Nitrogen Use Efficiency – State of the Art

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- Reactive N and nitrogen use efficiency (NUE)
- Assessment of NUE in agricultural systems
- Current status of NUE
- General strategies for increasing NUE

Emphasis on cereals: 60% of global N use and 20% of global creation of reactive N (Nr)

Outline

Global creation of anthropogenic and natural reactive N in the mid 1990s

	Anthropogenic (million t/yr)					Natural (million t/yr)			
Region	Fertilizer	BNF cult	Import	Deposition	Total	BNF n-cult	Lightning	Total	Total
Africa	2.1	1.8	0.5	2.9	**7.3**	25.9	1.4	27.3	**34.6**
Asia	44.2	13.7	2.3	3.8	**64.0**	21.4	1.2	22.6	**86.6**
Europe + FSU	12.9	3.9	1.0	2.9	**20.7**	14.8	0.1	14.9	**35.6**
Latin America	5.1	5.0	-0.9	1.8	**11.0**	26.5	1.4	27.9	**38.9**
N. America	12.6	6.0	-2.9	2.7	**18.4**	11.9	0.2	12.1	**30.5**
Oceania	0.7	1.1	-0.3	0.3	**1.8**	6.5	0.2	6.7	**8.5**
Total	**77.6**	**31.5**	**-0.3**	**14.4**	**123**	**107.0**	**4.5**	**111.5**	**235**

Reactive N (Nr) = all N compounds in the atmosphere and biosphere that are biologically, photochemically, or radiatively active

Includes inorganic reduced (e.g. NH_3, NH_4^+) and oxidized (e.g. NO_x, HNO_3, N_2O, NO_3^-) compounds, and organic compounds (e.g. urea, amines, proteins, amides)

Source: Boyer et al., 2004

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- Reduce emissions from fossil fuel combustion
- Transform Nr to non-reactive N (denitrification: Nr → N_2; sequester Nr in stable OM)
- Change human diet → food and feed demand, land use, crop yield growth, N fertilizer demand
- Improve NUE in agricultural systems: less N fertilizer per unit food produced
  - Better exploitation of crop yield potential
  - Better management of indigenous and external N sources in agricultural systems, including better fertilizers

Options for reducing the global Nr load

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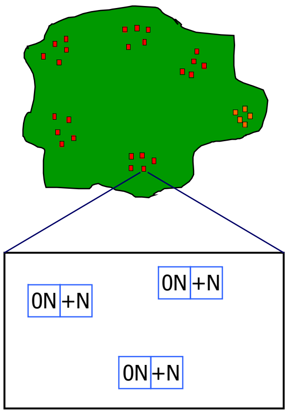
Agronomic indices of NUE

- Measurement of yield and N recovery in soil and crop in plots with and without N addition (zero-N plot) or in two plots with different N addition levels
- Primarily used in research on assessing the efficiency of applied fertilizer N, mainly for purposes that emphasize crop response to N
- Time scale: usually one cropping season or year.
- Spatial scale: varies, but mostly a field or plot.

Assessment of N use efficiency

0 N 100 N 300 N



Measurements:
F – amount of (fertilizer) N applied (kg N/ha)
U – crop N uptake in aboveground biomass (kg N/ha)
Y – crop yield or total dry matter (kg/ha)

$_N$ – plot with N applied

$_0$ – plot without N

Recovery efficiency of applied nitrogen ('apparent')

RE_N = kg increase in crop N uptake per kg N applied

$RE_N = (U_N - U_0)/F_N$

Physiological efficiency of applied nitrogen

PE_N = kg grain yield increase per kg increase in crop N uptake

$PE_N = (Y_N - Y_0)/(U_N - U_0)$

Agronomic efficiency of applied nitrogen

AE_N = kg grain yield increase per kg N applied

$AE_N = (Y_N - Y_0)/F_N$ $AE_N = PE_N \times RE_N$

Partial factor productivity from applied nitrogen

PFP_N = kg grain yield per kg N applied:

$PFP_N = Y_N/F_N$ $PFP_N = (Y_0 + \Delta Y_N)/F_N$
$= (Y_0/F_N) + AE_N$

Agronomic indices of NUE

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Difference method

- Recovery of N refers to aboveground crop N
- Single growing season as time scale.
- Reliable, simple & cheap. On-farm research.
- Major problems:
  - Can be confounded by added-N interactions:
    - Differences in root systems between +N and 0-N plots
    - Differences in N mineralization rates from SOM and residues between +N and 0-N plots
  - Contamination of zero-N plots
  - Sampling & measurement errors
  - Unsuitable for assessing NUE in long-term experiments because of depletion of soil N in permanent zero-N plots

Agronomic indices of NUE

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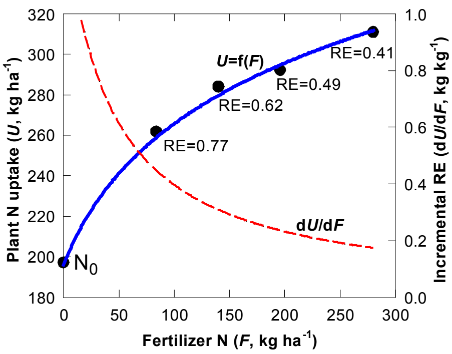
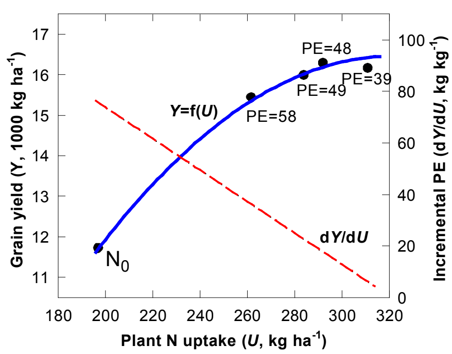
RE_N



PE_N



Irrigated maize, Clay Center, Nebraska, 2002

Agronomic indices of NUE

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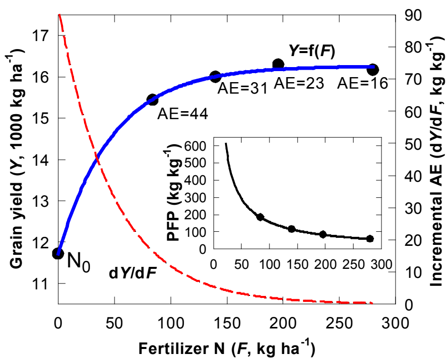
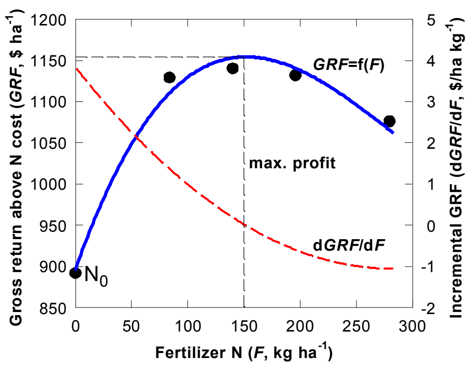
AE_N & PFP_N



Gross return above N cost



GRF_N = (Y_N x price of grain)
– (F_N x price of N)
– application cost

Irrigated maize, Clay Center, Nebraska, 2002

Agronomic indices of NUE

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^{15}N dilution method

- Addition of ^{15}N-labeled fertilizers & measurement of ^{15}N recovery in soil and crop
- Recovery of N can be followed over varying time scales/several years
- Major problems:
  - Cost
  - Sampling & measurement errors: more training and Q/C
  - Underestimation of N recovery due to pool substitution (RE on avg. 7% more than with difference method):
    - Immobilization of ^{15}N fertilizer in microbial biomass
    - Initial release of microbial-derived ^{14}N
  - Difficult to use for studies in larger regions

Agronomic indices of NUE

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^{15}N fertilizer recovery in aboveground biomass by subsequent crops

Soil	~15%
1st crop	44.0%
2nd crop	3.3%
3rd crop	1.3%
4th crop	1.0%
5th crop	0.4%
6th crop	0.5%
Crop	~50%

Source: Krupnik et al., 2004; cereals, compiled from published research data

N recovery in cereals

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- Should mainly be used for evaluating field-scale N management strategies & technologies.
- Always measure several indices to understand factors governing crop response to N & to compare NUE in different environments.
- Use mainly in systems that are at a relatively steady-state with regard to SOM.
- Use N budgets or life cycle analysis (LCA) for more complete assessment of the fate of N and system analysis, including other benefits and societal costs.

Agronomic indices of NUE

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System-level NUE in two continuous maize systems

	Recom.[1]	Intensive[2]
Average maize yield (t/ha)	14.0	15.8
Average fertilizer-N rate (kg/ha)	195	305
4-year C & N budget		
Crop residue input (t C/ha, abovegr.)	21.6	26.4
Soil+root respiration (t CO_2-C/ha)	26.8	26.0
Measured change in soil C (t/ha)	-1.1	+4.4
Fertilizer-N input (kg/ha)	780	1220
N removal with grain (kg/ha)	670	790
Measured change in soil N (kg/ha)	-230	+220
Nitrogen use efficiency		
kg grain/kg N applied (PFP)	72	52
kg grain N/kg N applied	0.86	0.65
kg grain N+change in soil N/kg N applied	0.56	0.83

[1] 7.5 plants/ha; soil-test based fertilizer rates, 2 N splits
[2] 10.5 plants/ha; increased fertilizer rates, 4 N splits+50 kg N ha^{-1} applied on crop residue

Irrigated continuous maize, Lincoln, Nebraska, 2000-2004

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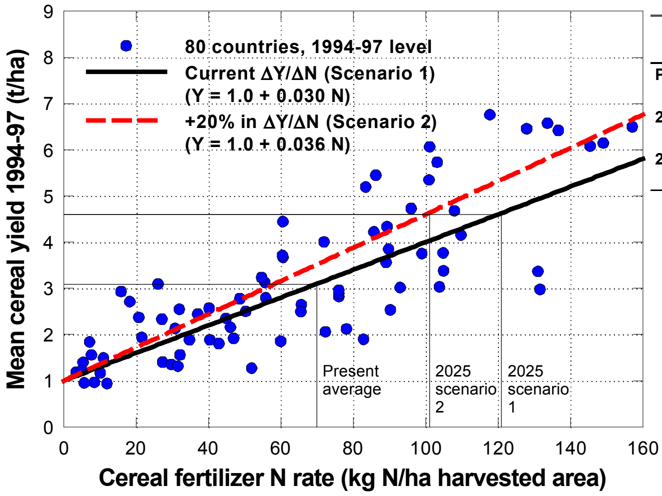


Yield (t/ha)	N rate kg/ha	dY/dN kg/kg	PFP_N kg/kg
Present average			
3.1	70	30	44
2025 scenario 1			
4.6	121	30	38
2025 scenario 2			
4.6	101	36	46

Increase in global N consumption (Mt):
Scenario 1: 60%
Scenario 2: 30%

Increase in average N rate (kg/ha) on cereals:
Scenario 1: 74%
Scenario 2: 44%

Both scenarios assume that world cereal area continues to decline at a rate of 0.3%/yr.

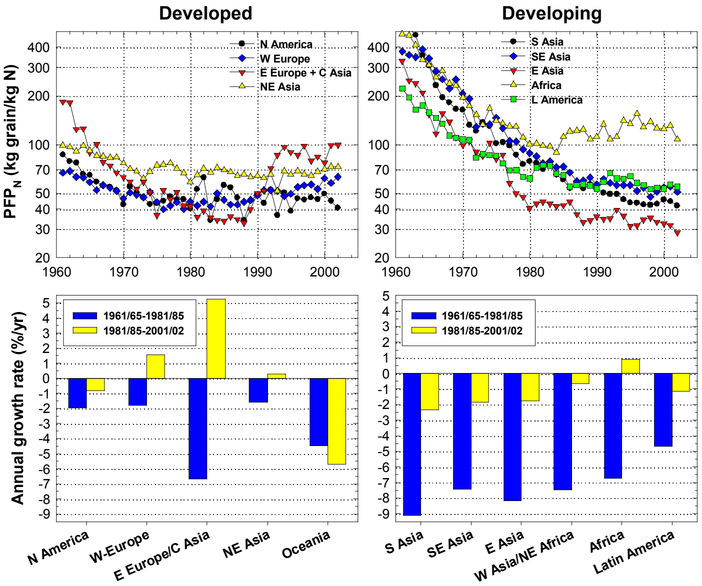
Source: Dobermann & Cassman, 2005

Current status of NUE in cereals

	Cereal yield t/ha	N rate kg N/ha	PFP_N kg/kg	Relative PFP
Africa	1.1	9	123	2.80
E Europe/FSU	2.1	25	90	2.10
Oceania	1.9	48	46	1.10
Latin America	2.9	55	55	1.30
S Asia	2.4	58	44	1.00
SE Asia	3.2	65	53	1.20
WANA	2.3	68	34	0.80
NE Asia	6.1	89	71	1.60
North America	5.1	112	45	1.00
W Europe	5.5	113	59	1.40
E Asia	4.8	155	32	0.70
World	**3.1**	**70**	**44**	**1.00**

Nitrogen use efficiency in cereals by world regions, 1999-2002/3
Estimated from FAO and IFA crop yield and fertilizer use statistics and fertilizer use by crops (IFA, 2002), weighted according to total N use by countries.

Current status of NUE in cereals



Sources: estimated from FAOSTAT (FAO, 2004) & Fertilizer use by crops (IFA et al., 2002)

Current status of NUE in cereals

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Crop	Region (observations)	N rate kg/ha	PFP_N kg/kg	AE_N kg/kg	RE_N %
Maize, reseach trials (1)	World (21-50)	102	70	16	63
Maize, on-farm (2)	USA (52)	158	61	12	36
Maize, on-farm (3)	Indonesia (20)	200	46	17	37
Rice, research trials (1)	World (295-307)	113	63	22	44
Rice, on-farm (4)	Asia (179)	117	49	12	31
Rice, on-farm (5)	West Africa (151)	106	46	17	36
Wheat, research trials (1)	World (286-507)	117	44	19	54
Wheat, on-farm (6)	India (46)	134	44	11	34

1 Ladha et al. (2005), Adv. Agronomy (in press), difference method
2 D. Walters, UNL, 1995-1998, 52 farm sites in IL, KS, MI, MN, MO, NE, WI, difference method
3 A. Dobermann, 2004-2005, 20 farms, difference method
4 Dobermann et al. (2002), farmers' practice, 179 farms in six countries, difference method
5 Wopereis et al. (1999) and Haefele et al. (2001), farmers' practice, difference method
6 A. Dobermann, 1998-1999, 23 farms in Uthar Pradesh, difference method

	PFP_N	AE_N	RE_N
Average in research trials[1]	54	20	51
Average in farmers' fields	40-50	10-20	30-40

Current status of NUE in cereals

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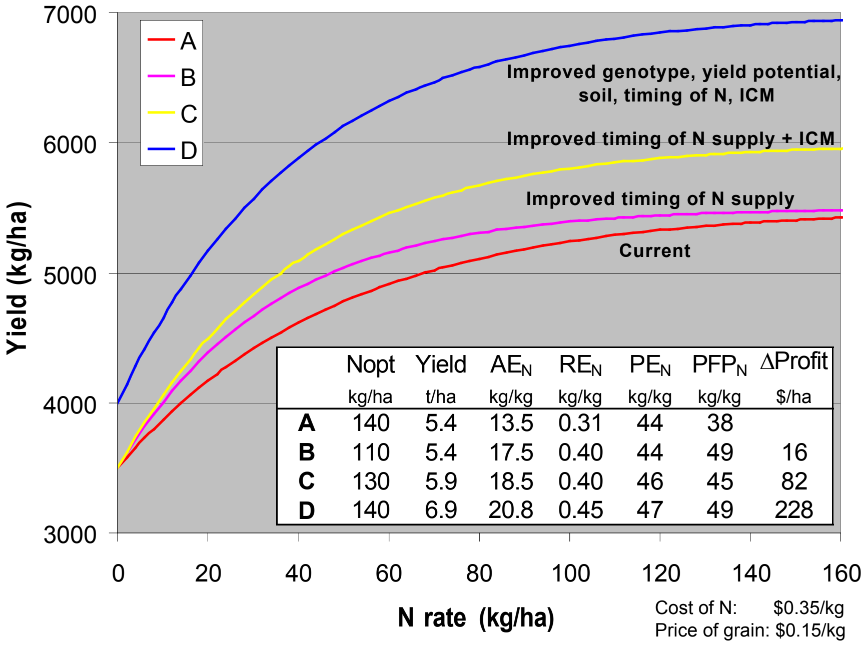
Factors that affect crop response to N

$PFP_N = (Y_0 + \Delta Y_N)/F_N$

Management and environmental factors	Influence on Y_0	Influence on ΔY_N (Y_{max}, RE_N, PE_N)
Climate	**	***
Genotype	**	**
Soil drying, longer fallow periods (rice)	**	*
Manure, crop residues, legume as previous crop	***	*
Land preparation and crop establishment	**	*
Balanced nutrition and amelioration of mineral toxicities/deficiencies	**	***
Water management	**	***
Weeds, insects and diseases	*	***
Timing and amount of N applications	-	***
New fertilizer products (slow/controlled release fertilizers, supergranules, tablets, N-inhibitors)	-	***
Placement of fertilizer (rice)	-	***

- no significant influence; * some influence; ** moderate influence; *** strong influence



	Nopt kg/ha	Yield t/ha	AE_N kg/kg	RE_N kg/kg	PE_N kg/kg	PFP_N kg/kg	ΔProfit $/ha
A	140	5.4	13.5	0.31	44	38	
B	110	5.4	17.5	0.40	44	49	16
C	130	5.9	18.5	0.40	46	45	82
D	140	6.9	20.8	0.45	47	49	228

Cost of N: $0.35/kg
Price of grain: $0.15/kg

	Indonesia (2004-05, N=20)	Nebraska, USA (2002-03, N=20)
Yield potential (t/ha)	8-14	15-20
Grain yield 0N (t/ha)	5.7	10.1
Grain yield +N (t/ha)	9.1	14.1
Fertilizer-N (kg/ha)	200	158
PFP_N (kg/kg)	46	89
AE_N (kg/kg)	17	25
RE_N (%)	37	65

Indonesia: rainfed and irrigated maize, on-farm trials, same N rate at all sites, 3 N applications

Nebraska: irrigated maize, on-farm trials, location-specific N rate based on UNL-algorithm (includes yield goal, SOM, soil NO_3-N, and other N credits), 2-3 N applications

Source: A. Dobermann, unpublished

NUE in two different maize environments

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- **Prescriptive N management**
  - Amount & timing prescribed before planting: expected crop response to fertilizer-N (soil supply, crop demand, fertilizer efficiency, risk, prices)
    - Better recommendation algorithms
    - Precision farming (site-specific N prescriptions)
    - Better rules for splitting & timing of N
    - Better N placement (tablets, supergranules)
    - Better N release: slow/controlled release fertilizers, N inhibitors,
- **Corrective N management**
  - Amount & timing prescribed during the growing season: diagnostic tools that assess soil/crop N status and yield potential
    - Tissue analysis, SPAD, LCC, on-the-go crop sensors, remote sensing
    - Real-time weather data
    - Simulation models
- **Prescriptive + corrective N management**

N management strategies

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Examples of site-specific N management strategies tested in on-farm studies

Crop, location	N treatment	Tools S	Tools M	Tools D	N rate kg/ha	Yield t/ha	PFP_N kg/kg
Maize, NE, USA	Conventional	x	-	-	142	10.3	73
	Site-specific (p)	x	-	-	113	10.2	90
Maize, CO, USA	Conventional	x	-	-	152	12.8	84
	Site-specific (p)	x	-	-	109	12.9	118
Wheat, UK	Conventional	x	-	-	174	7.4	43
	Site-specific (p)	x	-	-	155	7.2	46
Wheat, Netherlands	Conventional	x	-	-	240	9.4	39
	Site-specific (p)	x	x	-	189	9.5	50
Rice, India	Conventional	-	-	-	120	5.5	46
	Site-specific (c)	-	-	x	90	5.6	62
Rice, China	Conventional	-	-	-	171	6.0	37
	Site-specific (p, c)	x	x	x	126	6.4	52

p – prescriptive strategy; c – corrective strategy
Decision tools: S – soil analysis, M – model, D – crop diagnostics (leaf N)

Source: Dobermann et al., Intl. Crop Sci. Congress, Brisbane, 2004

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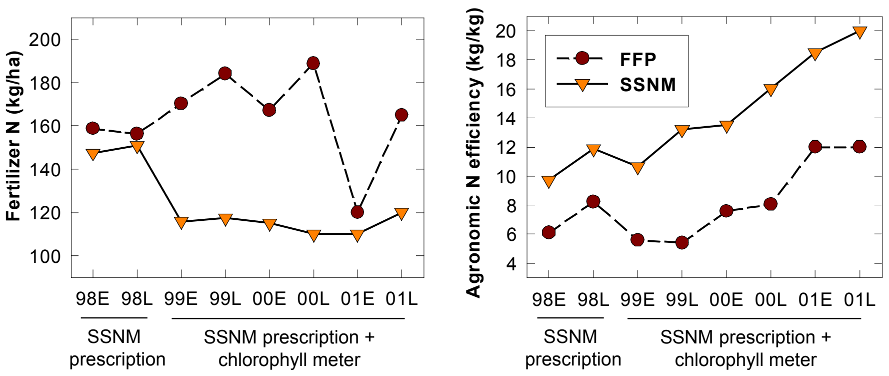
Effect of site-specific nutrient management on NUE in irrigated rice at Jinhua, Zhejiang, China



FFP – Farmers' fertilizer practice
SSNM – Site-specific nutrient management (field-specific adjustment of N, P, and K)
Means of 23 rice farms in Jinhua District, Zheijiang Province, China, 1998 to 2001
E – early season rice; L – late season rice

Source: G.H. Wang, A. Dobermann & C. Witt

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What are adequate performance standards?

	Published (excluding one site)				Recalculated (all sites)			
Treatment	N kg/ha	Yield kg/ha	PFP kg/kg	GRF $/ha	N kg/ha	Yield kg/ha	PFP kg/kg	GRF $/ha
Control	0	1182		118	0	1205		121
Uniform (45 midseason)	45	1562	35	131	45	1510	34	126
Variable (sensor midseason)	43	1835	43	160	47	1688	36	143
Uniform (45 + 45)	90	2105	23	161	90	1981	22	149
Variable (45 + sensor)	108	2292	21	170	109	2099	19	150

Dryland wheat, Oklahoma, four sites in 2000-2001

Uniform – conventional, uniform N application
Variable – on-the-go sensor (GreenSeeker) for midseason variable N application, with or without pre-plant N
GRF – gross return above N cost, not including extra technology costs for variable-rate N

Source: Raun et al., 2002, Agronomy J. 94: 815-820

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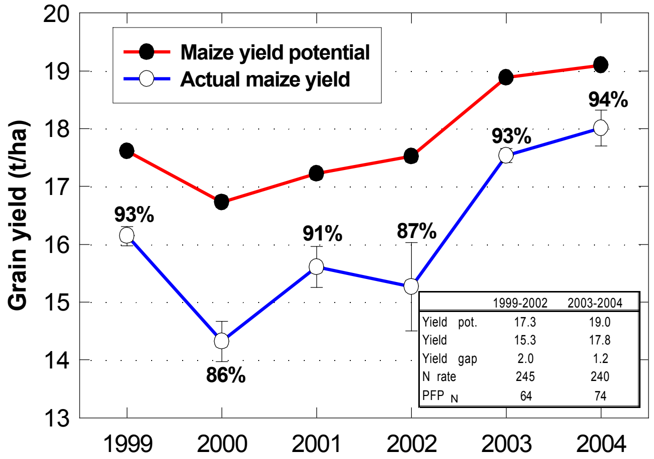

Yield potential: simulated with Hybrid-Maize model (hybridmaize.unl.edu); increased over time due to shifts in hybrid (maturity) and planting date.
Actual yield (maize following soybean):
intensive N management (4 splits) + P + K + high plant population, irrigated
increased over time due increase in yield potential and improved management

Maize yield trends at Lincoln, NE

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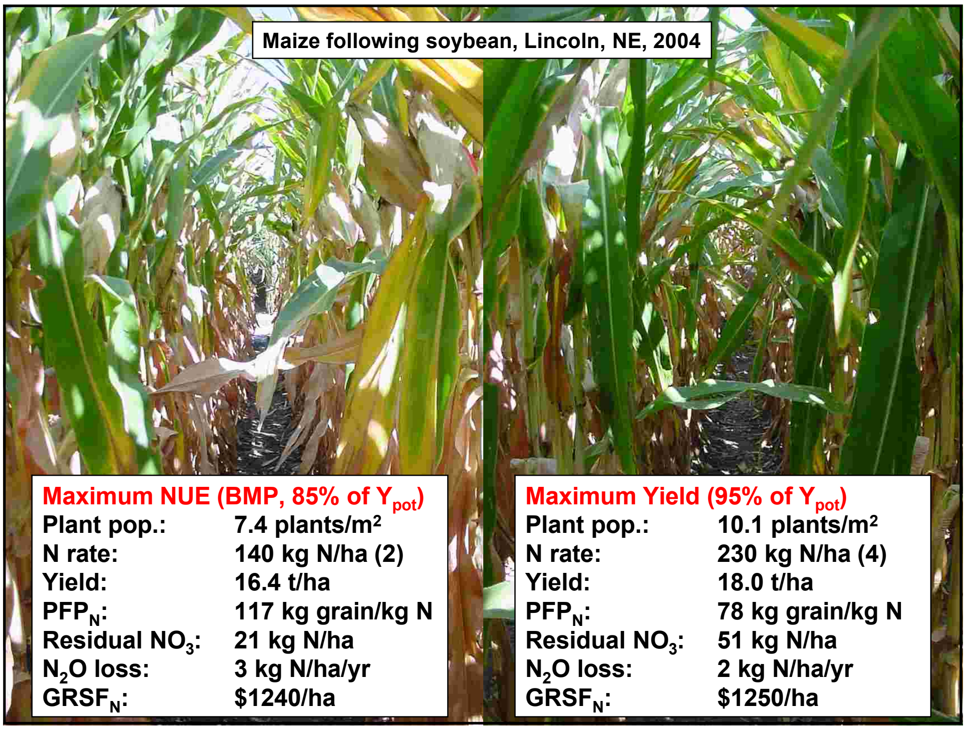

Performance of ESN® controlled-release N fertilizer in high-yielding irrigated maize at Lincoln, NE, 2004

Treatment (All: 200 kg N/ha)	# N appl.	Row spacing	Plant density	Maize yield	PFP_N	Seed + N cost	Gross return -(seed + N)
		cm	pl./m²	t/ha	kg/kg	$/ha	$/ha
Ammonium nitrate	3	76	7.5	16.8	84	313	1209
ESN®, Agrium	1	76	7.5	16.6	83	319	1181
ESN®, Agrium	1	38	10	17.6	88	351	1241

ESN® - Environmentally Smart Nitrogen (polymer-coated urea)

Source: A. Dobermann & D. Walters, UNL, unpublished

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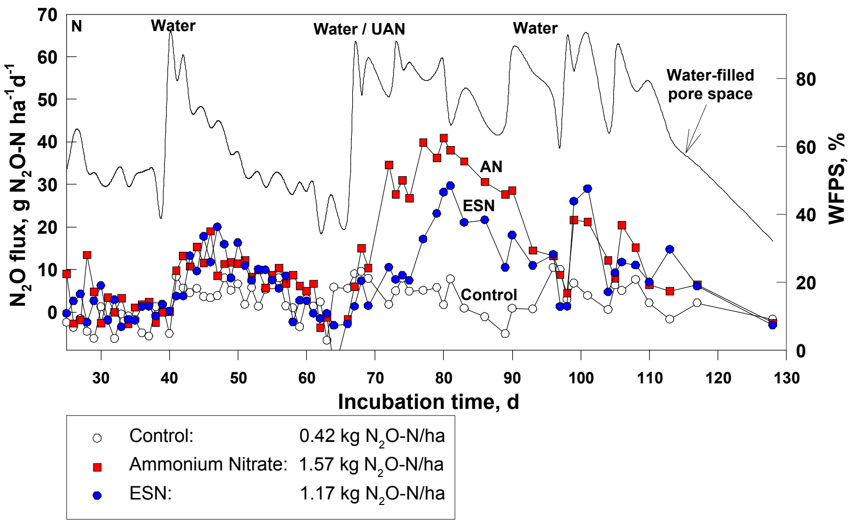

ESN® - Environmentally Smart Nitrogen (polymer-coated urea, Agrium)
Soil-box incubation study, Lincoln, NE 2004, unplanted SiCL Mollisol

Source: A. Adviento-Borbe & A. Dobermann, UNL, unpublished

- NUE has declined with increasing N use, but current trends differ among world regions
- Under farm conditions NUE averages about 70-80% of the NUE achieved in research trials
- Always use several NUE indices to assess new N technologies and do it under on-farm conditions
- Assess system level NUE over time, including other benefits (SOM, Nr)
- Managing crop N demand, indigenous N supply, and fertilizer efficiency are equally important for increasing NUE
- New fertilizer products:
  - Simple technology (embedded knowledge)
  - Adoption potential depends on robust performance and economics: consistent (small) yield increases and/or large gains in NUE
  - Government support for *green fertilization technologies* that reduce Nr load?

Summary