Management Impacts on Nitrous Oxide Emissions from Cropping Systems in Minnesota

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USDA
Agricultural Research Service

UNIVERSITY OF MINNESOTA
Driven to Discover℠

FUNDING SOURCES

- *NRI-USDA CSREES/NIFA Air Quality Program*
- *USDA-ARS GRACEnet Project*
- *International Plant Nutrition Institute's Foundation for Agronomic Research:*
- *Agrotain Intl.*
- *Agrium Inc.*
- *Minnesota Corn Growers Association*
- *John Deere & Company*
- *Kingenta Corporation*

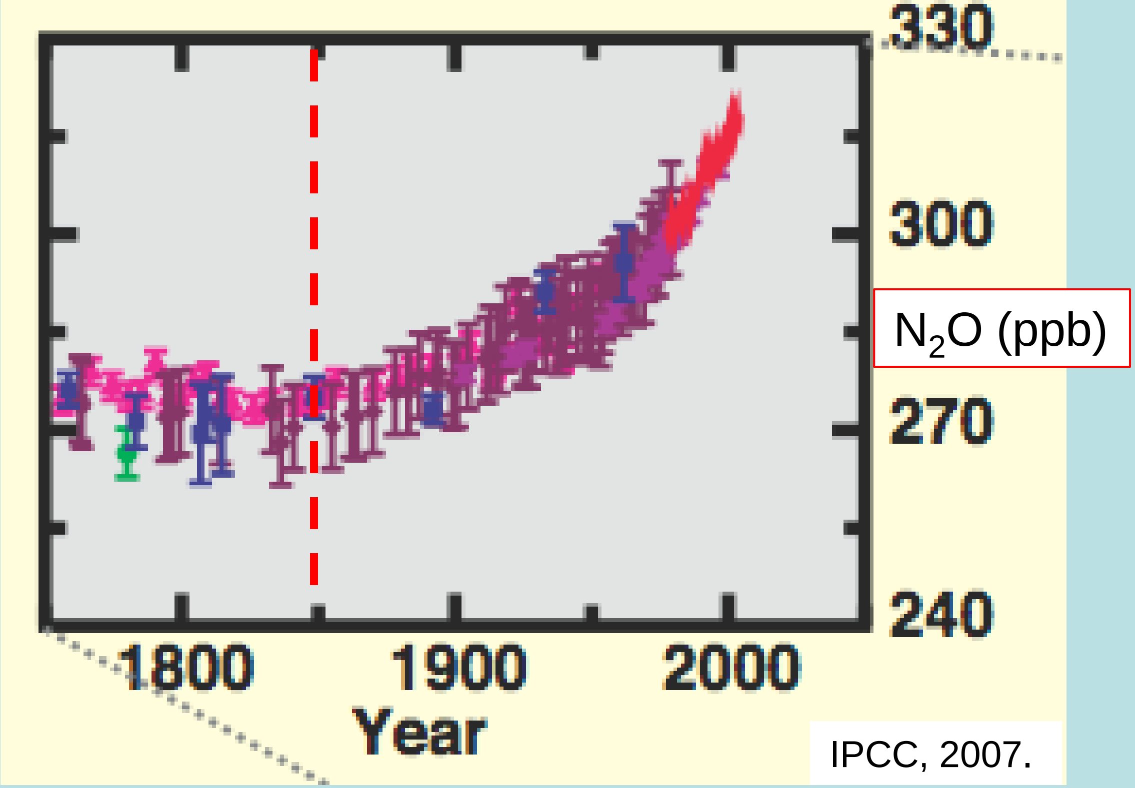
IS THERE ANYTHING WE CAN DO TO STOP THE LEAK(s) ?

The Deepwater Horizon oil spill (leak)
April 20 - July 15, 2010

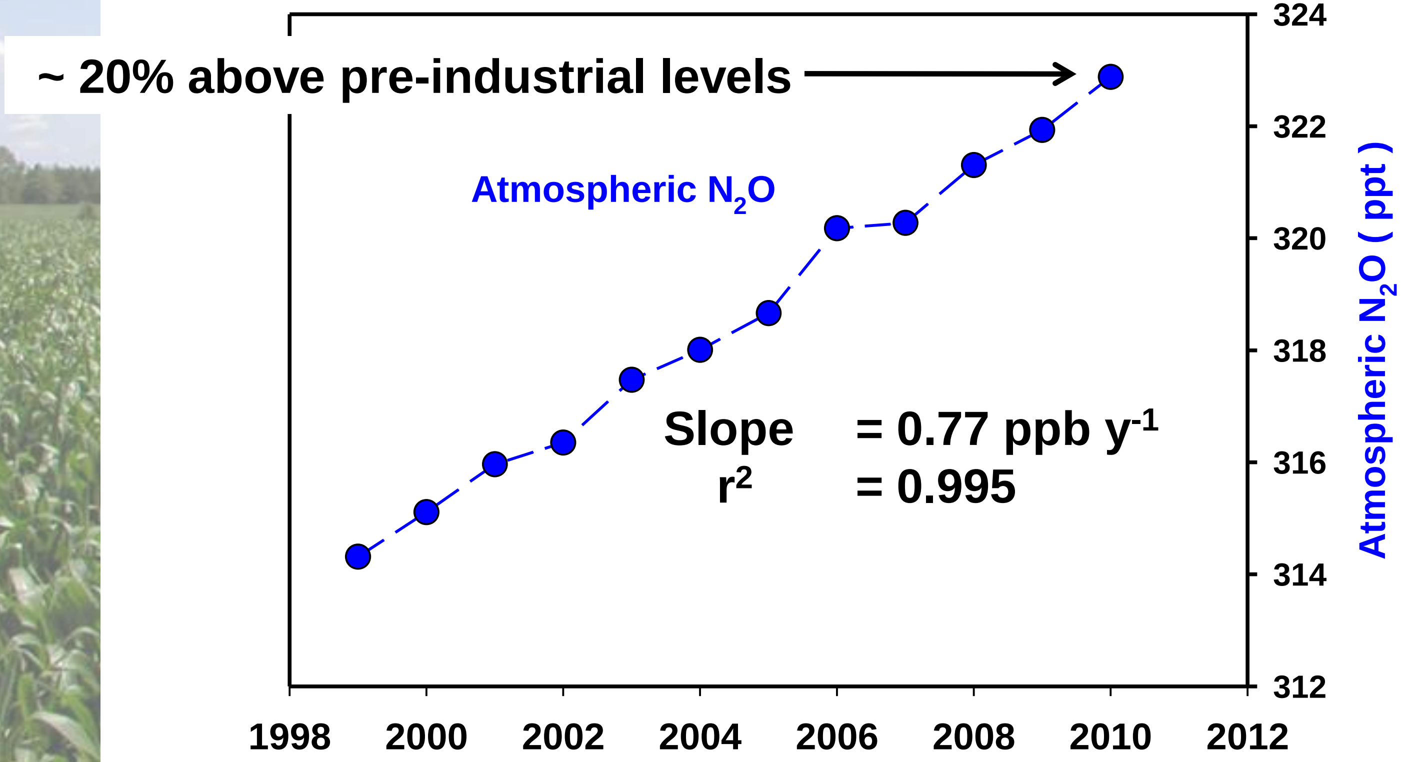
Fukushima Dai-ichi Nuclear Power Plant
March 11, 2011 - ??

IS THERE ANYTHING WE CAN DO TO STOP THE LEAK(s) ?

The Leaking Nitrogen Cycle
Atmospheric Nitrous Oxide (N_2O) Concentrations
1850 - ????



Rising Atmospheric N_2O



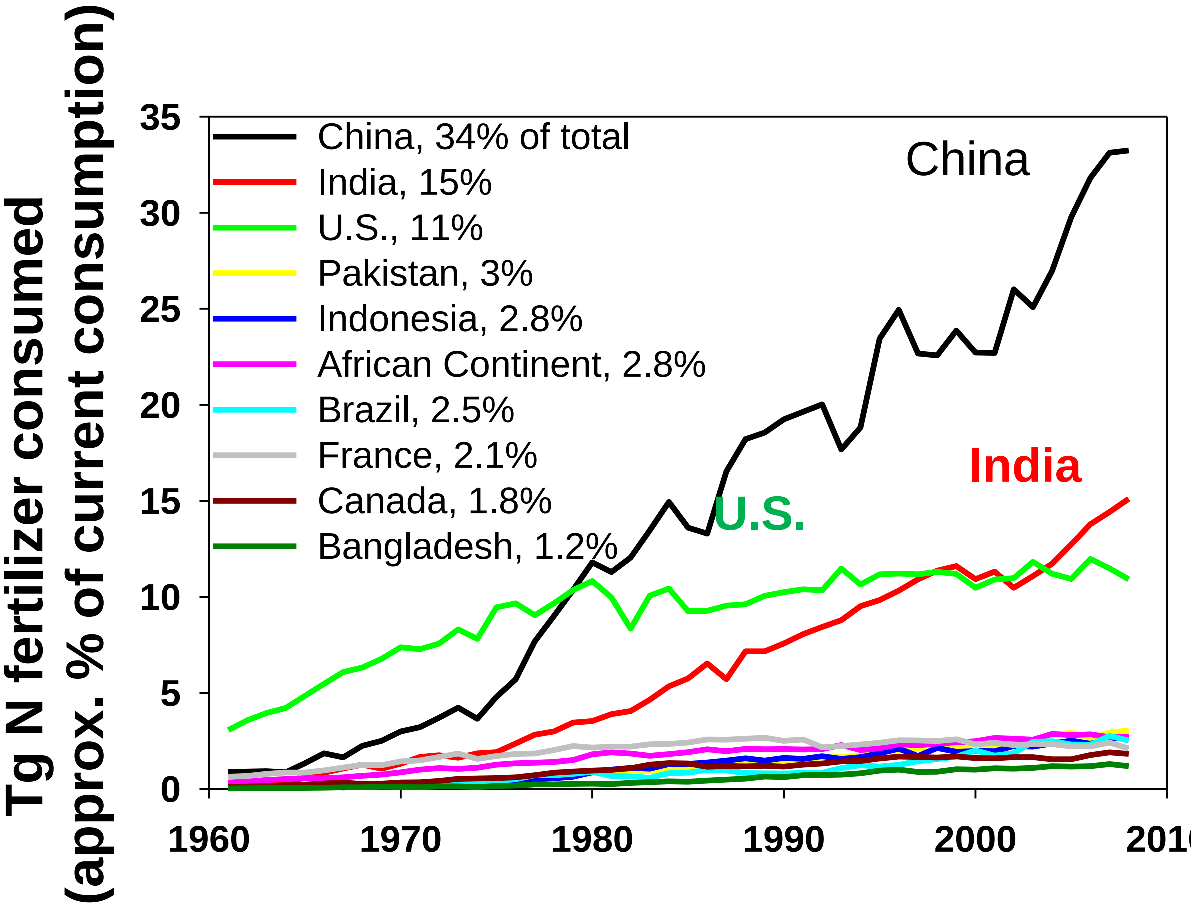
NOAA/ESRL halocarbons in situ program ftp://ftp.cmdl.noaa.gov/hats/n2o/insituGCs/CATS/global/insitu_global_

Anthropogenic N_2O Sources

Fertilizer application:	40%
Manure application & mgmt:	40%
Biomass burning :	7%
Industrial:	14%

Davidson, 2009; Mosier et al.,1998

World Fertilizer Use



87% of total increase since 1980 occurred in China and India

http://www.fertilizer.org/

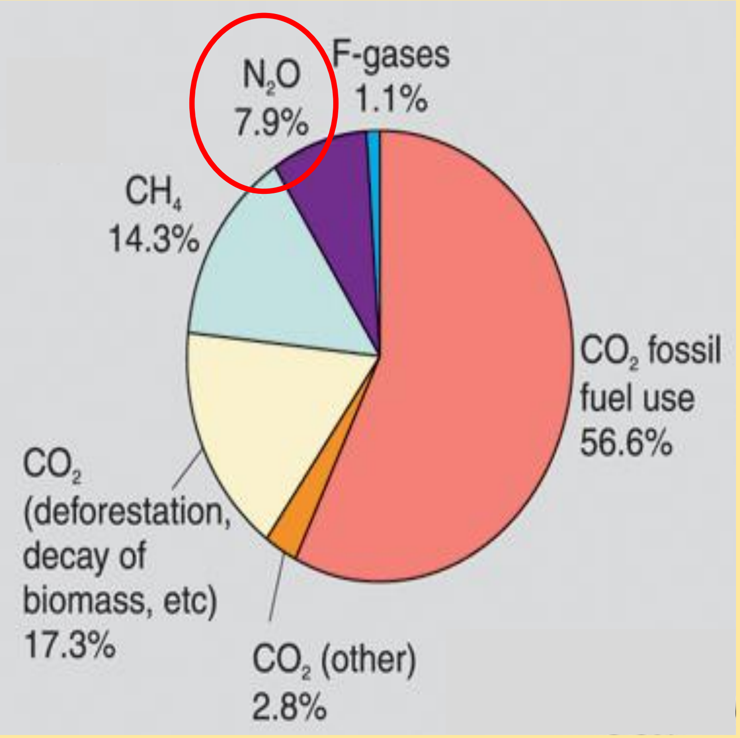
Global Warming Potential (GWP) = 300 times CO_2

2 kg N_2O-N ha^{-1} ≈ 1 Mg CO_2 ha^{-1}

2 kg N_2O-N = CO_2 from 100 gallons of gasoline

Global Warming Potential (GWP) = 300 times CO_2

IPCC, 2007



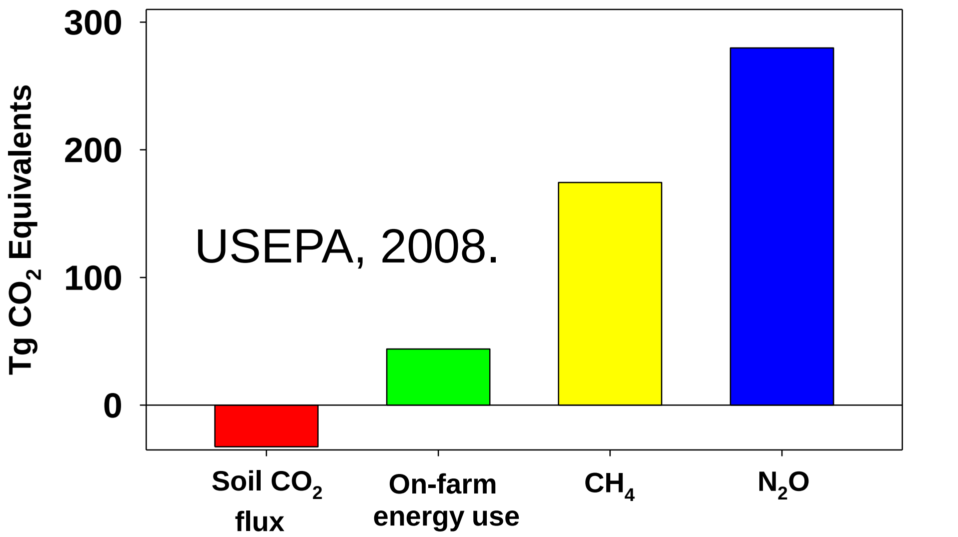
% of total anthropogenic GHG emissions

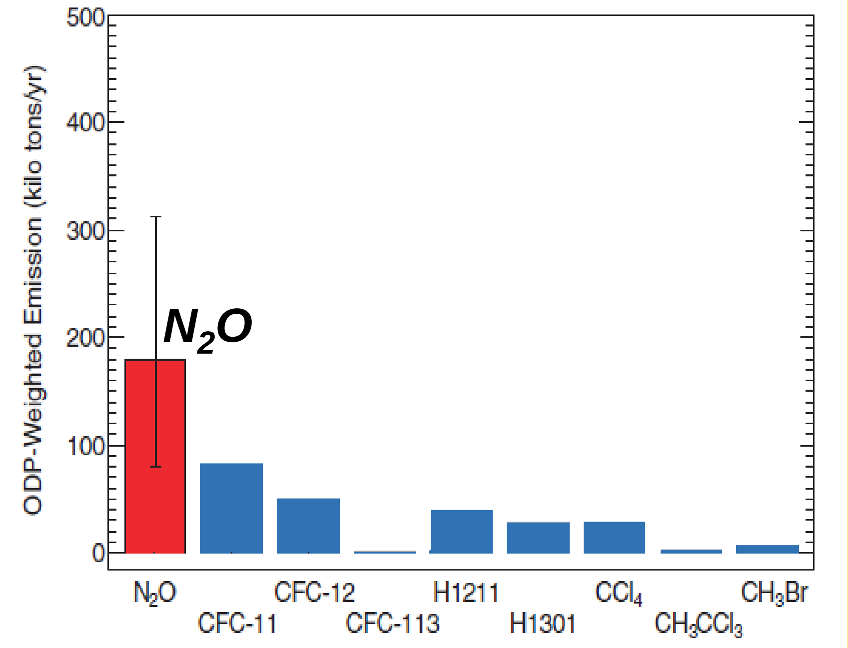
GWP= Global Warming Potential

ODP = Ozone Depleting Potential

Ravishankara et al. *Science.* 2009

Greenhouse Gas Sources in U.S. Agriculture (2006)





Policy activity & demands

<u>e.g., 2008 Farm Bill</u>

Requires USDA to develop scientifically-based guidelines to allow individual farming operations to quantify their N_2O and overall GHG emissions.

"By 2050, N_2O emissions could represent > 30% of peak CFC emissions of 1987."

Fertilizer Management Effects

Few studies examining N fertilizer management practices

- Comparison of fall- vs. spring- applied AA: 1 study (0 in MN)
- Comparison of AA with and w/out N serve: 1 study (0 in MN)
- Single versus split applications: 1 study (0 in MN)

- Few empirically-based guidelines for reducing N_2O while maintaining crop yields

Outline

Review our recent research regarding synthetic N fertilizer mgmt effects:

1. Controlled release fertilizers (CRFs)
2. Effects of different chemical fertilizer forms
3. Placement (depth and banding) effects
4. Mechanisms & modeling
5. Tillage effects
6. Nitrogen use efficiency (NUE)

Study Sites

Irrigated Site
-Corn
-Potato

Dryland/
Tile-drained site
-Corn

Dryland/naturally drained site
-Corn

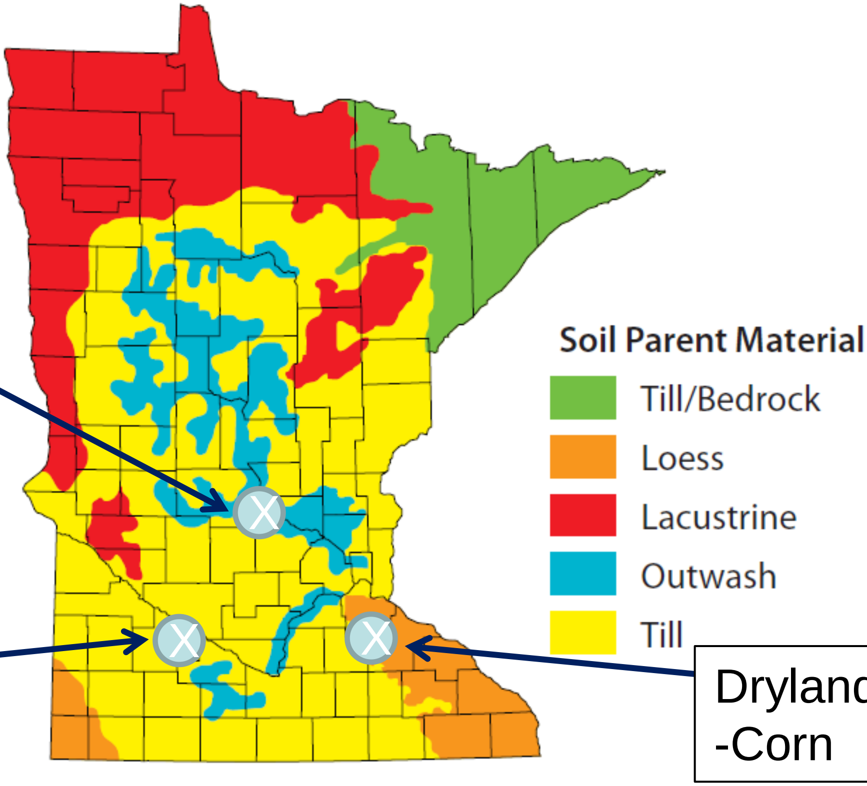


Figure 1. Parent materials of Minnesota.

Methods: Gas Flux Chambers

Pro:

• Plot-scale studies & treatment comparisons

• Inexpensive

Con:

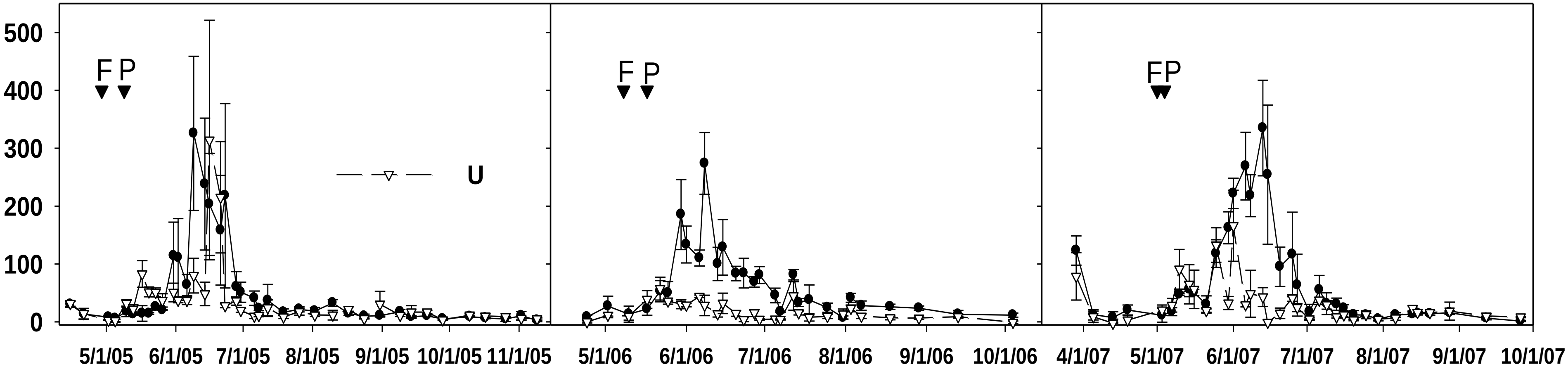
• Limited spatial and temporal coverage

• Physical disturbance

Methods: Automated Chambers

Methods: Data Analysis

Daily N_2O flux (μg N m^{-2} h^{-1})

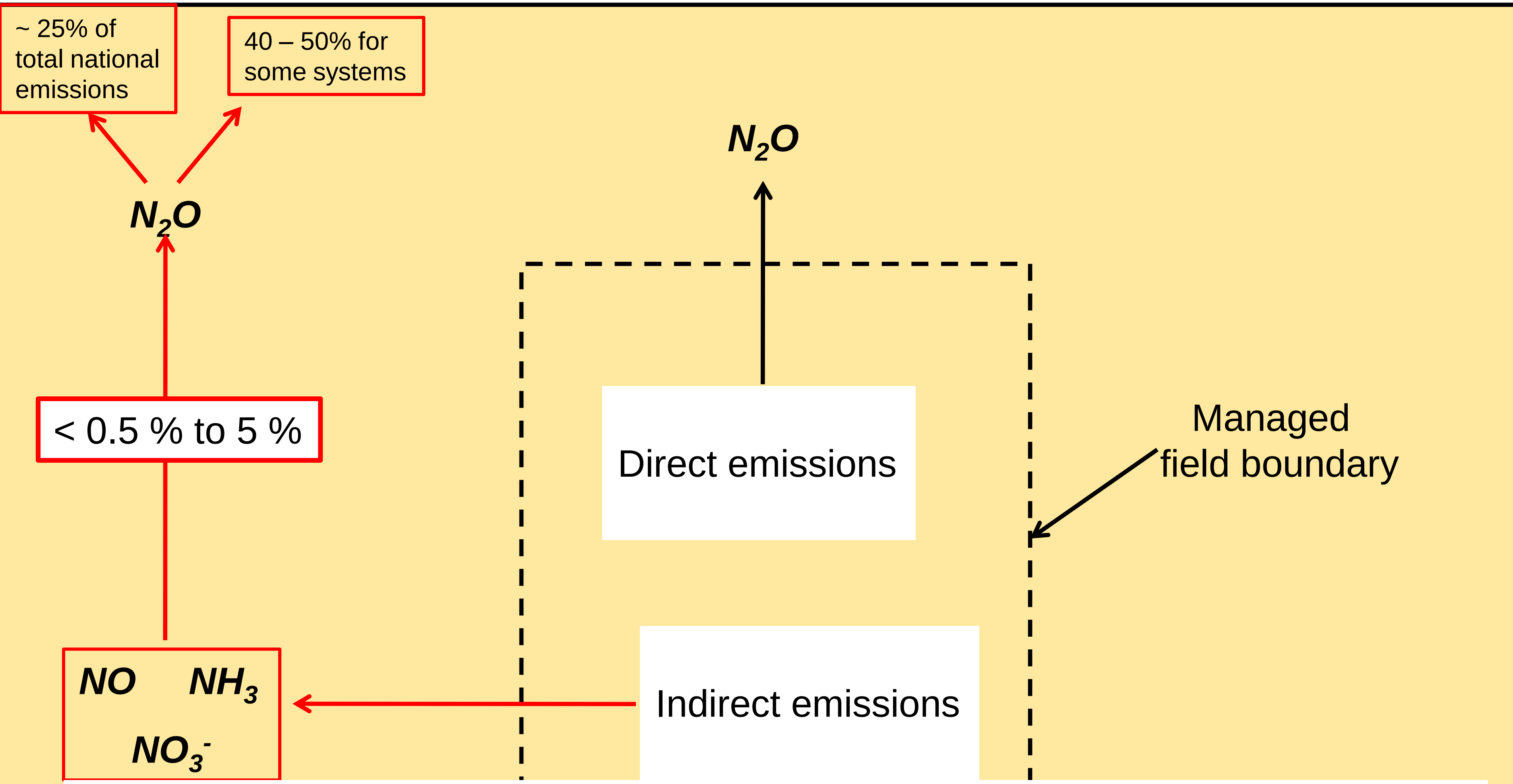


F = Fertilizer application date
P = Planting date

Flux versus Time Data **ug N m^{-2} h^{-1}** → Trapezoidal Integration → Cumulative Emissions mg N m^{-2}

(1 kg N ha^{-1} = 100 mg N m^{-2})

Direct and Indirect N_2O Emissions



Challenges:

1. Logistical - measuring all forms of N loss in a single experiment

Chambers for ***NO and NH_3;*** Lysimeters, water sampling for ***NO_3^-***

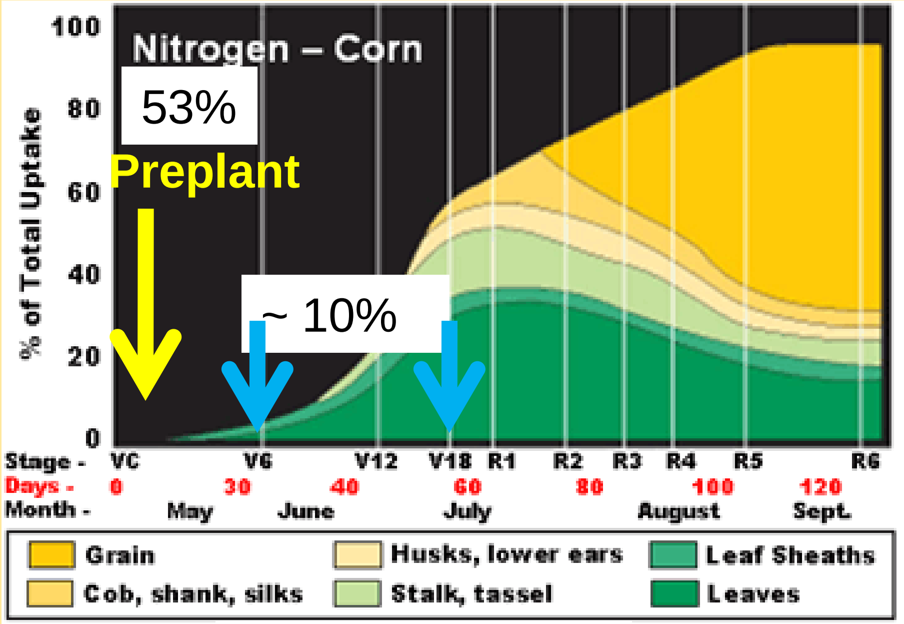
2. Estimating fraction of off-site N losses converted to N_2O

Asynchrony between N fertilizer application and crop N demand

Corn N Uptake

Fall application

35%



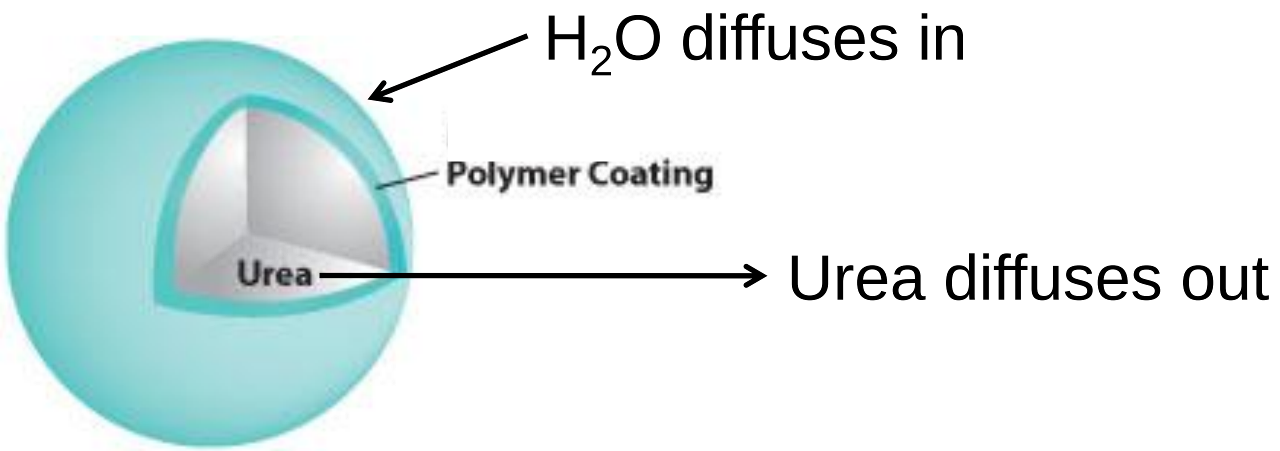
Iowa State University Extension

High potential for generating N losses:
Provide substrate for soil microbial population

Controlled Release Fertilizers (CRFs) for Reducing N_2O Emissions

GOAL: Achieve more gradual N release over growing season:

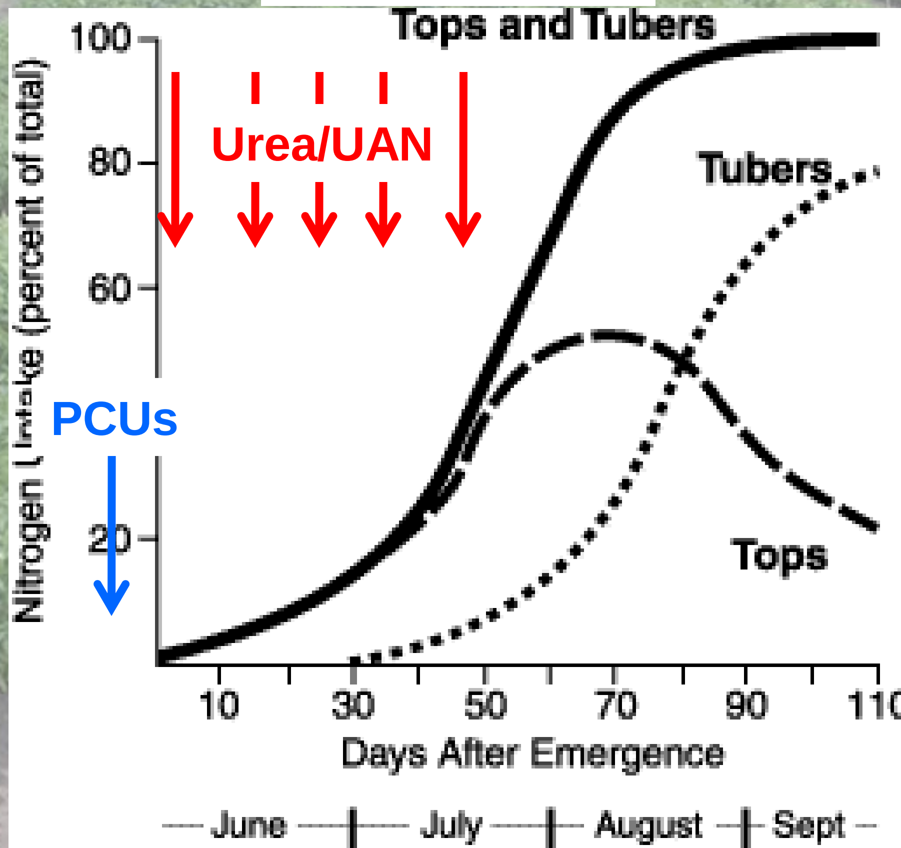
1. Polymer–coated urea (PCU): Slow diffusion through porous coating



Polymer-coated Urea (PCU) for Irrigated Potato Production

Source	Timing	Rate (kg N ha^{-1})
1. Conventional urea (47%N)	4 split applications	270
2. PCU-1 (44%N)	Before planting	270
3. PCU-2 (42%N)	Before planting	270

Potato N Uptake



North Dakota State University Extension

Controlled Release Fertilizers for Irrigated Potato Production

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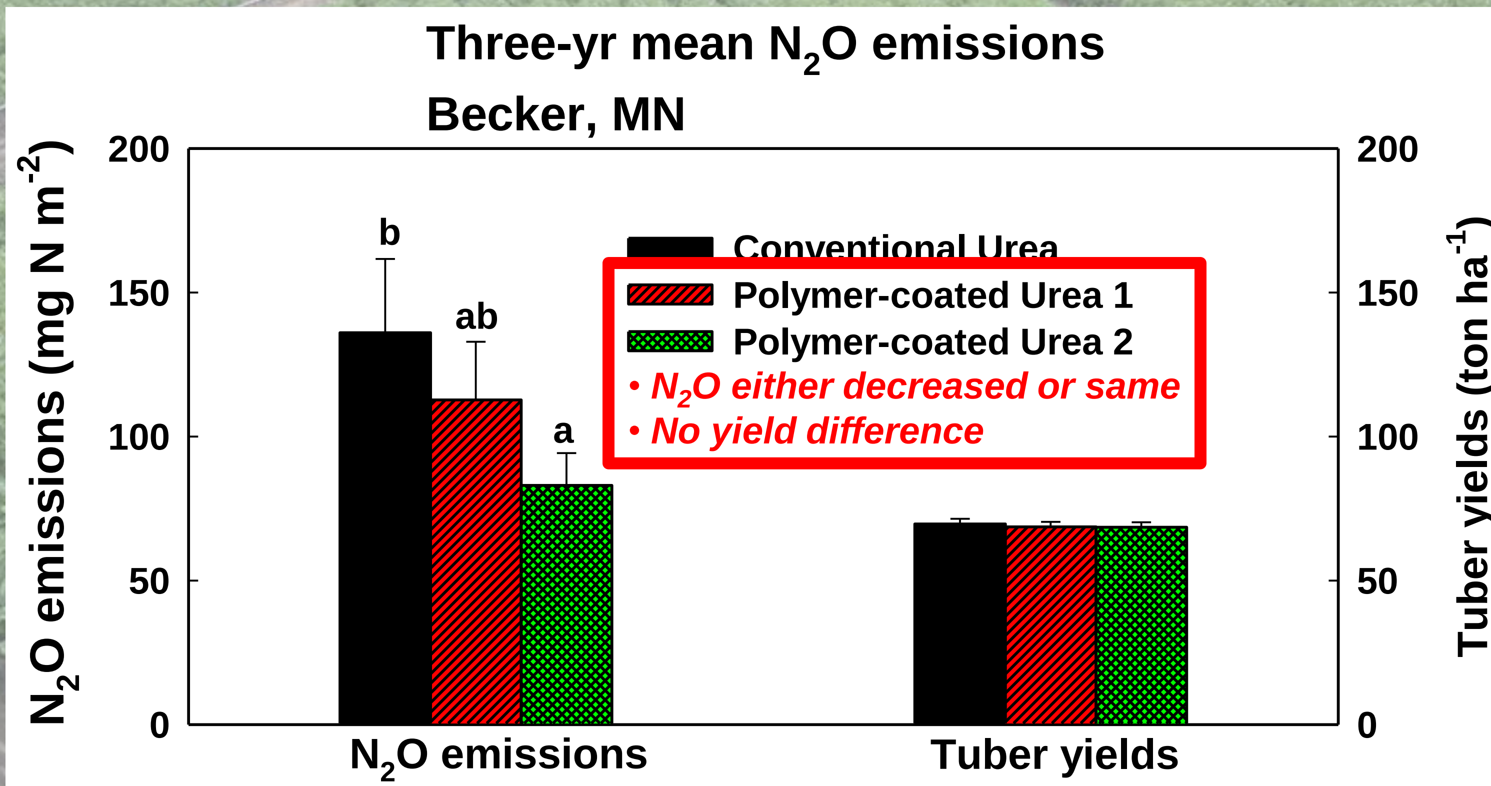

Hyatt et al. 2010. SSSAJ.

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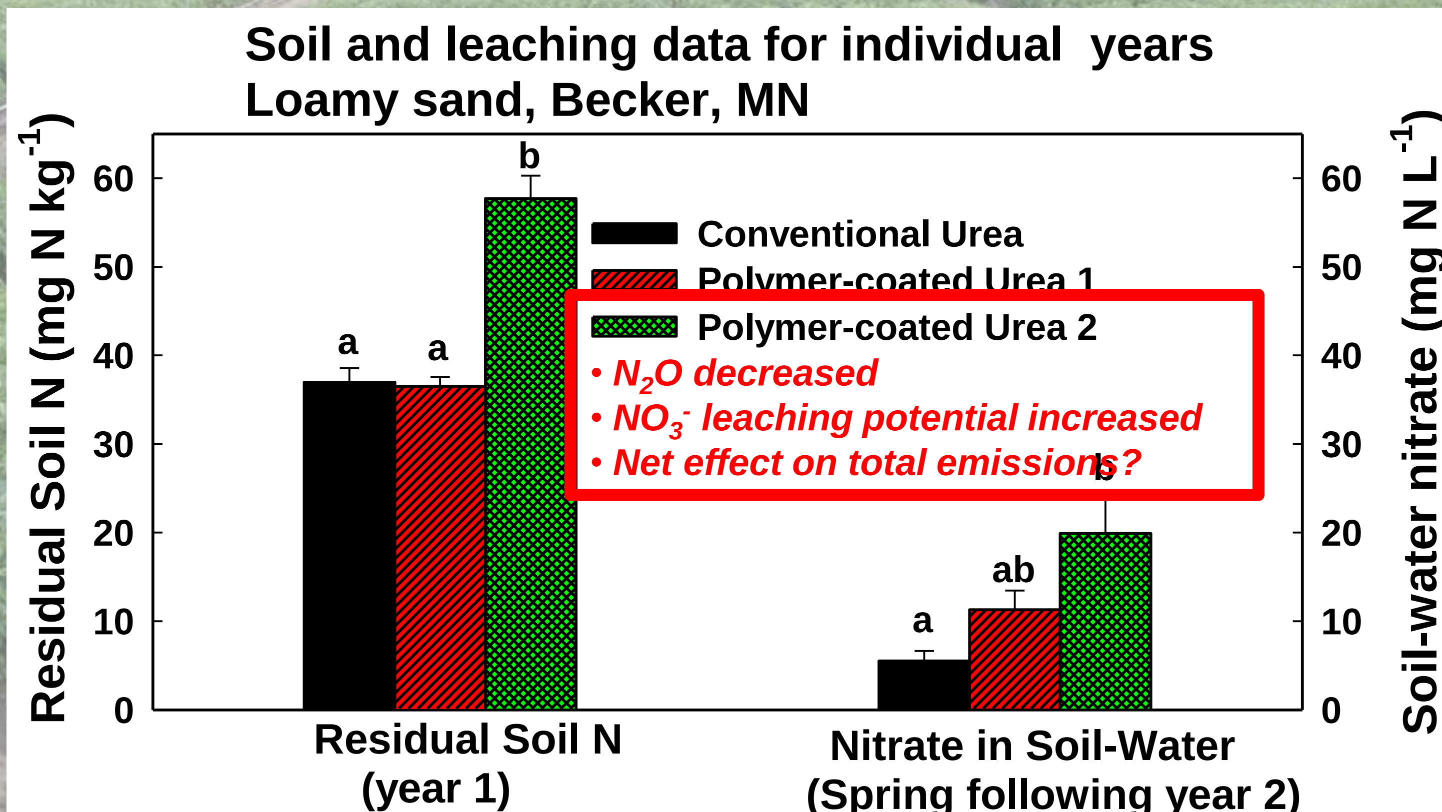


Venterea et al. 2011. JEQ

Polymer-coated urea for reducing N_2O emissions

Other studies:

- PCU-1 in irrigated and dryland corn at Becker: No decrease in N_2O
- PCU-1 in dryland corn at Rosemount: No decrease in N_2O

1. Potential advantages if product release rate is well matched to crop demand.
2. No set of guidelines for knowing when/where specific products will be effective for reducing N_2O emissions.
3. Widespread adoption of PCU-1 (ESN) in potato production: due to work of Rosen et al. showing potential reduction in leaching (indirect N_2O).
4. Minimal adoption for corn production (< 3%). Yield benefits required to justify increased cost are not consistent.

Controlled Release Fertilizers (CRFs) for Reducing N_2O Emissions

GOAL: Achieve more gradual N release over growing season:

<u>2. Nitrification (NI) inhibitors</u>: Blended or co-applied with fertilizer

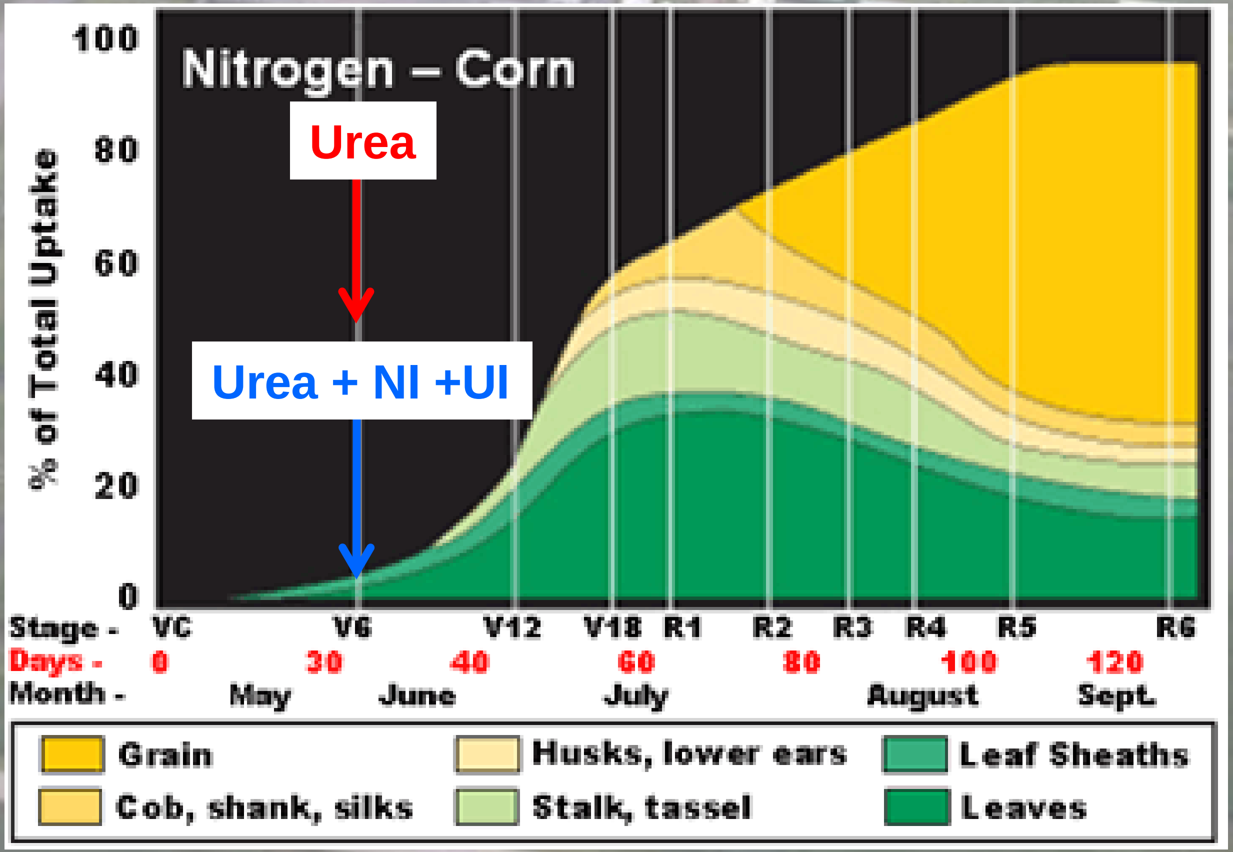
$$NH_4^+ \rightarrow NO_3^-$$

enzyme inhibitor

Controlled Release Fertilizers for Dryland Corn Production

Source		Timing	Rate (kg N ha^{-1})
1. Conventional urea	(47%N)	Sidedress (V4-V6)	146
2. Urea + DCD + NBPT	(47%N)	Sidedress (V4-V6)	146

Treatments applied to both CT and NT treatments (in place for > 15 yr)



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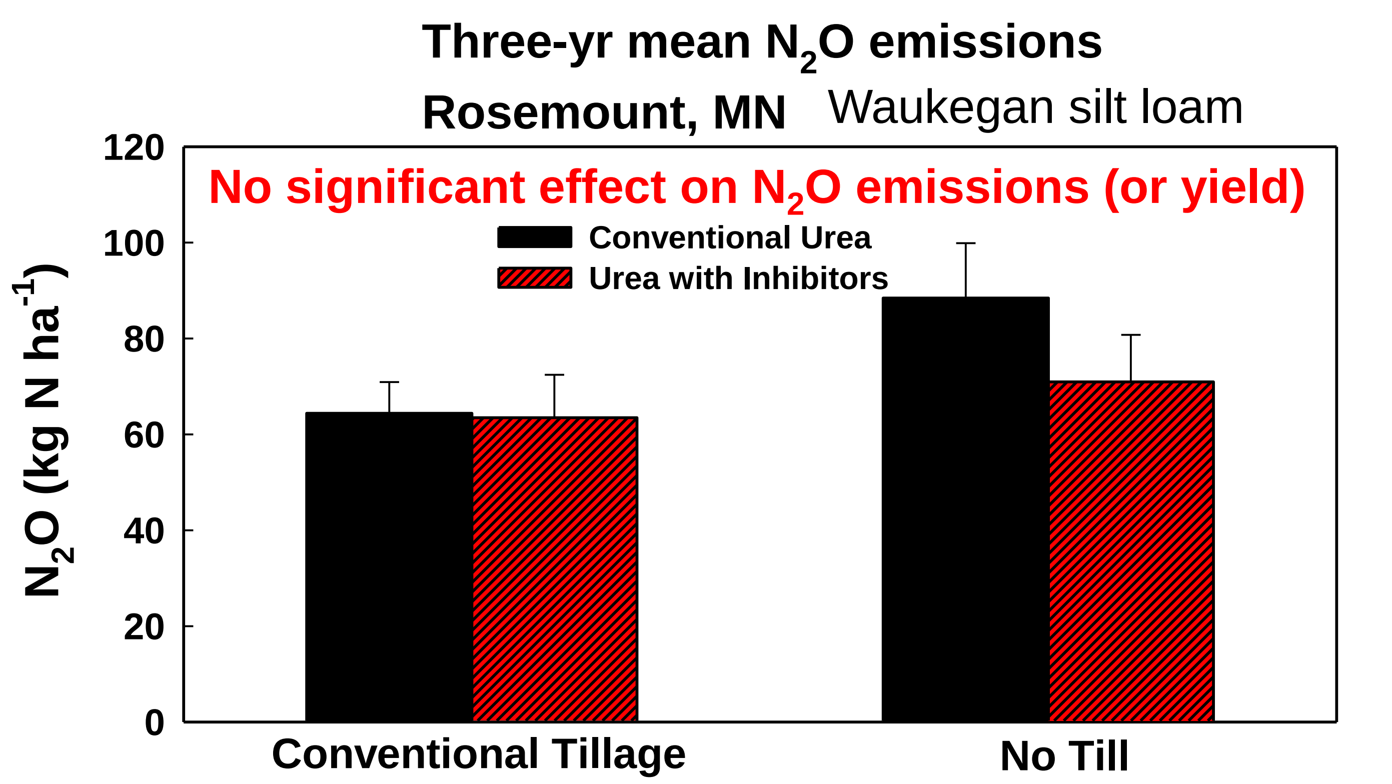


Venterea et al. 2011. JEQ

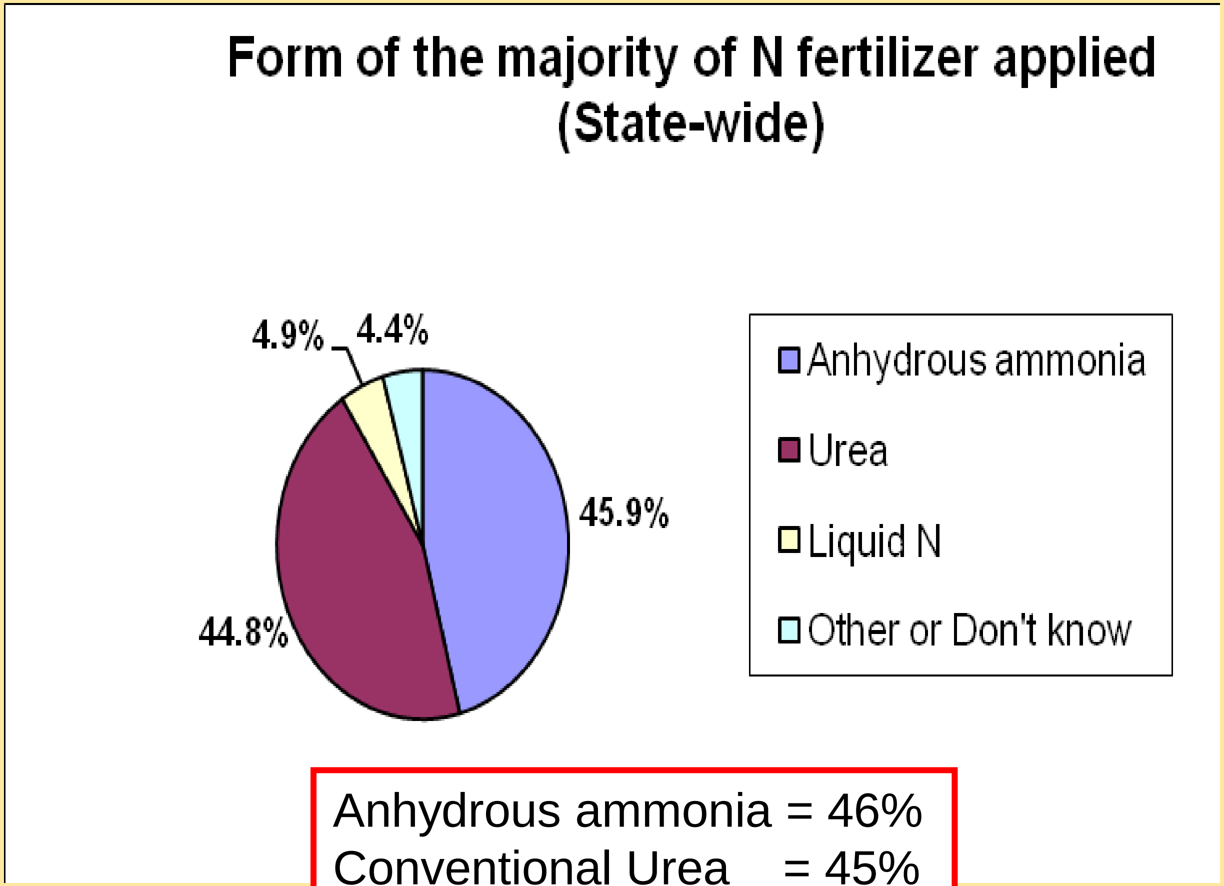
Nitrification inhibitors for reducing N_2O emissions

Other studies:

- In irrigated and dryland corn at Becker: No decrease in N_2O
- In dryland corn at Rosemount: No decrease in N_2O

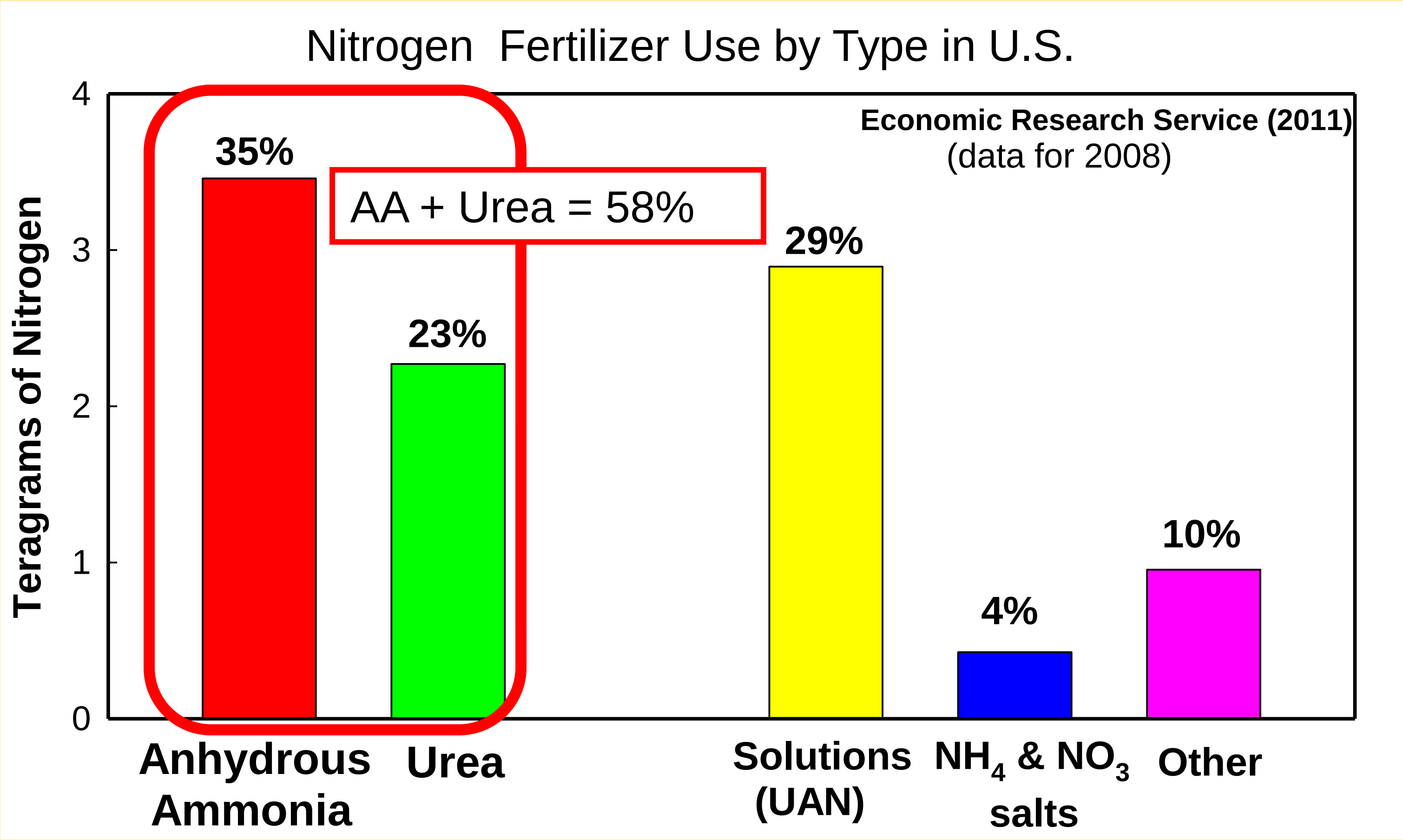
1. Several studies, some potential for reductions, but varying success.
2. Many different chemical formulations, but little systematic comparison.
3. Few guidelines for knowing when/where specific products will be effective for reducing N_2O emissions.
4. Yield benefits required to justify cost are not consistent, not widespread use.
5. One exception: ~ 10% of MN corn producers use N-serve (nitrapyrin), mostly with fall-applied N. Some studies: decreased Nitrate leaching potential. Recent study in IA showed no reduction in direct N_2O with N-serve.

Survey of MN corn producers (MDA/ UMN/ NASS, 2010)



Anhydrous ammonia = 46%
Conventional Urea = 45%
\> 90%

Fertilizer Source Effects: Conventional Sources

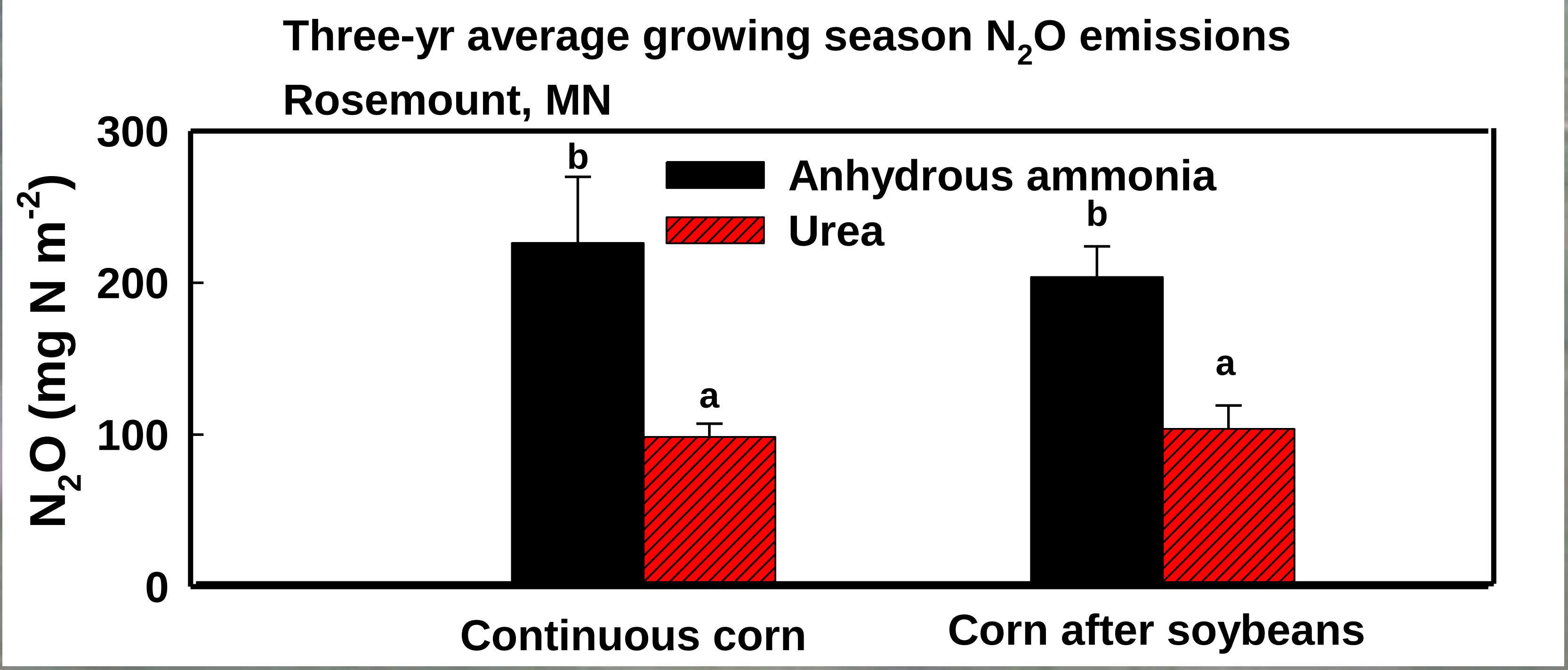


Only 1 site-year of data comparing N_2O emissions with AA and Urea prior to 2005 (Thornton et al., 1996)

Anhydrous Ammonia versus Urea: Dryland Corn

Source	Timing	Placement	Rate (kg N ha^{-1})
1. Urea (47%N)	Pre-plant	Broadcast and incorporated	146
2. AA (82%N)	Pre-plant	Injected into subsurface band	146

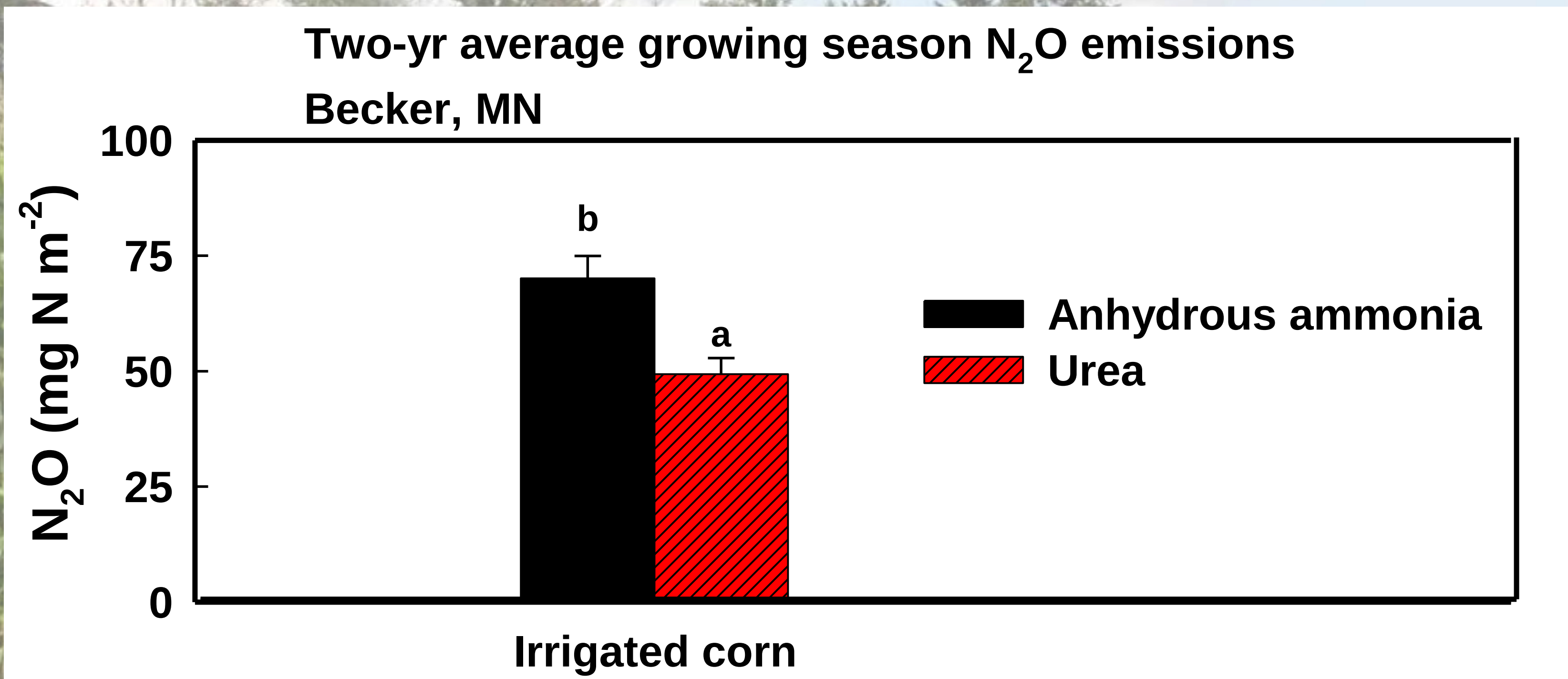
Treatments applied to both Corn following Corn and Corn following Soybean



Venterea et al. 2010. SSSAJ.

Anhydrous Ammonia versus Urea: Irrigated Corn

Source	Timing	Placement	Rate (kg N ha^{-1})
1. Urea (47%N)	Pre-plant/Sidedress	Broadcast and incorporated	90 / 90
2. AA (82%N)	Pre-plant/Sidedress	Injected and banded	90 / 90



Fujinuma et al., 2011 (submitted.)

Anhydrous Ammonia versus Urea

Summary of studies in corn systems

Emissions Factor (EF) Assessment	
Study	**EF_{AA}: EF_{urea}**
Thornton et al. (1996)	**1.94**
Venterea et al. (2010)	**2.60**
Fujinuma et al. (2011)	**1.53**
Average	**2.0**

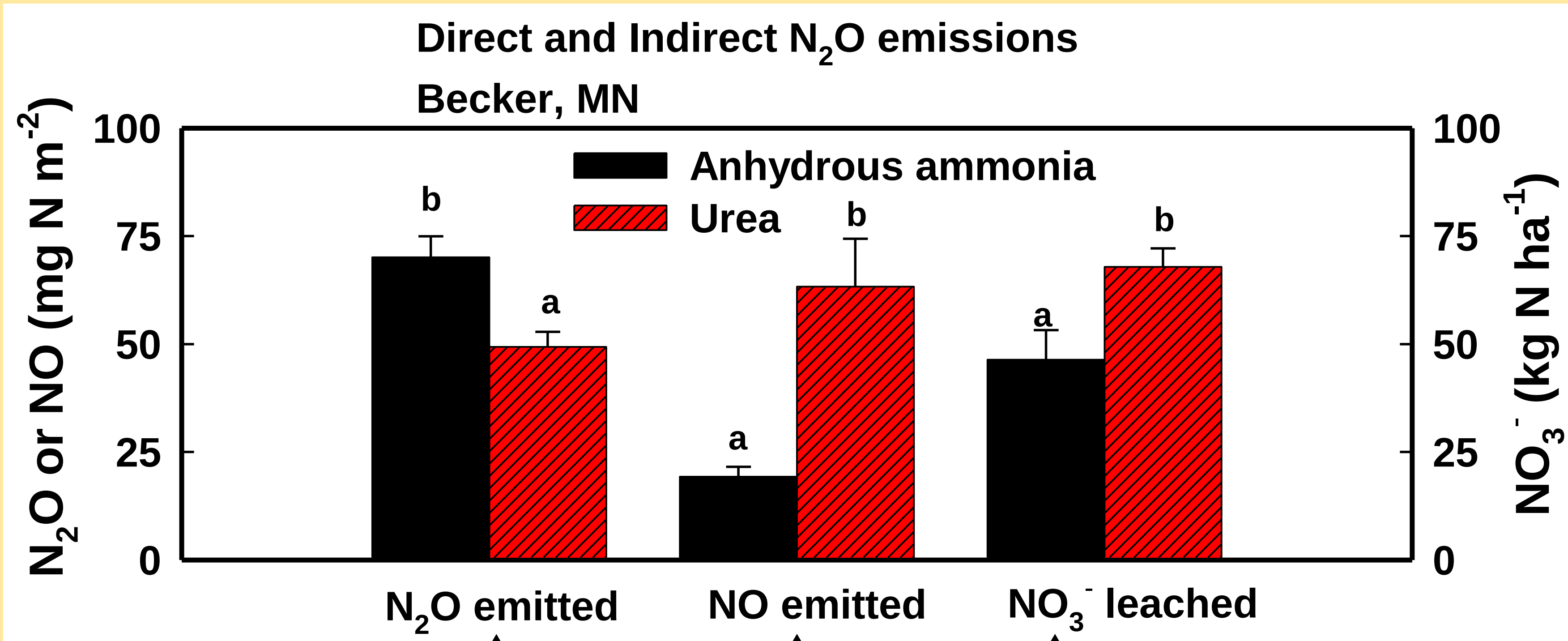
1 study in Canada wheat system: No difference in emissions.
* Lower N application rate (80 kg N ha^{-1})

Is this enough evidence to drive a policy recommendation or do we need more studies ?

Worldwide AA Use	
U.S.	**85%**
Canada	**13%**
Mexico	**1%**
Rest of world	**1%**

(IFA Statistics)

Anhydrous Ammonia versus Urea: Indirect N_2O Emissions

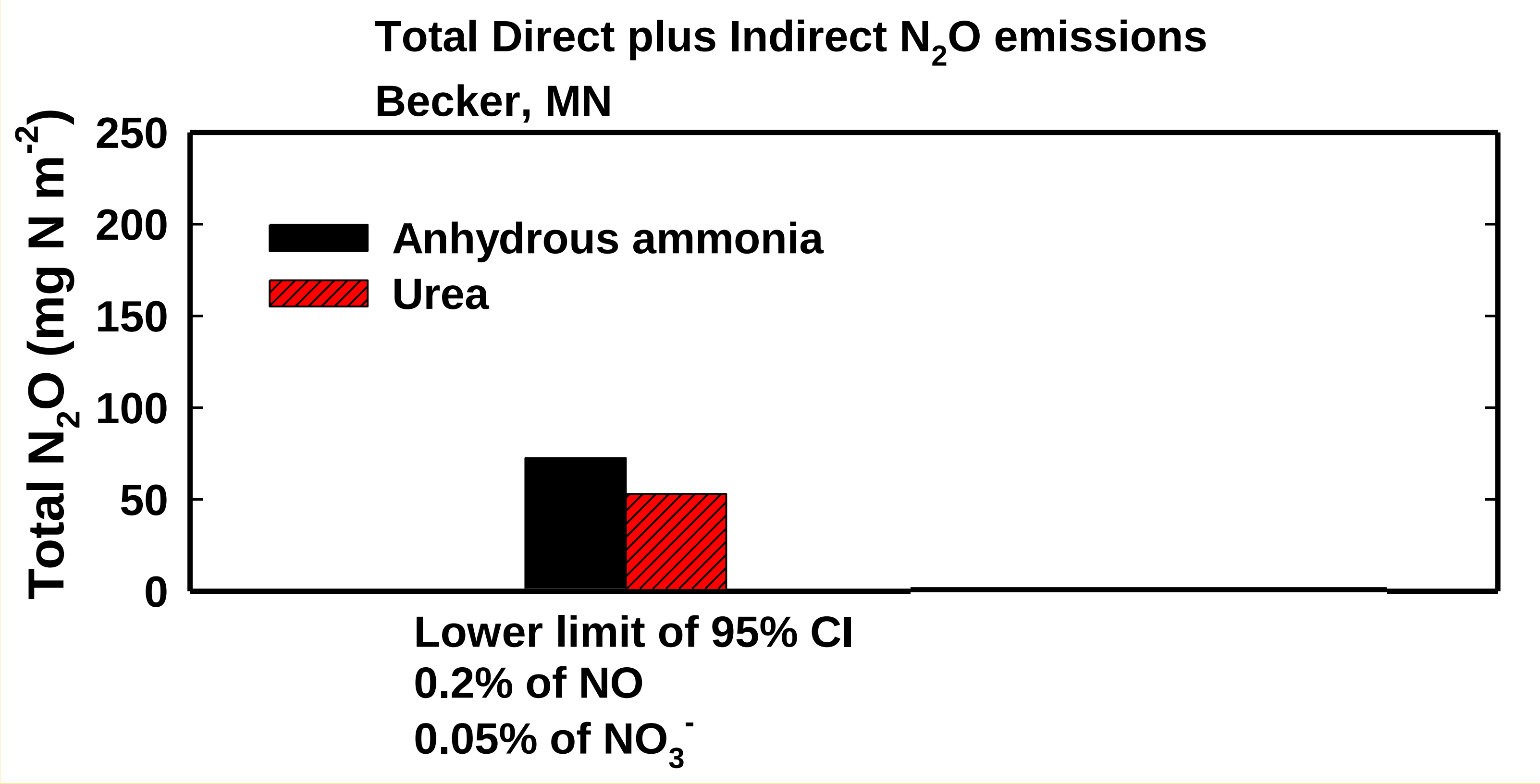


Direct emissions decreased with urea

Indirect emissions increased with Urea

Fujinuma et al., 2011 (submitted); Maharjan et al., 2011 (in preparation)

Anhydrous Ammonia versus Urea: Indirect N_2O Emissions

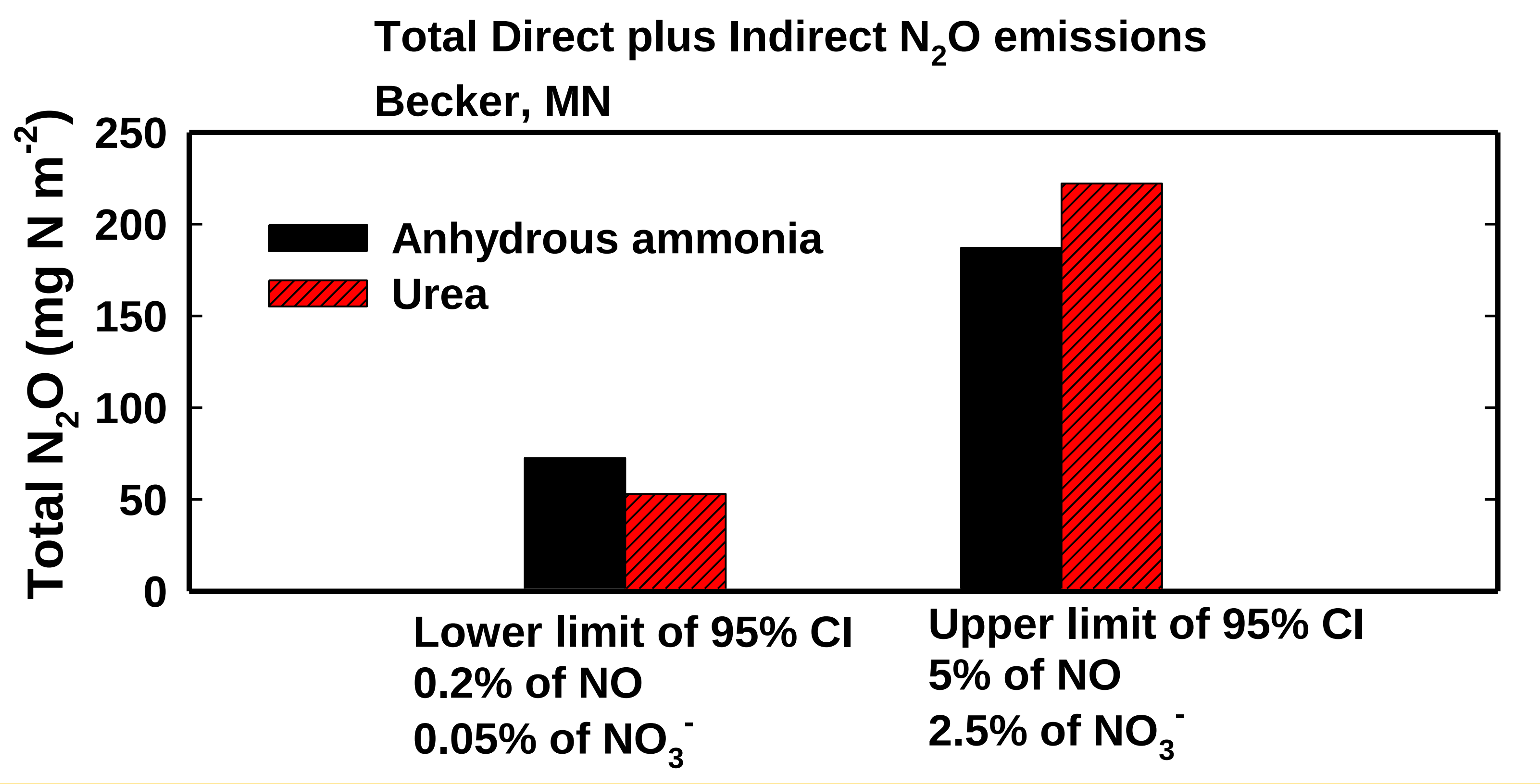


2006 IPCC Guidelines for National Greenhouse Gas Inventories. De Klein et al.

Fujinuma et al., 2011 (submitted); Maharjan et al., 2011 (in preparation)

Anhydrous Ammonia versus Urea: Indirect N_2O Emissions

Quantifying Indirect emissions one of biggest challenges



2006 IPCC Guidelines for National Greenhouse Gas Inventories. De Klein et al.

Fujinuma et al., 2011 (submitted); Maharjan et al., 2011 (in preparation)

Fertilizer Placement Effects

(very few studies)

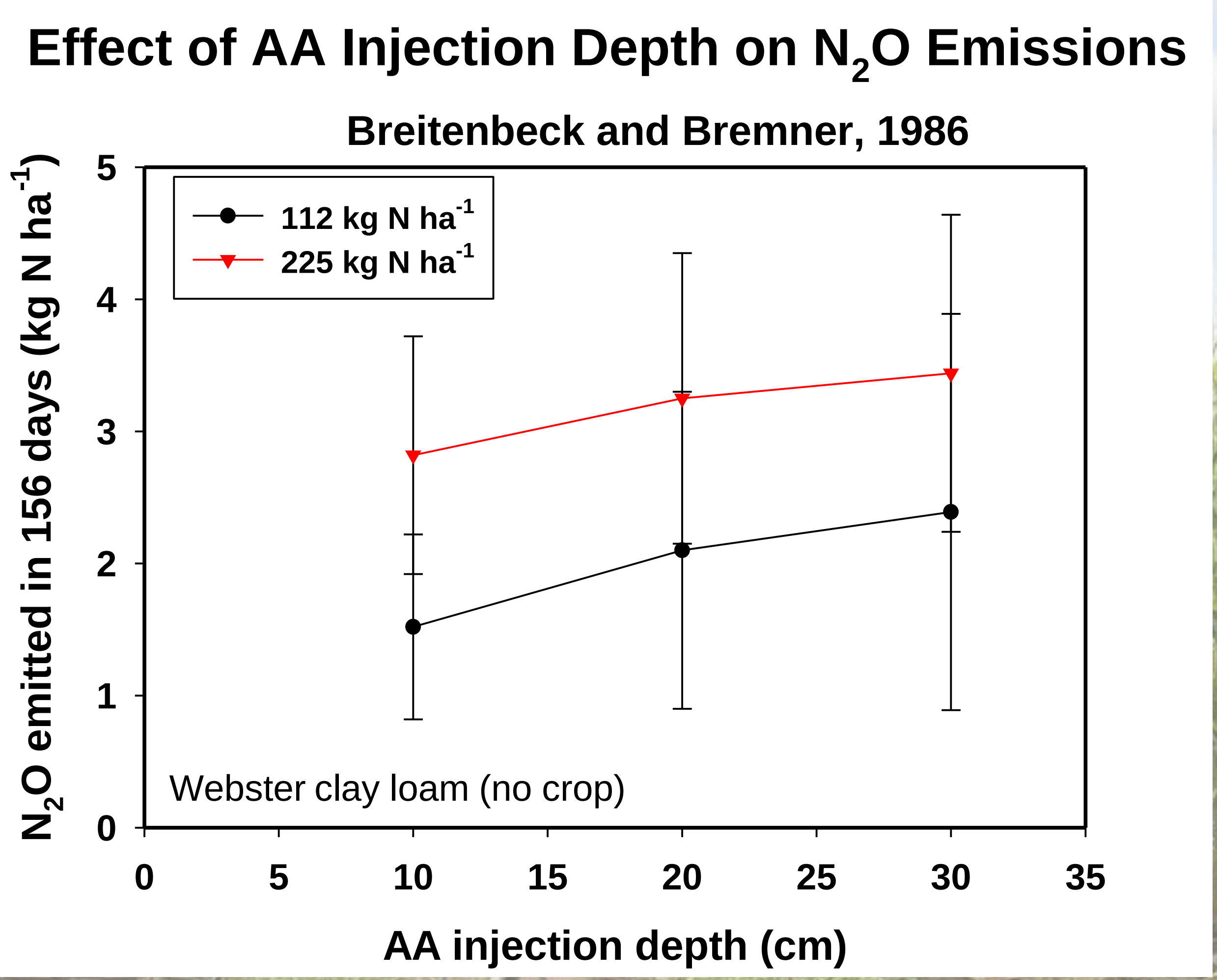
Conventional "Deep" Applicator

New "Shallow/Fast" Applicator

Conventional AA Injection
- Slow tractor speed with high fuel use
- 15-18 cm deep band

Shallow AA injection
- Faster speed
- 10-12 cm deep band
- Improved soil closure
- Less fuel use

Fertilizer Placement Effects

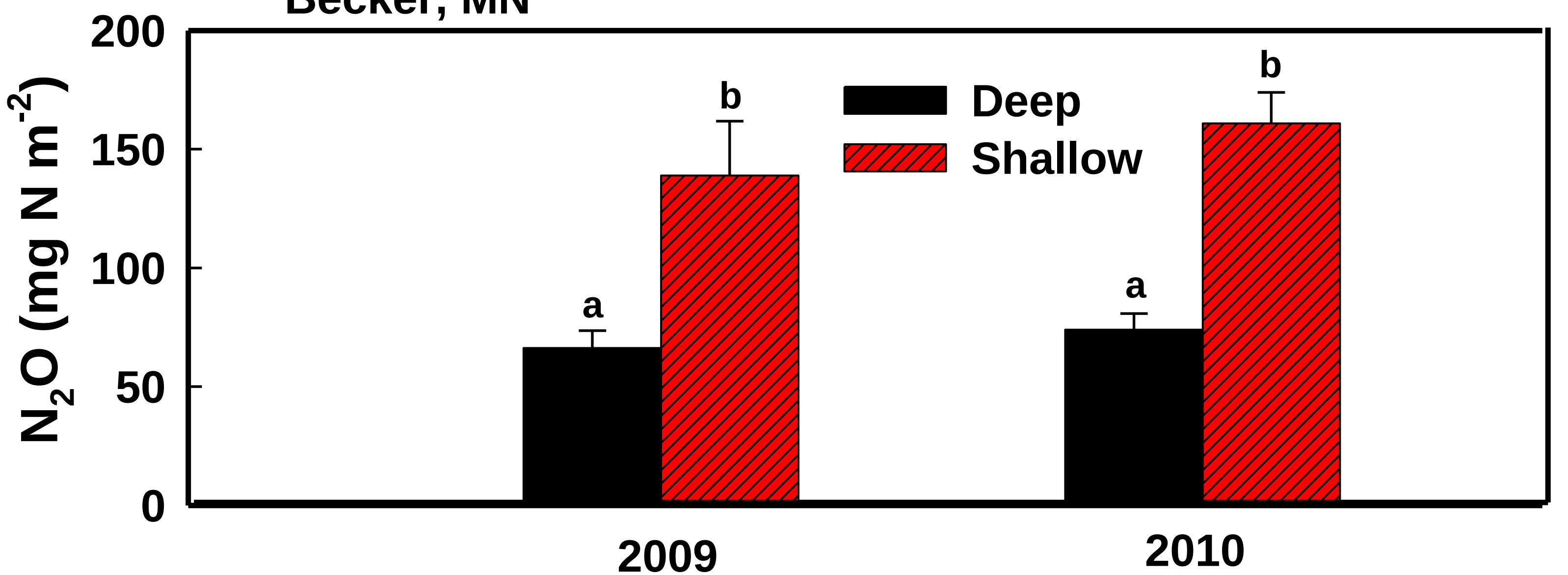


Anhydrous Ammonia Placement Effects: Irrigated Corn

Source	Timing	Placement	Rate (kg N ha^{-1})
1. AA	Pre-plant/Sidedress	18 cm	90 / 90
2. AA	Pre-plant/Sidedress	12 cm	90 / 90

Effects of AA placement depth on N_2O emissions

Becker, MN



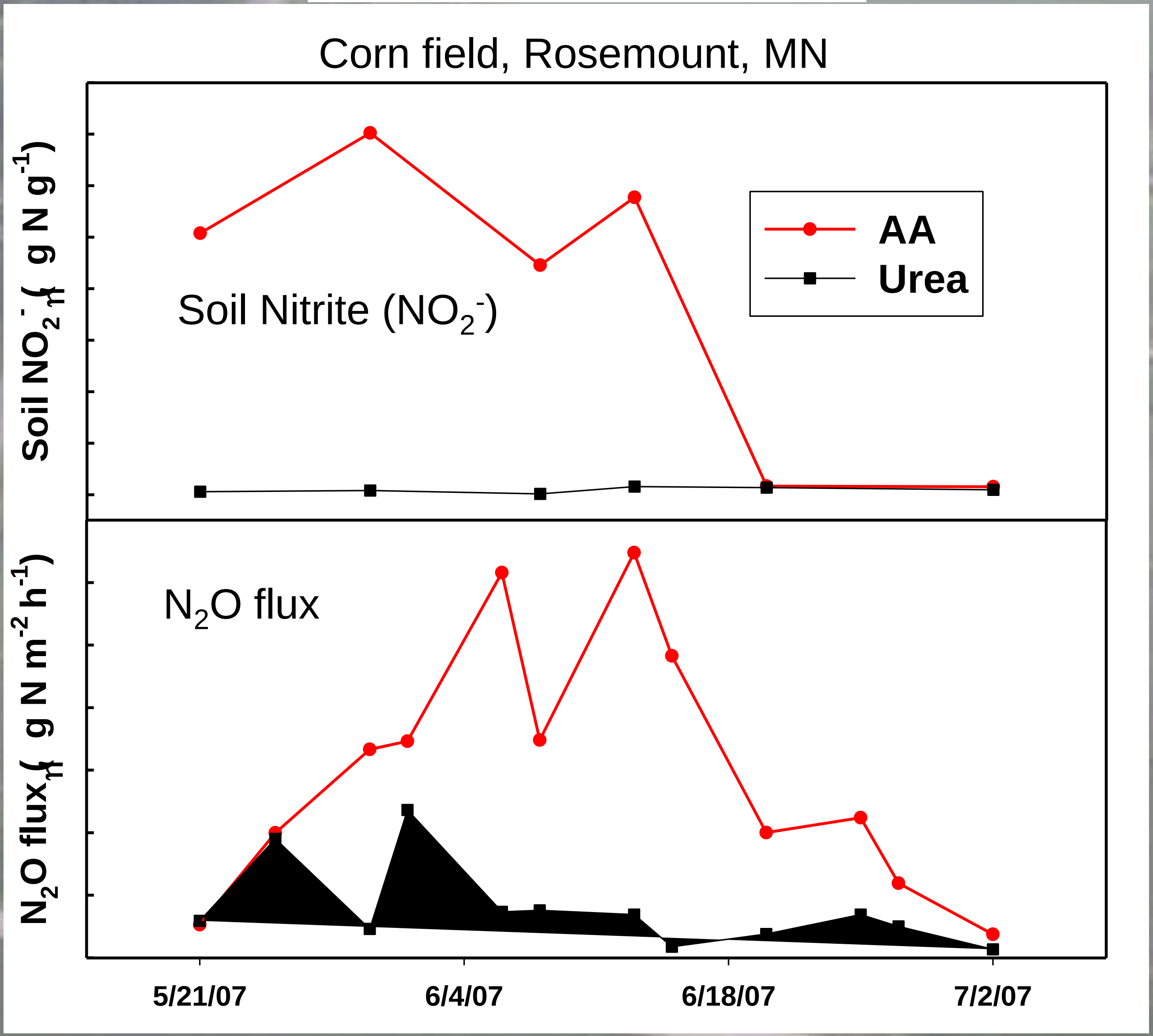
WHY ?

Replicating experiment in Lamberton and Rosemount in finer texture soils

Fujinuma et al., 2011 (submitted.)

Greater N_2O Emissions with Anhydrous Ammonia

Elevated Soil Nitrite (NO_2^-)



Venterea et al. 2010. Soil Sci. Soc. Am. J.

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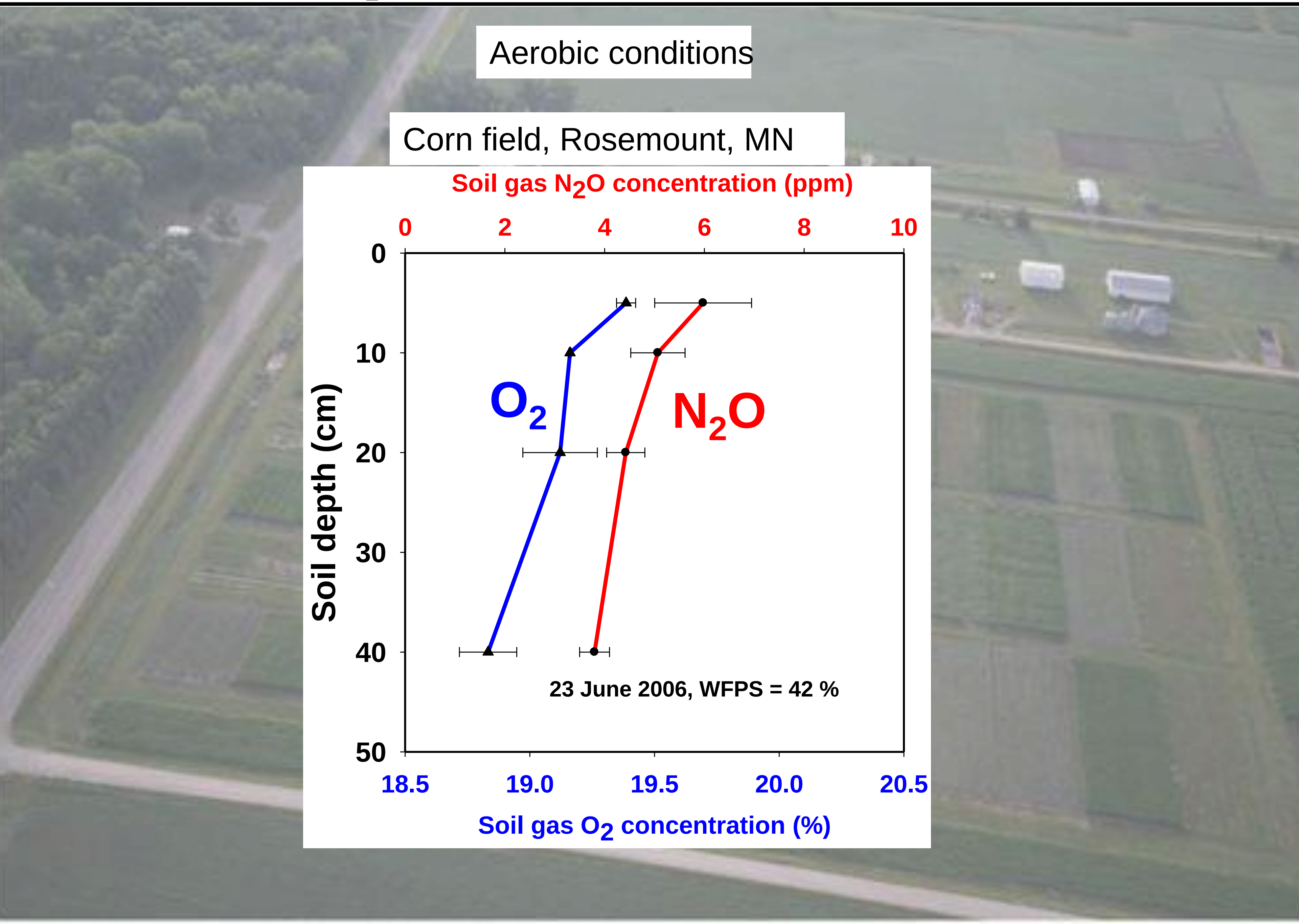
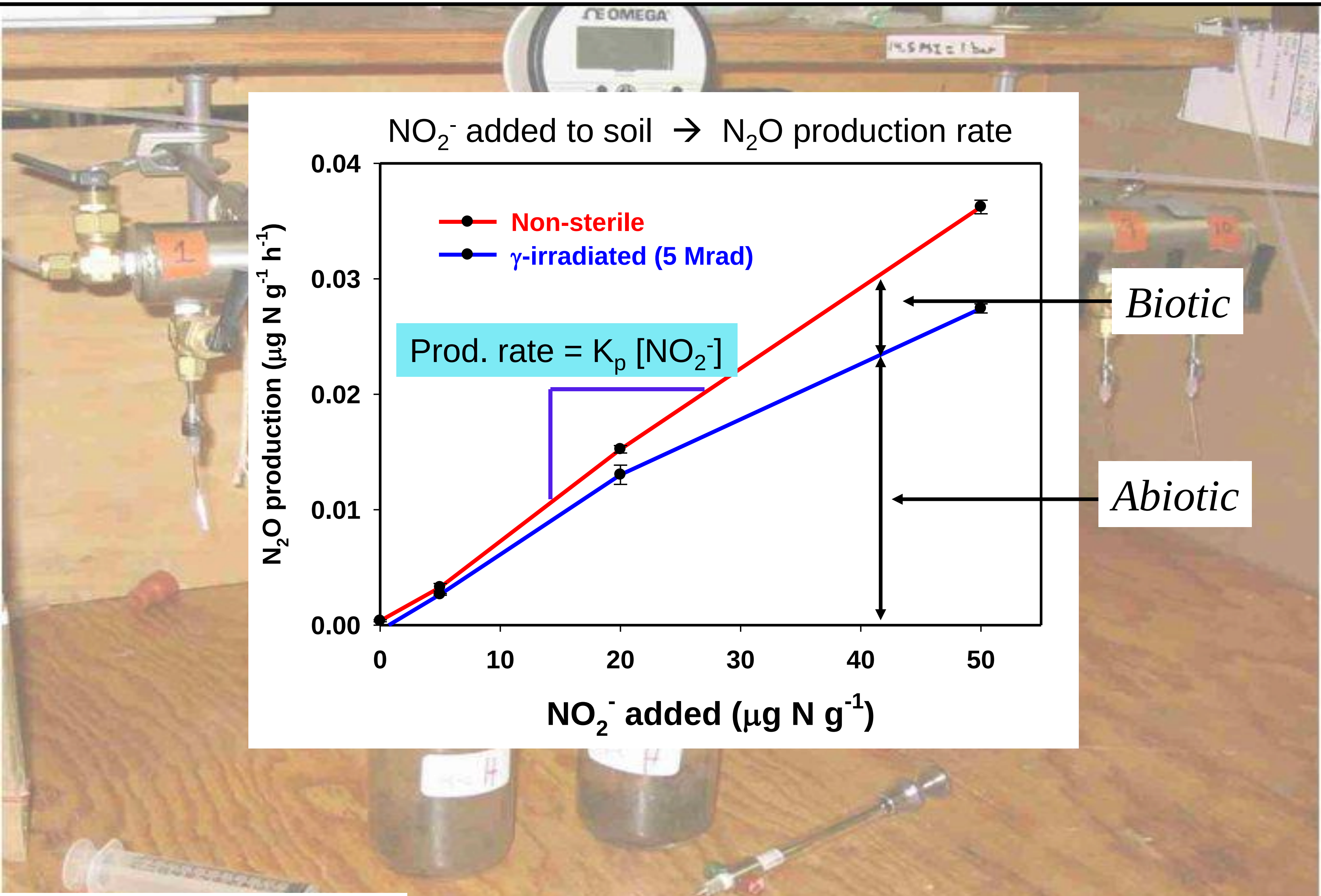


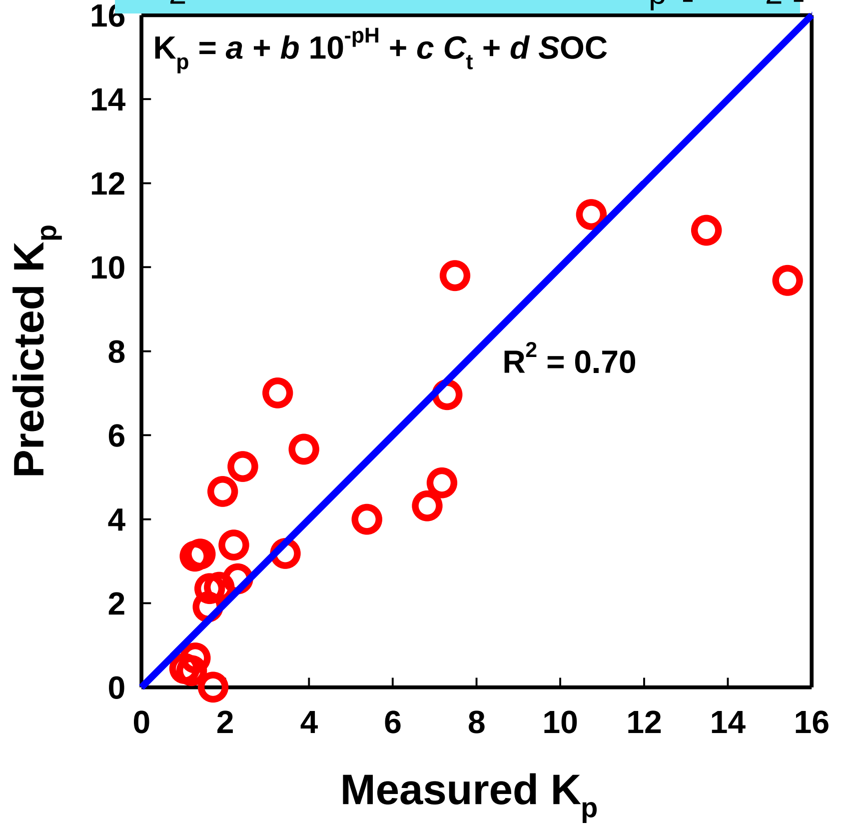
Laboratory kinetics experiments: N_2O production under aerobic conditions



Venterea, 2007. Global Change Biol.

Laboratory kinetics experiments: N_2O production under aerobic conditions

N_2O Production rate = $K_p\,[NO_2^-]$

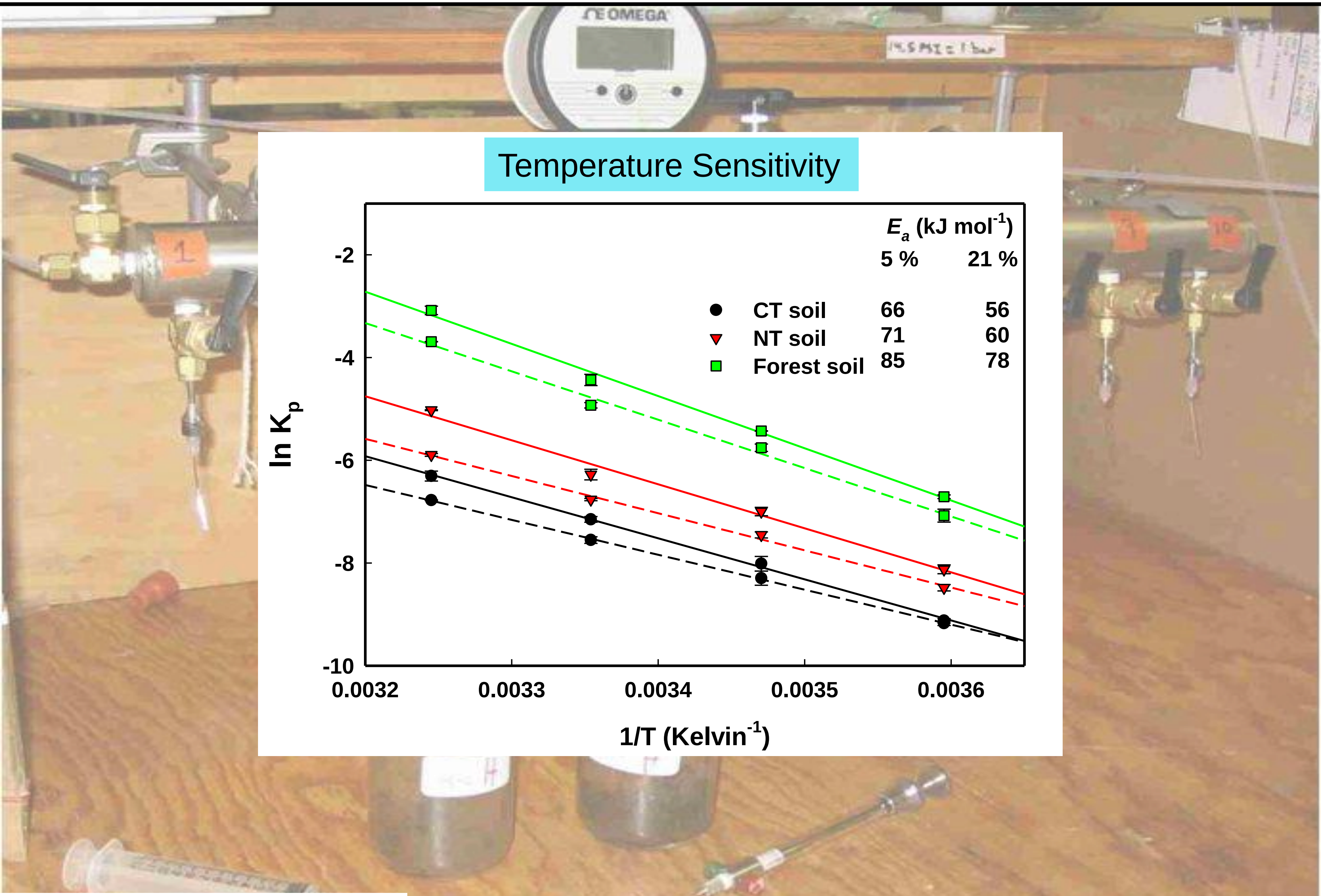


Rate coefficient correlated with:

- Acidity (10^{-pH})
- Total organic carbon (C_t)
- Soluble organic carbon (SOC)

Venterea, 2007. Global Change Biol.

Laboratory kinetics experiments: N_2O production under aerobic conditions



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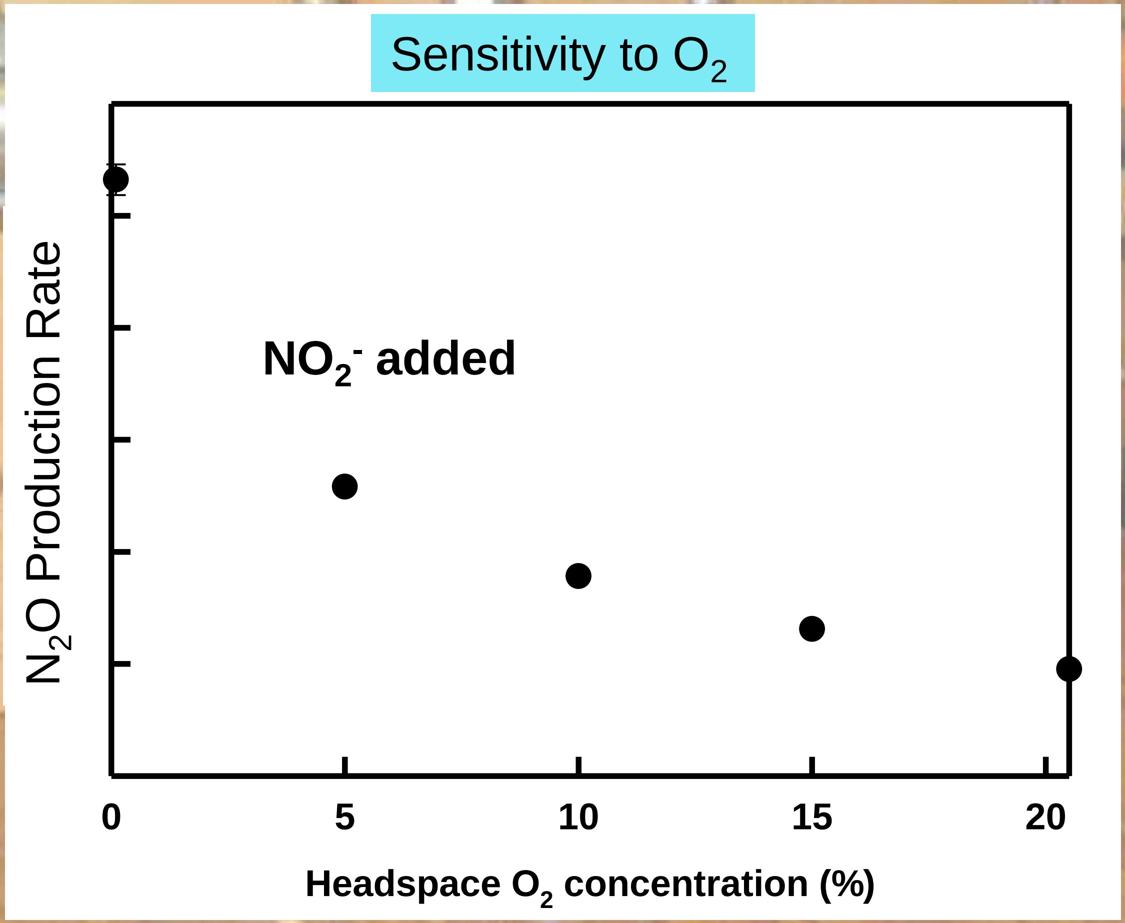

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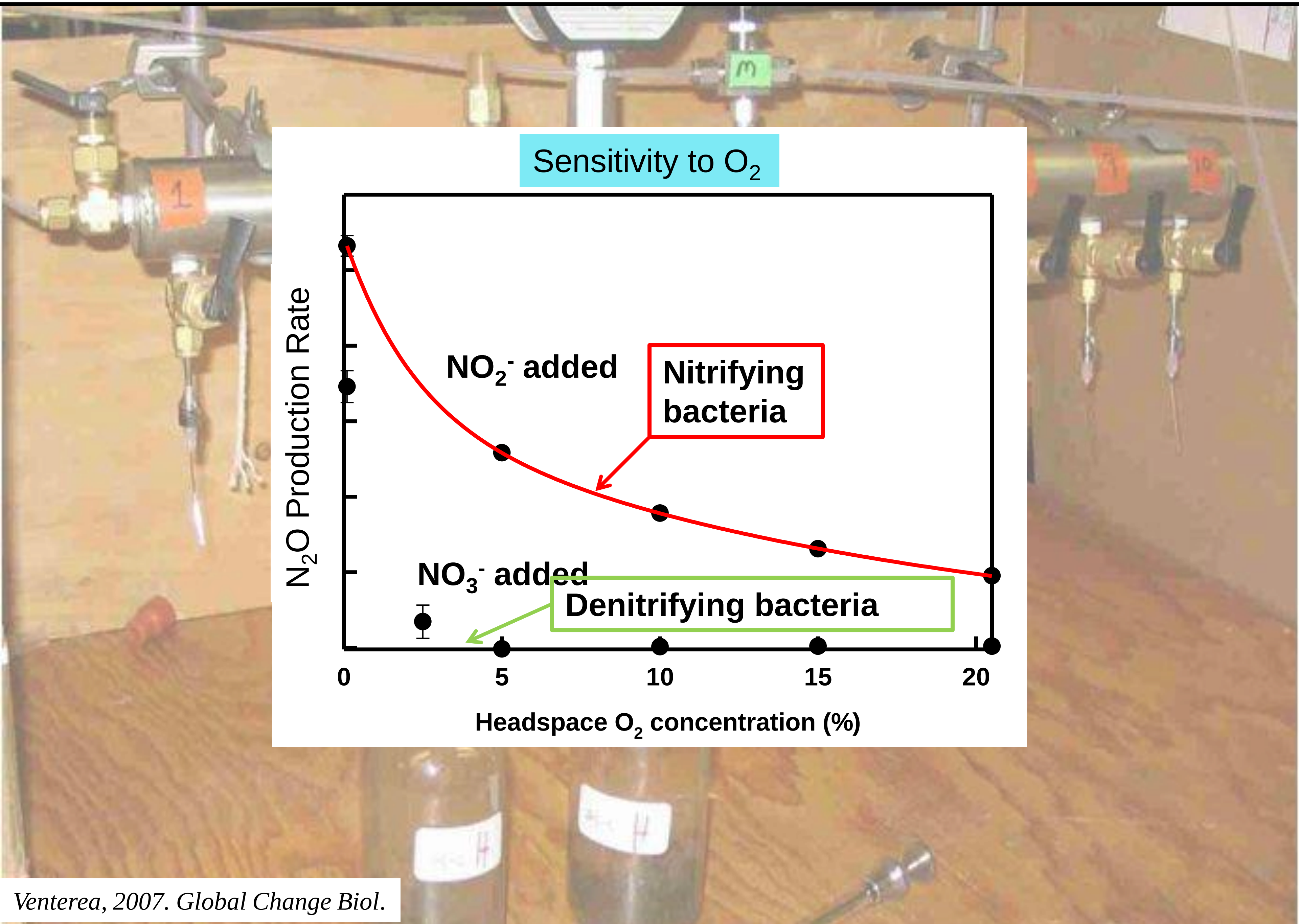
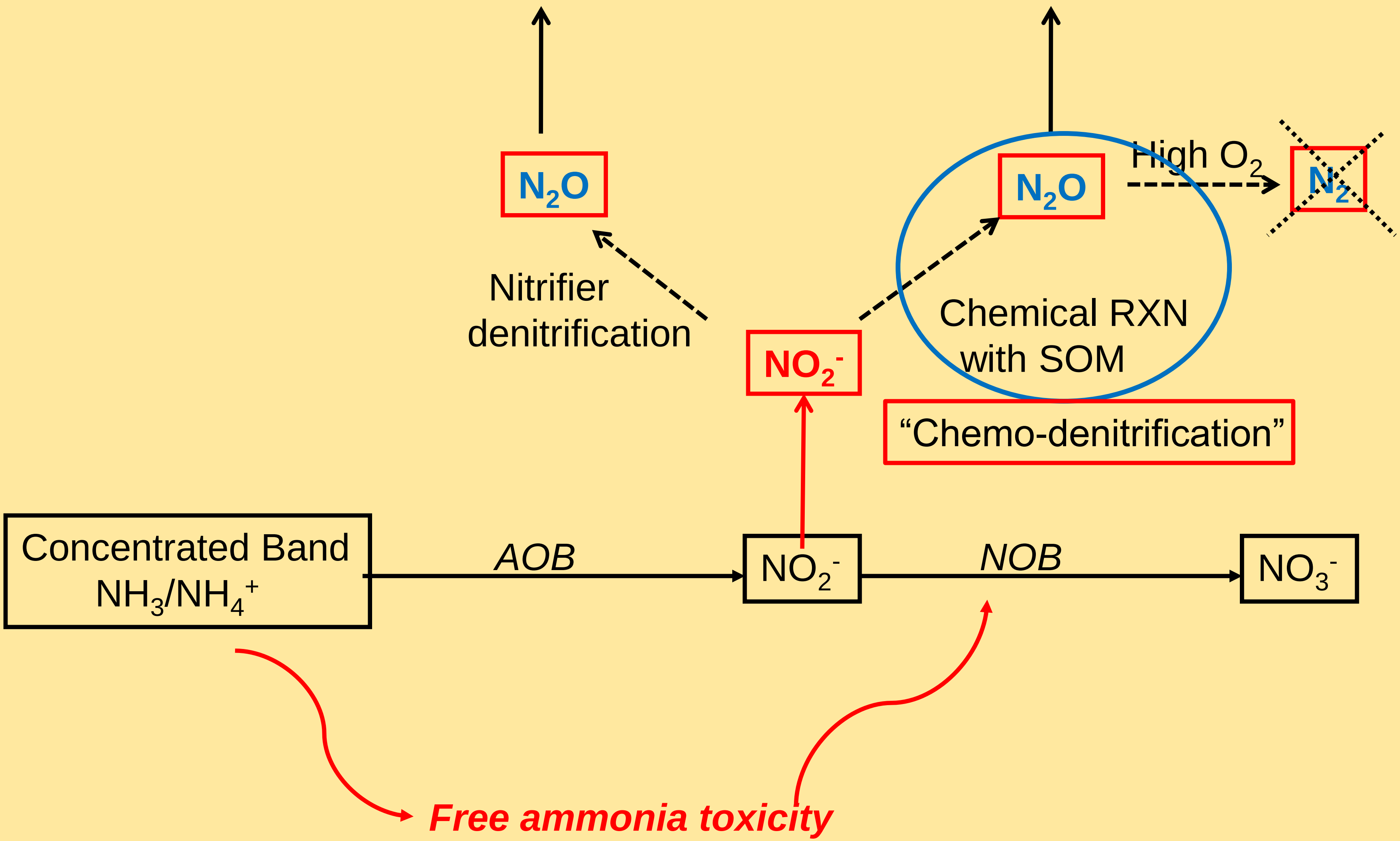


Venterea, 2007. Global Change Biol.

Nitrite-driven N_2O production



Venterea, 2007. Global Change Biol.

Nitrite-driven N_2O production

"Chemo-denitrification"

Overlooked and understudied process

Stevenson and Swaby, 1964

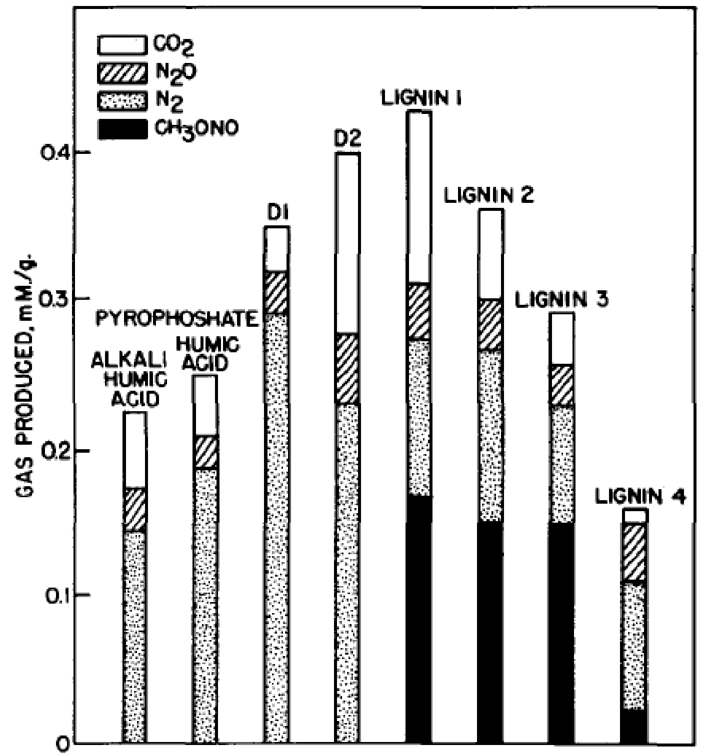
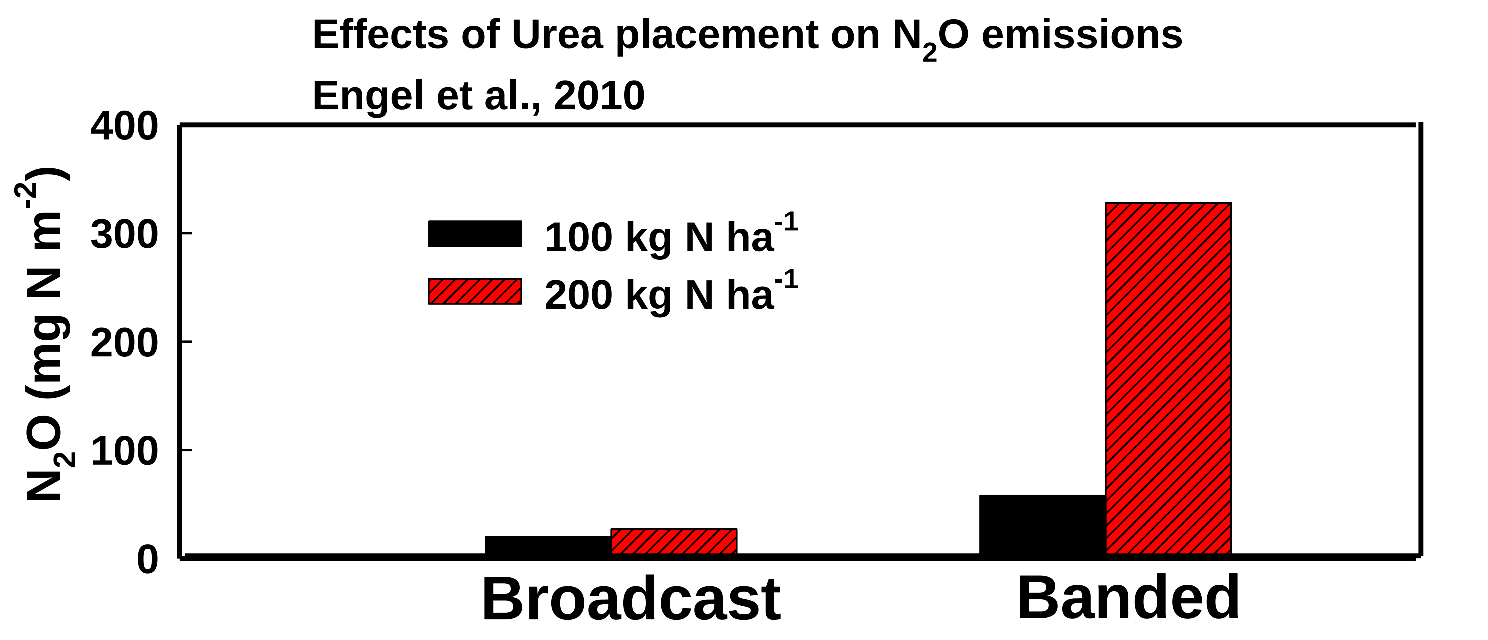


Fig. 4—Composition of the gases obtained by reaction of HNO_2 with lignins and humic substances. In each case, a 100-mg. sample was used. The reaction time was 20 minutes.

$NO_2^- + H^+ +$ Lignins / Humic acids / Phenolics / Aromatics → N_2O

Nitrite-driven N_2O production

Banding of Urea



Low NO_2^-

High NO_2^-

Nitrite-driven N_2O production

Banding as a beneficial fertilizer management practice

<u>Conserves Nitrogen/ Increases NUE</u>
-Slows nitrification and nitrate leaching
-Limits contact with soil microbes
-Increases root access to N
-Decreases distance from plant to N source

Malhi et al., 1985. 1991; Yadvinder-Singh et al., 1994
Robertson and Vitousek, 2009

- With banding, it may be possible to have:
  - -Greater overall NUE
  - -And greater N_2O emissions

- N_2O emissions usually are < 3% of applied N.

Nitrite-driven N_2O production

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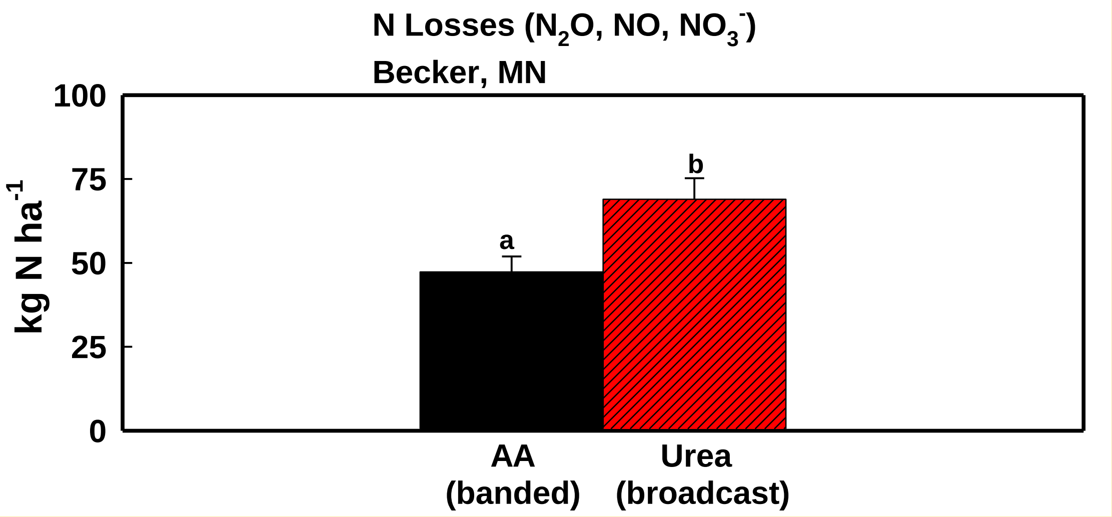
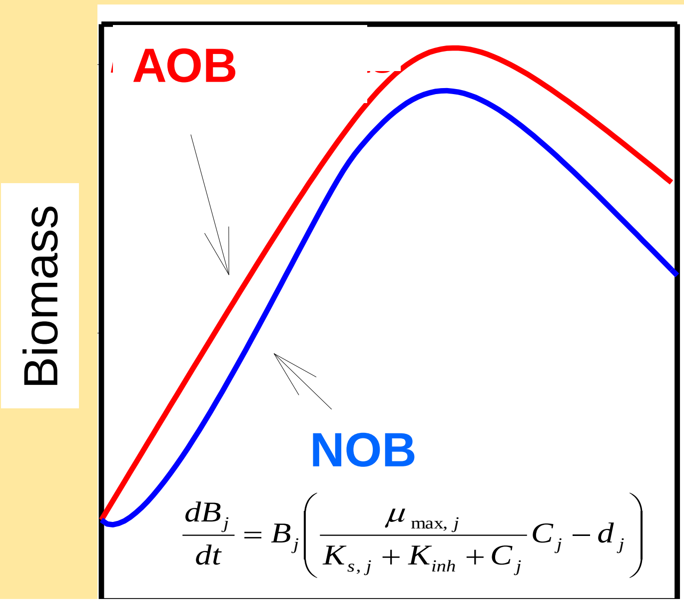
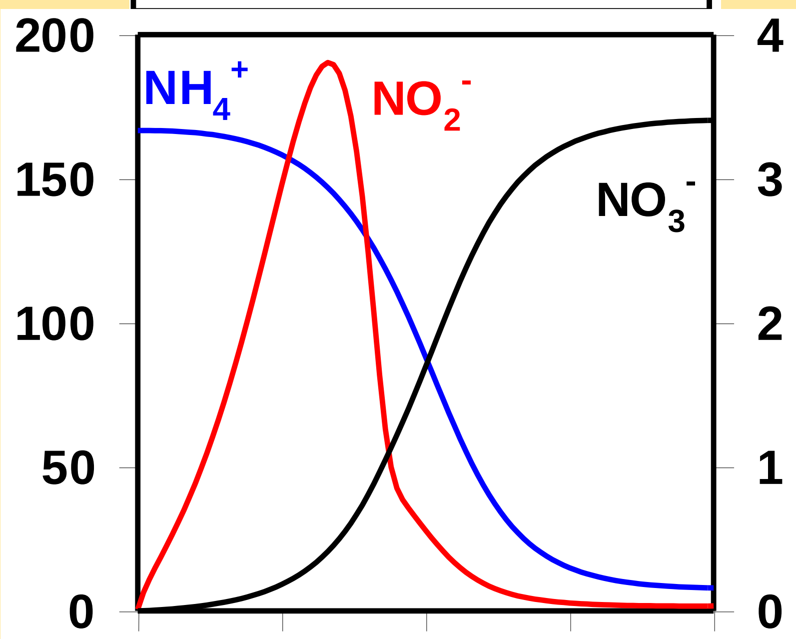


Is there an optimum banding intensity or geometry that maximizes NUE and minimizes N_2O emissions ?

Modeling nitrite-driven N_2O emissions





Venterea and Rolston, JEQ. 2000

Two-step Nitrification Model

- Model can generate curves of nitrite accumulation but we can't predict actual behavior
- Little to no information on toxicity kinetics in soil
- Critical / threshold concentrations ?
- Wastewater treatment kinetic models:
  Applicable to soils ?

Modeling nitrite-driven N_2O emissions

Diffusion-reaction model: simplified: NO_2^- is not modeled

$$R\frac{\partial C}{\partial t} = \frac{\partial}{\partial z}\left(D\frac{\partial C}{\partial z}\right) + \frac{\partial}{\partial y}\left(D\frac{\partial C}{\partial y}\right) + K_p(T, O_2)[NO_2^-]$$

2D gas diffusion

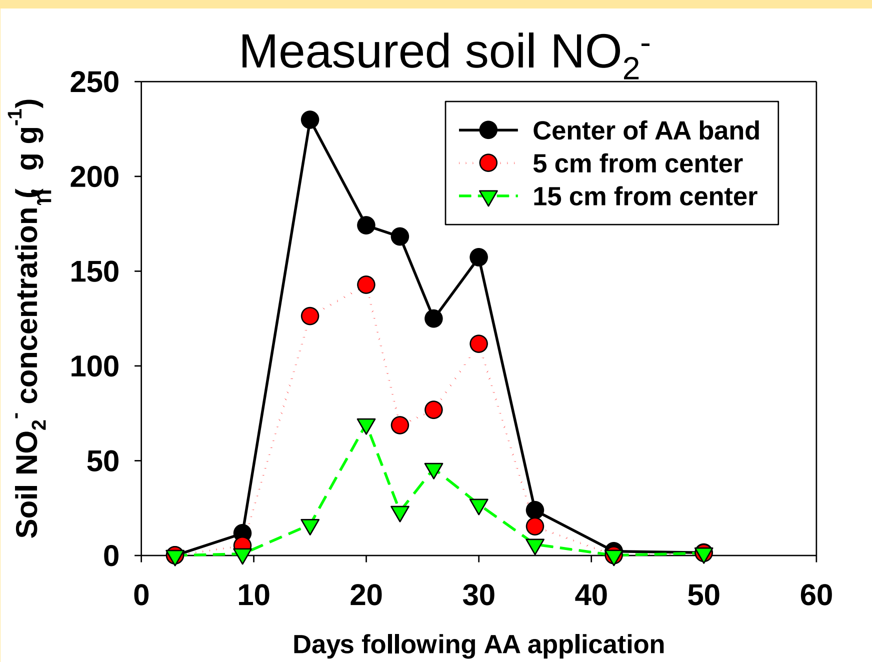
Source term:

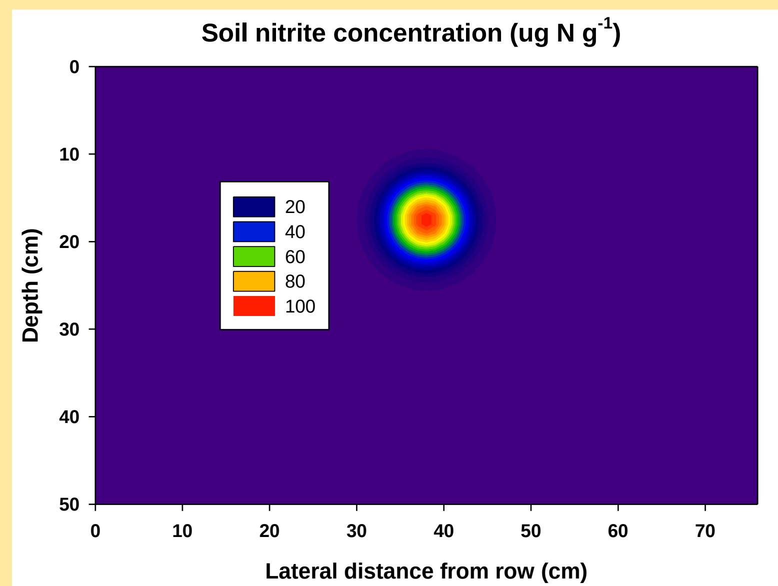
K_p

temp

O_2

NO_2^-

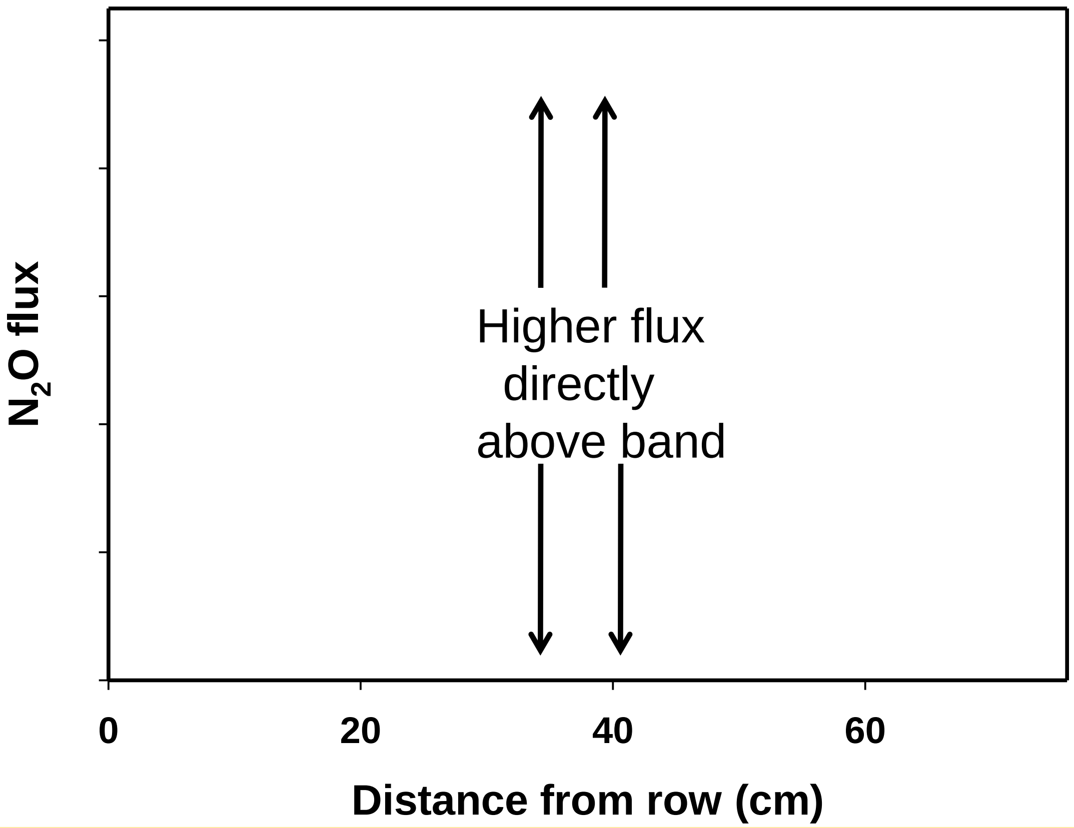




Modeling nitrite-driven N_2O emissions

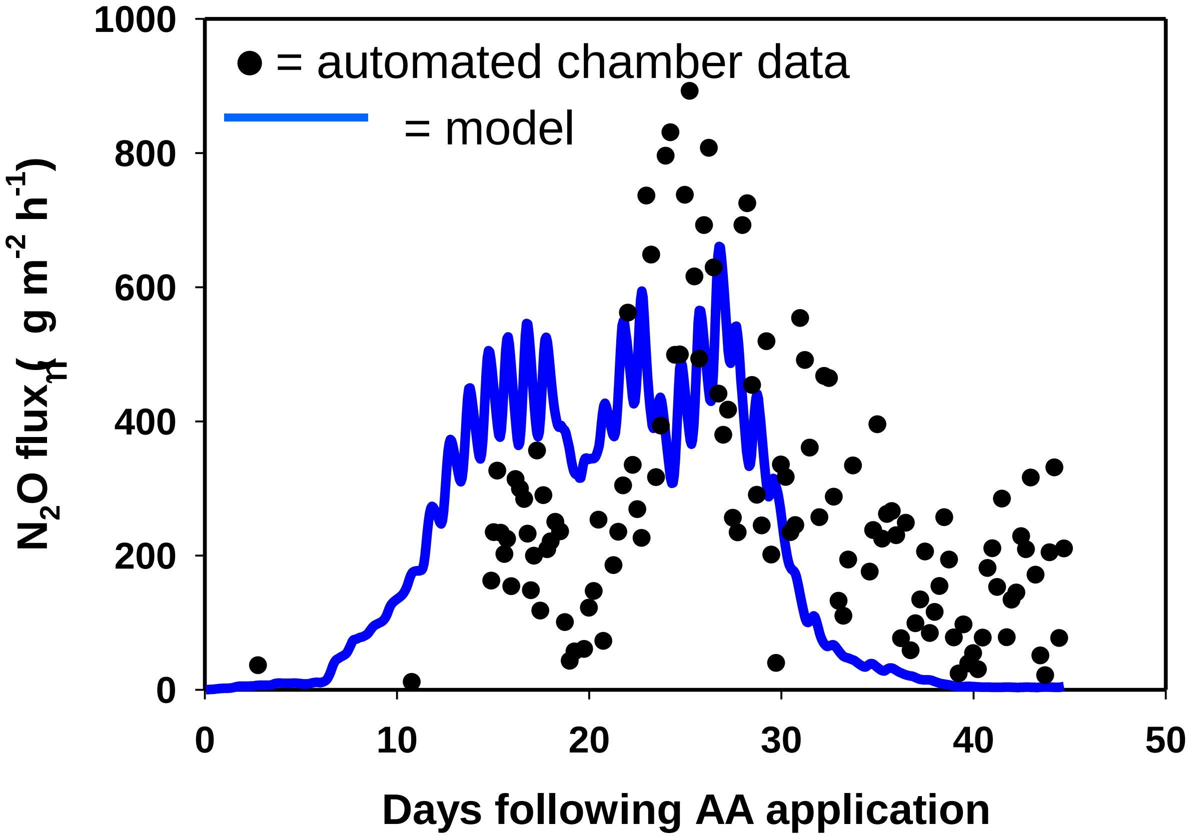
Model output

N_2O flux varies with position in row due to 2D effects



Model output

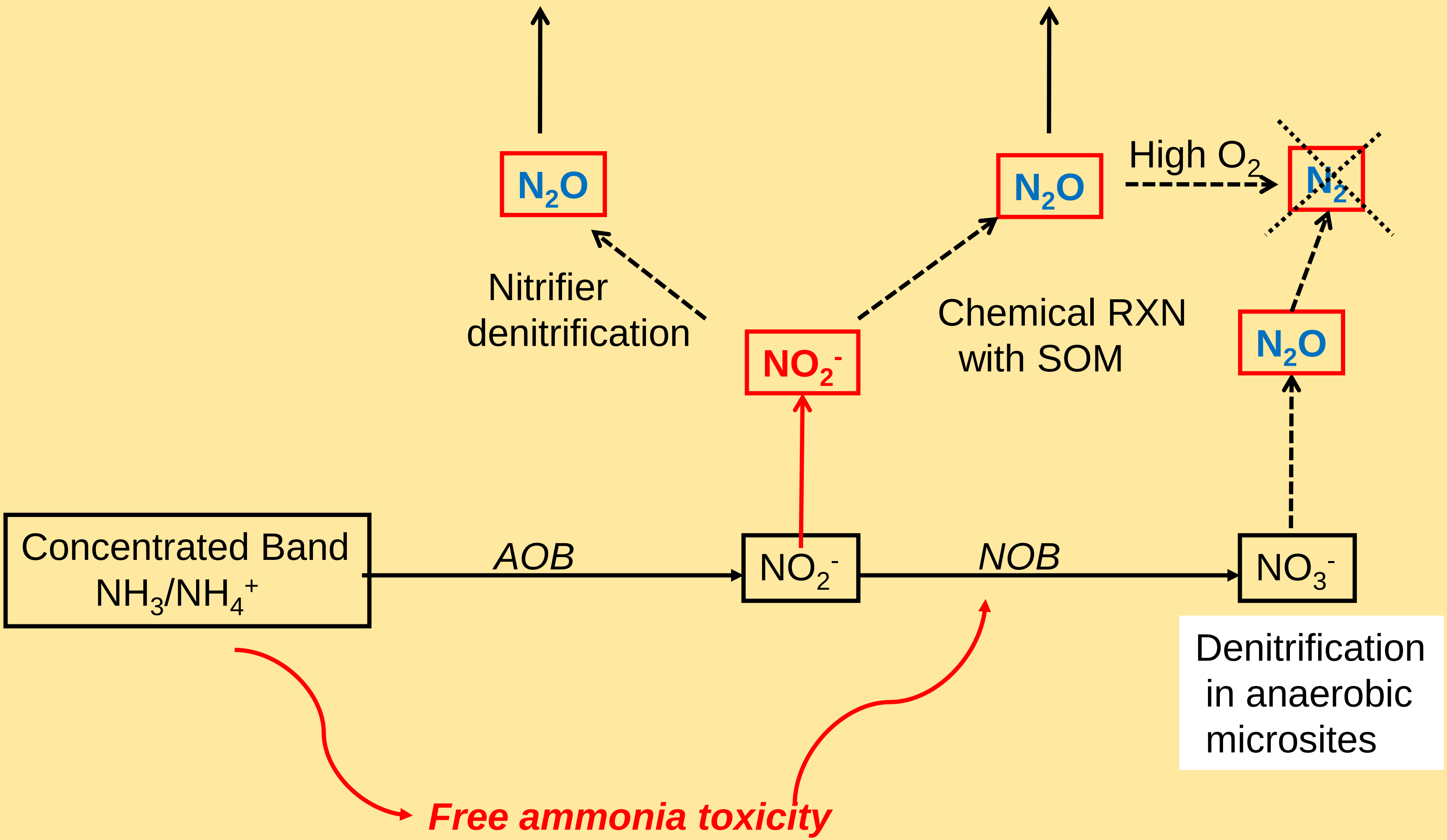
Model versus measured fluxes
(integrated across chamber width)



Assumes:

All N_2O comes from nitrite-driven production
No sink term (no reduction to N_2)

Nitrite-driven N_2O production



Venterea, 2007. Global Change Biol.

Tillage Management Effects on N_2O Emissions

Does reduced tillage decrease (or increase) N_2O emissions ?

Potential for N_2O emissions to enhance (or offset) GHG benefits of reduced tillage

<u>Properties affected by long-term tillage mgmt</u>

Bulk density
Water content
Temperature
Inorganic N
Organic carbon
Dissolved organic carbon
Soil structure

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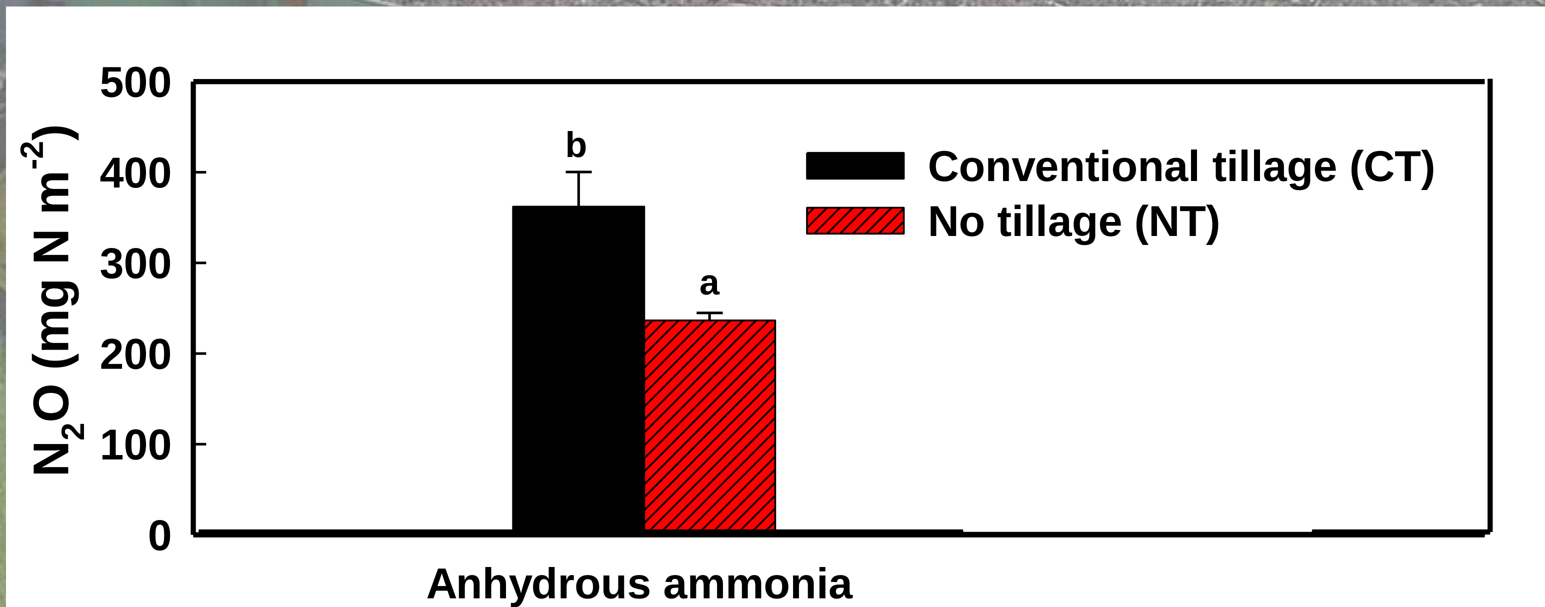
NT Greater

CT Greater

NT > CT	CT > NT
Aulakh et al. 1984	Jacinthe and Dick, 1997
MacKenzie et al. 1998	Kessavalou et al. 1998
Ball et al., 1999	Lemke et al. 1999
Yamulki and Jarvis 2002	Kaharabata et al. 2003
Baggs et al., 2003	Liu et al., 2005
Koga et al. 2004	Venterea et al., 2005
Venterea et al., 2005	Ussiri et al., 2009
Rochette et al., 2008	Halvorson et al., 2010
Grageda-Cabrera et al., 2011	Omonode et al., 2011

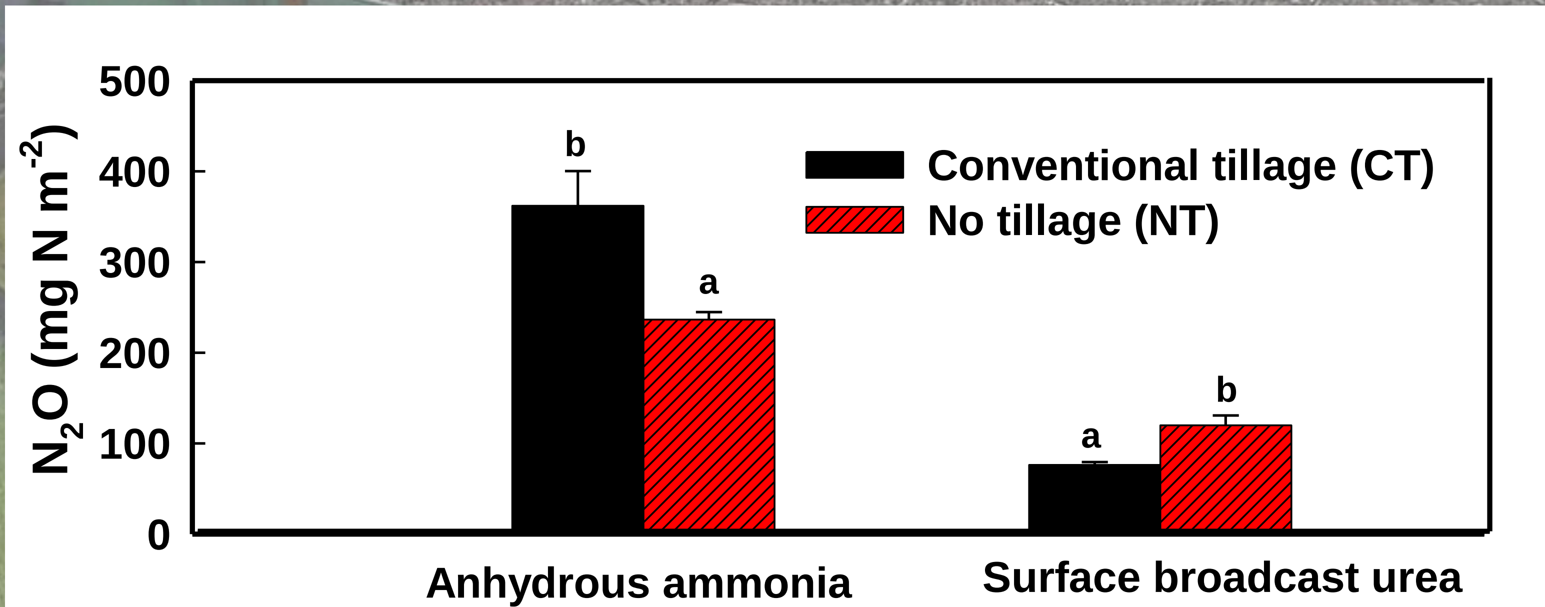
Tillage Management Effects on N_2O Emissions



CT > NT

Venterea et al. 2005. JEQ.

Tillage Management Effects on N_2O Emissions

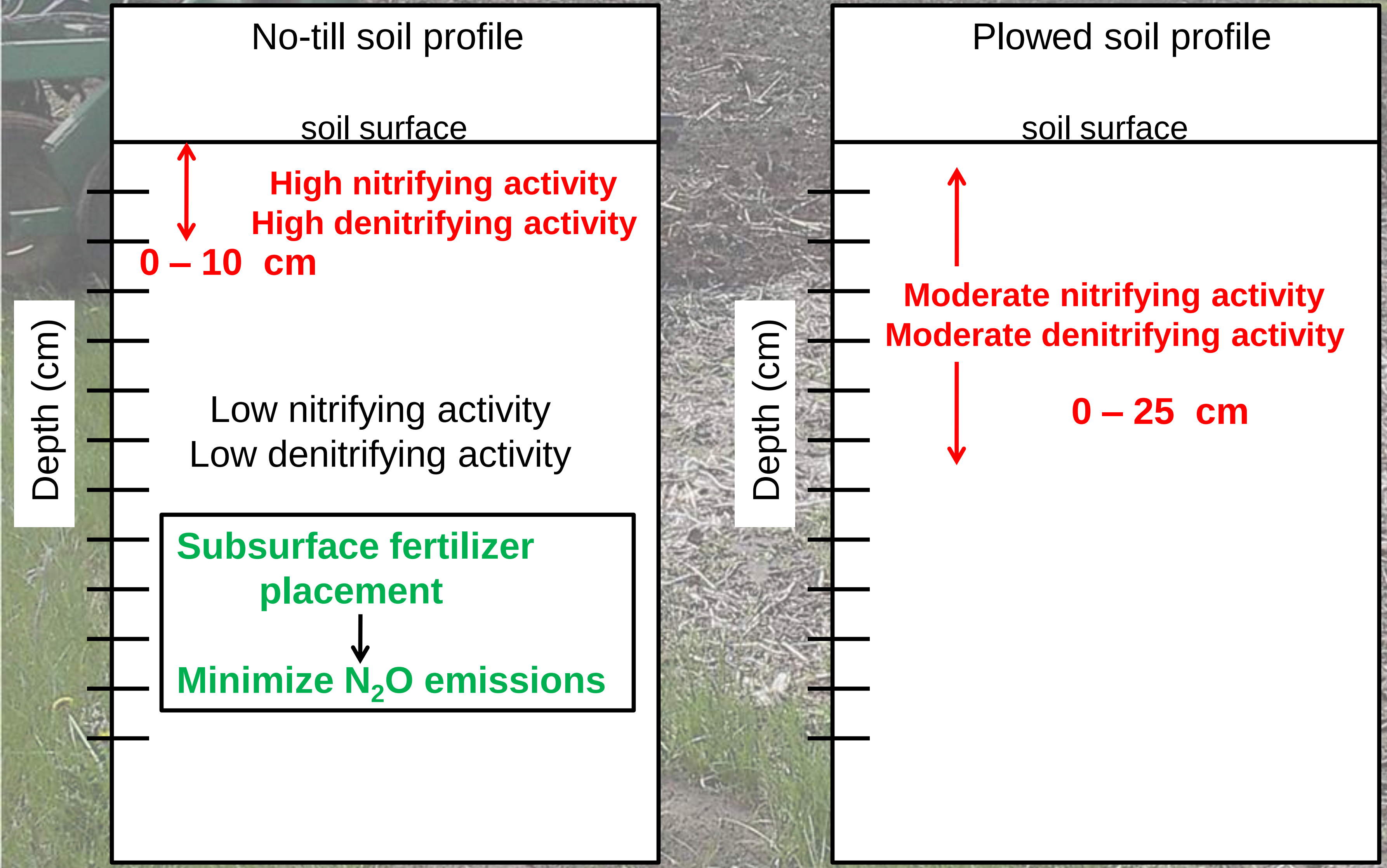


CT > NT

NT > CT

Venterea et al. 2005. JEQ.

Vertical Profiles of Potential N_2O Production



Venterea and Stanenas. 2008. JEQ.

Tillage Management Effects on N_2O Emissions

NT Greater | CT Greater

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Aulakh et al. 1984	
	Halvorson et al., 2010

Agrees with tillage-by-placement pattern (12/18)

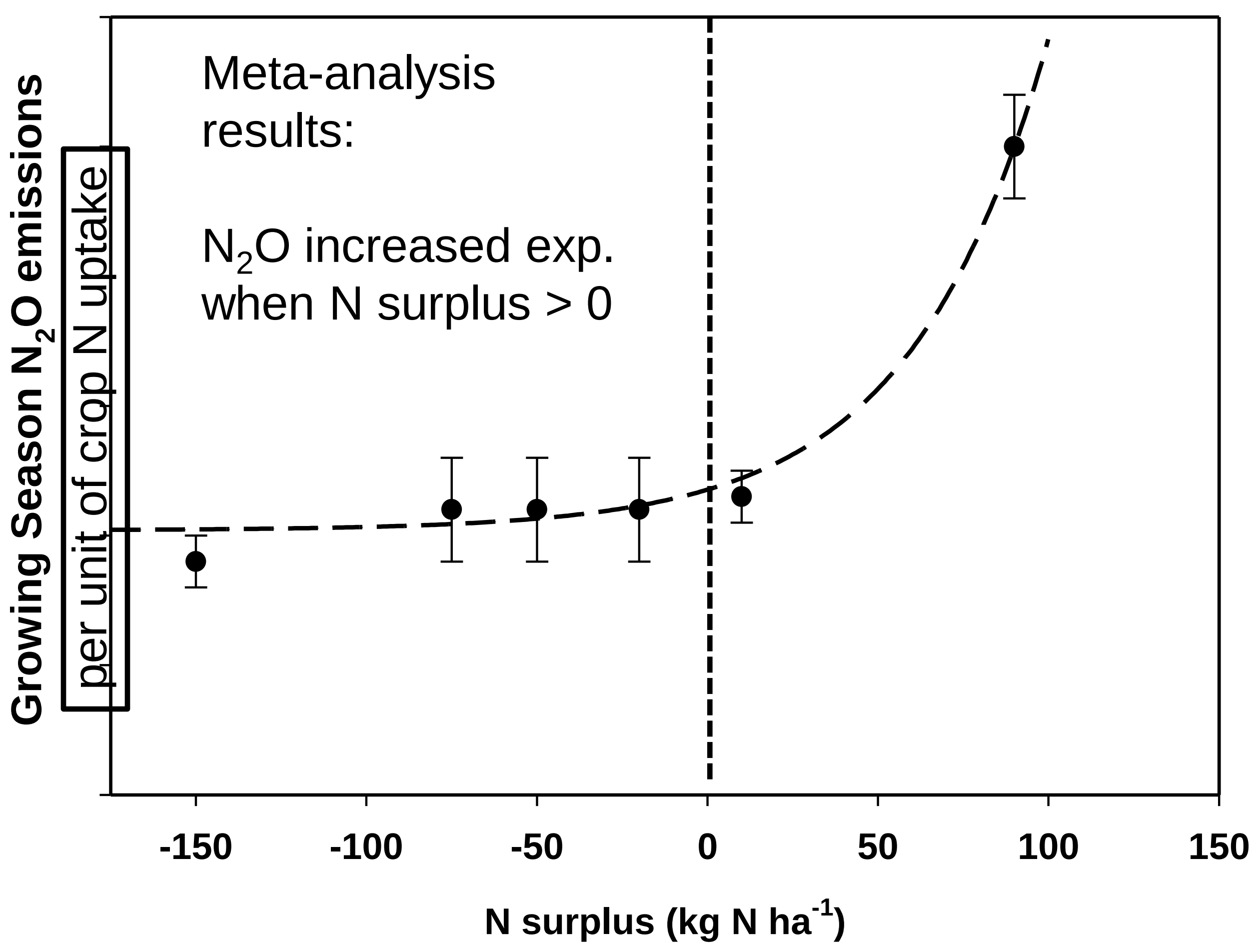
Mixed application or no information (5/18)

Disagrees with tillage-by-placement pattern (1/18)

Recommendation for no-till: Subsurface N application, but not AA

Nitrogen Use Efficiency and N_2O emissions

An elegant idea: N_2O emissions will be minimized when NUE is maximized

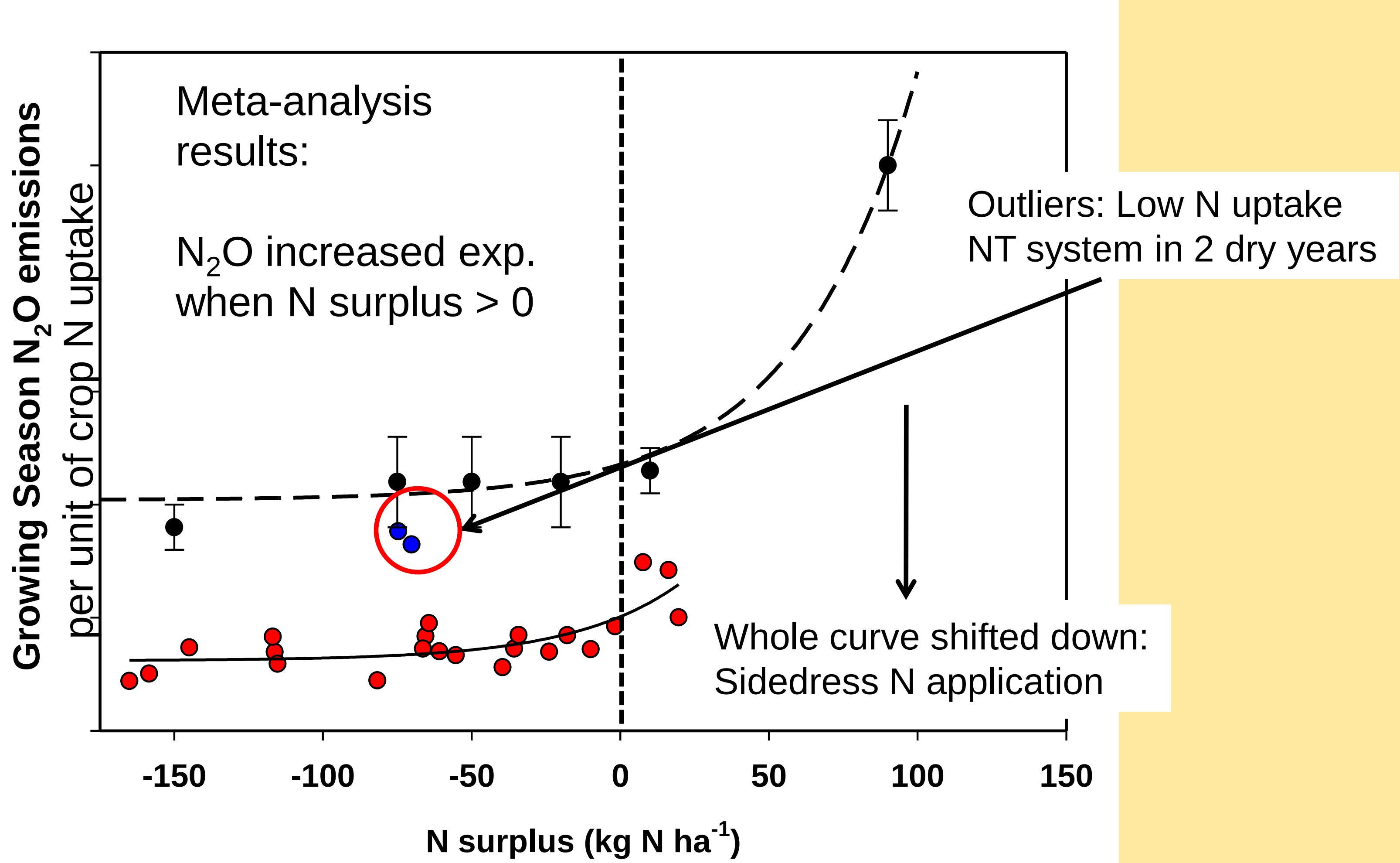


N surplus = Fertilizer N inputs – above-ground crop N uptake

Van Groenigen et al. 2010

Nitrogen Use Efficiency and N_2O emissions

Not clear if this simple relationship is going to hold in the majority of cases



N surplus = Fertilizer N inputs – above-ground crop N uptake

Van Groenigen et al. 2010

Summary & Conclusions

1. In general, we think that any practice that increases NUE would tend to also minimize N_2O emissions – more studies needed to confirm.

   e.g. * Split versus single applications
   * N rate that is well-matched with yield potential
   * Variable rate application where appropriate
   * Optimizing other nutrients (P, K, S)

   *Also expect these practices to minimize indirect emissions

2. However, it's not clear if all practices that increase overall NUE will decrease N_2O emissions: Banding ?

3. Some alternative practices that may have the same overall NUE may have higher N_2O emissions:
   - Depth of placement
   - Fertilizer source (AA vs. urea)

3. Need more studies looking at these factors.

4. Need better emissions models that account for these factors, because direct measurement of N_2O emissions on farmer's fields is impractical

Broader Implications / Questions

Optimization of fertilizer management is only part of solution; range of activities is required:

1. Cover cropping / companion cropping / more diverse rotations to reduce N requirements and retain more N during non-growing season

2. Restoration of riparian vegetation

3. Edge of field denitrification barriers / bioreactors or controlled drainage systems to reduce stream nitrate inputs
(current research area, some practices may increase N_2O emissions)

Is there any hope of actually decreasing global N_2O emissions in light of rising population and demand for food ?
---With CO_2, we have hope that renewable fuels can reduce emissions.

Or is best we can hope for to minimize N_2O emissions per unit of production?

What will be long-term effects (GHG and ozone), even if we can minimize emissions on a yield-scaled basis?