CENSA: Circular Economy for Nitrogen Sustainability in Agriculture
Moving Nitrogen from the Farm to the Barn

Edward Buckler and TEAM
USDA-ARS
www.maizegenetics.net
### Molecules of Life in Our Atmosphere

<table>
<thead>
<tr>
<th>Molecule</th>
<th>Bond-dissociation Energy (kcal/mol)</th>
<th>Atmospheric Abundance</th>
<th>Challenge</th>
<th>Approach</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO₂</td>
<td>127</td>
<td>0.04%</td>
<td>Concentration</td>
<td>Massive Collector</td>
</tr>
<tr>
<td>N₂</td>
<td>226</td>
<td>78.08%</td>
<td>Energy</td>
<td>Industrial</td>
</tr>
<tr>
<td>O₂</td>
<td>119</td>
<td>20.94%</td>
<td>None</td>
<td></td>
</tr>
<tr>
<td>H₂O</td>
<td>119</td>
<td>0↔4%</td>
<td>Variability</td>
<td>Flex demand + Storage</td>
</tr>
</tbody>
</table>
Solar & Hydrogen

80% Efficiency

Plants

Masters at capturing carbon
Evolved to have low energy biomass
CENSA: Broad Perspective on Ag Nitrogen

Lisa Ainsworth
Plant Physiology + GHG

Mark Boggess
Livestock & Range

Virginia Jin
Cropping Systems

Edward Buckler
Plant Genetics

CENSA
Circular Economy for Nitrogen Sustainability in Agriculture

Peter Kleinman
Manure Management
By mid-century Agriculture could be responsible for 38% of US GHG

Modeled with Energy Policy Simulator (EPS) by Energy Innovation LLC
88% of nitrogen inputs are lost

Nitrogen Inputs:
- Synthetic Fertilizer (11.6 Tg N) 67%
- Natural Fixation (5.8 Tg N) 33%

Crop Production
- NH₄
- NO₃
- DON
- Nₐ

Animal Production
- NH₄
- NO₃
- DON
- Nₐ

Atmosphere
- NH₃
- N₂O
- NOₓ
- N₂

Ground & Surface Water
- 25%

Bioenergy, Fiber
- 10%

Consumed Crops
- 12%

Consumed Animal Products
- 28%

Adapted from Oenema et al 2009
Synthetic Nitrogen (Haber-Bosch) itself is **not** the Problem

Points made by Vaclav Smil:
- Much more land/time efficient
- 2/3 of global population dependent on it by mid-century
- **Only** uses 1% of global energy (renewable sources now viable)
Trophic Levels Have Large Costs

Urea

Soil/Microbes

Plants

Crude plant protein & DDG

~50% Losses

2-3X Higher Efficiency

Amino Acids

Urea/Nitrate

~50% Losses
Agriculture has a nitrogen problem...11% total US GHGs

Leveraging Circular Economies could reduce GHG & water pollution by 80%

EPA 2019 Green House Gas Inventory
What scale changes do we think are tenable:

- Urea: -30%
- NPN: +1000%
- Livestock Production: -50%
- Soil Management: +50%
- Cropping Systems: -30%
- Amino Acids: -50%
- Alternative & Cultured Proteins: +500%

Diagram showing the relationships and scale changes between different agricultural and nutritional components.
Shifting the Use Synthetic Nitrogen Across the US

Urea

Broad scale N application

Urea

Targeted N use at higher trophic level

Crude plant protein & DDG

Amino Acids (high efficiency)
A CENSA approach could reduce Agriculture GHG by 50% or more

Modeled with Energy Policy Simulator (EPS) by Energy Innovation LLC
A Keystone Effort for Maize
~ 45% of the US problem

CERCA
Circular Economy
that Reimagines Corn Agriculture
Nitrogen Soil Cycle

**Conventional**
- Nitrogen Fertilizer
- Crop
- NO$_3^-$
- Residue-N Recycling
- Nitrogen Fertilizer
- Immob.
- N$_{min}$
- NH$_3$/NH$_4^+$
- Leaching
- N$_2$O

**CERCA**
- Nitrogen Fertilizer
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M. Castellano
Modern Maize Nitrogen Cycle

- **Soil nitrate production**
- **Nitrate leaching**
- **N\textsubscript{2}O release**
- **Maize nitrate uptake**
- **Residue N**

Spring  
Winter  

M. Castellano
CERCA Maize Nitrogen Cycle

- Nitrate leaching, $N_2O$ release reduced
- Shift nitrate uptake timing
- Increase Soil Organic N

Rate

Spring  Winter
CERCA Strategies

Season shifting

- Dec
- Jan
- June
- Dec

Max

Light

Water & Natural N

CERCA Corn

Corn

Early Spring

Winter Annual

CERCA Corn

Nutrient Recycling

Grain
- Protein 8% → 4%
- P 0.32% → 0.16%

N Remobilization to root
- 0% → 75%

Nitrification Inhibition
- 400 → 100
- $N_2O\ N_{per\ m^2\ per\ year}$
Maize Relatives Especially Perennials Have These Traits

- Zea mays ssp. mexicana
- Elite Maize
- Diverse Inbreds
- Zea Landraces
- Tripsacum northern
- Tripsacum southern
- Zea diploperennis
- Zea sp.

Andropogoneae

- 1200 species
- 0.6 Myr
- 18 Myr

Vossia
- Coelorachis
- Saccharum
- Miscanthus

CERCA: Circular Economy the Reimagines Corn Agriculture

27 Public Labs

5 Industry Partners

Grantham Foundation for the Protection of the Environment
Most promising opportunities for improvements in low-emissions cropping systems and what do they get us in terms of emissions reductions?

- Feed livestock and humans with synthetic nitrogen directly – reduces feed demand, fertilizer for starch crops (up to −50%)
- Annuals behave more like perennials (up to −25%)
- Year-round cropping systems (up to −25%)
- Precision & more continuous N application (up to −25%)

USDA
If you time traveled to 2050, what kind of food systems would shock you?

• It looks just like today
• Nitrogen fixing cereals are used
  – Yield reduction is not competitive to synthetic N
• Oil legumes are important
  – Green hydrogen and hydrogenation will be more efficient
• Plants are more than 2% efficient
  – Currently <=1.5%
If yields and required inputs were not substantially different from today:

• Why yields same?
  – Extreme weather, disease pressure
  – Inputs did not increase in Africa

• Why inputs same?
  – High input regions – green hydrogen made fertilizer very cheap & no regulation
  – Low input regions – African energy/transport revolution did not occur
How Close to Maximal Efficiency can we get?

$57 \text{ grams of protein per day}$

$1 \text{ person}$

$0.056/\text{day} \cdot \text{person}$

$24 \text{ million hectare per year}$

$158 \text{ trillion grams per year}$

$7.6 \text{ billion people}$

$1.5\%$ of Global Arable Land could Fix all Carbon needed for Global Protein Demand
Cold tolerance for year round N uptake: winter and spring grasses and legumes, cover crops

N recycling, Precision and novel N applications (seed coating, aerial, etc)

Enhanced rotations, relay and intercropping

Perennials in certain environments
Land needs to be covered year round.

- Cover crops
- Perennial Grasses
- Trees
Other key targets

- Increase Winter/Spring Legumes
- Residue Burning: $\text{CH}_4 + \text{N}_2\text{O} - 3.5\% \text{ (Global)}$
- Rice: $\text{CH}_4 - 1.3\% \text{ (Global)}$
Radical protein transformation?

Precision Fermentation: high quality proteins

- $10/kg by 2024
- $1/kg by 2035
- 70% reduction in cows

https://www.rethinkx.com/food-and-agriculture
Radical protein transformation?

ReThinkX assumes scaling and engineering with continue rapid drops in cost for the next decade.

https://www.rethinkx.com/food-and-agriculture
Radical protein transformation?

ReThinkX: Fermentation based milk protein will drop below casein and whey by 2024.

https://www.rethinkx.com/food-and-agriculture
Radical protein transformation?

ReThinkX:
Beef proteins below beef by 2021
Cell-based beef below beef by 2025

https://www.rethinkx.com/food-and-agriculture
Landscape of Protein Prices

Animal Proteins

Plant Proteins

Feed stocks & fermentation products
Current US cost of protein

Wholesale prices if you were buying the product only for the protein

64.8-fold

Ethanol
Current US cost of protein

RethinkX predicts disruption of these markets – with 6 to 30X fold lower cost
Is $1/kg of protein possible

Assume >2X loss

Cannot refine from soybean or soybean meal
Is $1/kg of protein possible?

Feed lysine made in a fermenter is already under this price.
Is $1/kg of protein possible

Ammonia and maize starch are cheap enough to do this

By 2035, even cheaper with onsite ammonia and increased yields.