N_2O Emissions – Is there anything we can to do cap the well?

Rodney Venterea
US Dept. of Agriculture - ARS
Dept. of Soil, Water, Climate / University of Minnesota

Ryo Fujinuma
John Baker
Kurt Spokas
Michael Dolan
Jason Leonard

USDA

Agricultural Research Service

Carl Rosen
Charles Hyatt
Bijesh Maharjan

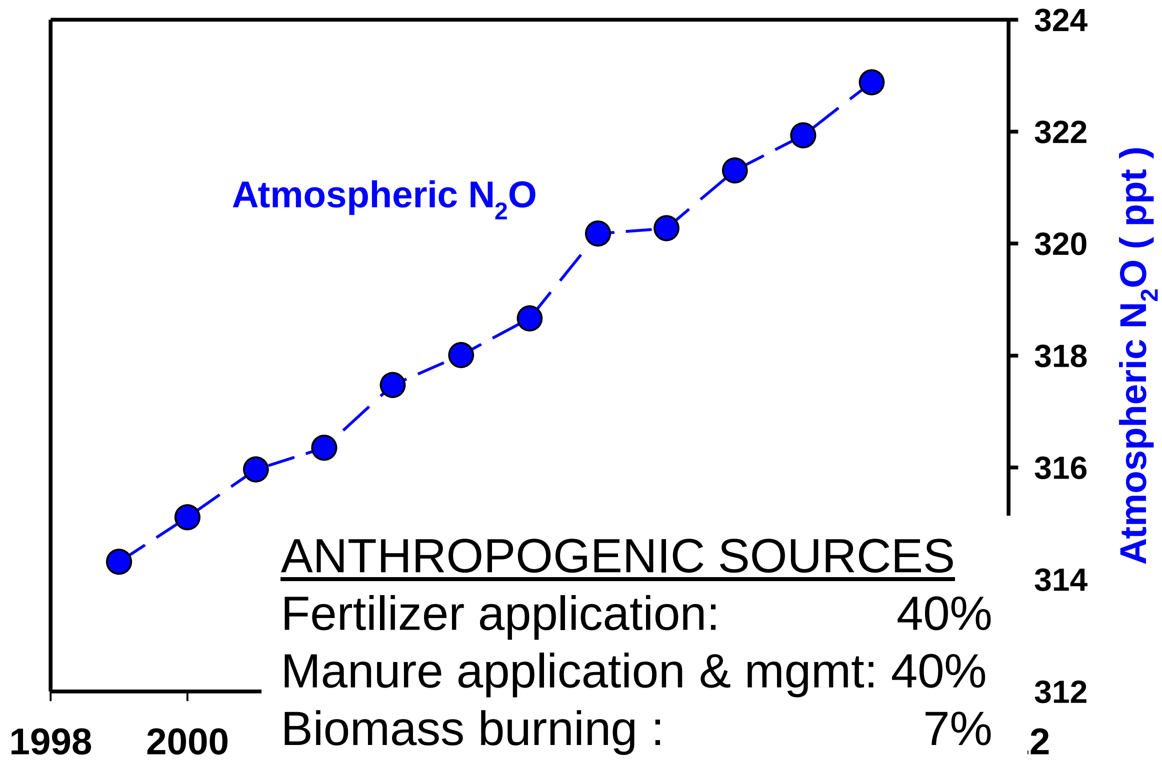
UNIVERSITY OF MINNESOTA
Driven to Discover℠

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

Is there anything we can to do cap the well?

Atmospheric N_2O: + 0.25% per year

20% above pre-industrial levels



<u>ANTHROPOGENIC SOURCES</u>

Fertilizer application: 40%

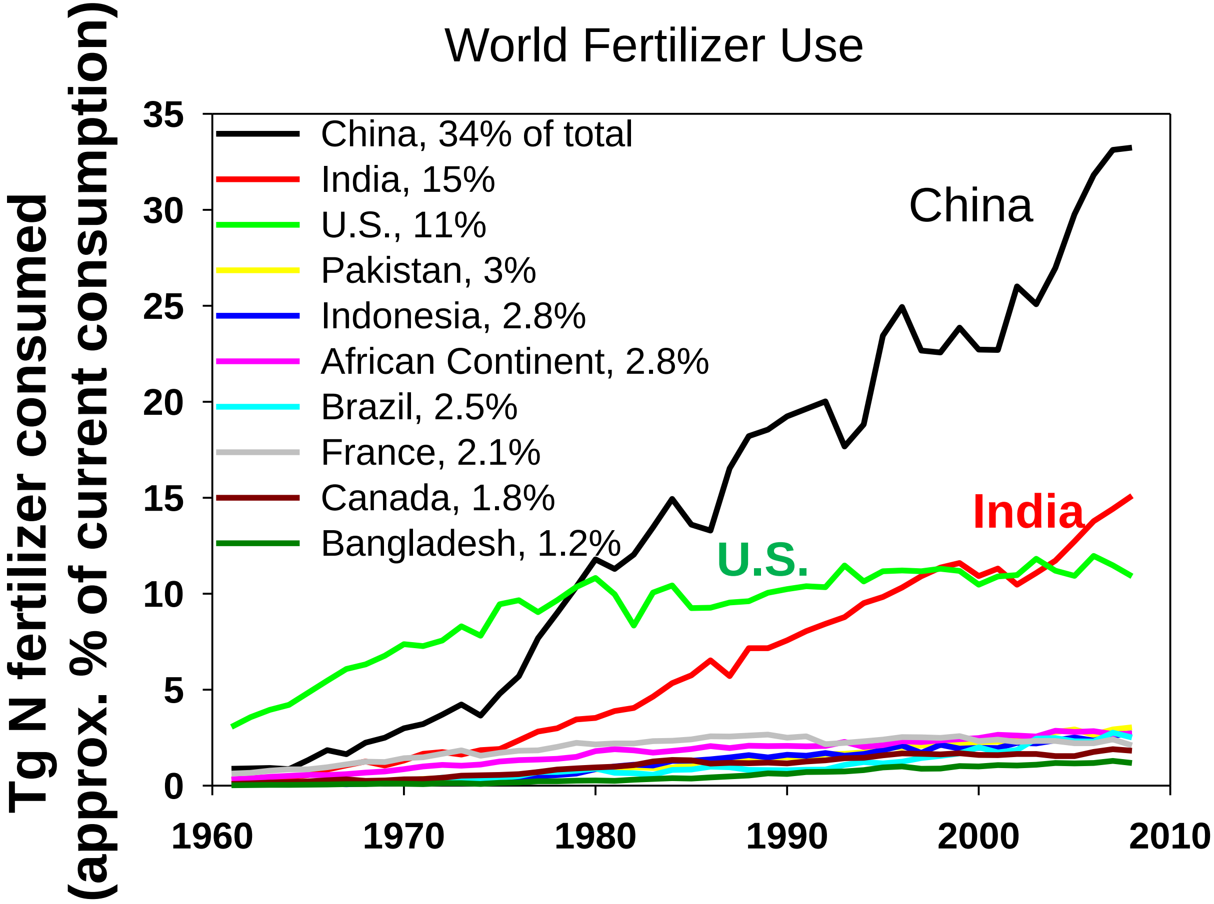
Manure application & mgmt: 40%

Biomass burning : 7%

Industrial: 14%

Davidson, 2009; Mosier et al.,1998

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



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

http://www.fertilizer.org/

GWP = 300 times CO_2

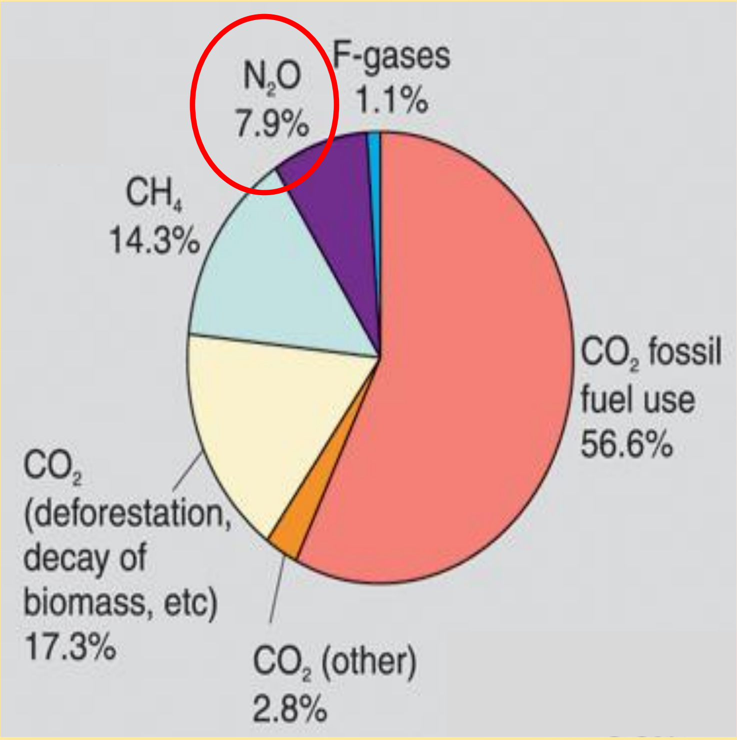
- 1 kg N_2O-N ha^{-1} ≈ 0.5 Mg CO_2 ha^{-1}

•Potential C Sequestration (CCX):
Conversion of cropland to reduced tillage = 1 to 1.5 Mg CO_2 ha^{-1}

1 kg N_2O-N = CO_2 from
50 gallons of gasoline

GWP= Global Warming Potential

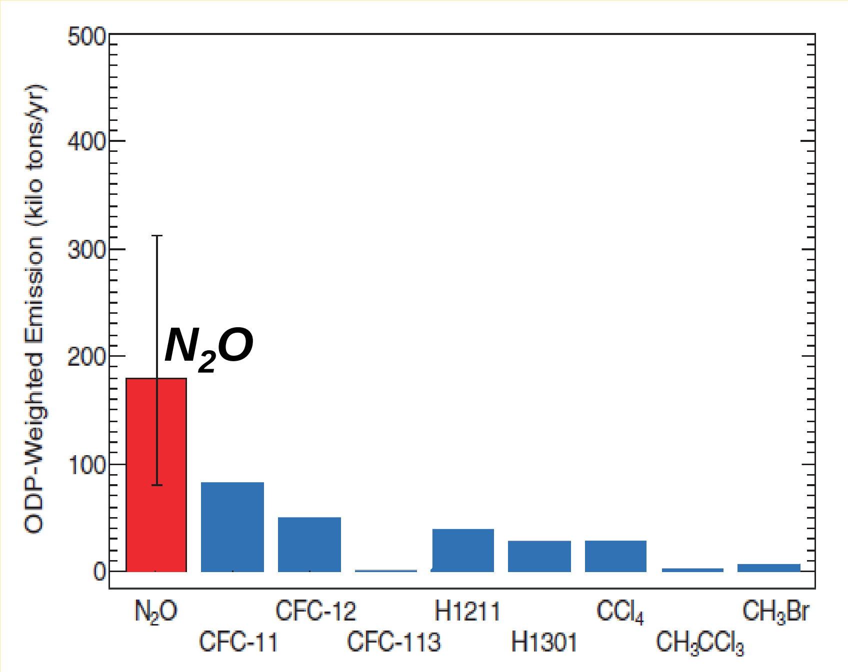
IPCC, 2007



% of total anthropogenic GHG emissions

ODP = Ozone Depleting Potential

Ravishankara et al. *Science.* 2009



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

30+ Years of Soil N_2O Emissions Research

1. Developed measurement systems
2. Put constraints on emissions estimates
3. Identified major emissions controls, regulators, and key process
4. Developed emissions models

- Recent emphasis: Develop practical field methods to reduce emissions
- Few empirically-based guidelines for reducing N_2O while maintaining crop yields

Objective

- Review our recent research as it relates to N_2O mitigation efforts
  - -Management of synthetic Nitrogen fertilizer
  - -Challenges & recommendations for future study

Irrigated Site
-Corn
-Potato

Dryland/
Tile-drained site
-Corn

Dryland/naturally drained site
-Corn

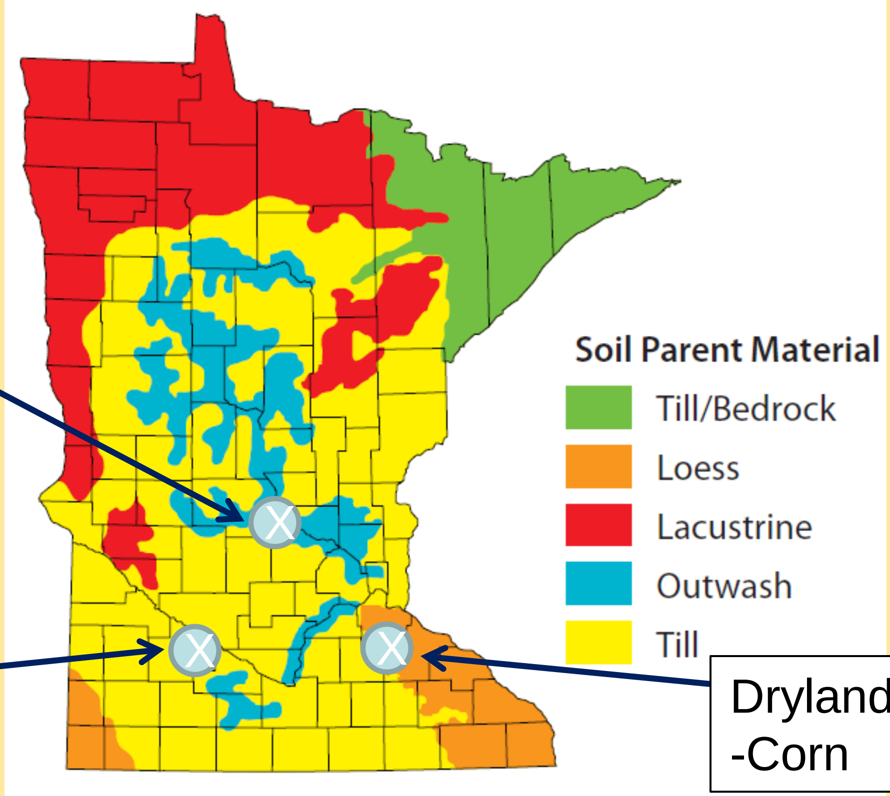


Figure 1. Parent materials of Minnesota.

Gas Flux Chambers

<u>Pro:</u>

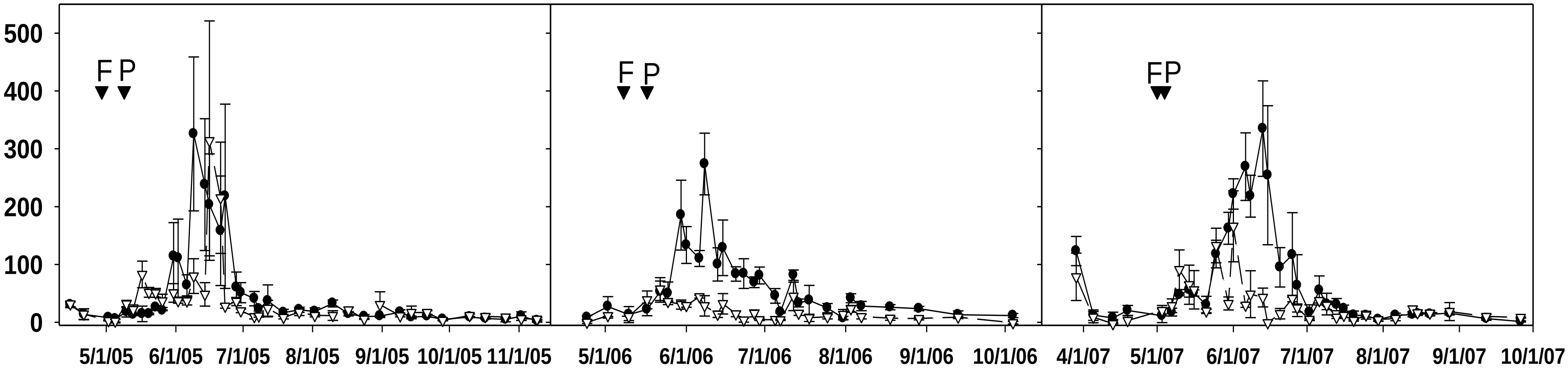
- Plot-scale studies & treatment comparisons
- Inexpensive

<u>Con:</u>

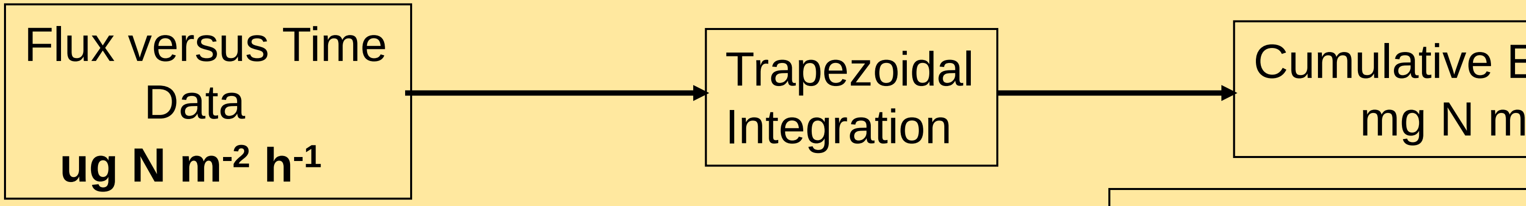
- Limited spatial and temporal coverage
- Physical disturbance

Automated Chambers

N_2O flux (μg N m^{-2} h^{-1})
2005, 2006, 2007 Growing Seasons



F = Fertilizer application date
P = Planting date



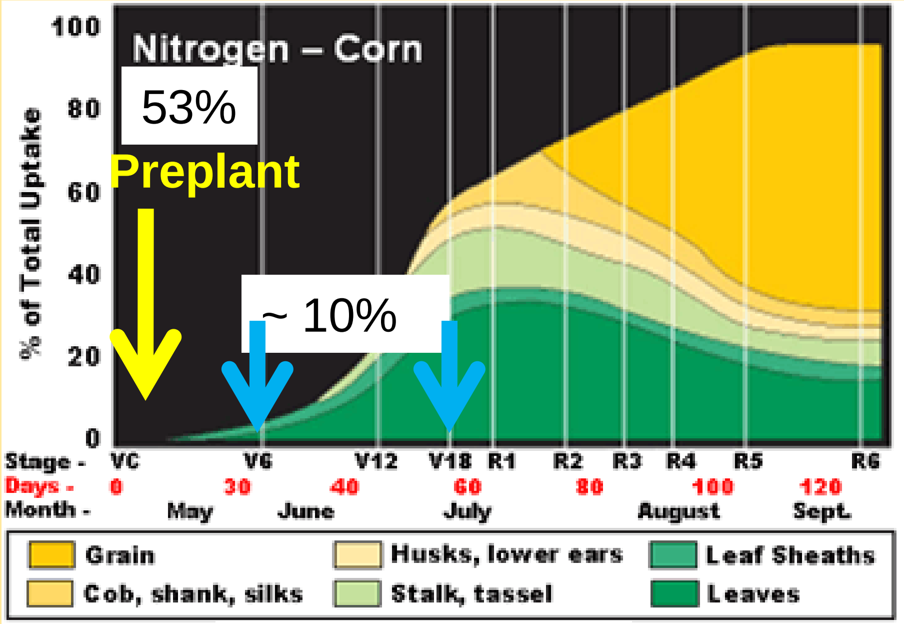
(1 kg N ha^{-1} = 100 mg N m^{-2})

Asynchrony between N fertilizer application and crop N demand

Fall application

35%

Corn N Uptake



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): Diffusion through porous coating
2. Nitrification (NI) inhibitors: Blended or co-applied with fertilizer

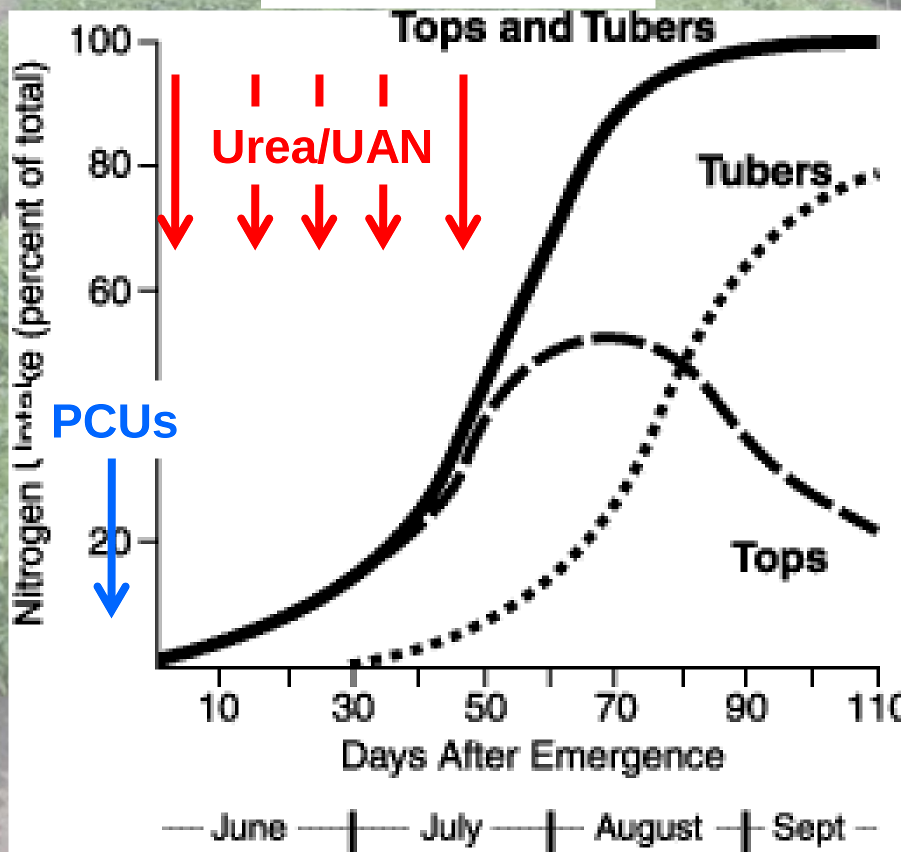
Meta-analysis of 35 studies (Akiyama et al., 2009)

- On average 35% to 38 % reduction in N_2O emissions
- Wide variation in effectiveness.
- Yield benefits req'd to justify cost have been inconsistent.

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

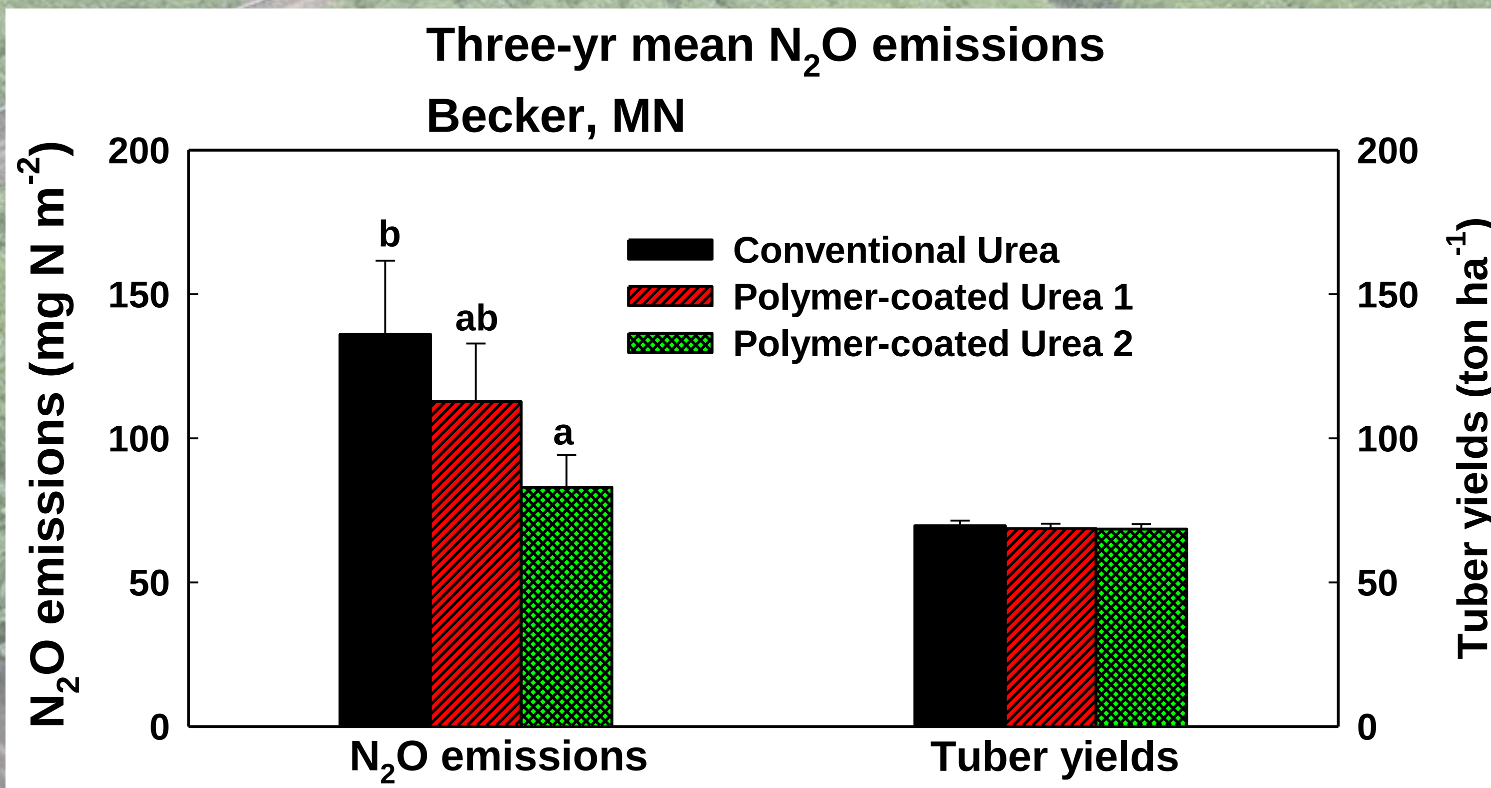
Potato N Uptake



North Dakota State University Extension

Controlled Release Fertilizers for Irrigated Potato Production

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

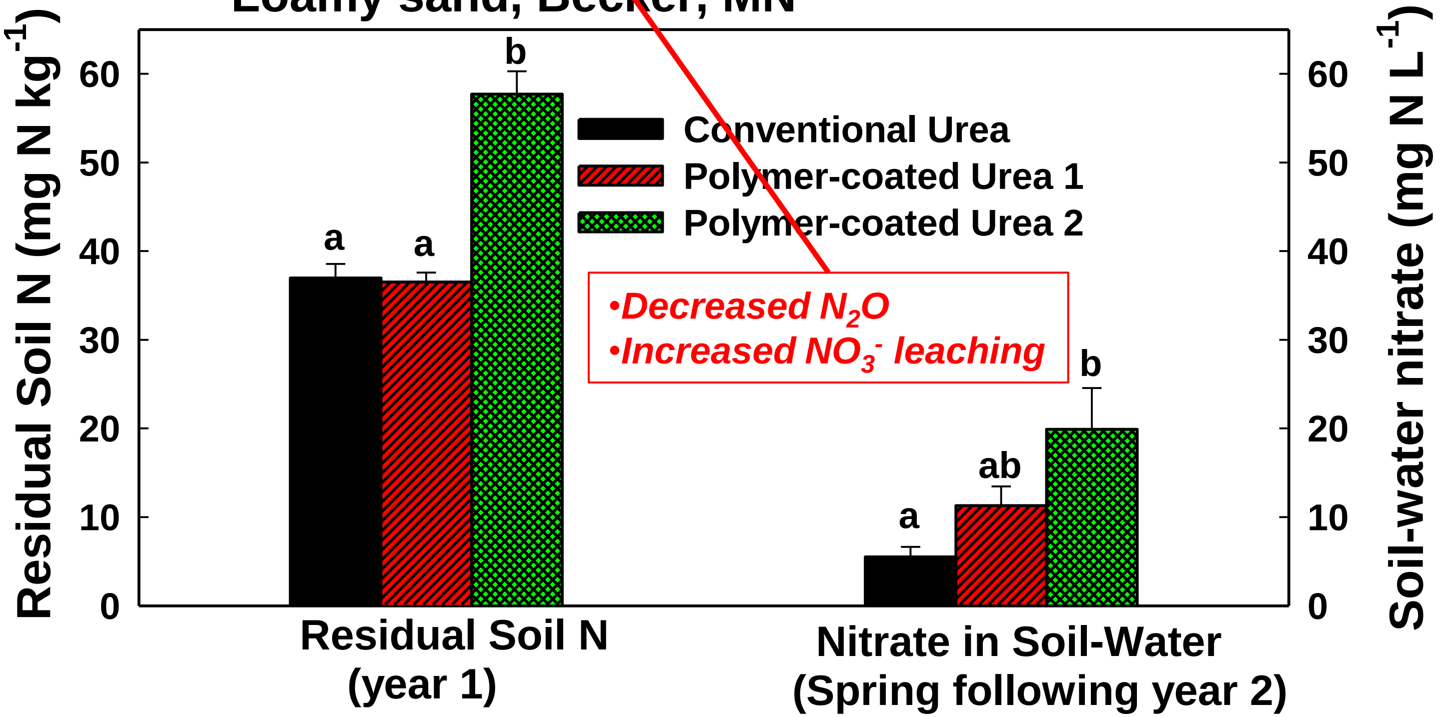


Hyatt et al. 2010. SSSAJ.

Controlled Release Fertilizers for Irrigated Potato Production

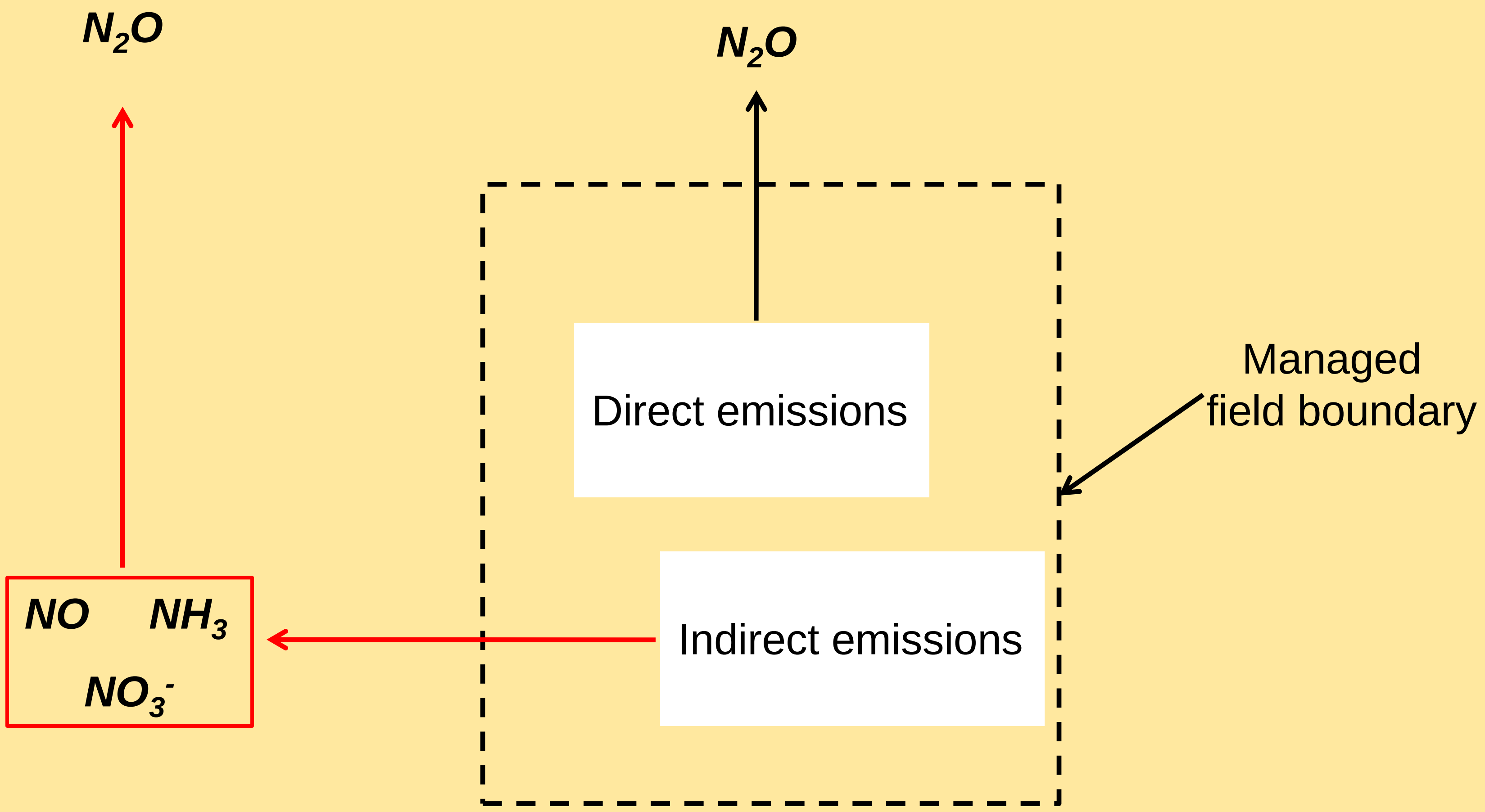
Source		Timing	Rate (kg N ha^{-1})
1. Conventional urea	(47%N)	4 split applications	270
2. PCU-1	(44%N)	Before planting	270
3. PCU-2	(42%N)	Before planting	270

Soil and leaching data for individual years
Loamy sand, Becker, MN



Venterea et al. 2011. JEQ (In press)

Direct and Indirect N_2O Emissions



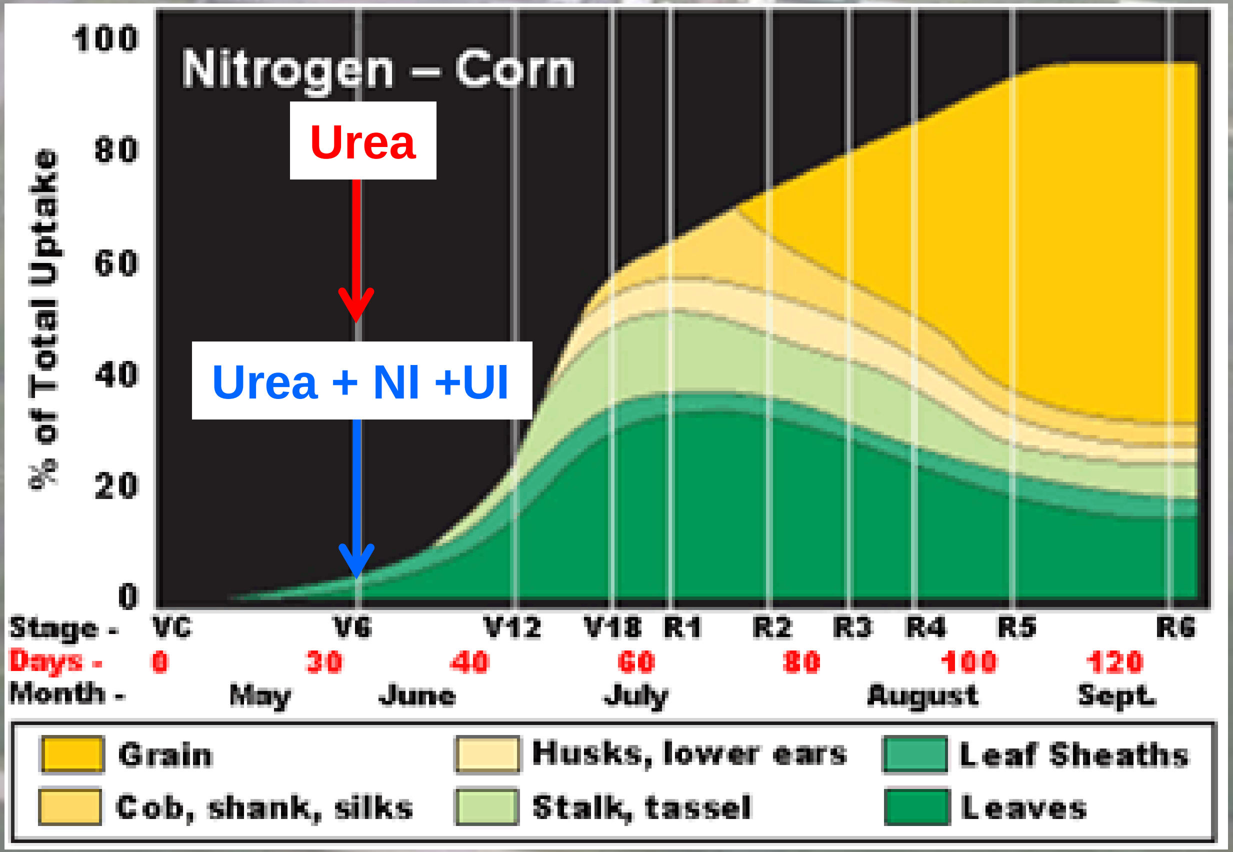
Challenges:

1. Logistical - measuring all forms of N loss in a single experiment
2. GHG budgeting - estimating fraction of indirect losses converted to N_2O

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

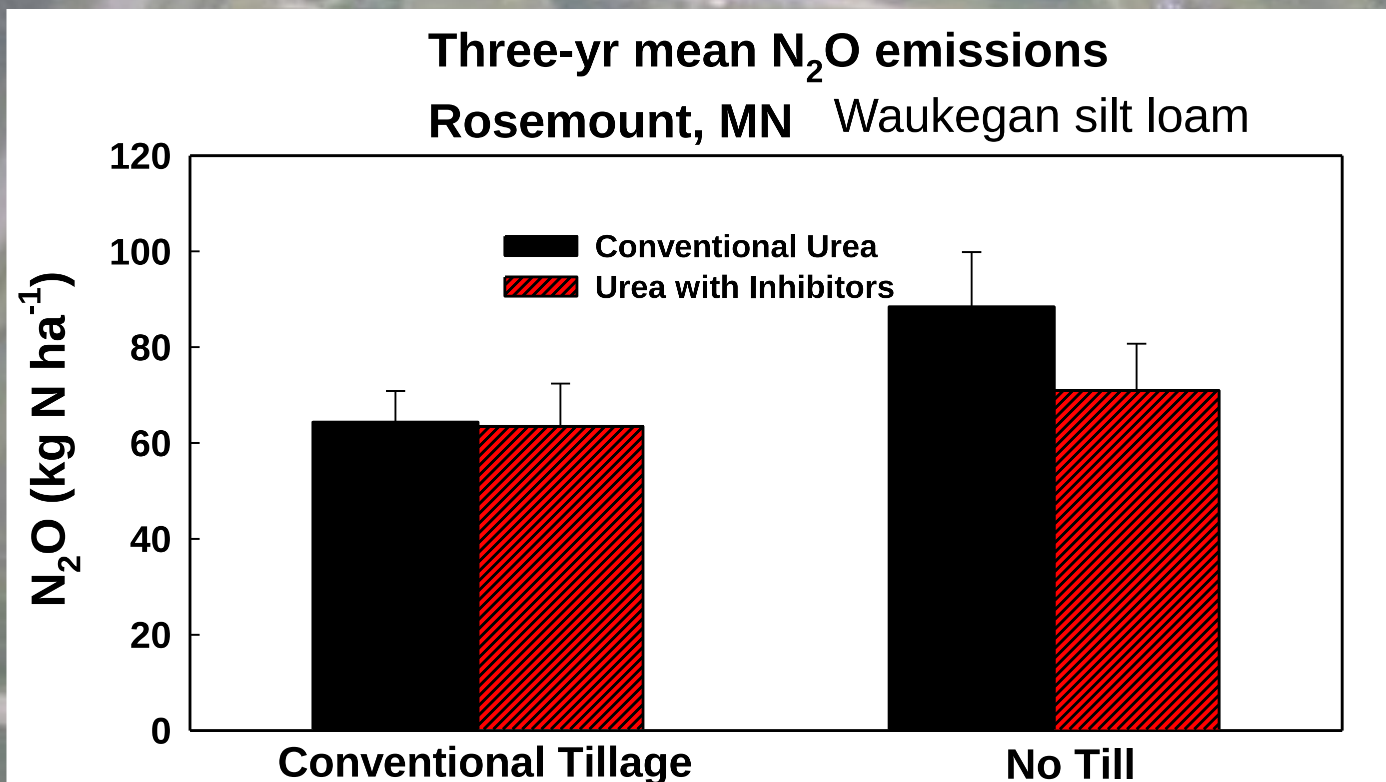
Treatments applied to both CT and NT treatments (in place for > 15 yr)



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)

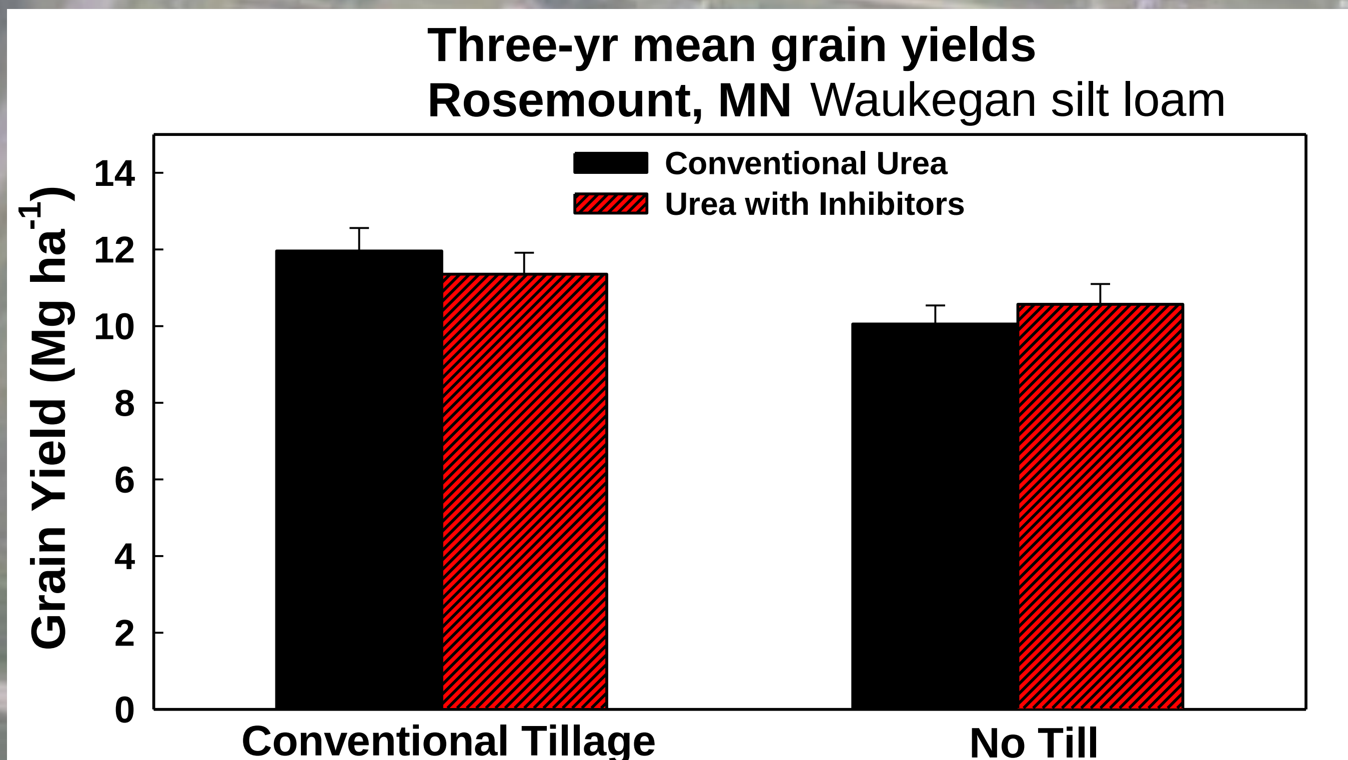


Venterea et al. 2011. (In review)

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)



Venterea et al. 2011. (In review)

Controlled Release Fertilizers

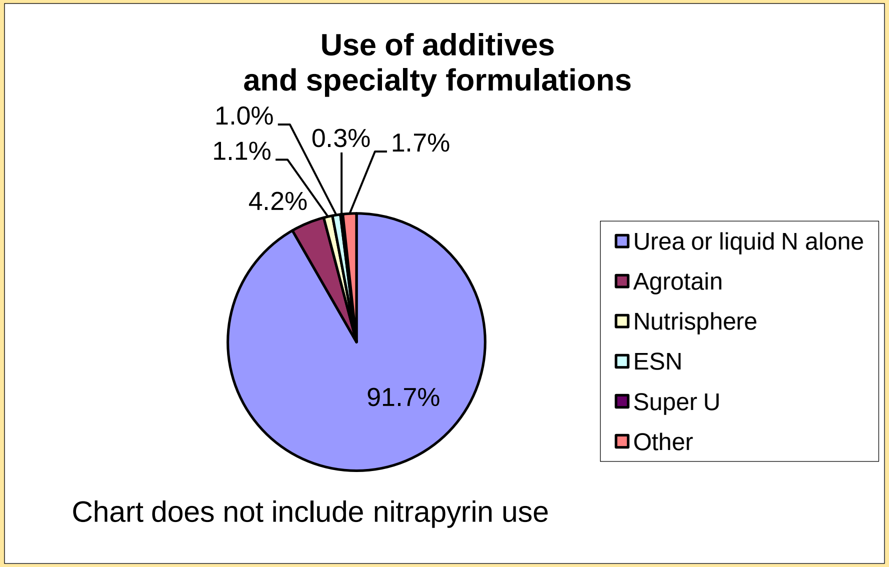
1. No guidelines for knowing when/where specific products will be effective.

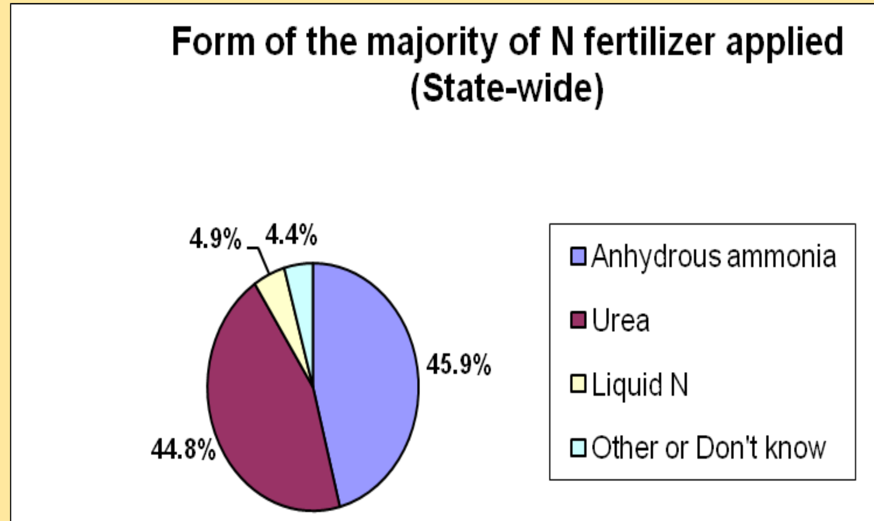
2. Many different formulations available, but little systematic comparison.

3. Appears to have potential, but needs to be optimized to site conditions (soil, climate, crop phenology).

   -PCUs: Select correct release rate
   -NIs: Can have short duration of effectiveness (half life decreases with temp)
   -Alternatives may have longer duration are being (e.g. biochar)

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

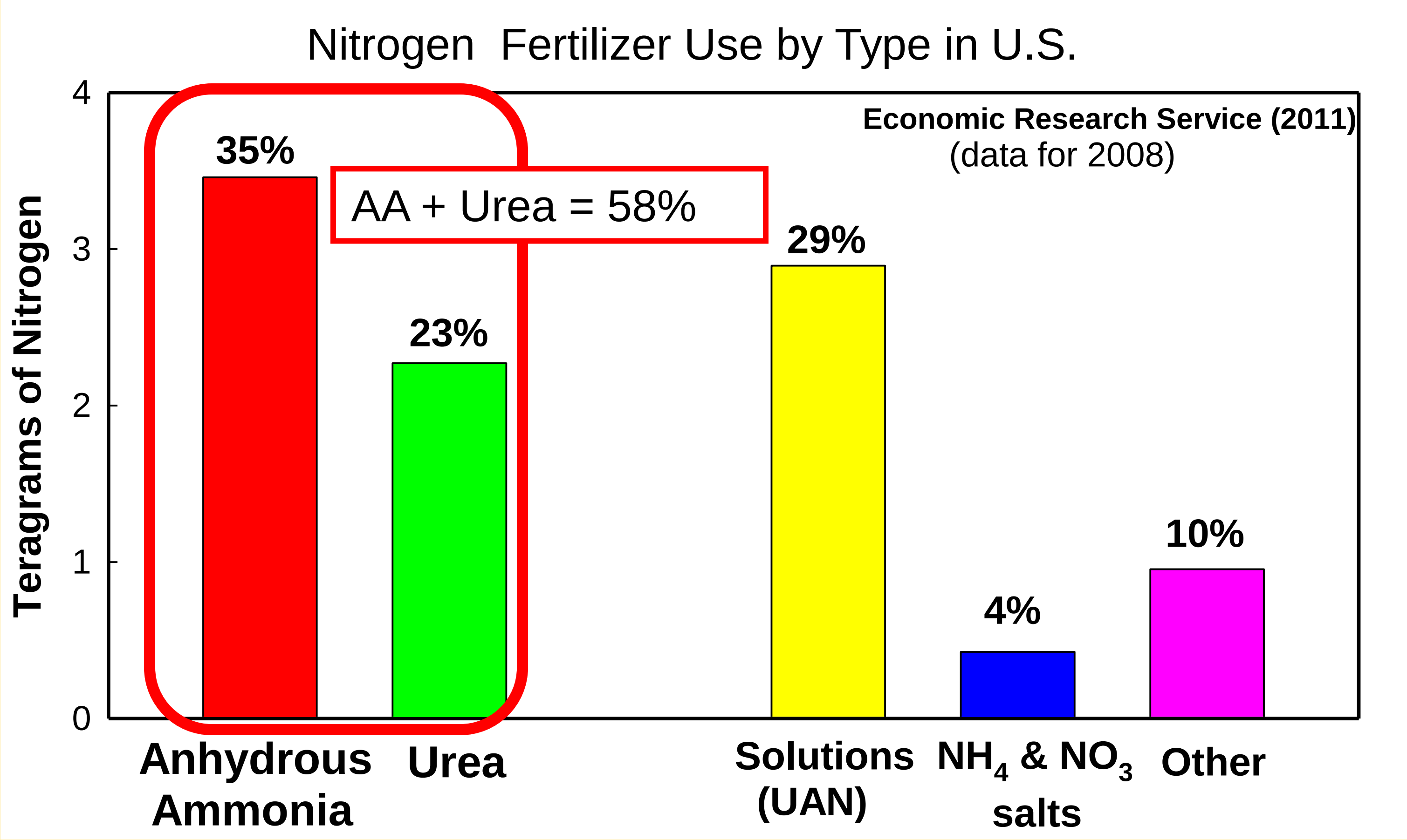




AA + Urea = 91%

- 8.3% : CRFs other than nitrapyrin
- 9.5% : nitrapyrin (fall AA application)

Fertilizer Source Effects: Conventional Sources

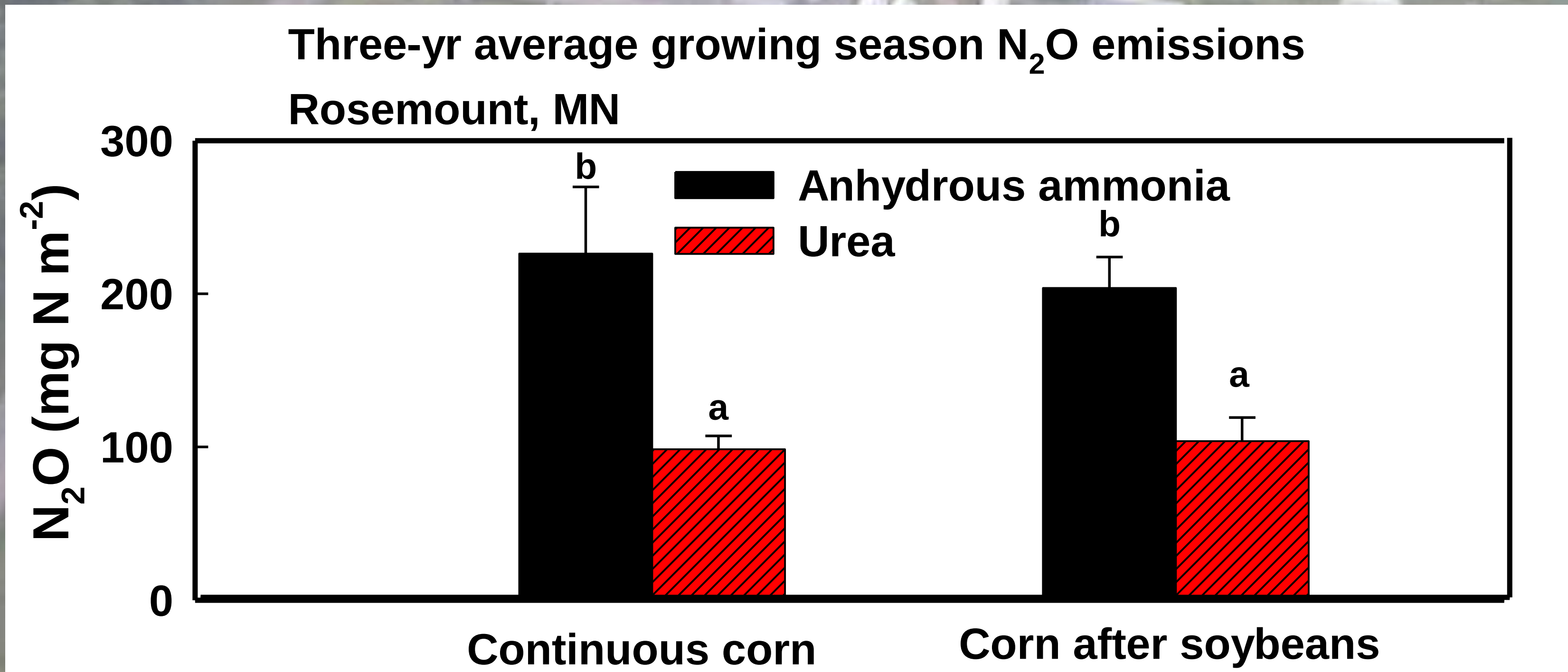


Only 1 site-year of data comparing N_2O emissions with AA and Urea prior to 2005 (Thornton et al., 1996)

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

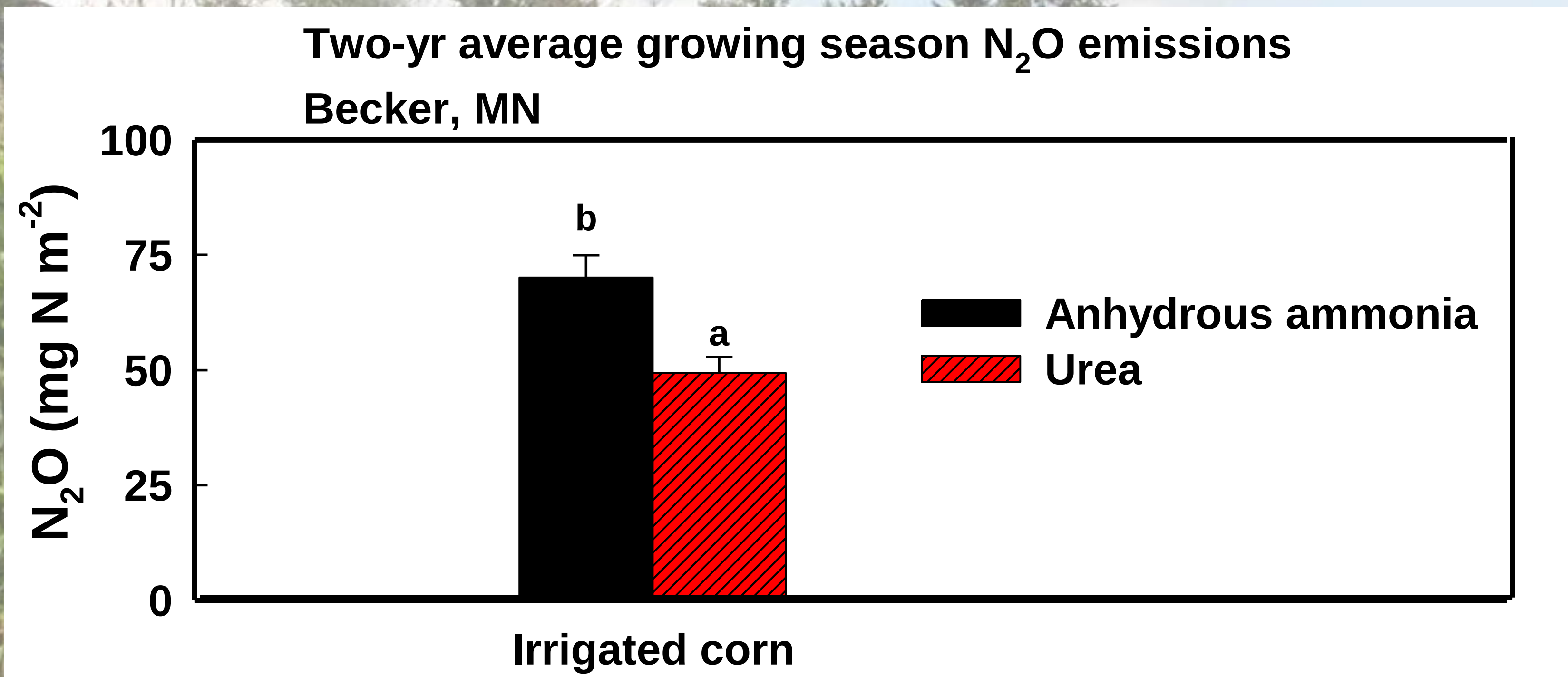
Treatments applied to both Corn following Corn and Corn following Soybean



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

GHG Impact of Change in Practice
(some wild extrapolations)

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

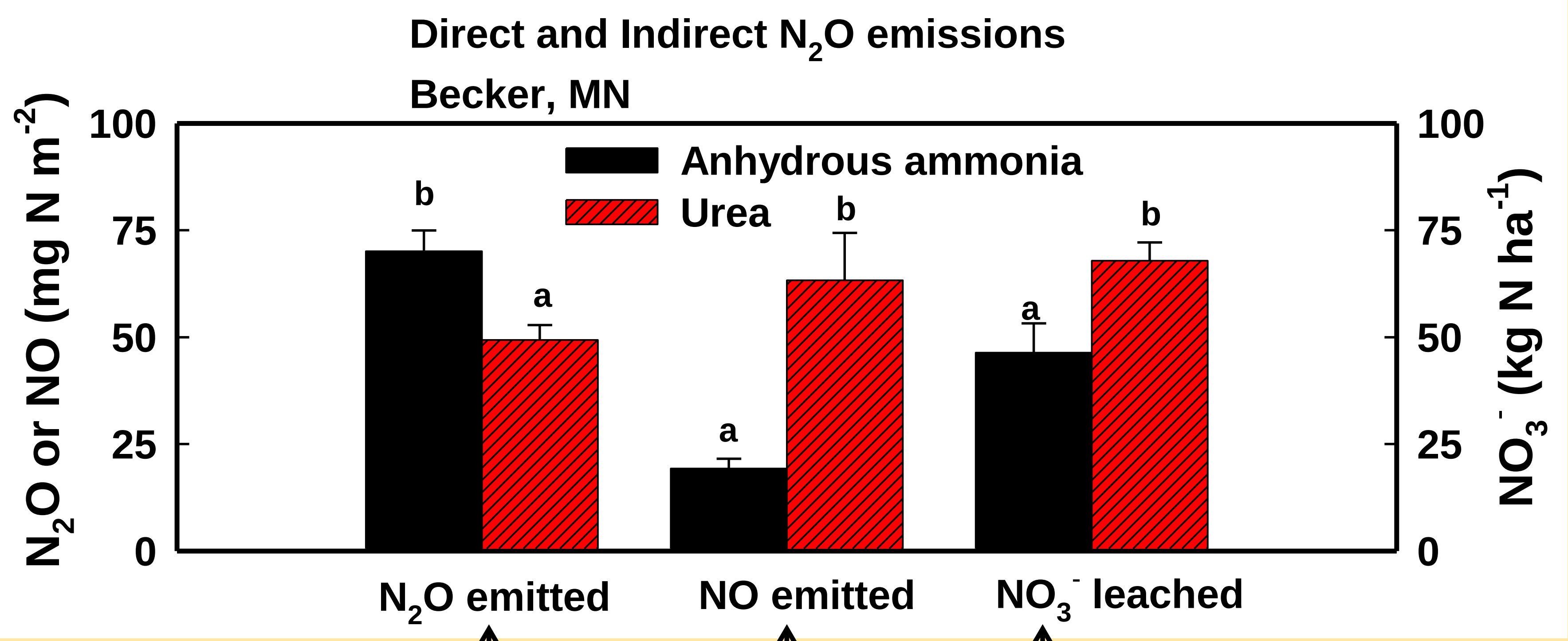
- Assume EF ratio applies to all non-AA sources
- Complete shift away from AA ➔ 25% reduction in fertilizer-derived N_2O emissions across the U.S.
- But it's probably not that simple, more studies needed.

Worldwide AA Use

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

(IFA Statistics)

Anhydrous Ammonia versus Urea: Indirect N_2O Emissions

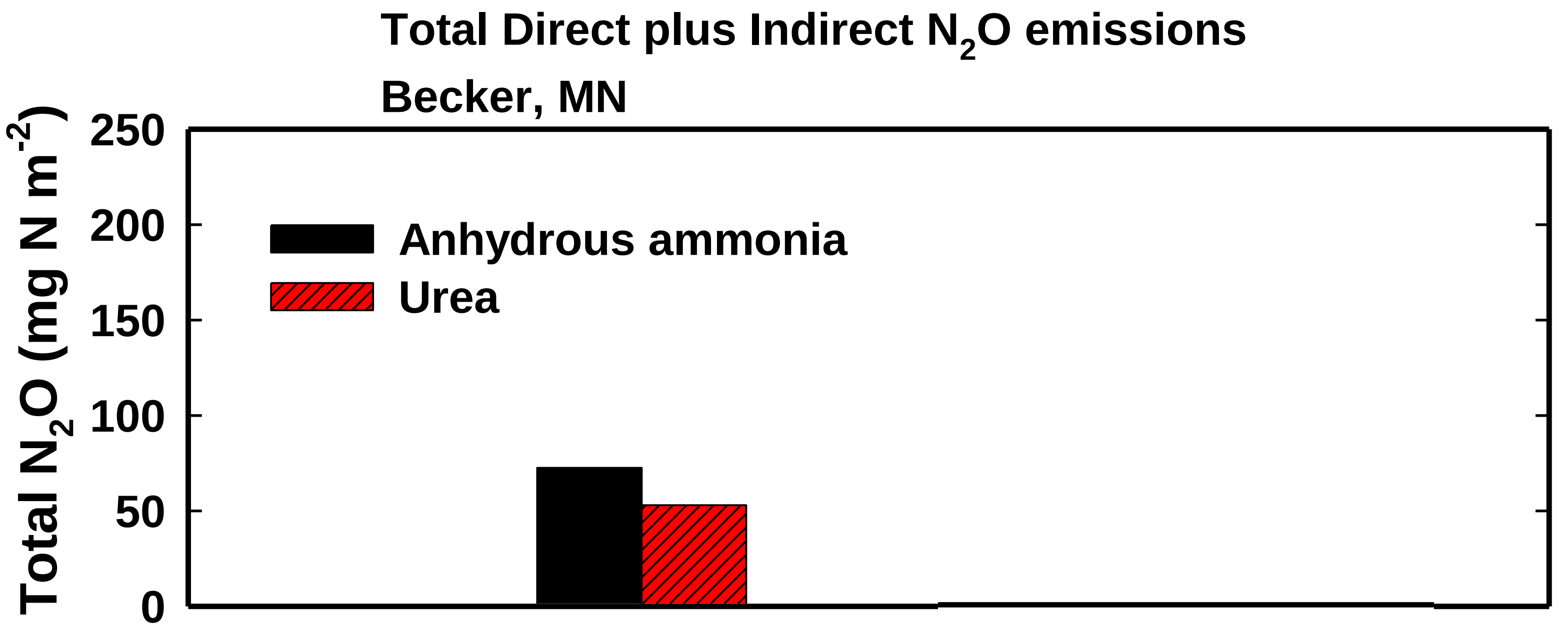


Direct emissions decreased with AA

Indirect emissions increased with Urea

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

Anhydrous Ammonia versus Urea: Indirect N_2O Emissions

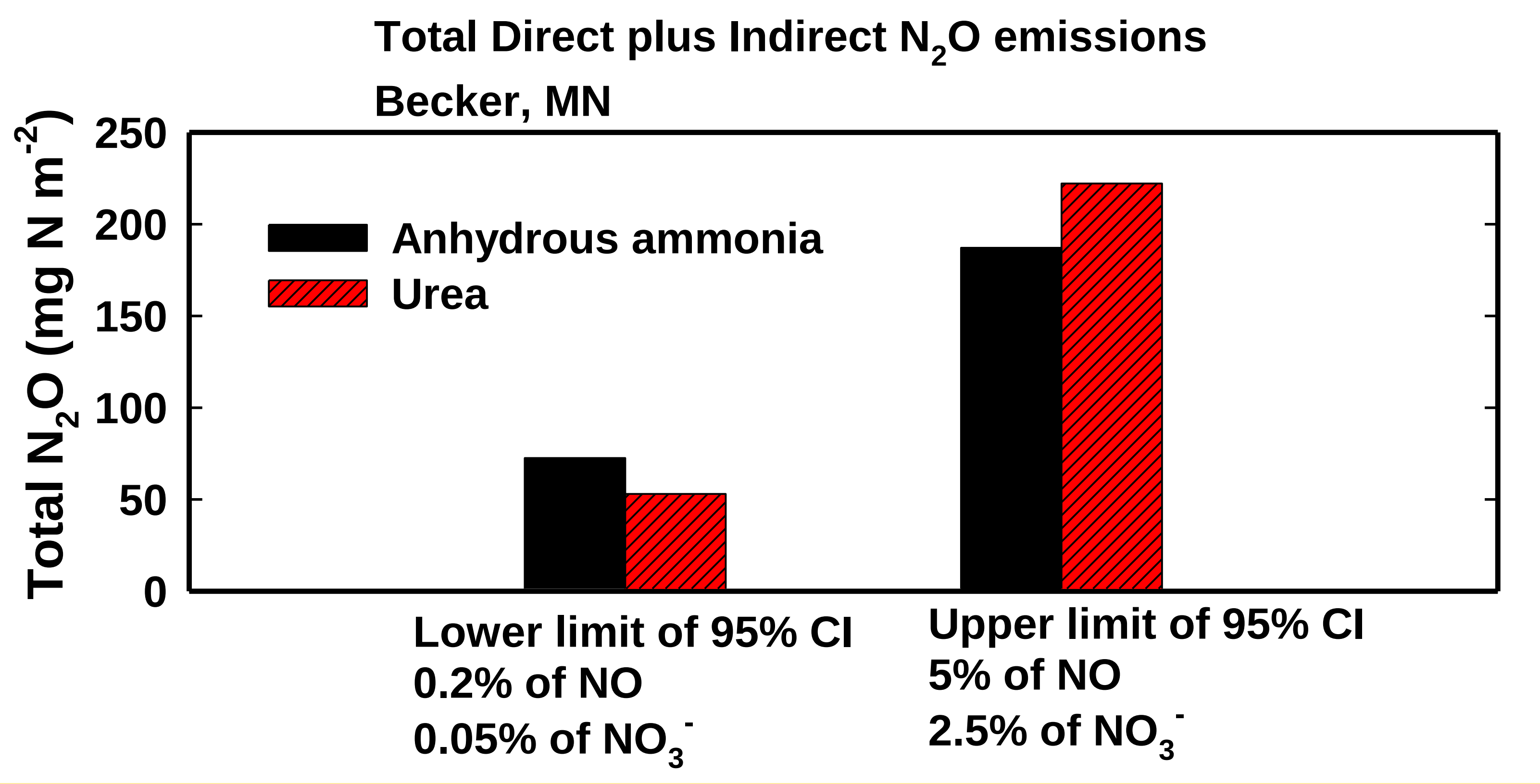


Lower limit of 95% CI
0.2% of NO
0.05% of NO_3^-

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



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)

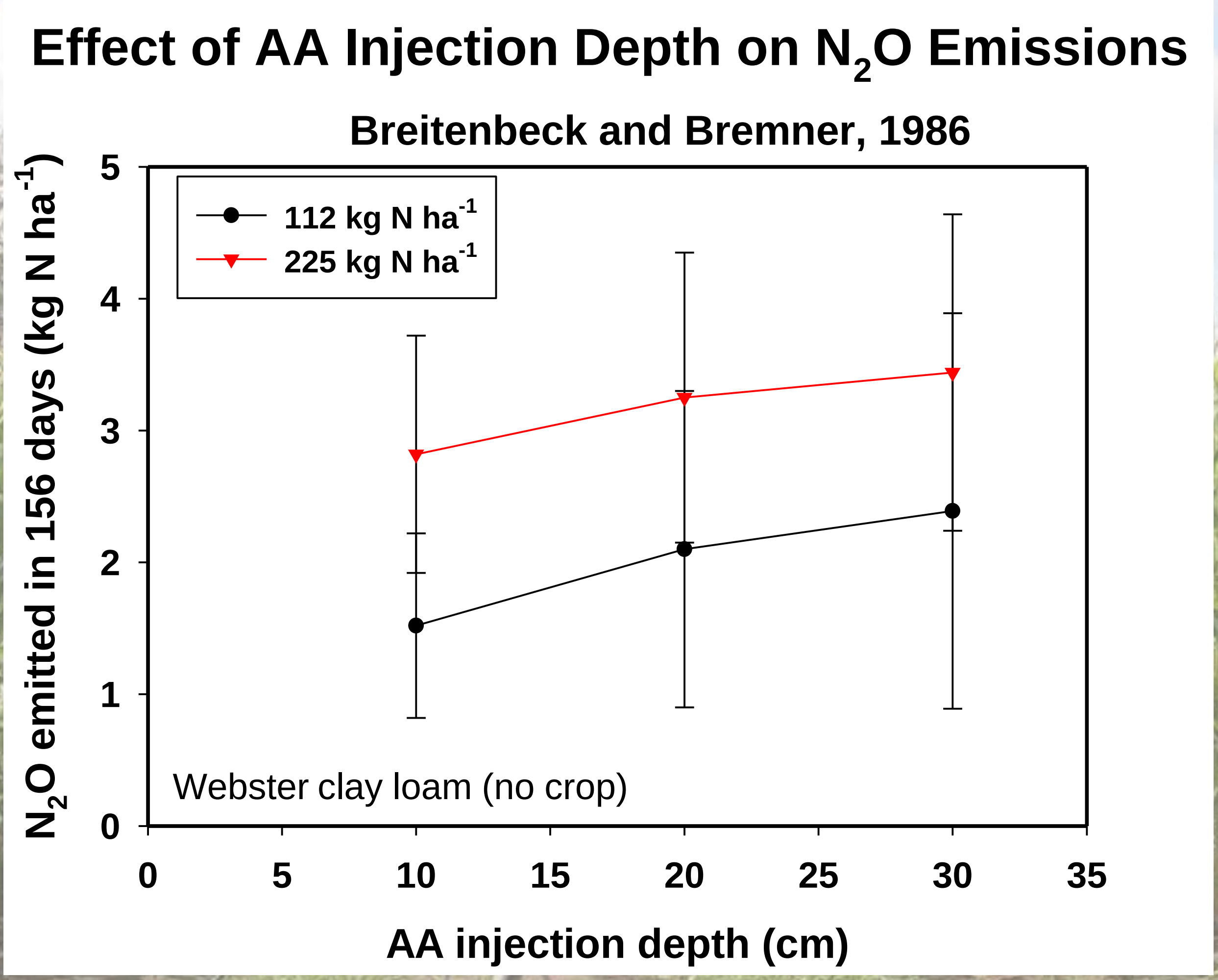
Conventional “Deep” Applicator

New “Shallow” 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

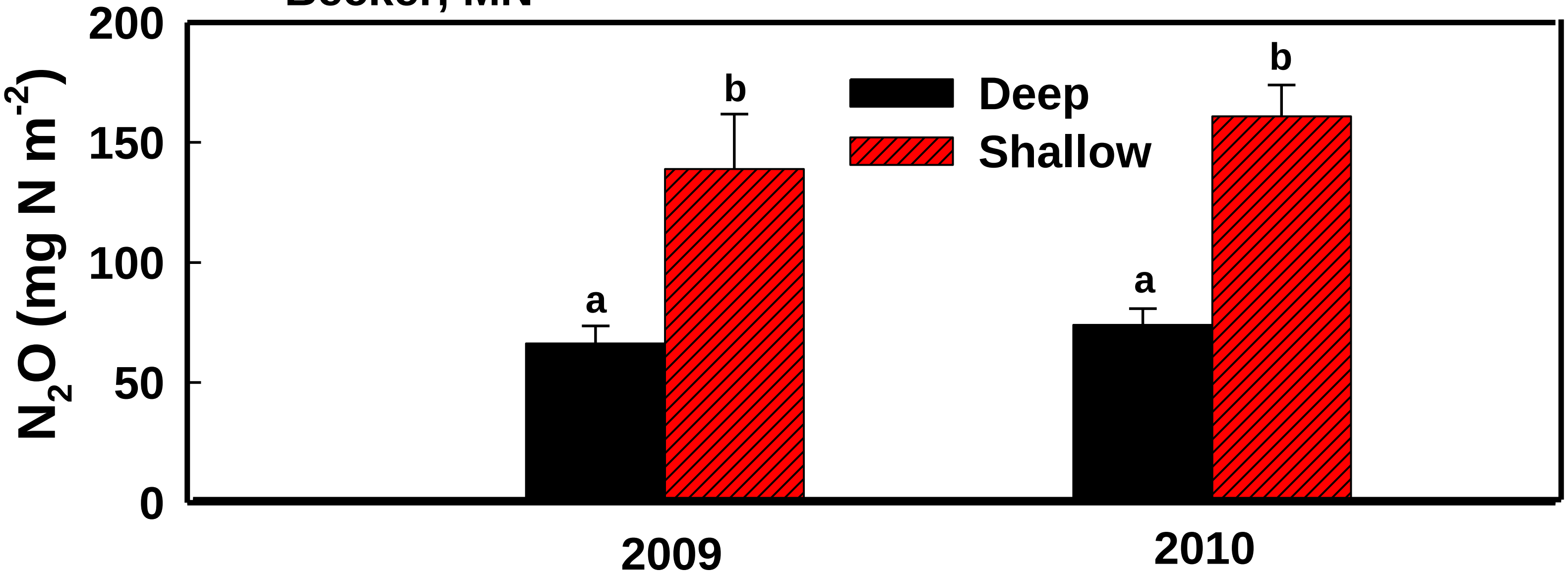


Anhydrous Ammonia Placement Effects: Irrigated Corn

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



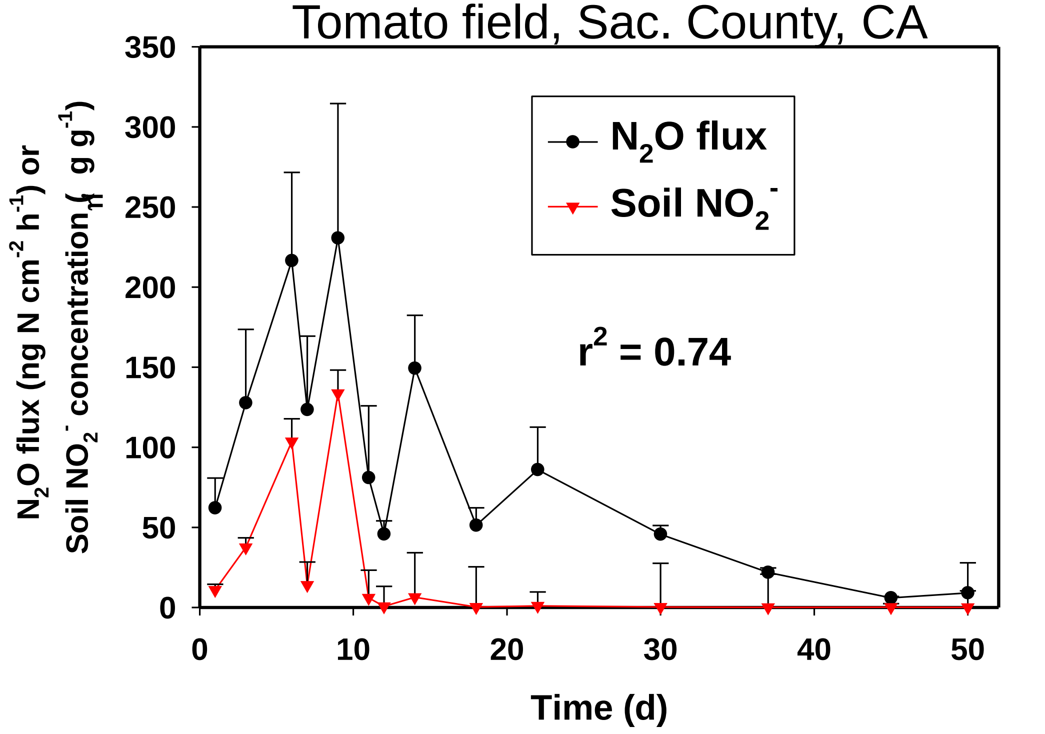
<u>WHY ?</u>

Repeating experiment in finer texture soil

Fujinuma et al., 2011 (submitted.)

Greater N_2O Emissions with Anhydrous Ammonia

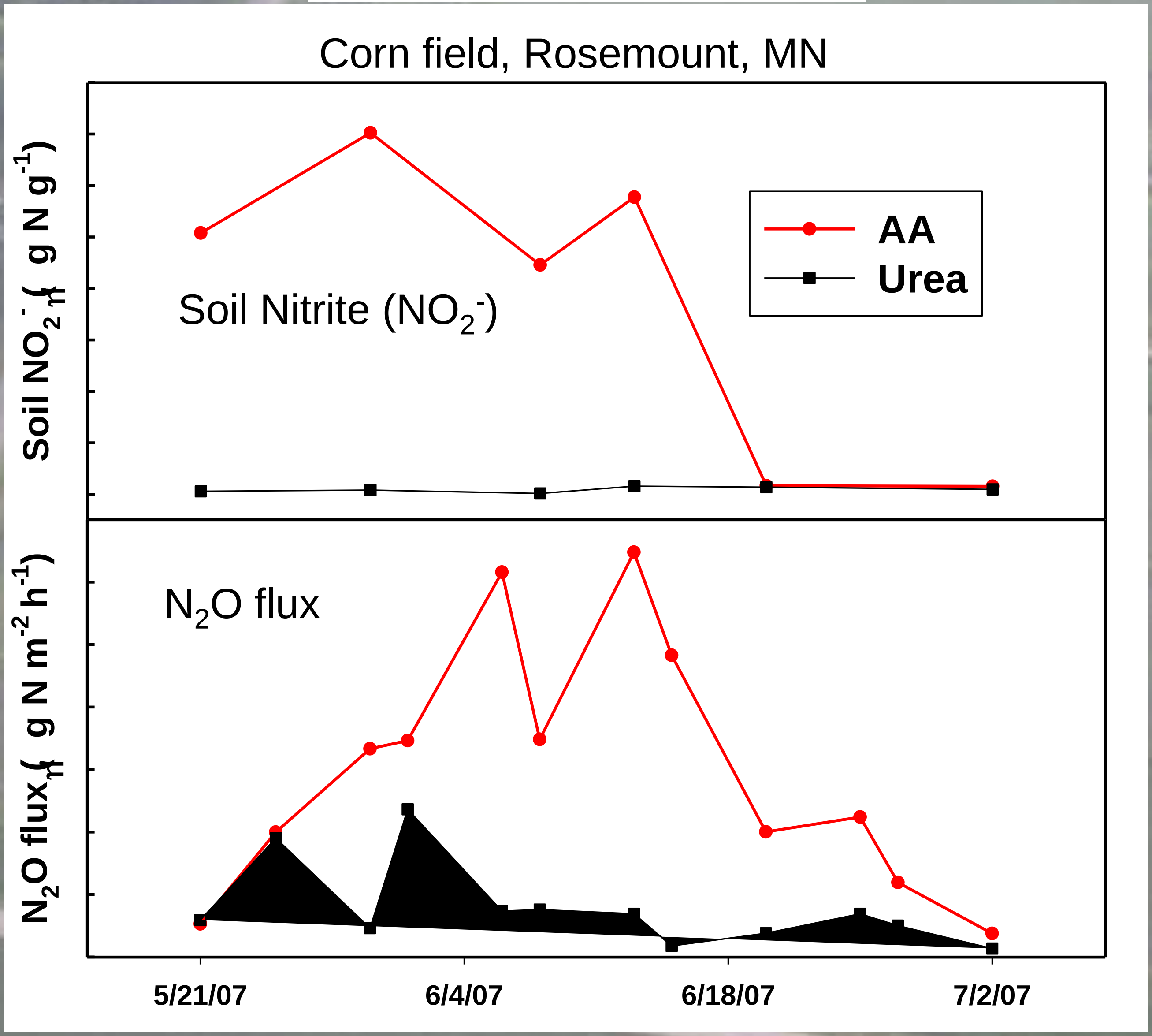
Elevated Soil Nitrite (NO_2^-)



Venterea and Rolston, 2000. J. Geophys. Res.

Greater N_2O Emissions with Anhydrous Ammonia

Elevated Soil Nitrite (NO_2^-)

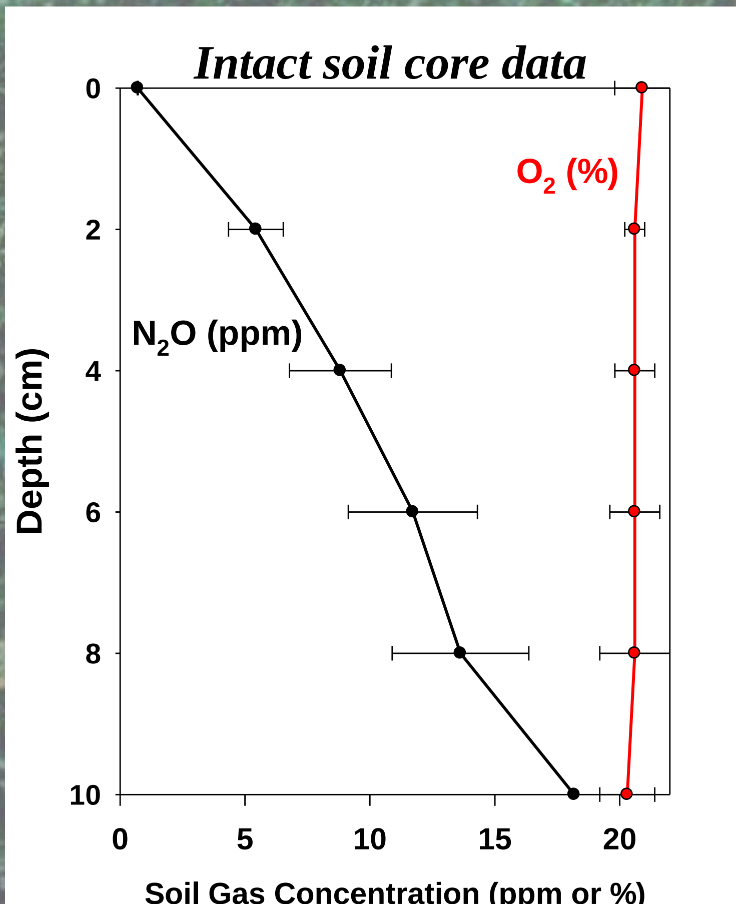


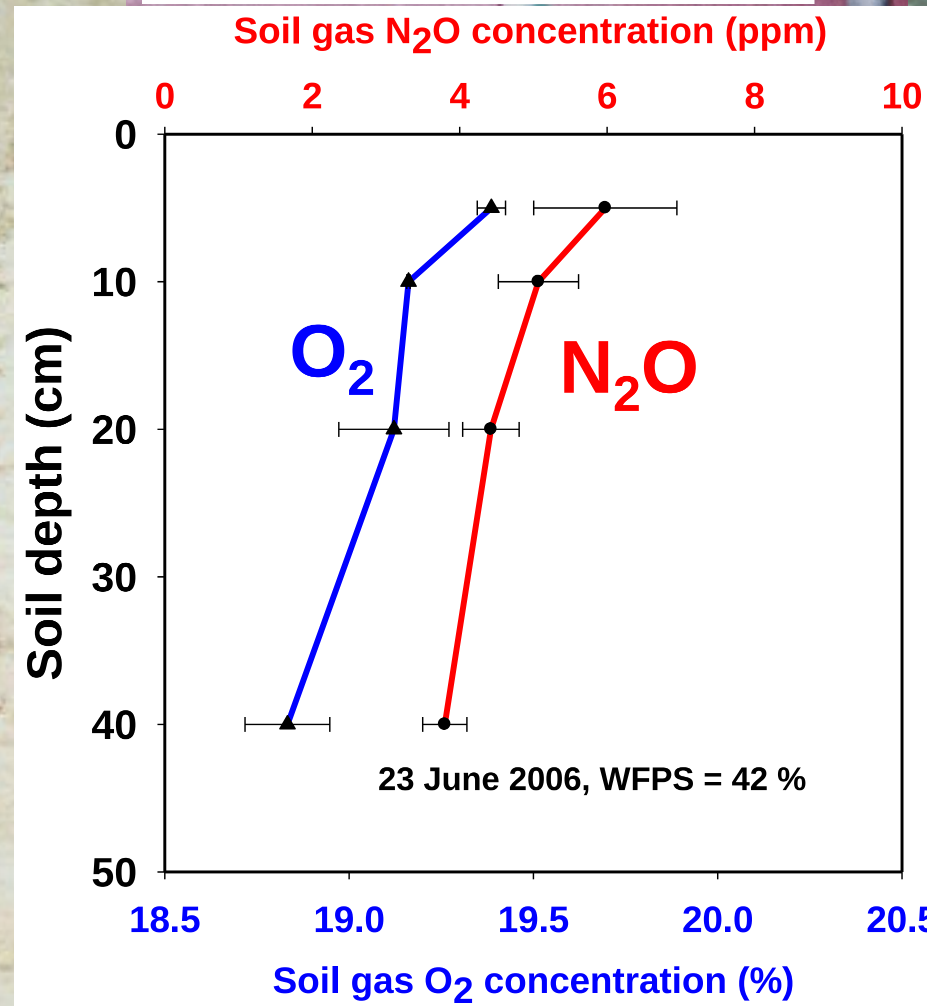
Venterea et al. 2010. Soil Sci. Soc. Am. J.

Greater N_2O Emissions with Anhydrous Ammonia

Aerobic conditions

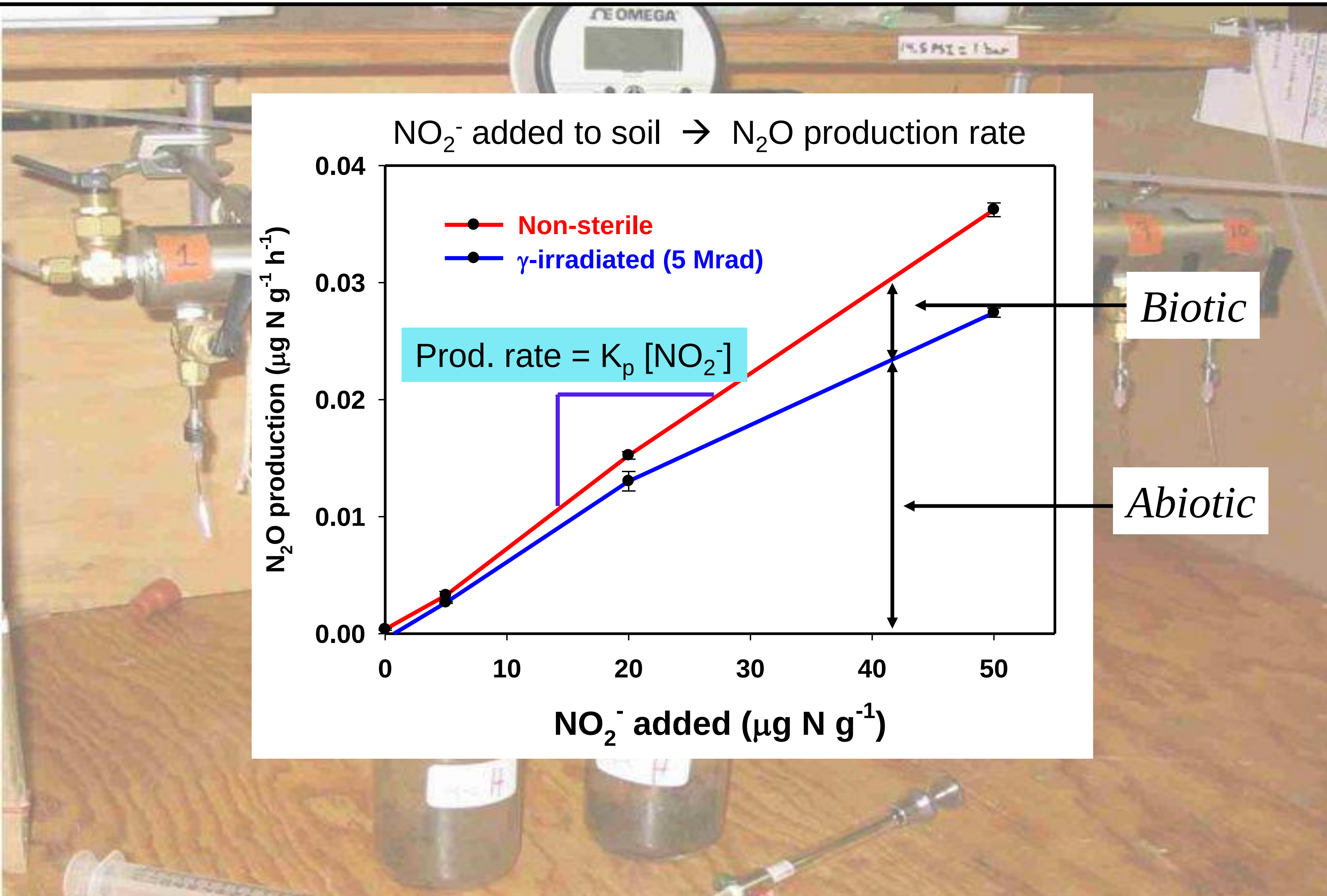
Corn field, Rosemount, MN





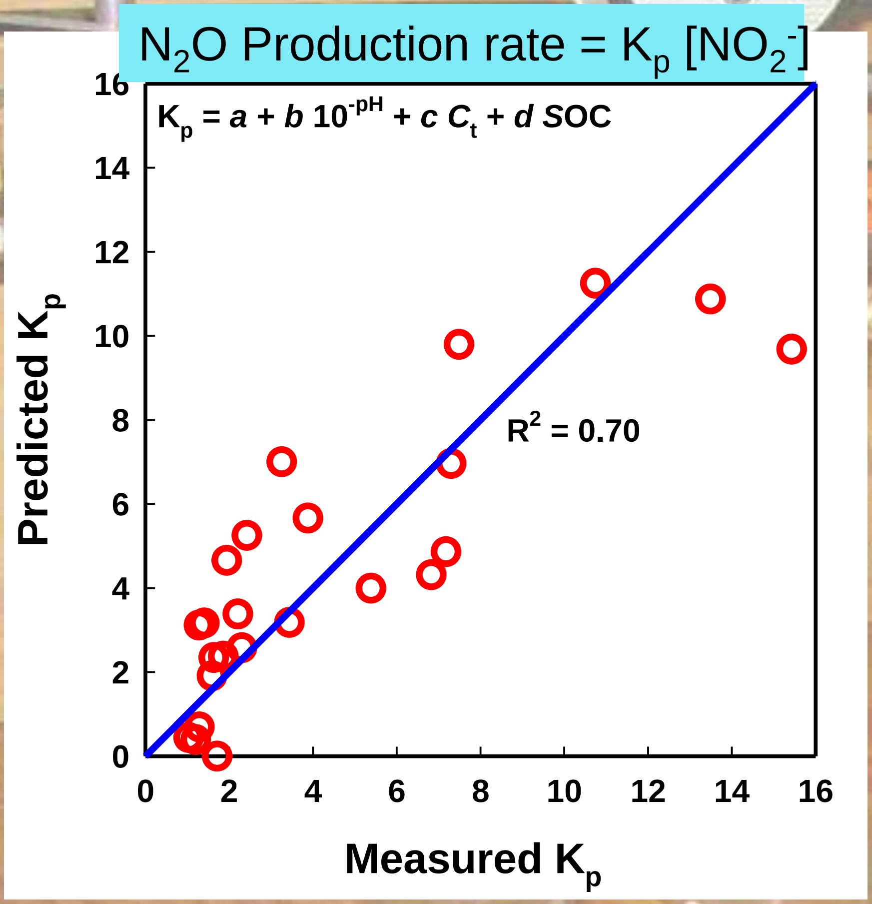
Venterea and Rolston, 2002.
Soil Sci. 167.

Laboratory kinetics experiments: N_2O production under aerobic conditions



Venterea, 2007. Global Change Biol.

Laboratory kinetics experiments: N_2O production under aerobic conditions

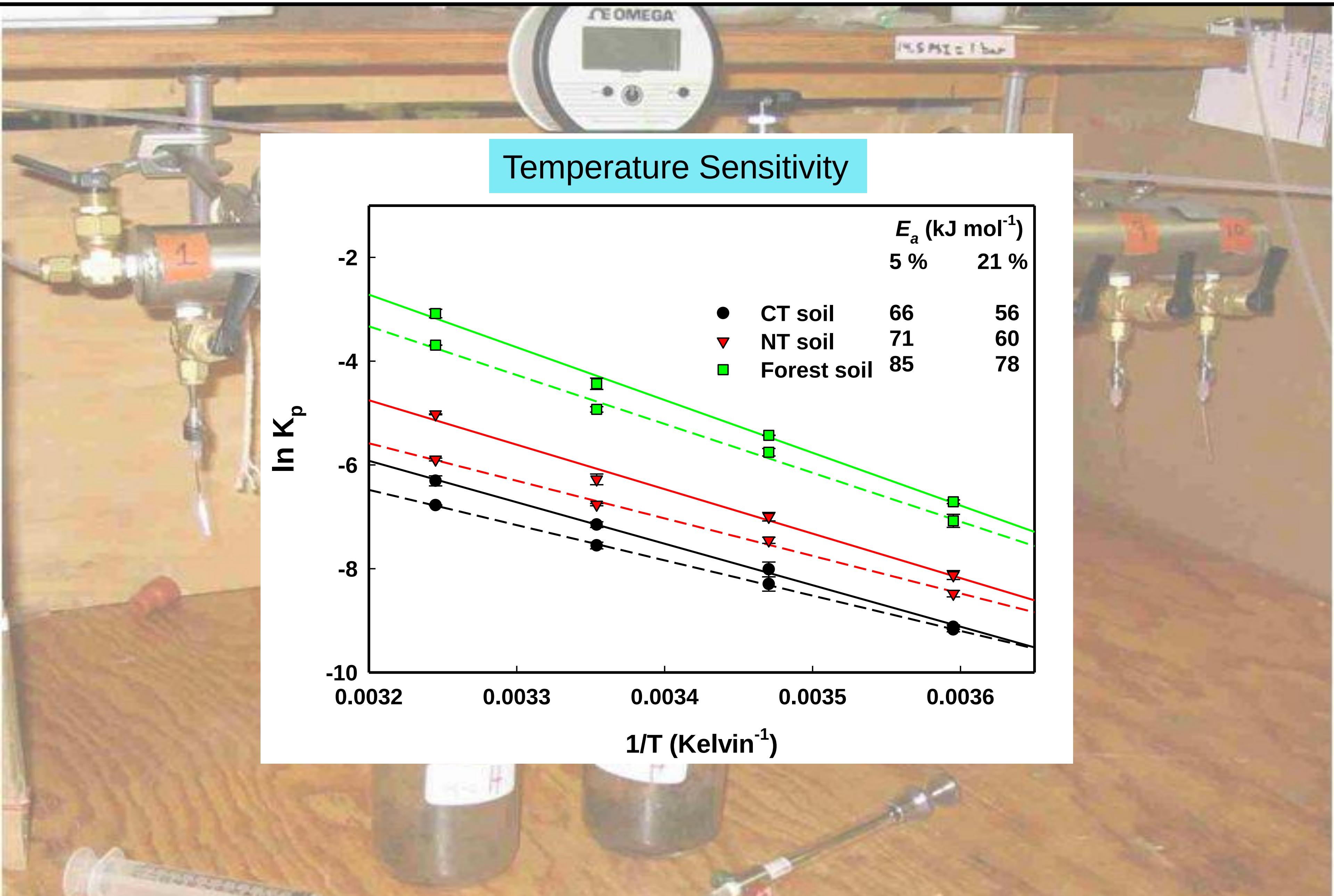


Rate coefficient correlated with:

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

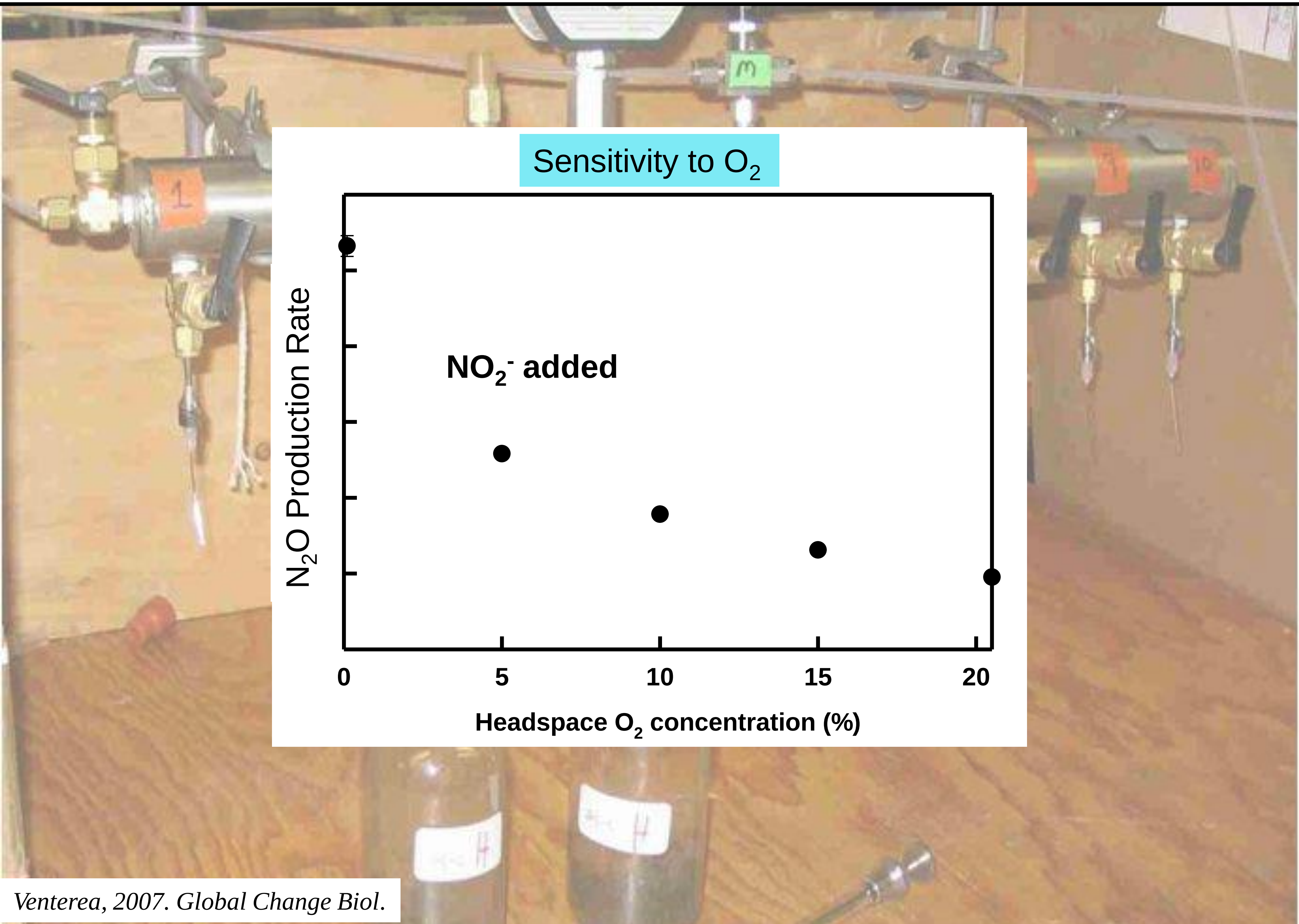
Venterea, 2007. Global Change Biol.

Laboratory kinetics experiments: N_2O production under aerobic conditions



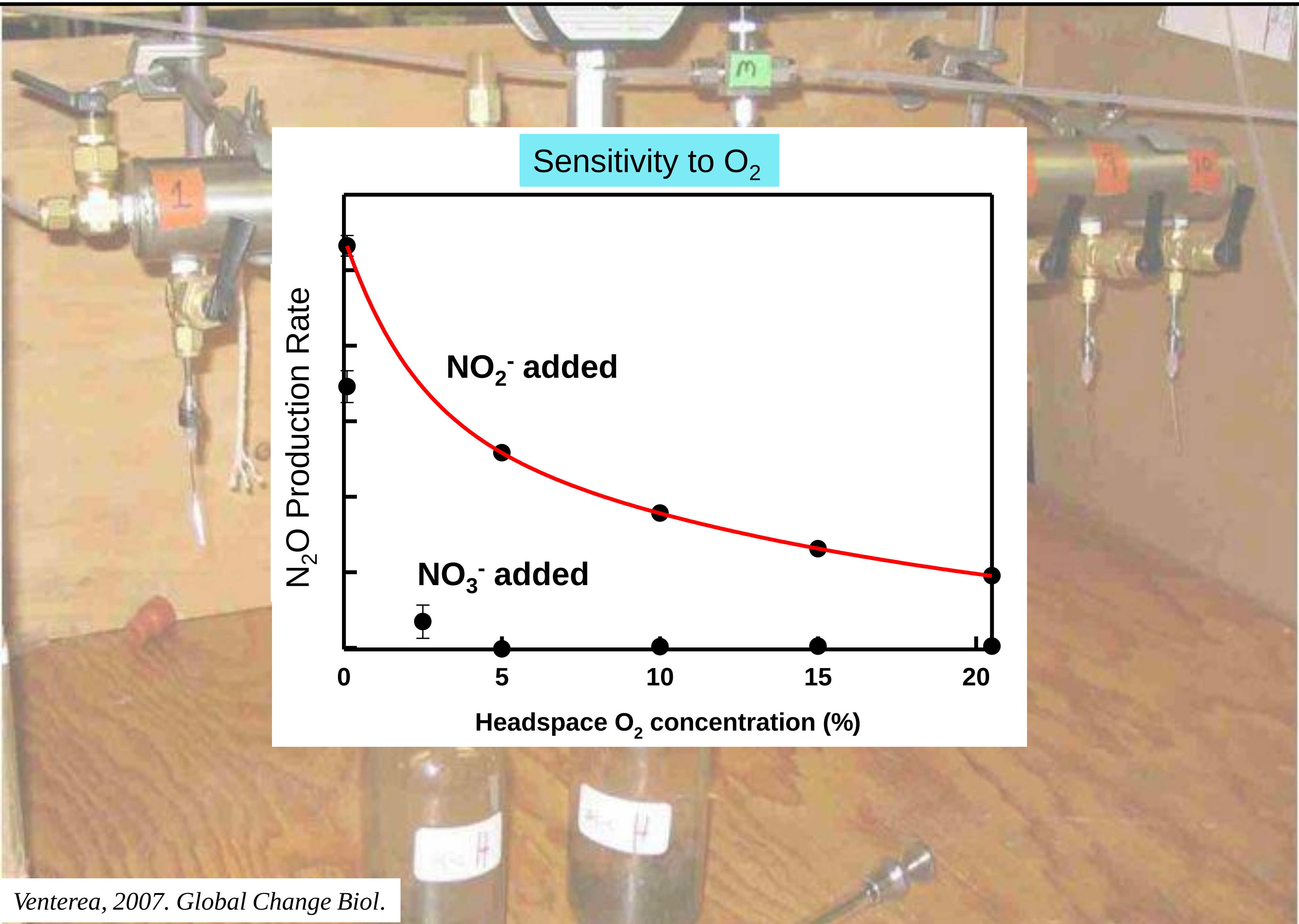
Venterea, 2007. Global Change Biol.

Laboratory kinetics experiments: N_2O production under aerobic conditions



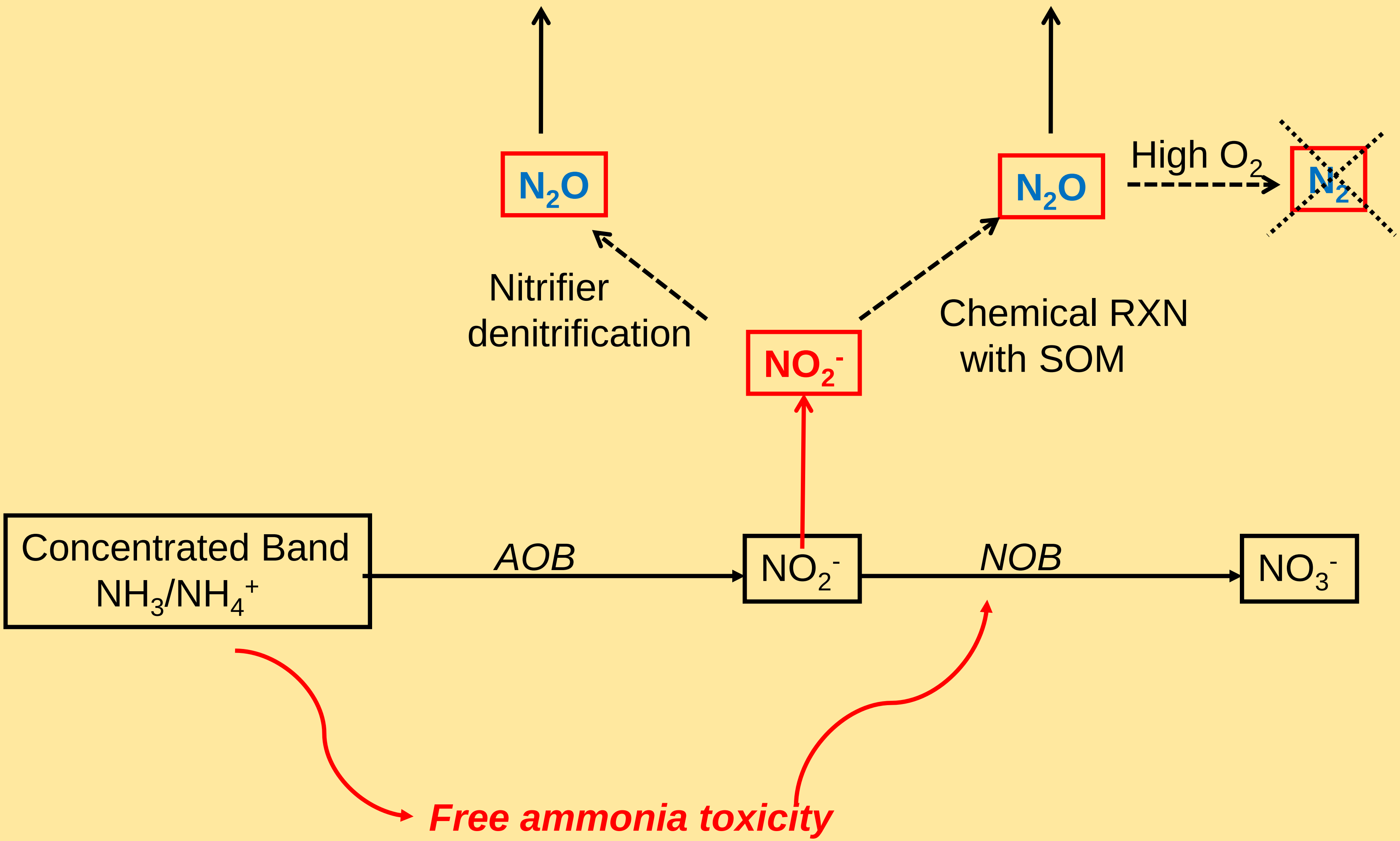
Venterea, 2007. Global Change Biol.

Laboratory kinetics experiments: N_2O production under aerobic conditions



Venterea, 2007. Global Change Biol.

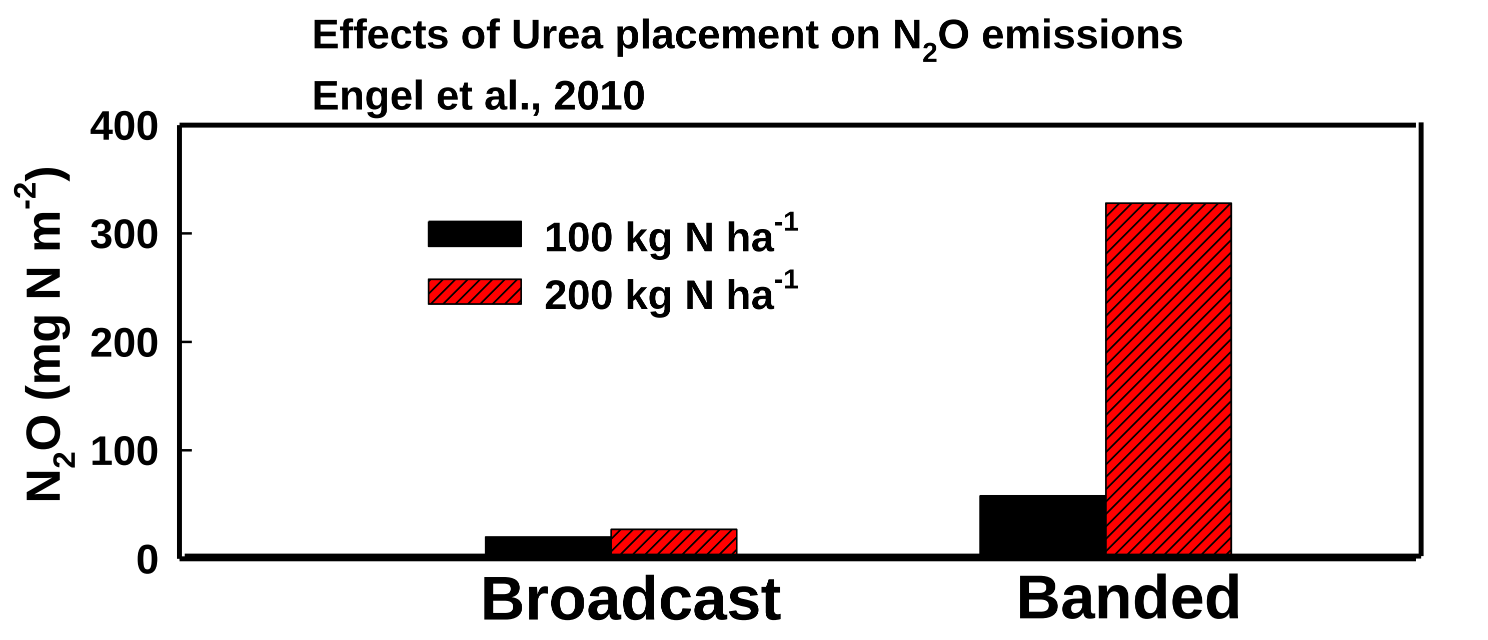
Nitrite-driven N_2O production



Venterea, 2007. Global Change Biol.

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

Conserves Nitrogen/ Increases NUE
-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

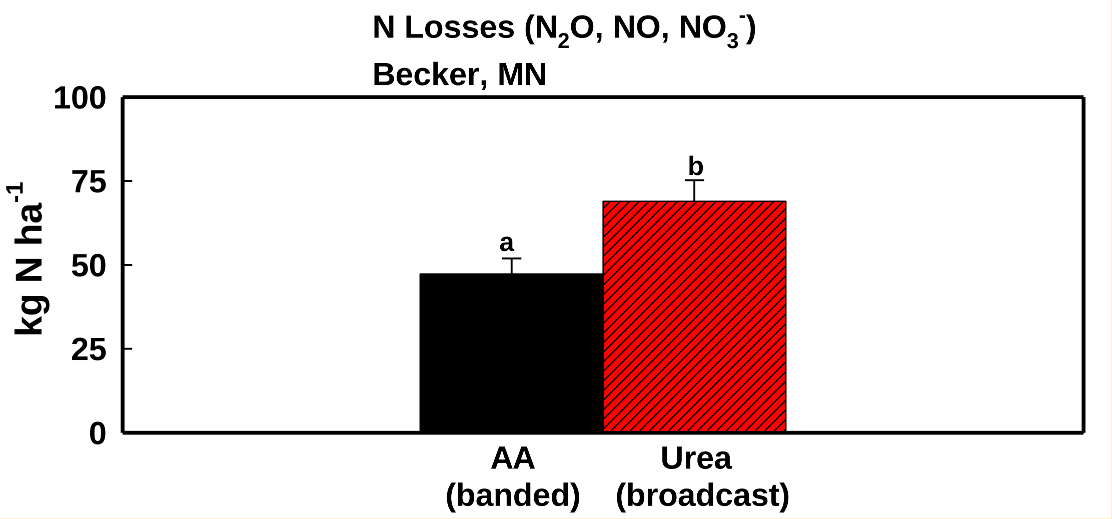
- With banding, it may be possible to have:
  - -Greater overall NUE
  - -And greater N_2O emissions
- N_2O emissions usually are < 5% of applied N.
- More study needed.

Nitrite-driven N_2O production

Banding as a beneficial fertilizer management practice

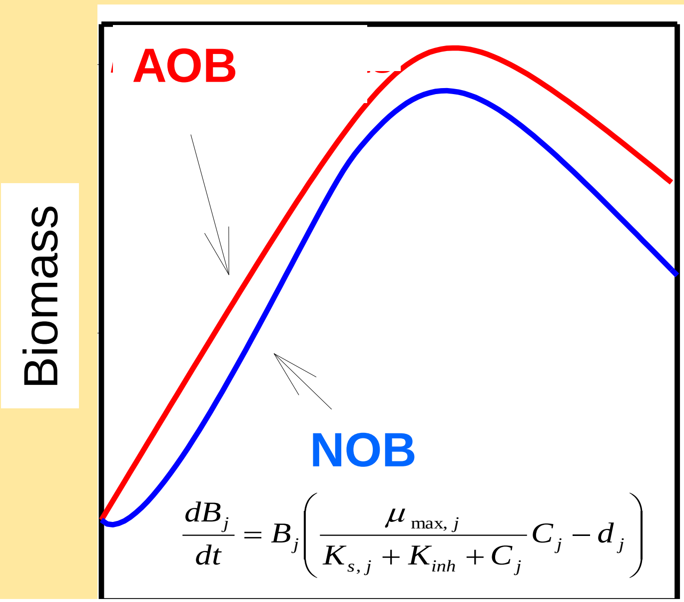
<u>Conserves Nitrogen/ Increases NUE</u>
-Slows nitrification and nitrate leaching
-Limits contact with soil microbes
-Increases root access to N
-Decreases distance from plant to N source

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

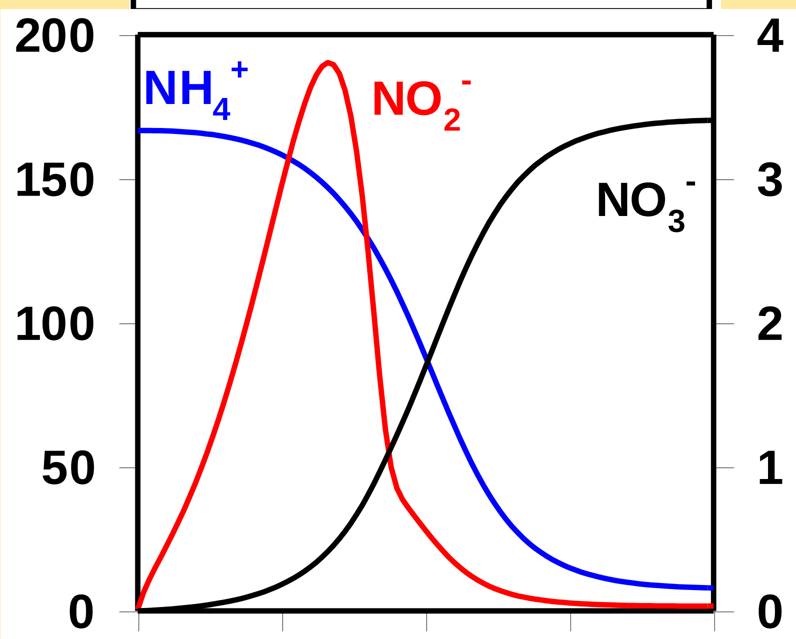


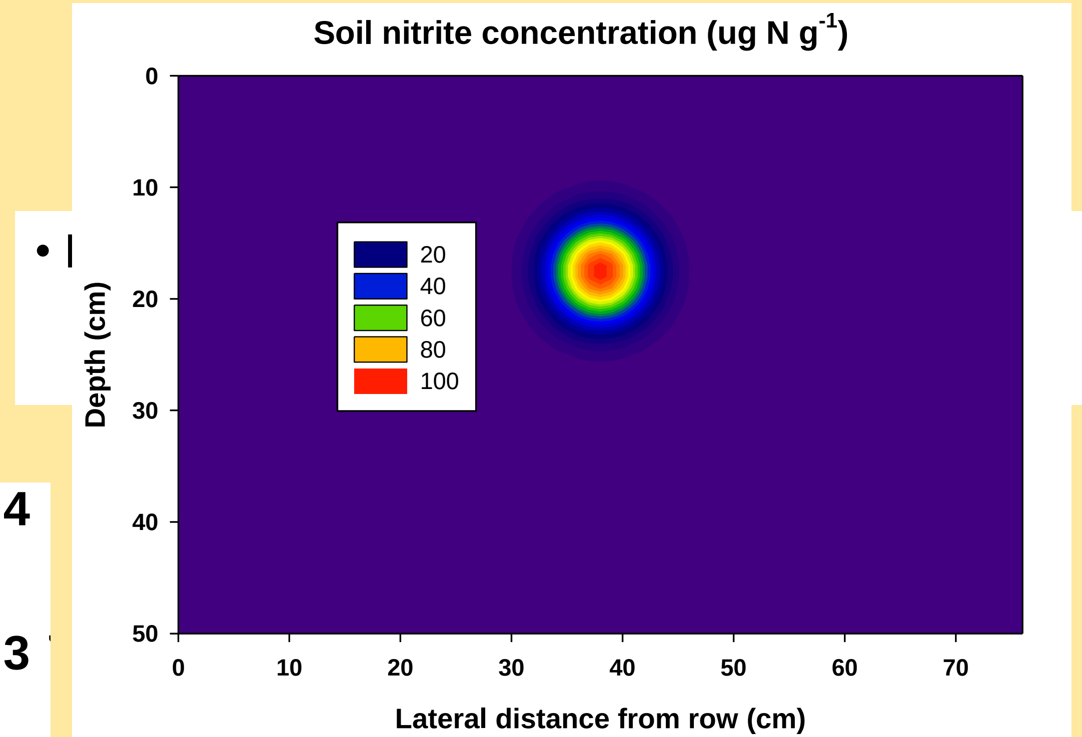
Is there an optimum banding intensity or thickness that maximizes NUE and minimizes N_2O emissions ?

Modeling nitrite-driven N_2O emissions



$$\frac{dB_j}{dt} = B_j\left(\frac{\mu_{\max,j}}{K_{s,j} + K_{inh} + C_j} C_j - d_j\right)$$





Venterea and Rolston, JEQ. 2000

Tillage Management Effects on 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

Tillage Management Effects on N_2O Emissions

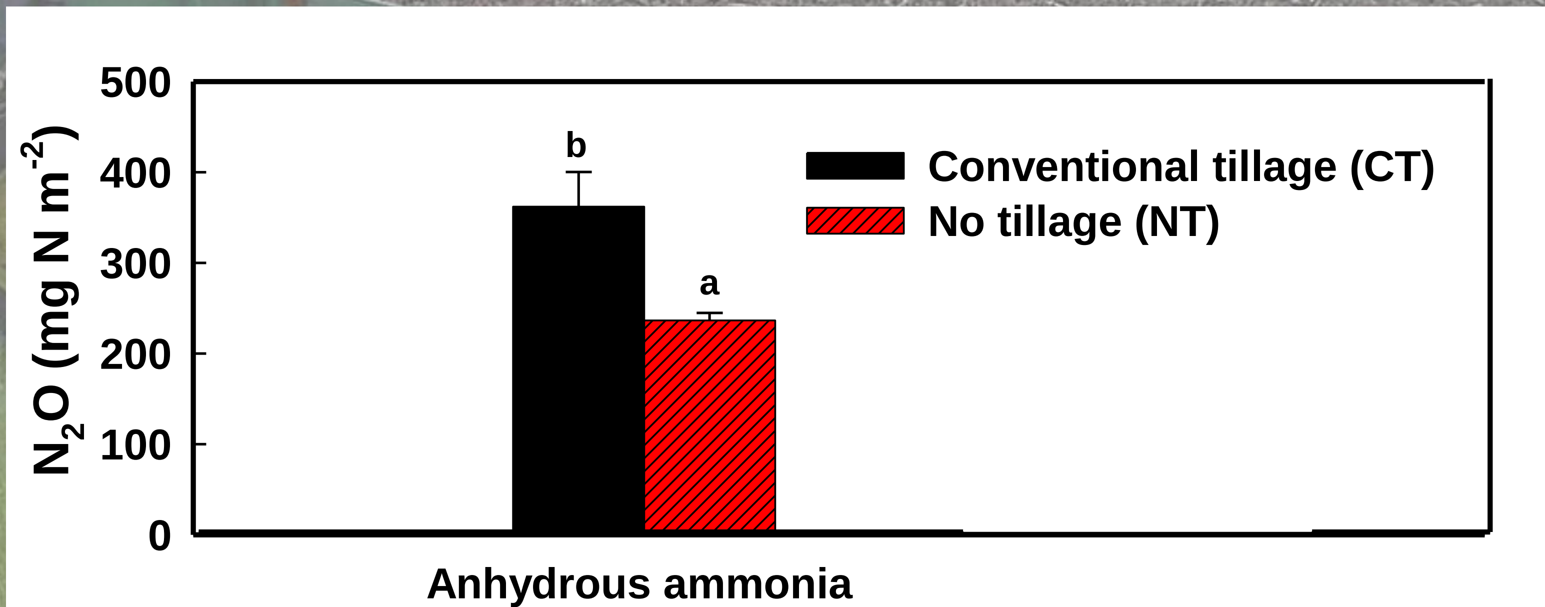
Potential for N_2O emissions to enhance (or offset) GHG benefits of reduced tillage

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

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

NT Greater	Not different	CT Greater
NT > CT	NT = CT	CT > NT
Aulakh et al. 1984	Lemke et al. 1999	Jacinthe and Dick, 1997
MacKenzie et al. 1998	Robertson et al. 2000	Kessavalou et al. 1998
Ball et al., 1999	Choudhary et al. 2002	Lemke et al. 1999
Yamulki and Jarvis 2002	Kaharabata et al. 2003	Kaharabata et al. 2003
Baggs et al., 2003	Liu et al., 2005	Liu et al., 2005
Koga et al. 2004	Rochette et al., 2008	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

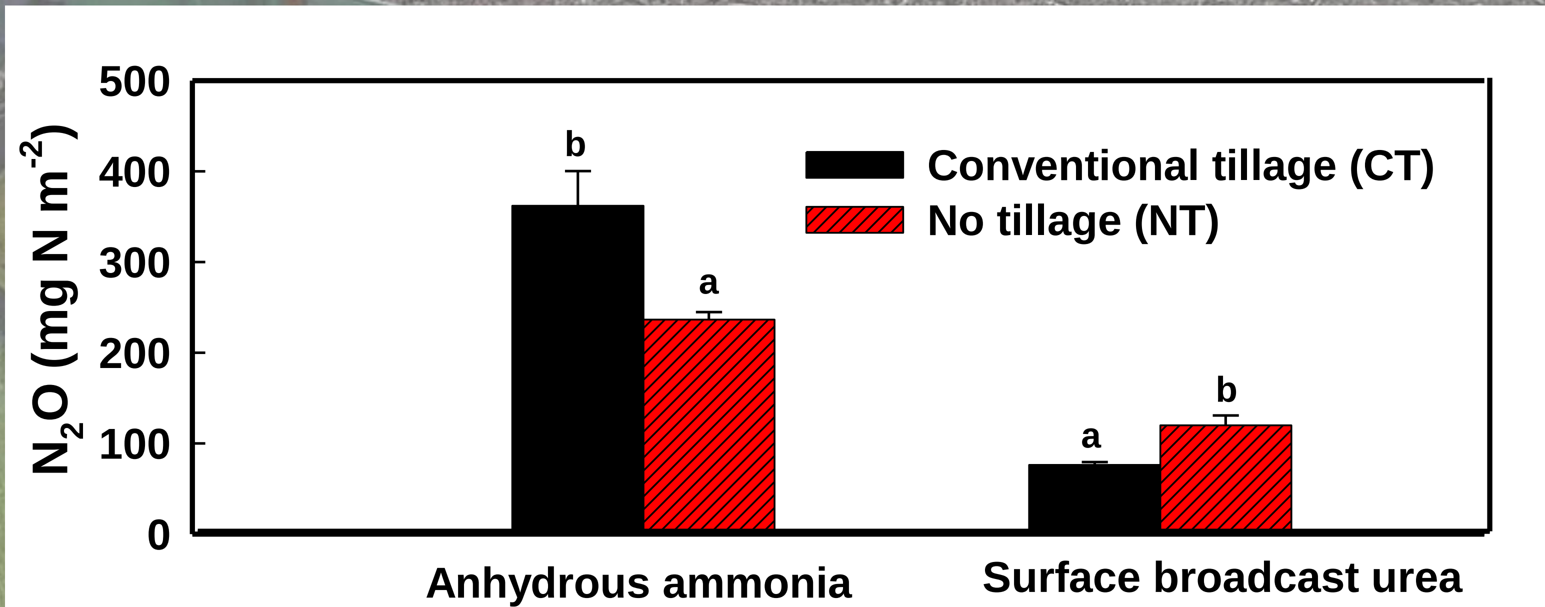
Tillage Management Effects on N_2O Emissions



CT > NT

Venterea et al. 2005. JEQ.

Tillage Management Effects on N_2O Emissions

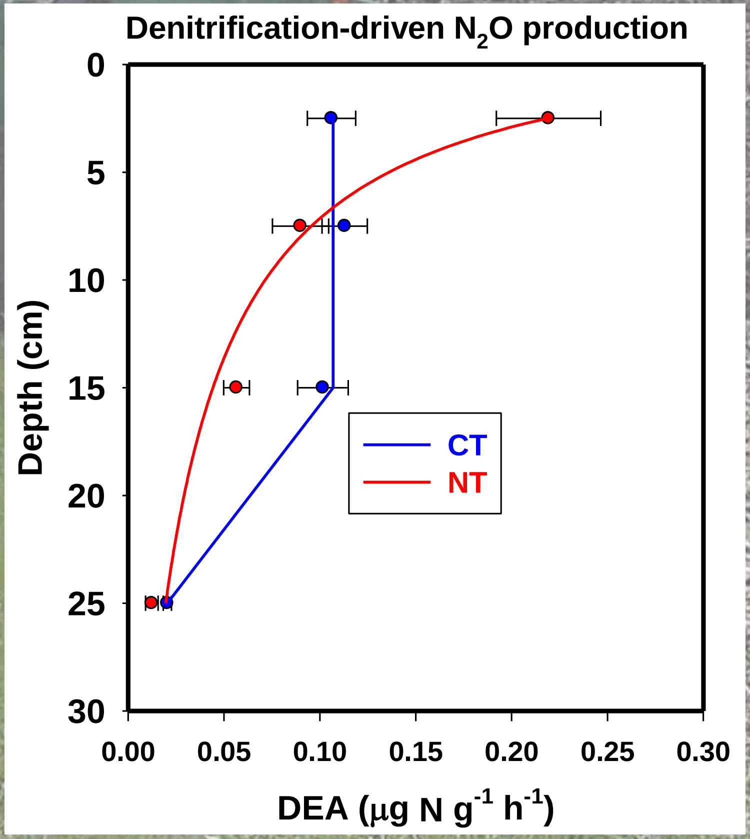


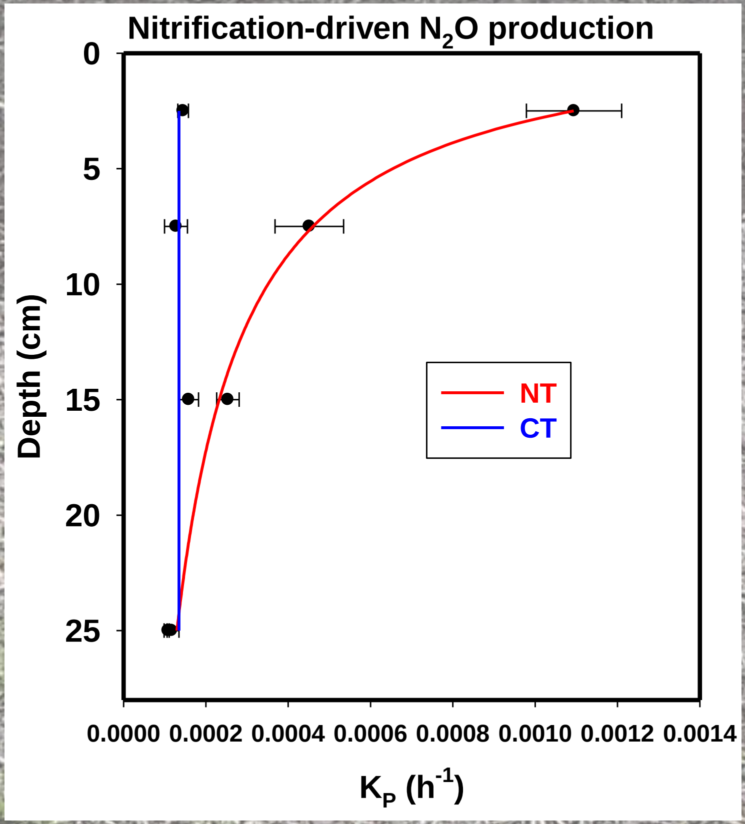
CT > NT

NT > CT

Venterea et al. 2005. JEQ.

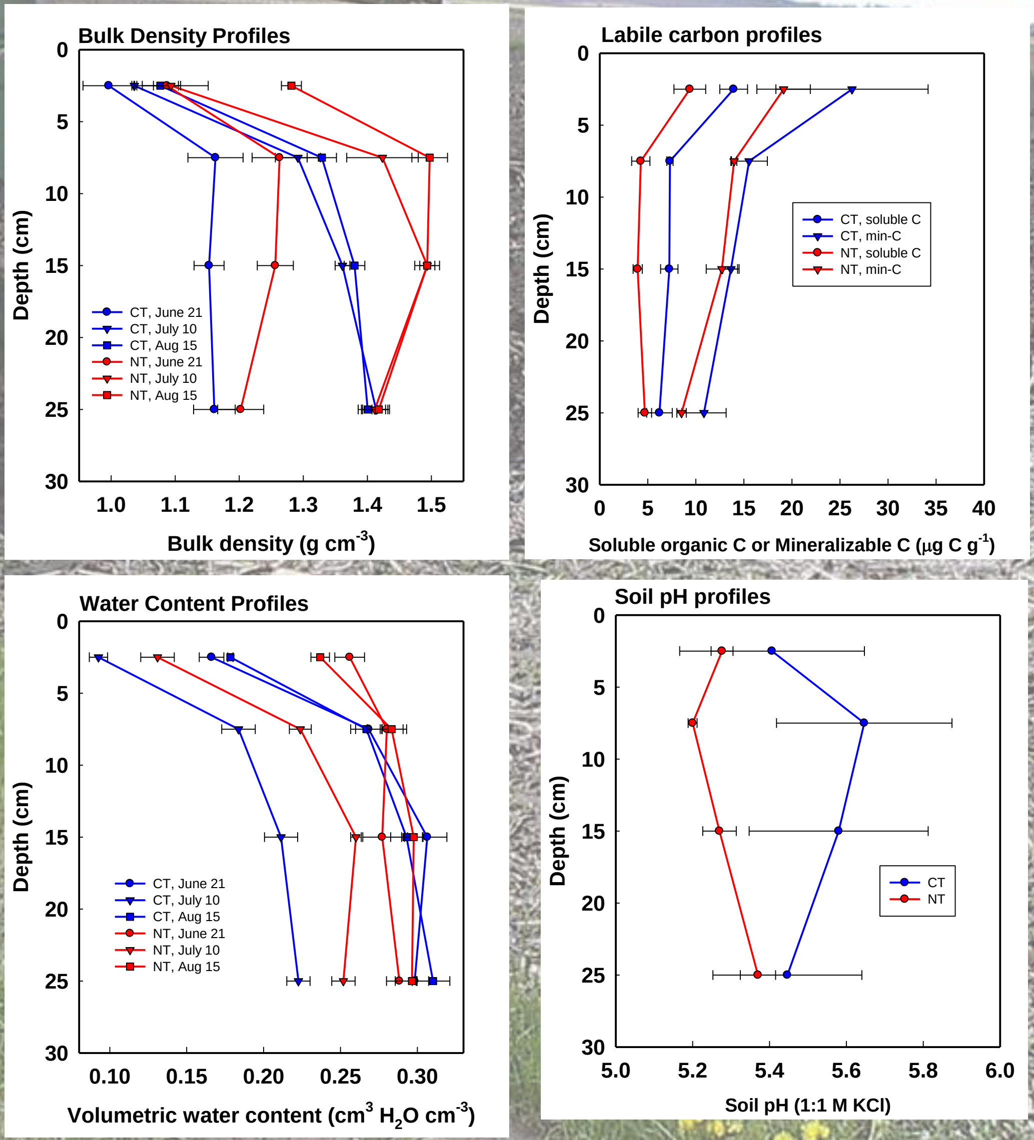
Vertical Profiles of Potential N_2O Production





Venterea and Stanenas. 2008. JEQ.

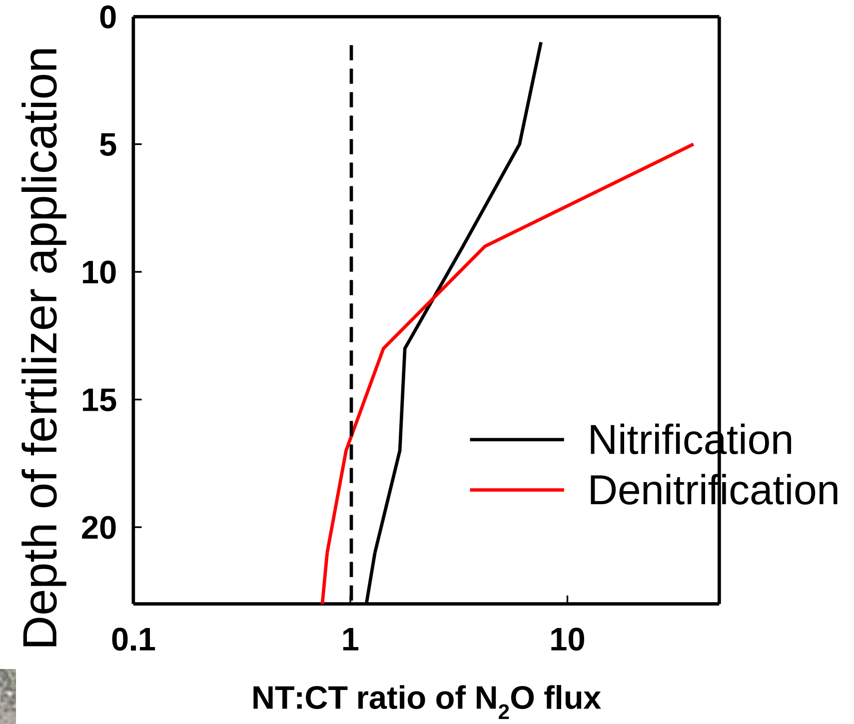
Vertical Profiles of Physical and Chemical Properties



Venterea and Stanenas. 2008. JEQ.

Modeling Tillage-Fertilizer Interaction Effects

	Source Term	Sink Term
Diffusion model	$-\frac{d}{dz}\left(D_p \frac{d[N_2O]}{dz}\right) = \rho[P - S]$	
Denitrification	$P = \varphi\left(\frac{V_{\max}^{NO_3^-}[NO_3^-]}{K_m^{NO_3^-} + [NO_3^-]}\right)\left(\frac{[C]}{K_m^C + [C]}\right)$	$S = \varphi\left(\frac{V_{\max}^{N_2O}\, H[N_2O]}{K_m^{N_2O} + H[N_2O]}\right)\left(\frac{[C]}{K_m^C + [C]}\right)$
Nitrification	$P = K_p[NO_2^-]$	$S = 0$



Model predictions

Venterea and Stanenas. 2008. JEQ.

Tillage Management Effects on N_2O Emissions

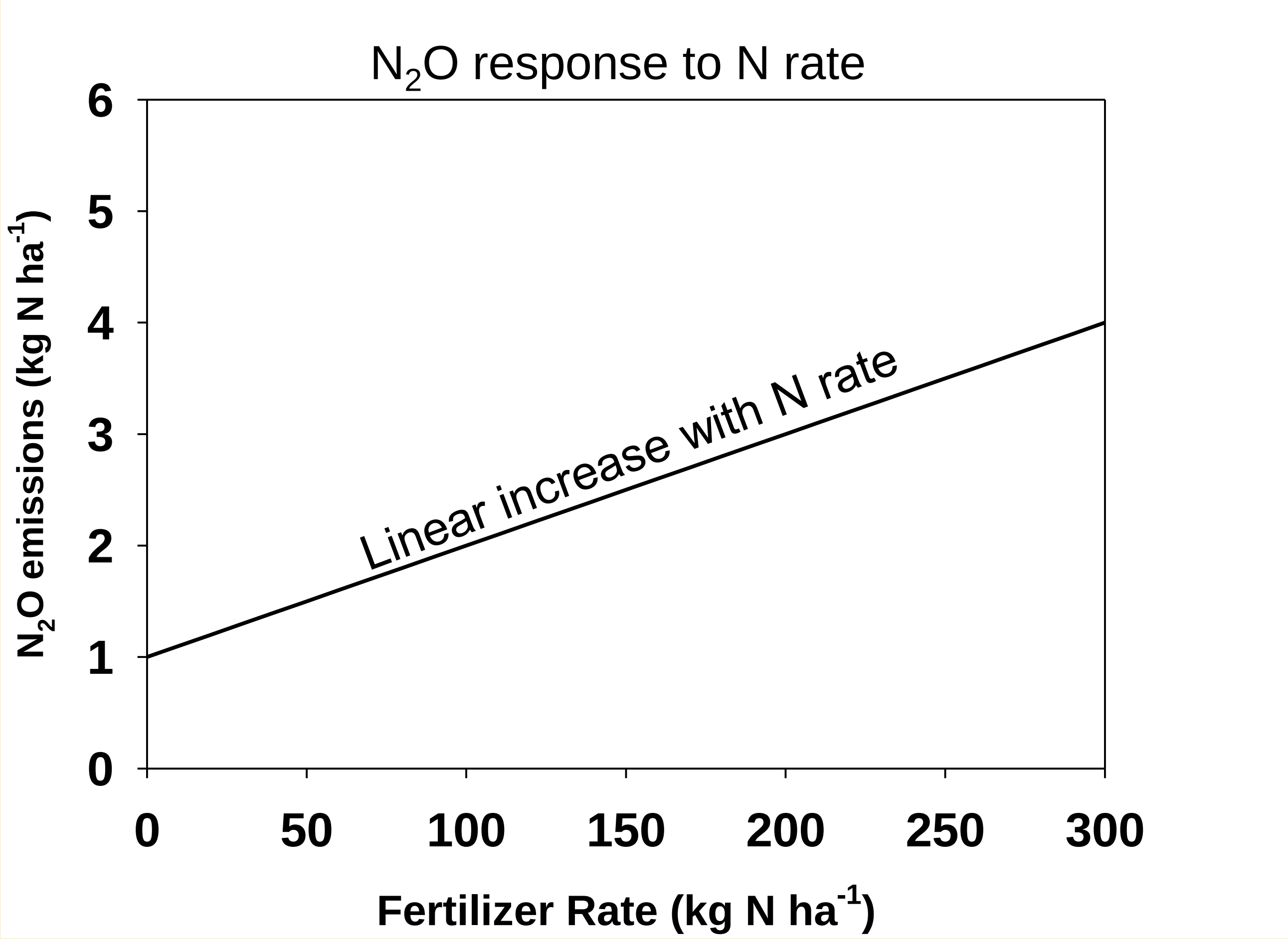
NT > CT	NT = CT	CT > NT
MacKenzie et al. 1998	Lemke et al. 1999	Jacinthe and Dick, 1997
Ball et al., 1999	Robertson et al. 2000	Lemke et al. 1999
Yamulki and Jarvis 2002	Choudhary et al. 2002	Liu et al., 2005
Baggs et al., 2003	Kaharabata et al. 2003	Venterea et al., 2005
Venterea et al., 2005	Liu et al., 2005	Ussiri et al., 2009
Grageda-Cabrera et al., 2011	Rochette et al., 2008	Omonode et al., 2011
Koga et al. 2004		Kaharabata et al. 2003
Rochette et al., 2008		Kessavalou et al. 1998
Aulakh et al. 1984		
		Halvorson et al., 2010

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

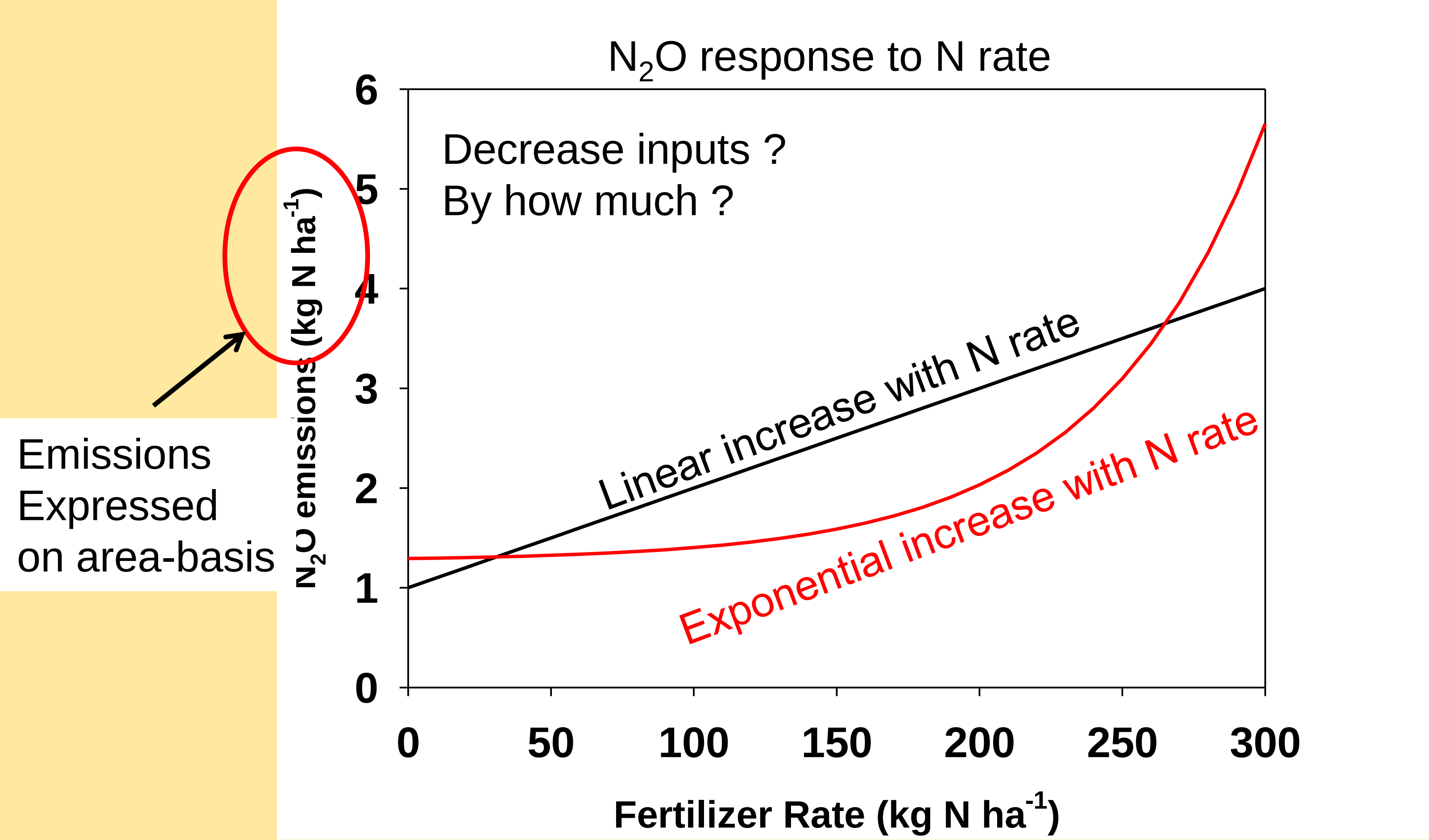
Mixed application or no information (5/18)

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

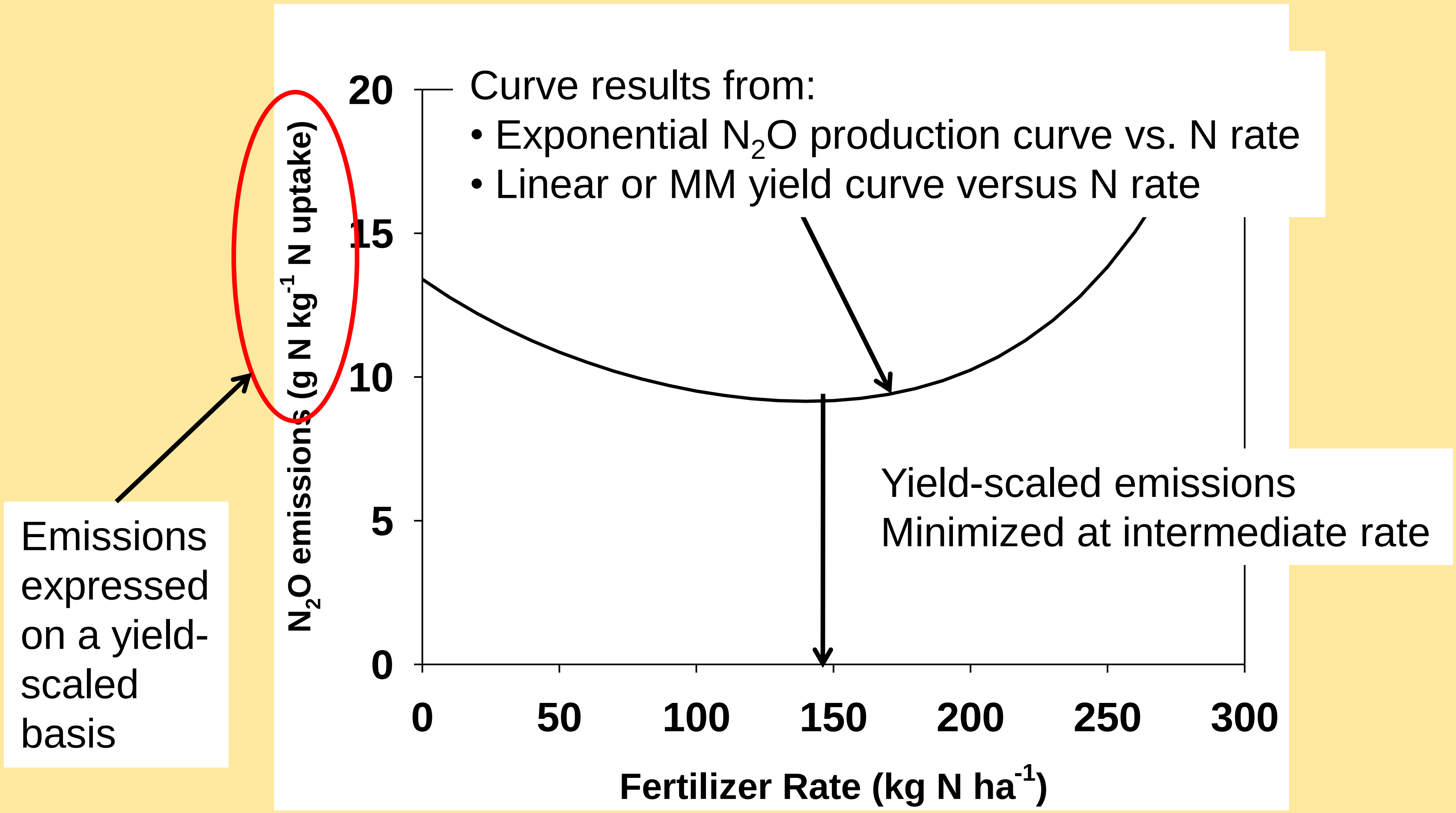
Fertilizer Rate Effects on N_2O emissions



Fertilizer Rate Effects on N_2O emissions

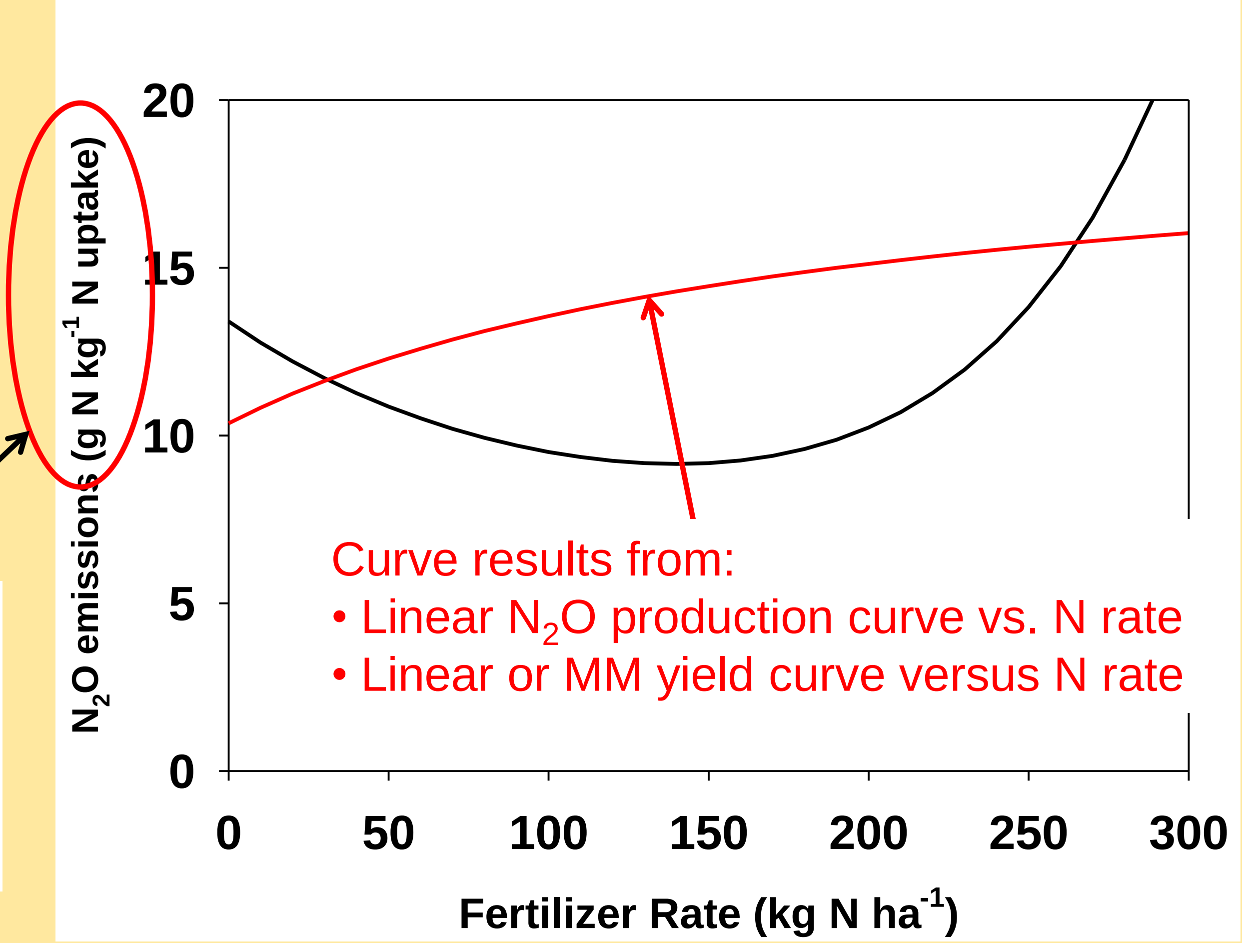


Fertilizer Rate Effects on N_2O emissions



Van Groenigen et al. 2010

Fertilizer Rate Effects on N_2O emissions

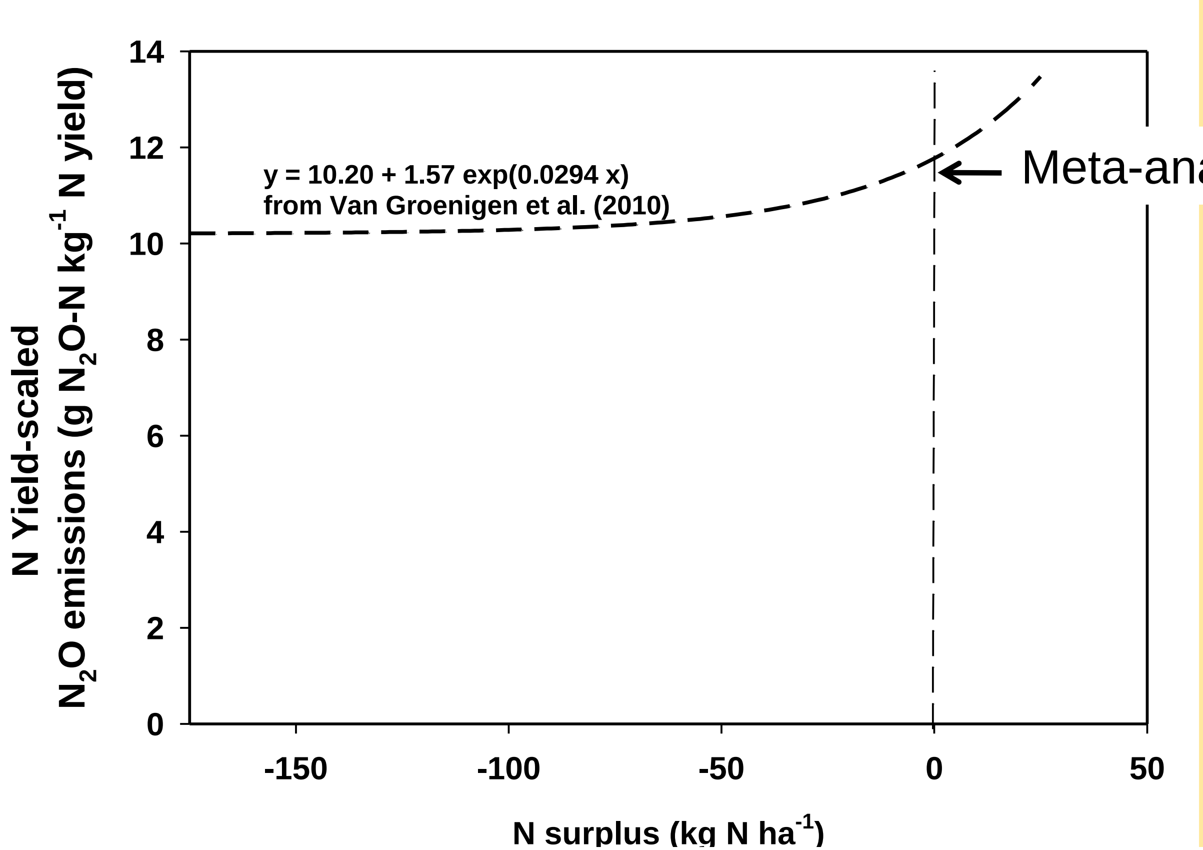


Emissions expressed on a yield-scaled basis

Van Groenigen et al. 2010

Nitrogen Use Efficiency and N_2O emissions

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



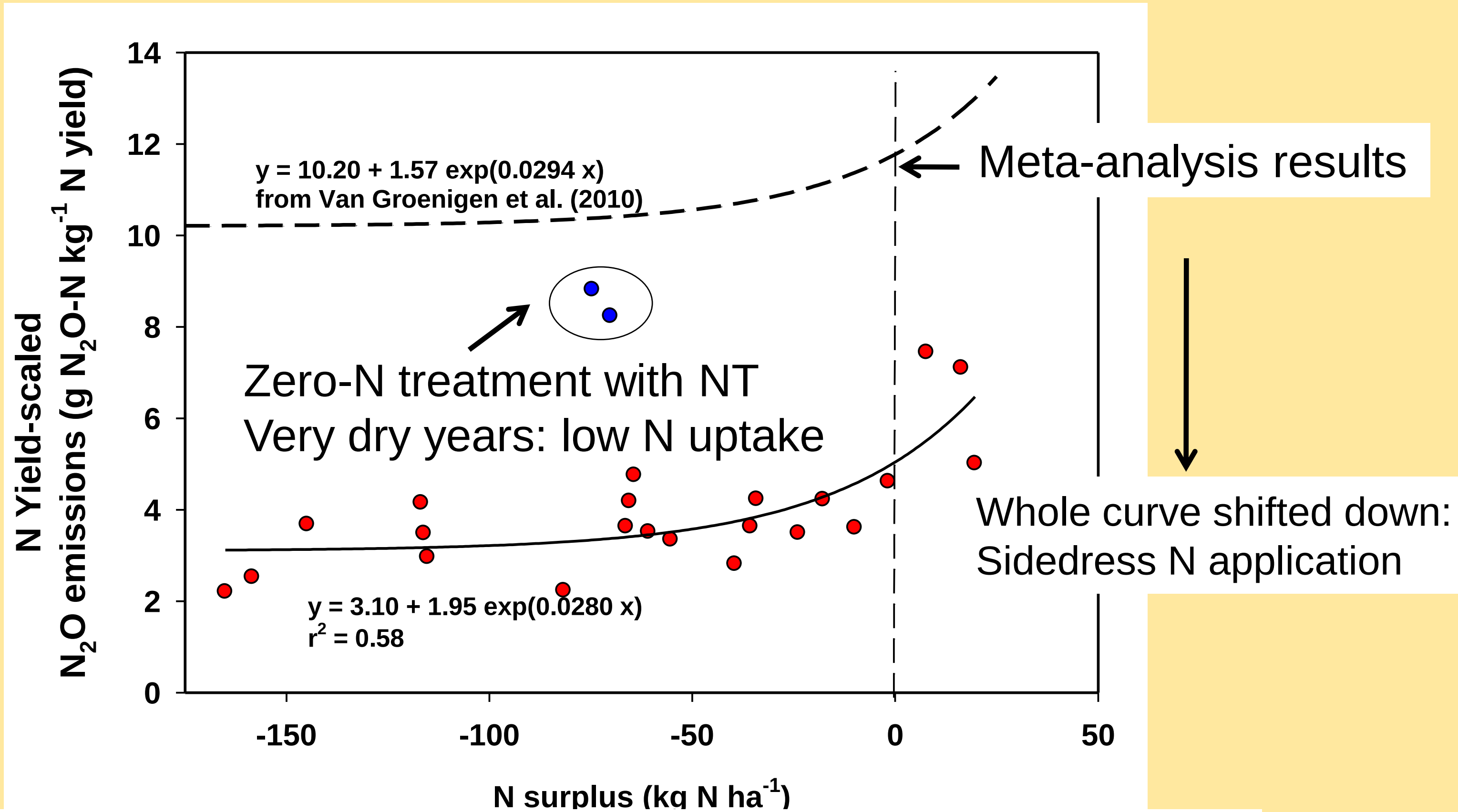
Meta-analysis results

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

Van Groenigen et al. 2010

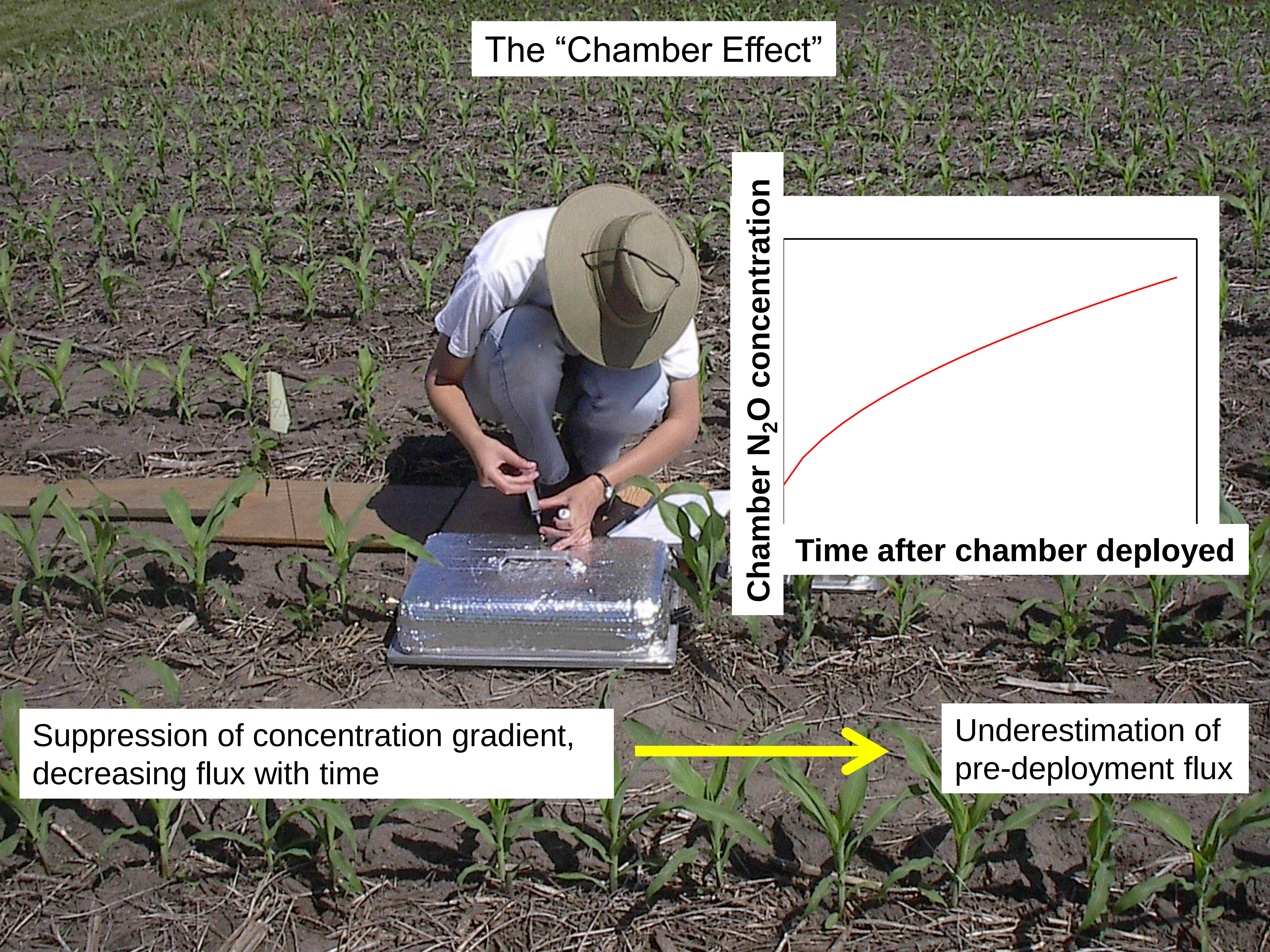
Nitrogen Use Efficiency and N_2O emissions

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



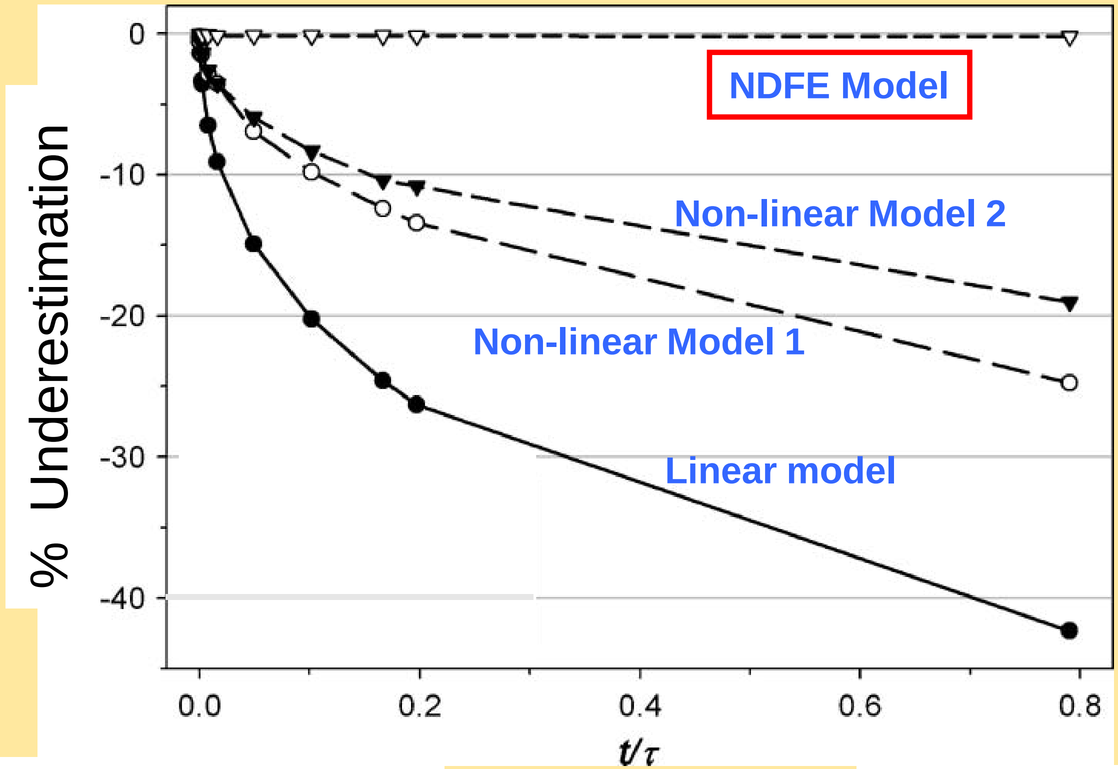
N surplus = Fertilizer N inputs – above-ground crop N uptake

Van Groenigen et al. 2010



The “Chamber Effect”
Chamber N_2O concentration
Time after chamber deployed
Suppression of concentration gradient, decreasing flux with time
Underestimation of pre-deployment flux

The “Chamber Effect”



Smaller chamber
Shorter deployment time

Larger chamber
Longer deployment time

Less porous soil

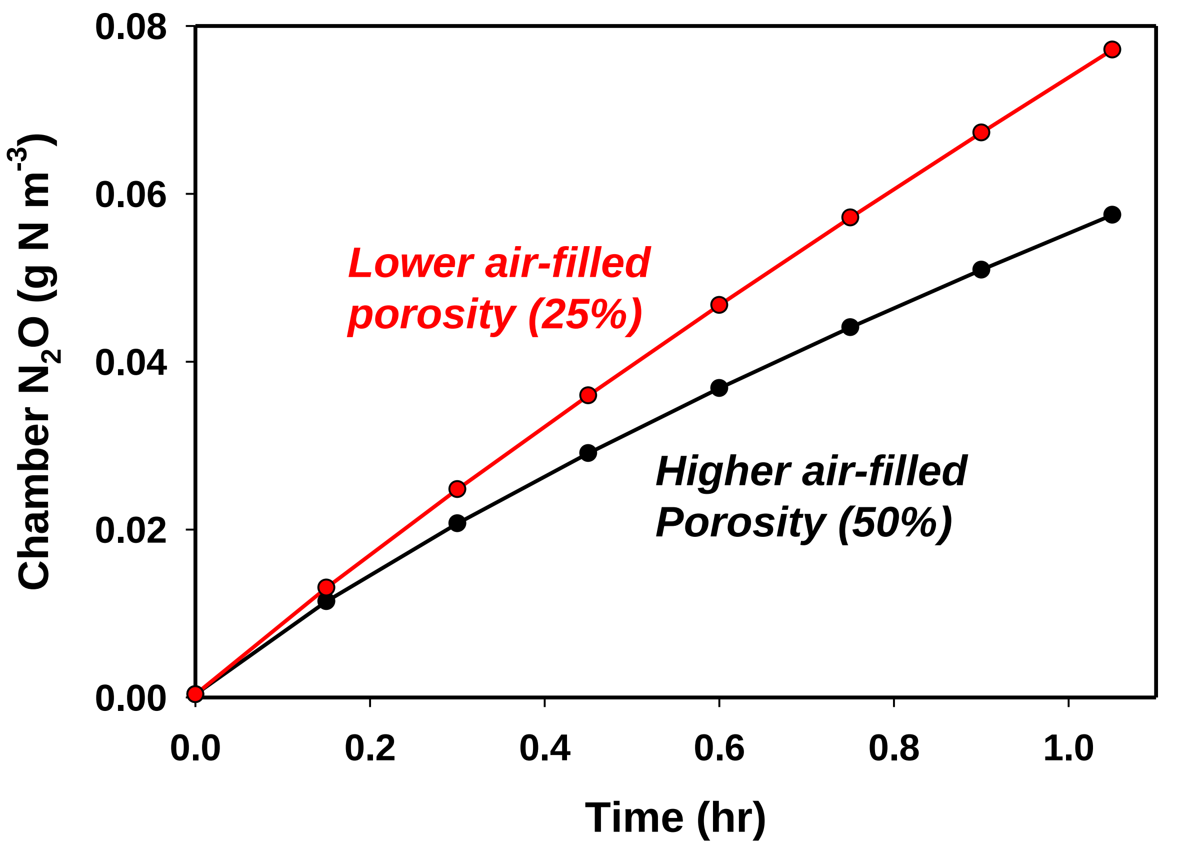
More porous soil

Livingston et al. 2006. Soil Sci. Soc. Am. J.

Underestimation of fluxes in more porous soil

Artifacts can confound treatment effects:

•Tillage, organic amendments → bulk density or water content

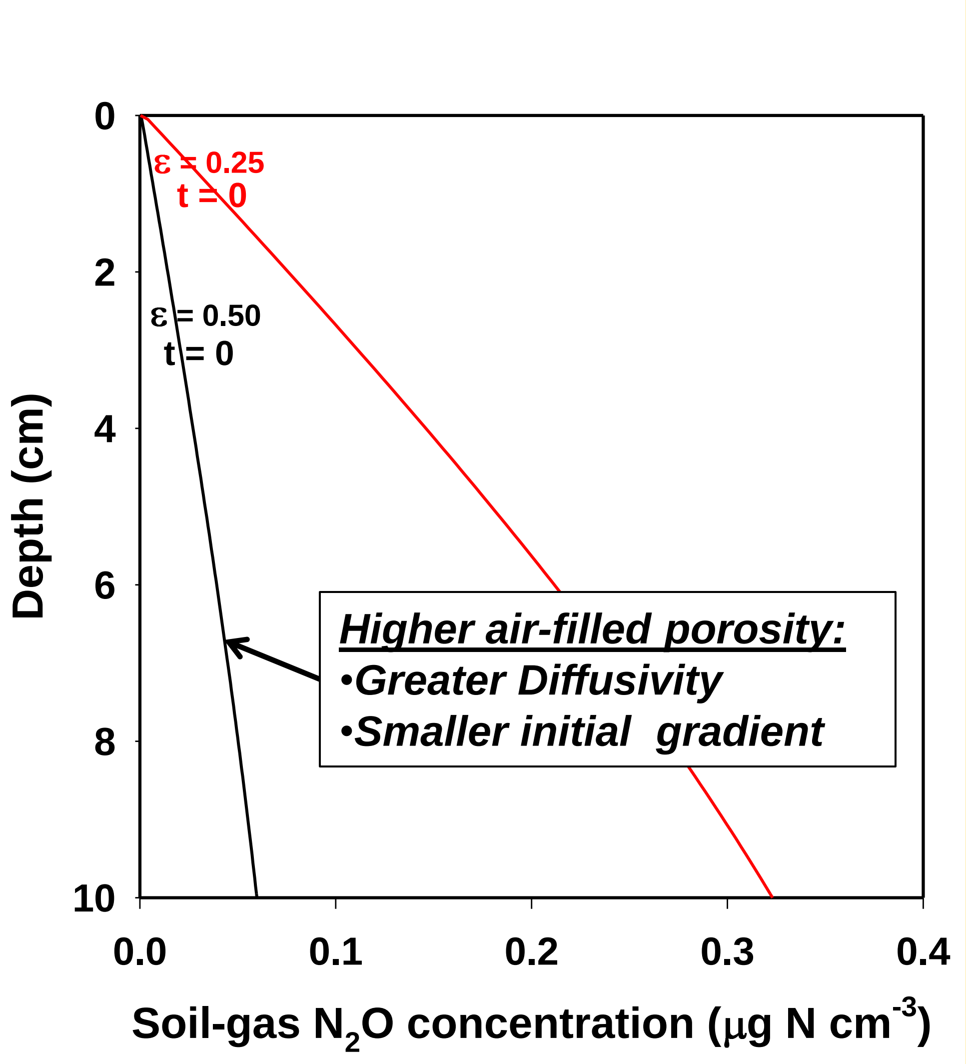


Curves generated by numerical model

•Both soils have same pre-deployment flux

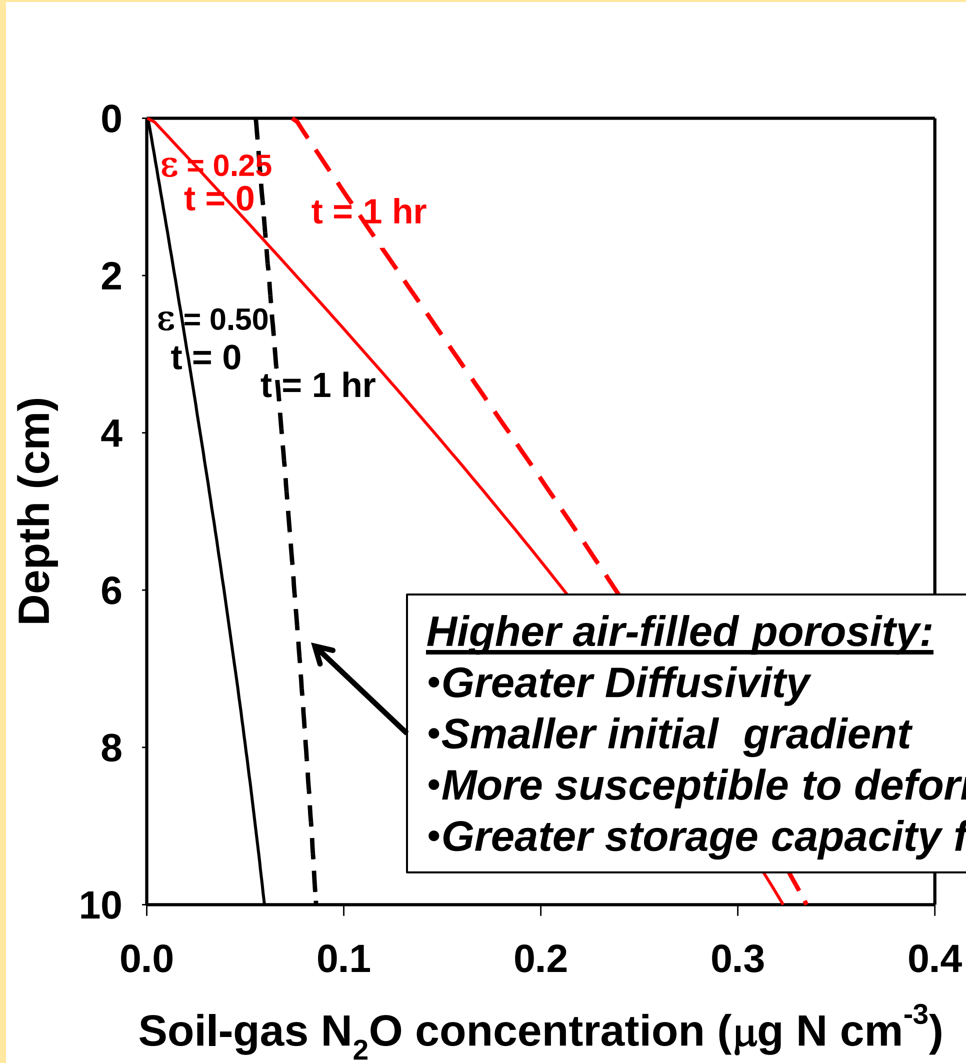
Venterea and Baker. 2008. Soil Sci. Soc. Am. J.

Underestimation of fluxes in more porous soil



Venterea and Baker. 2008. Soil Sci. Soc. Am. J.

Underestimation of fluxes in more porous soil



<u>Higher air-filled porosity:</u>

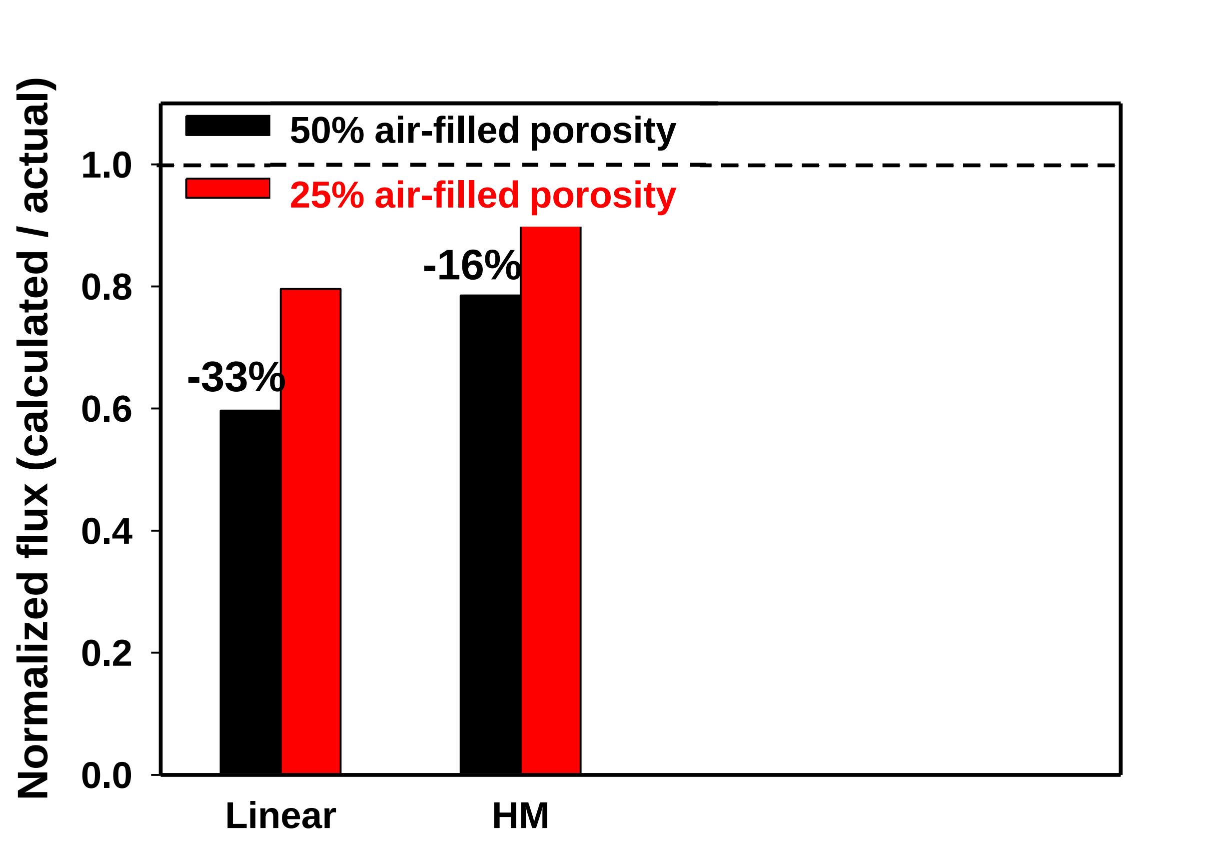
- ***Greater Diffusivity***
- ***Smaller initial gradient***
- ***More susceptible to deformation***
- ***Greater storage capacity for gas to accumulate***

Venterea and Baker. 2008. Soil Sci. Soc. Am. J.

Underestimation of fluxes in more porous soil

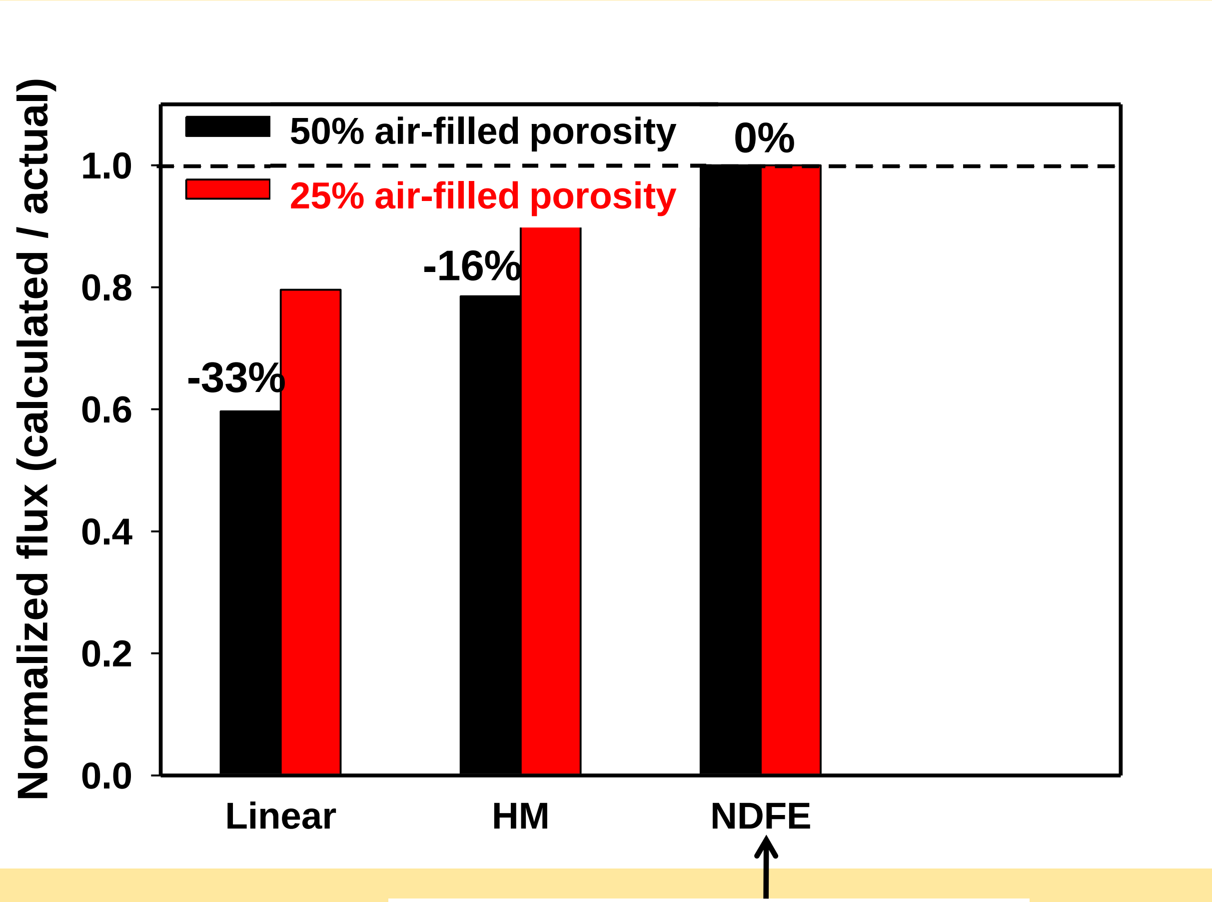
Artifacts can confound treatment effects:

•Tillage, organic amendments → bulk density or water content



Venterea and Baker. 2008. Soil Sci. Soc. Am. J.

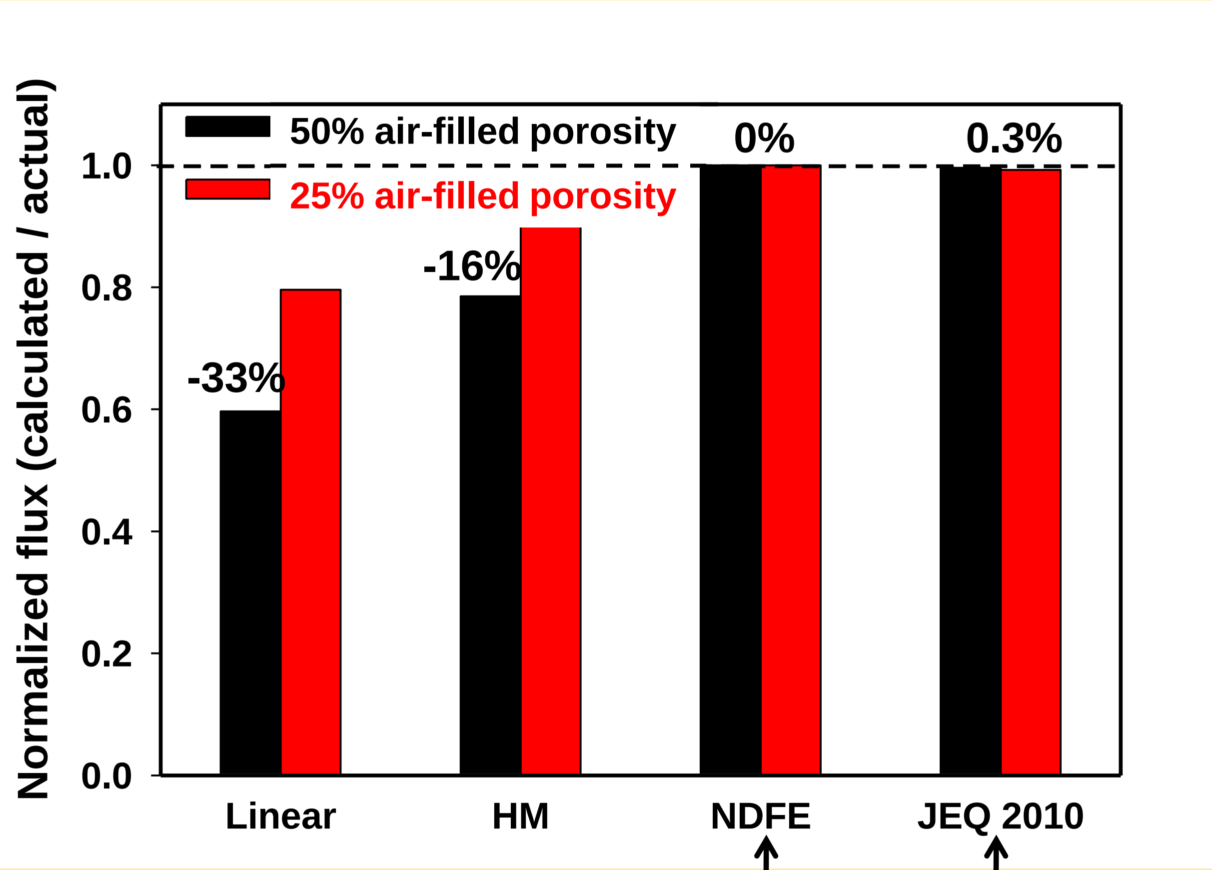
Underestimation of fluxes in more porous soil



- Gives multiple solutions
- *Inefficient*
- *Not exact for non-uniform soil*

Venterea and Baker. 2008. Soil Sci. Soc. Am. J.

Underestimation of fluxes in more porous soil

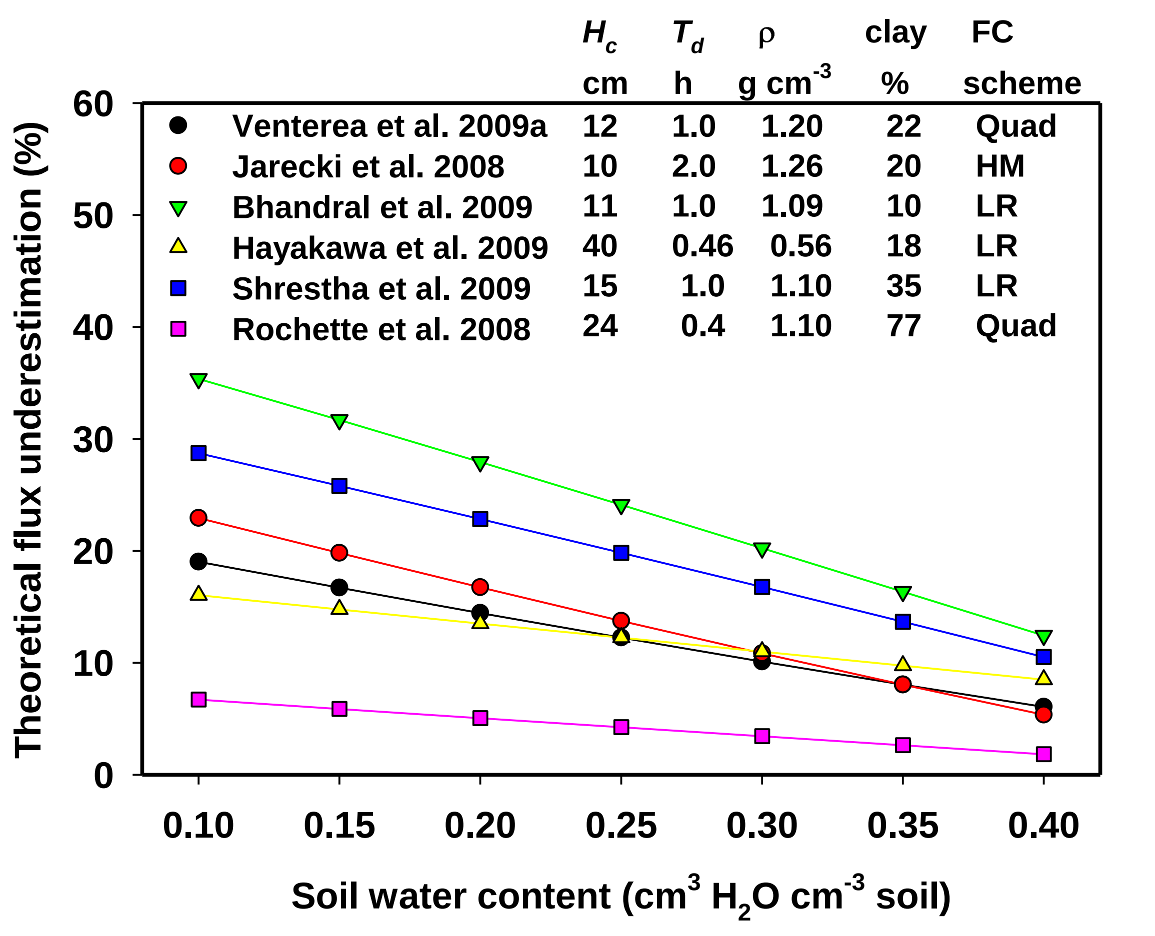


- *Gives multiple solutions*
- *Inefficient*
- *Not exact for non-uniform soil*

- *Requires bulk density, water content data (sources of error)*

Venterea. 2010. JEQ.

Non-uniformity of Flux Measurement Methods



1. More consensus in methods needed
2. Refinement necessary to improve absolute accuracy:
   - More use of micro-meteorological methods
   - Faster response/higher precision instruments (shorter deployment times)

Venterea. 2010. JEQ.

Conclusions

1. More studies needed to better determine optimization fertilizer management practices:

    1. Depth of placement
    2. Banding intensity
    3. Source and timing

2. GPS-guided N application technology to better match rate and placement with crop demand and yield potential

3. Emissions models that better account for differences due to (i) source, (ii) placement, and (iii) interactions among multiple factors

Conclusions

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

1. Edge of field denitrification barriers / bioreactors or controlled drainage systems to reduce stream nitrate inputs:
    - -Do practices designed to stimulate denitrification increase net N_2O emissions ?

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

3. Restoration of riparian vegetation

4. Improved animal mgmt to reduce excess N in manures

5. Improved manure mgmt….