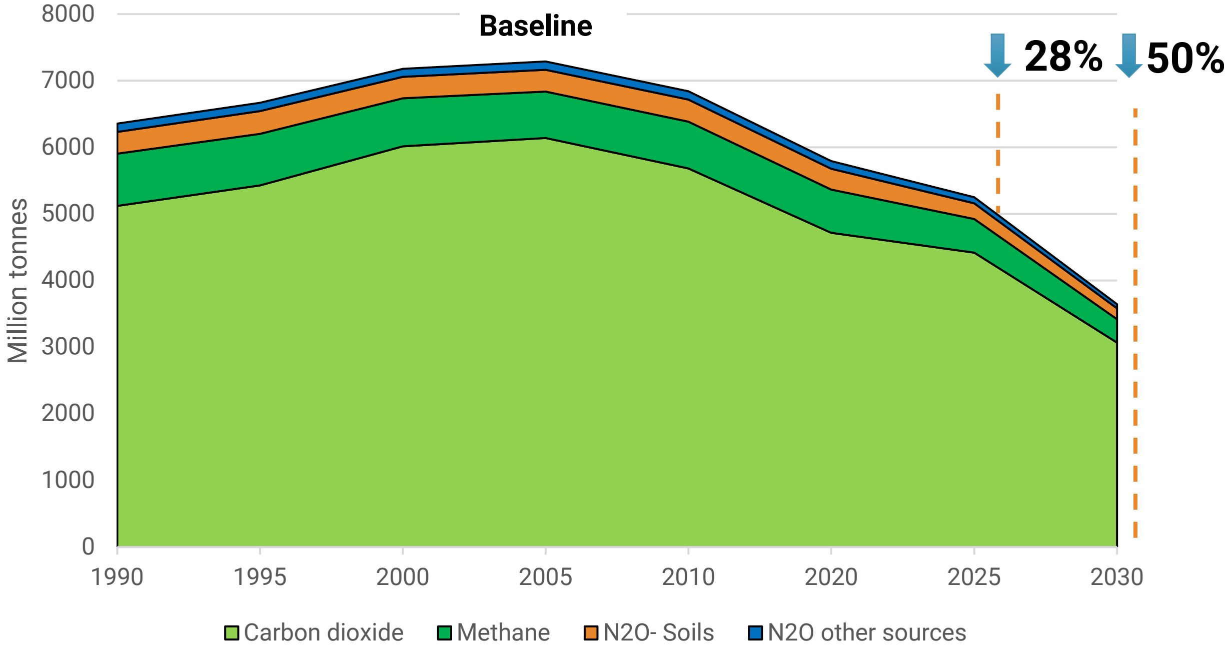
Combining biological approaches with precision agriculture

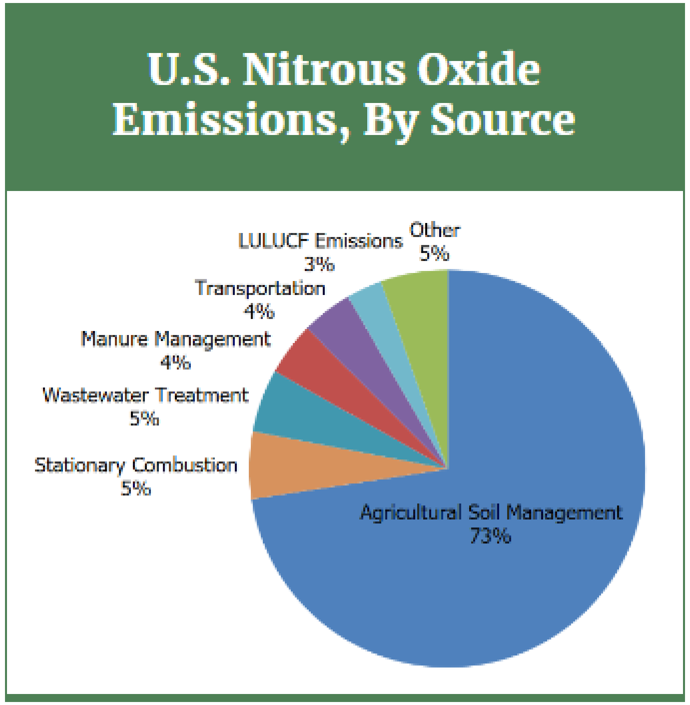


Thilakarathna, Malinda S., and Manish N. Raizada. *Agronomy* 8.5 (2018): 78.

Establishing program metrics: 50% N_2O emissions reduction

- **Paris agreement:**
  - Reduce GHG emissions by ~50% below 2005 base year levels by 2030 (U.S. nationally determined contribution)
  - Mitigating other GHGs will become increasingly important
  - 73% of N_2O emitted originates from agricultural soil


U.S. Greenhouse Gas Emissions with 2030 target


U.S. Nitrous Oxide Emissions, By Source

Data from EPA (2021). *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990–2021*.

Year	CO_2 (Mt)	CH_4 (Mt)	Total N_2O(Mt)	N_2O Soils (Mt)
2005	6137.6	697.5	453.3	330.9
2025	3848.7	502.2	326.4	238.3
2030	2764.4	348.7	226.7	165.5

Data from EPA Climate Change Indicators: U.S. Greenhouse Gas Emissions (2021)

N_2O emission reduction: reduce synthetic N fertilizer application

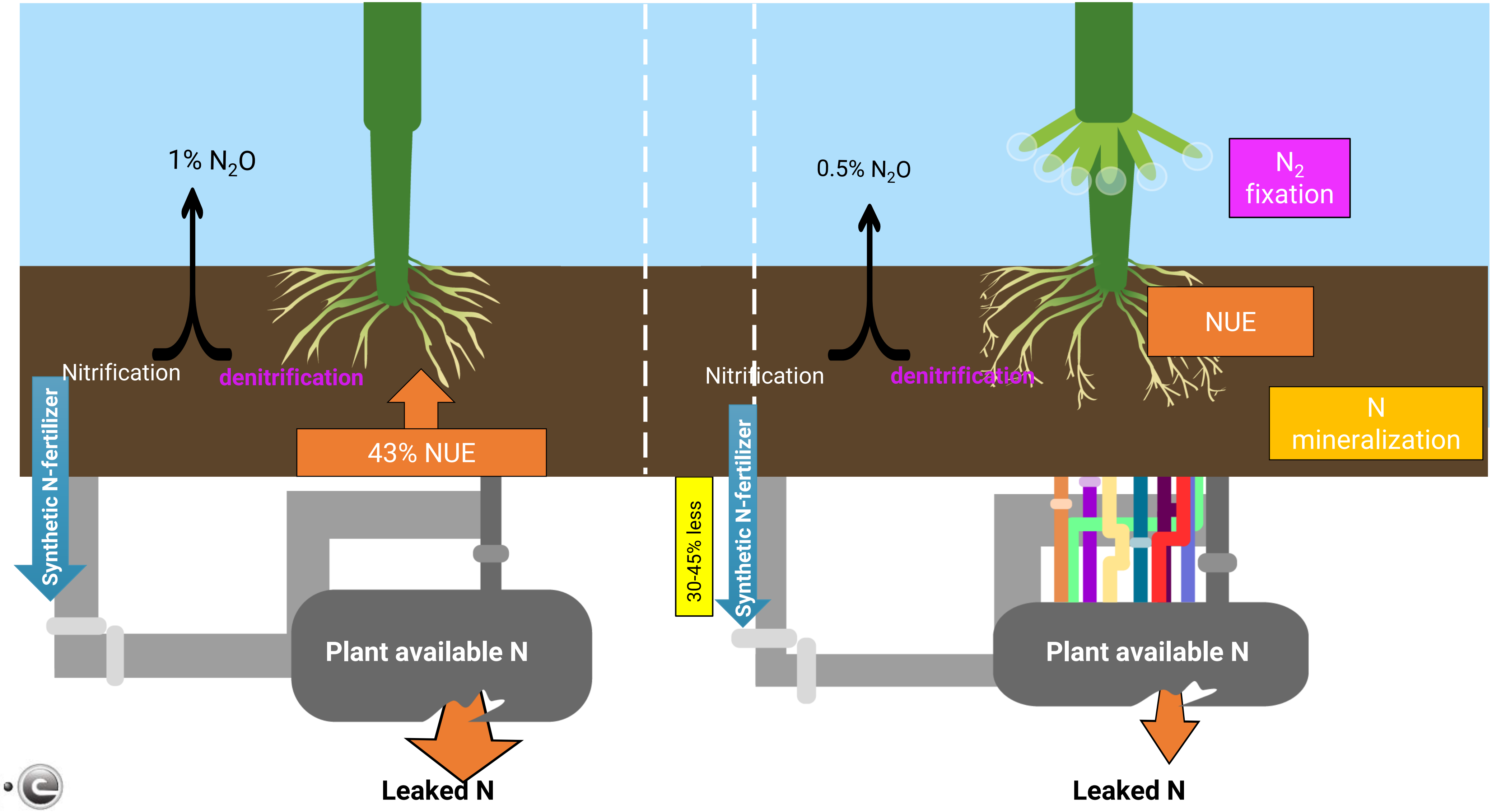
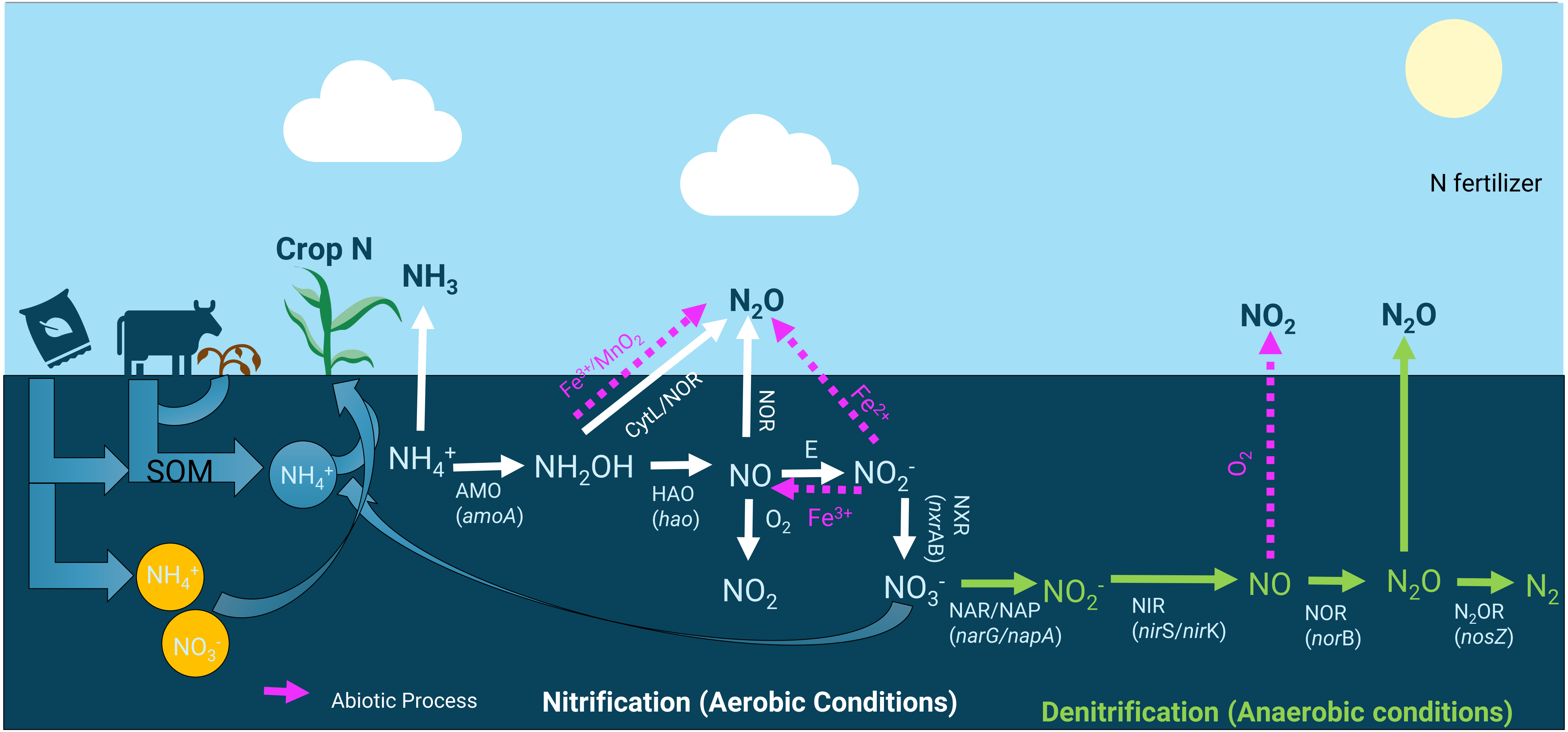


Figure adapted from Grady et al. 2022. Soil Biology and Biochemistry 175:108856

N_2O emission reduction: direct N_2O mitigation



Speakers

- Chris Voigt, Massachusetts Institute of Technology

  Future Low-Energy Sources of Nitrogen for Agriculture

- Ed Buckler, USDA ARS/Cornell University

  Create a Sustainable Food System for Nitrogen: Moving Synthetic Nitrogen from the Field to Barn

- Wendy Yang, University of Illinois-Champaign-Urbana

  Manipulating Microbes to Mitigate Soil Nitrous Oxide Emissions from Bioenergy Cropping Systems

- Jean-Michel Ane, University of Wisconsin-Madison

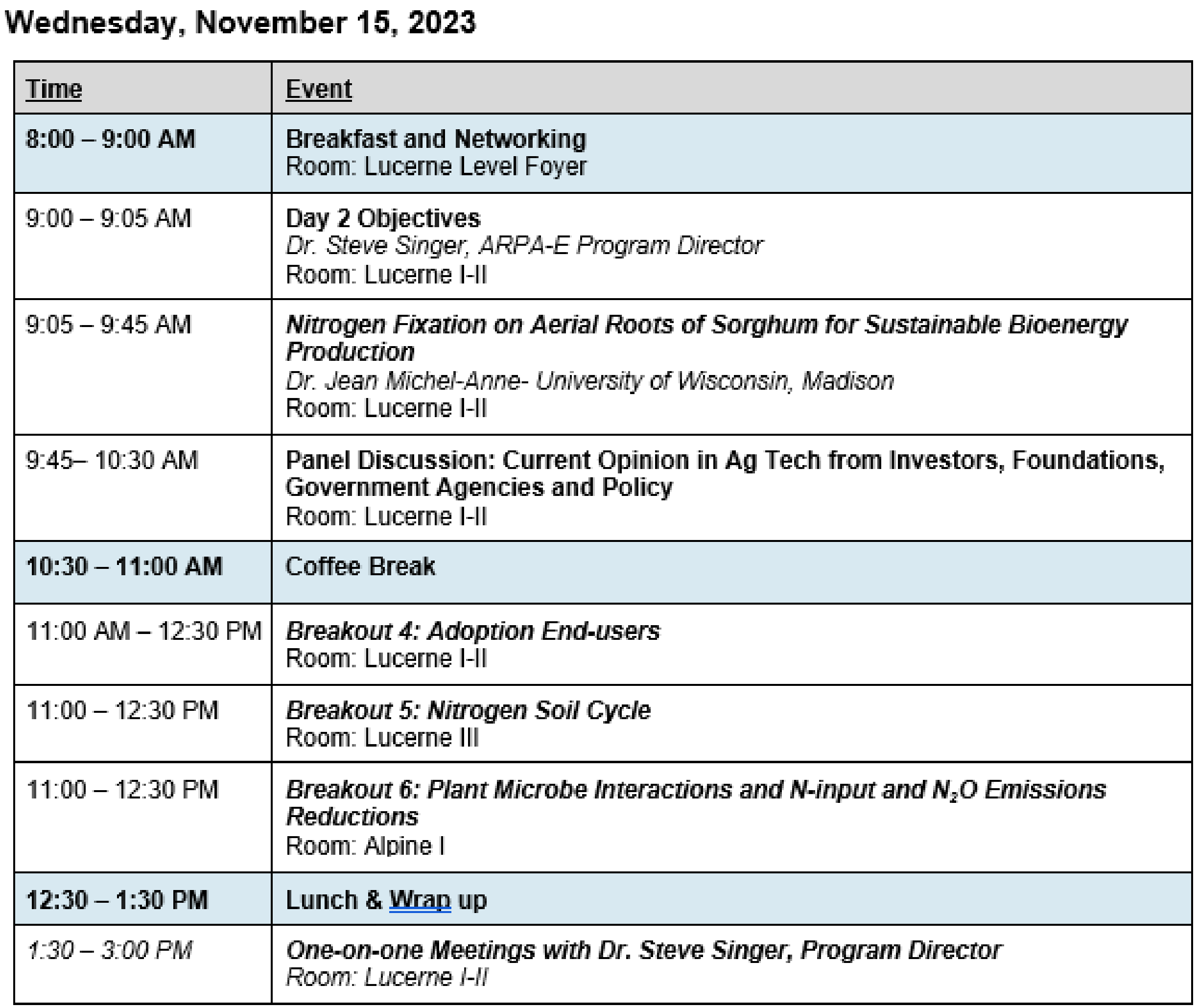
  Nitrogen Fixation on Aerial Roots of Sorghum for Sustainable Bioenergy Production

Workshop agenda

Tuesday, November 14, 2023

Time	Event
8:00 – 9:00 AM	**Registration and Breakfast** Room: Lucerne Level Foyer
9:00 – 9:15 AM	**Welcome and Introduction to ARPA-E** *Dr. Jen Shafer, ARPA-E Associate Director of Technology* Room: Lucerne I-II
9:15 – 9:45 AM	**Introductory Presentation** *Dr. Steven Singer, ARPA-E Program Director* Room: Lucerne I-II
9:45 – 10:15 AM	**Future Low-Energy Sources of Nitrogen for Agriculture** *Dr. Chris Voigt, Massachusetts Institute of Technology* Room: Lucerne I-II
10:15 – 10:35 AM	**Coffee Break**
10:35 – 11:05 AM	***Create a Sustainable Food System for Nitrogen: Moving Synthetic Nitrogen from the Field to Barn*** *Dr. Ed Buckler, Cornell University* Room: Lucerne I-II
11:05 – 11:25 AM	***Manipulating Microbes to Mitigate Soil Nitrous Oxide Emissions from Bioenergy Cropping Systems*** *Dr. Wendy Yang- University of Illinois, Urbana-Champagne* Room: Lucerne I-II
11:25 AM – 12:05 PM	**Panel discussion: Starting with the End in Mind – Insights to Developing New Technologies by End Users.** Room: Lucerne I-II
12:05 – 1:00 PM	**Lunch**
1:05 – 2:35 PM	***Breakout 1: Frontiers in Nitrogen Fixation*** Room: Lucerne I-II
1:05 – 2:35 PM	***Breakout 2: Microbial N_2O Emissions Mitigation*** Room: Lucerne III
1:05 – 2:35 PM	***Breakout 3: Plant pathways towards reducing Nitrogen inputs and N_2O Emissions*** Room: Alpine 1
2:35 – 3:00 PM	**Coffee Break**
3:00 – 4:00	***SMART FARM N_2O Measurement and Modeling Showcase*** Room: Lucerne I-II
4:00 – 5:00 PM	***One-on-one Meetings with Dr. Steve Singer, Program Director*** *15 minutes per person/group* *Room: Lucerne III*
4:10 – 6:00 PM	***Concept Poster Sessions and Networking Reception*** *Room: Alpine II*

Workshop agenda



Wednesday, November 15, 2023

Time	Event
8:00 – 9:00 AM	**Breakfast and Networking** Room: Lucerne Level Foyer
9:00 – 9:05 AM	**Day 2 Objectives** *Dr. Steve Singer, ARPA-E Program Director* Room: Lucerne I-II
9:05 – 9:45 AM	***Nitrogen Fixation on Aerial Roots of Sorghum for Sustainable Bioenergy Production*** *Dr. Jean Michel-Anne- University of Wisconsin, Madison* Room: Lucerne I-II
9:45– 10:30 AM	**Panel Discussion: Current Opinion in Ag Tech from Investors, Foundations, Government Agencies and Policy** Room: Lucerne I-II
10:30 – 11:00 AM	**Coffee Break**
11:00 AM – 12:30 PM	***Breakout 4: Adoption End-users*** Room: Lucerne I-II
11:00 – 12:30 PM	***Breakout 5: Nitrogen Soil Cycle*** Room: Lucerne III
11:00 – 12:30 PM	***Breakout 6: Plant Microbe Interactions and N-input and N_2O Emissions Reductions*** Room: Alpine I
12:30 – 1:30 PM	**Lunch & Wrap up**
1:30 – 3:00 PM	***One-on-one Meetings with Dr. Steve Singer, Program Director*** *Room: Lucerne I-II*