Agriculture's Contribution to the Global Reactive Nitrogen Load

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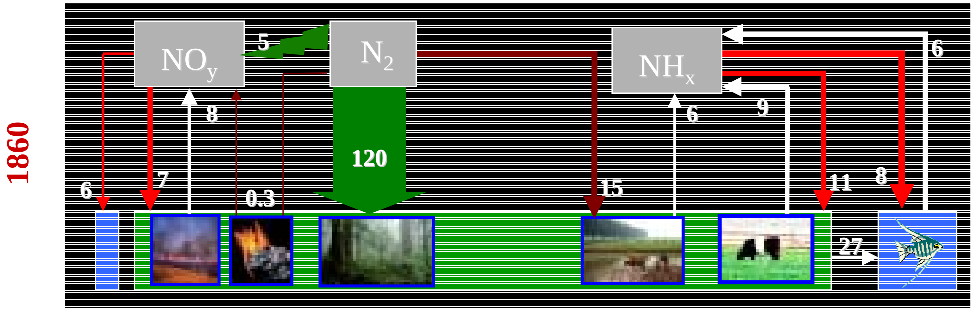
What is reactive nitrogen?

- **Reactive N (Nr) refers to all N compounds in the atmosphere and biosphere that are biologically, photochemically, or radiatively active**
- **The Nr pool 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)**
- **Nr compounds are produced by both natural and anthropogenic activities.**

The Global Nitrogen Budget in 1860, TgN/yr



<u>1898</u>

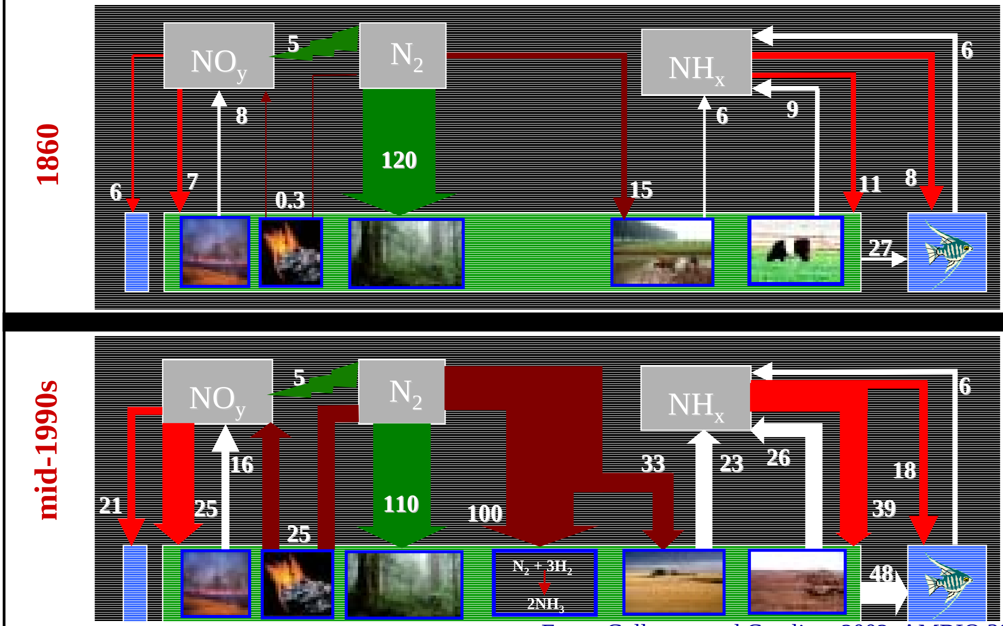
Global human population of 1.5 billion

“All England and the civilized world stand in deadly peril of not having enough to eat due to increasing demand for food and lack of sufficient biologically active nitrogen”

---Sir William Crookes, Pres. British Assoc. Adv. of Science

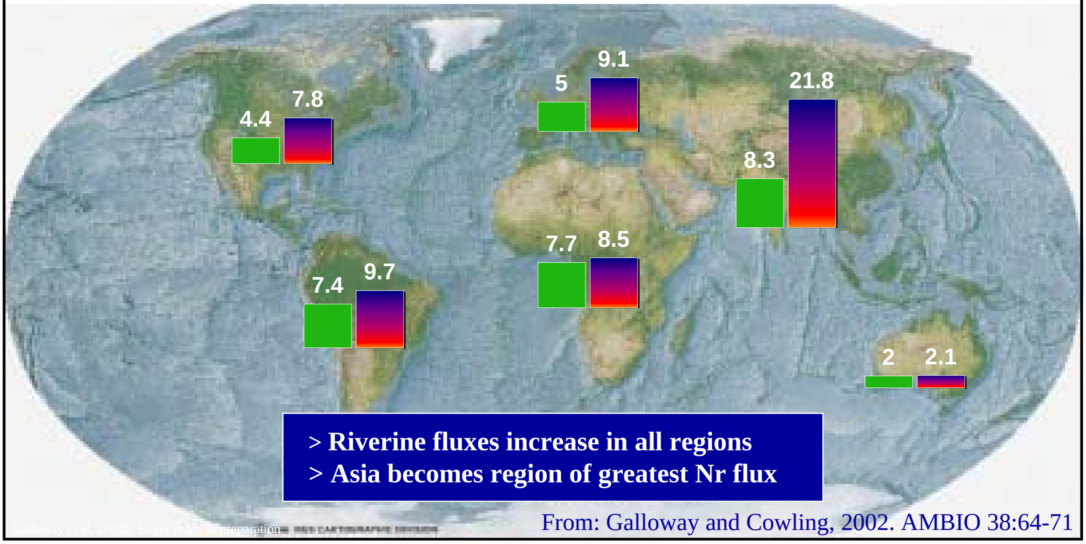
From: Galloway and Cowling, 2002. AMBIO 38:64-71

The Global Nitrogen Budget in 1860 and mid-1990s, TgN/yr



From: Galloway and Cowling, 2002. AMBIO 38:64-71

Nr Riverine Fluxes
1860 (left) and 1990 (right)
TgN/yr

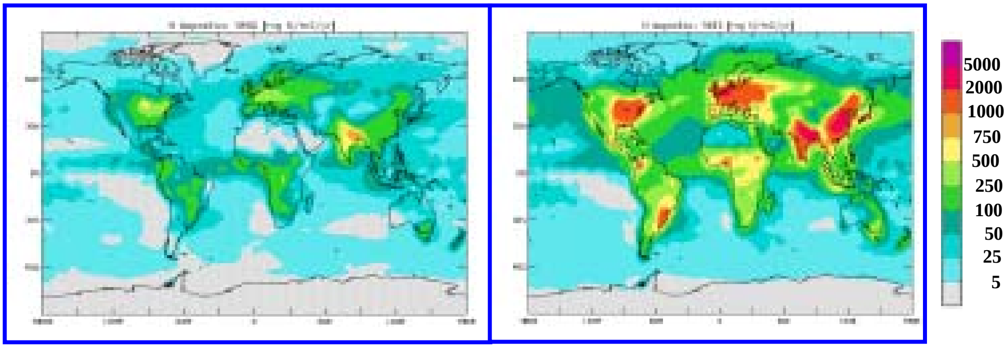


> Riverine fluxes increase in all regions
> Asia becomes region of greatest Nr flux

Galloway et al, 2002b; Boyer et al., in preparation

From: Galloway and Cowling, 2002. AMBIO 38:64-71

Nitrogen Deposition
Past and Present
mg N/m^2/yr



1860 **1993**

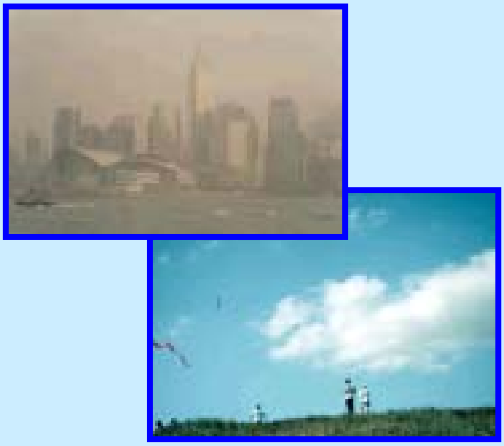
From: Galloway and Cowling, 2002. AMBIO 38:64-71

Nr and Agricultural Ecosystems

- N fertilizer from the Haber-Bosch process has allowed agricultural intensification
- 40% of world's population is alive because of Nr from commercial fertilizer
- An additional 3 billion people by 2050 will be sustained by it
- About 50% of the N input to agroecosystems is released to the environment

Modified from Galloway, 2003 AAAS presentation

Nr and the Atmosphere



- NO_x emissions from industry contribute to OH, which defines the oxidizing capacity of the atmosphere
- NO_x emissions are responsible for tens of thousands of deaths per year in the United States
- O_3 and N_2O contribute to atmospheric warming
- N_2O emissions contribute to stratospheric O_3 depletion

Modified from Galloway, 2003 AAAS presentation

Nr and Terrestrial Ecosystems

- N is the limiting nutrient in most temperate and polar ecosystems
- Nr deposition increases and then decreases forest and grassland productivity
- Nr additions probably decrease biodiversity across the entire range of deposition

Modified from Galloway, 2003 AAAS presentation

Nr and Freshwater Ecosystems

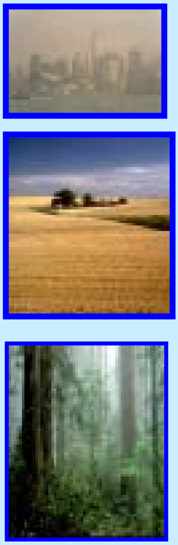
- Surface water acidification
  - Tens of thousands of lakes and streams
  - Significant biodiversity losses
  - Negative feedbacks to forested ecosystems

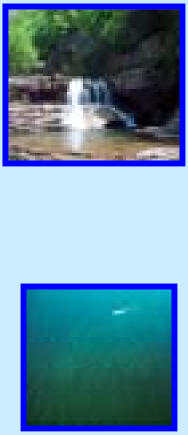
Modified from Galloway, 2003 AAAS presentation

Nr and Coastal Ecosystems

- Riverine and atmospheric deposition are significant Nr sources to coastal systems
- Nr inputs into coastal regions result in eutrophication, biodiversity losses, emissions of N_2O to the atmosphere (hypoxia)
- Most coastal regions are impacted.

Modified from Galloway, 2003 AAAS presentation

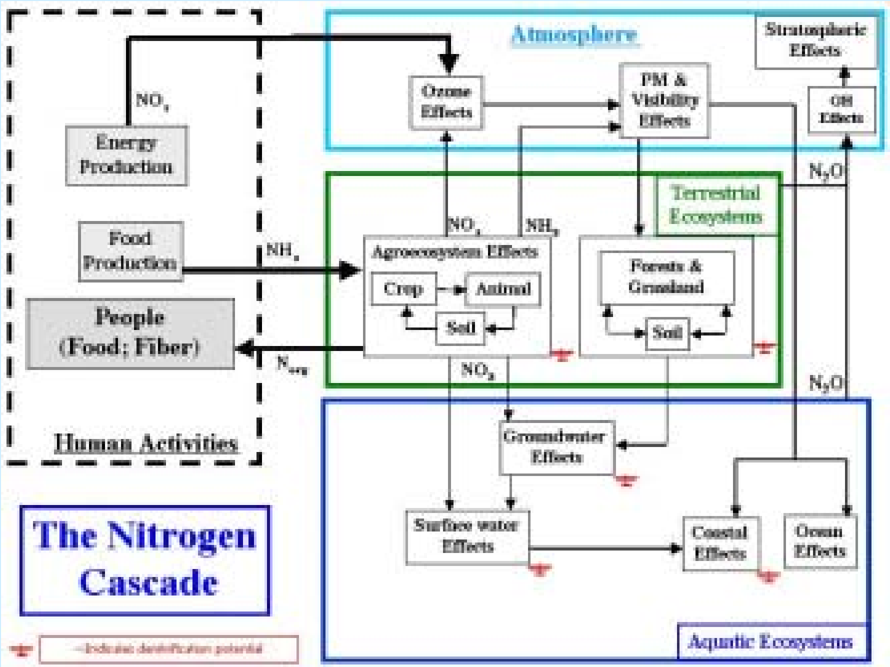




There are significant effects of Nr accumulation within each reservoir

These effects are linked temporally and biogeochemically in the **Nitrogen Cascade**

Modified from Galloway, 2003 AAAS presentation



From: Galloway and Cowling, 2002. AMBIO 38:64-71

Sources and estimated amounts of annual reactive N (Nr) creation terrestrial ecosystems and nitrogen fertilizer production in 1990 (Smil, 1999; Galloway and Cowling, 2002)

Source	Annual Nr creation ($MMT\ N\ yr^{-1}$)	Percent of annual global Nr load
BNF* in natural ecosystems	89	39
BNF* in agro-ecosystems	33	15
Haber-Bosch reduced N	85 (78)**	37 (34)**
Fossil fuel combustion	21	9
Total	228	100

*BNF = biological nitrogen fixation by legumes and other N-fixing plants and microbes.

**Nr attributable to nitrogen fertilizer.

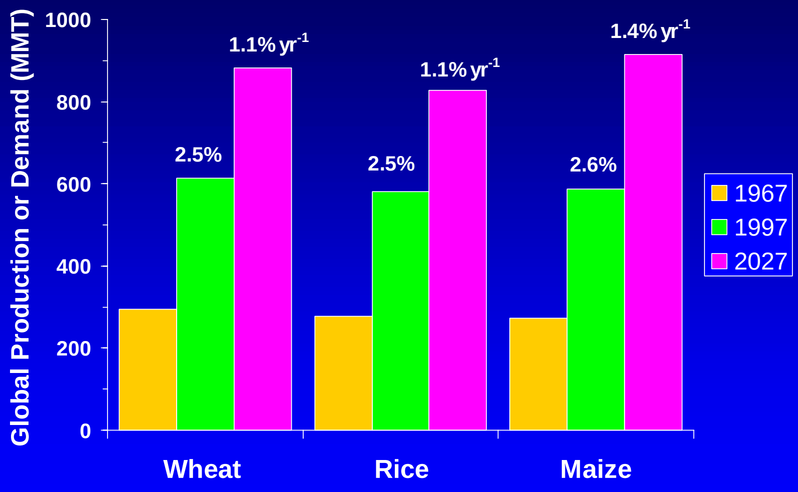
Annual anthropogenic creation of reactive N and per capita reactive N creation in the mid-1990s (Galloway and Cowling, 2002)

Region	Annual Nr load (MMT N yr^{-1})	Per capita Nr load (kg N per person yr^{-1})
Asia	69	17
North America	29	100
Europe and FSU	27	44
Latin America	9	19
Africa	5	7
World	140*	24

*Also includes a relatively small contribution from Oceania (not shown).

Perhaps the single greatest scientific challenge facing humankind is the need to sustain rates of growth in crop production without a net increase in cultivated area (intensification) to meet food demand of about 9 billion by 2050 while reducing the global reactive N load in the environment well below current levels.

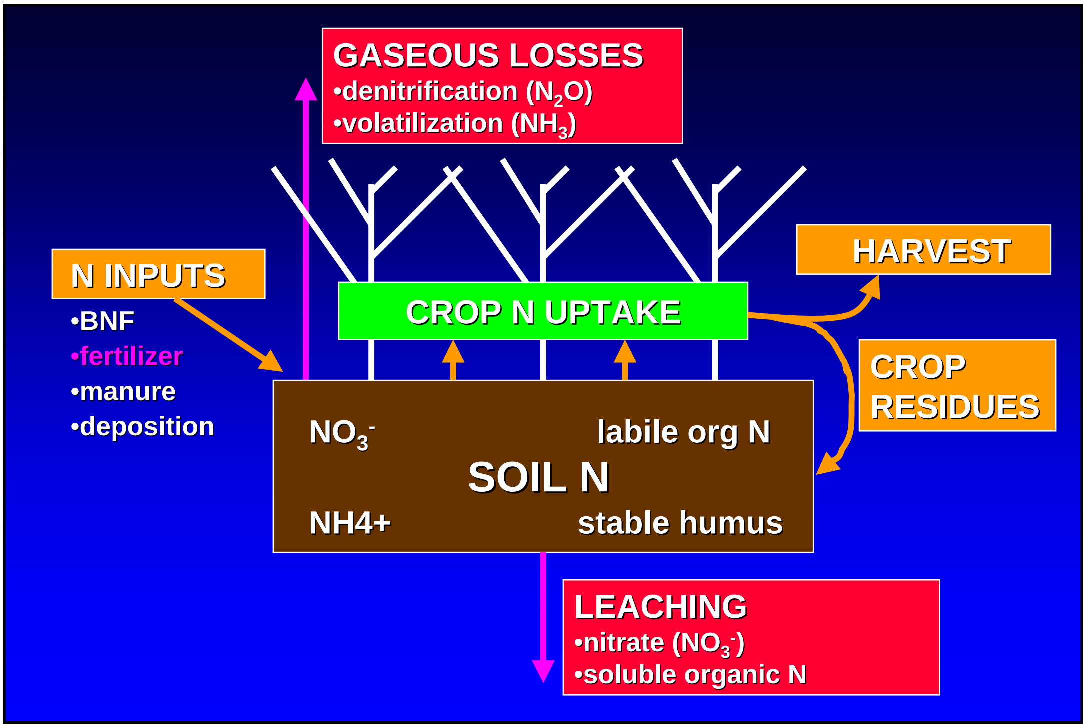
Growth in Grain Supply-Demand



From: Cassman, 1999. Proc Natl Acad. Sci. (USA) 96: 5952-5959.

What is current status of N fertilizer efficiency?

- Estimates needed from ‘on-farm’ measurements
  - Paucity of reliable data from the major cereal cropping systems
  - Measurements from small research plots tend overestimate current efficiencies by a large margin
- Available data indicate low N fertilizer uptake efficiency
  - Very low for rice
  - Low for maize despite improvements in recent years
  - Low to high on wheat depending on cropping system and yield levels



GASEOUS LOSSES
- denitrification (N_2O)
- volatilization (NH_3)

N INPUTS
- BNF
- fertilizer
- manure
- deposition

CROP N UPTAKE

HARVEST

CROP RESIDUES

SOIL N

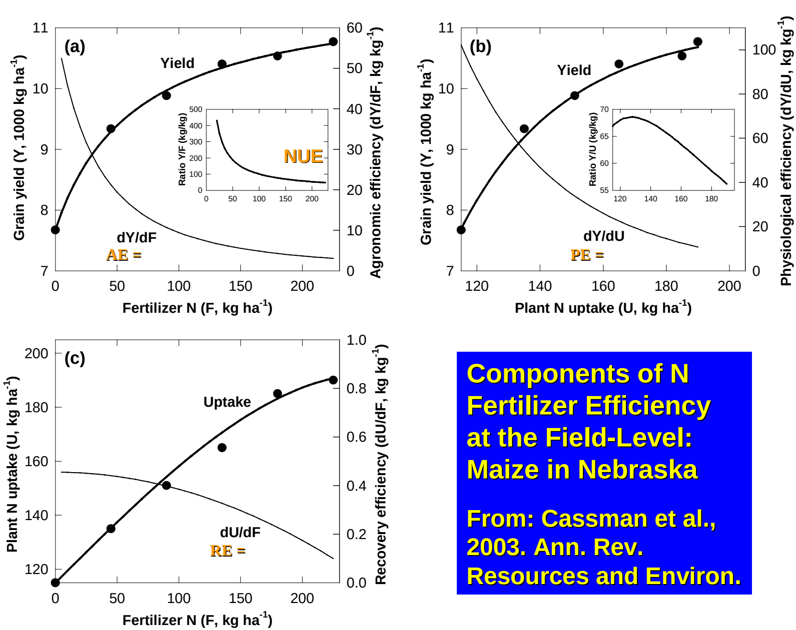
NO_3^-

labile org N

NH4+

stable humus

LEACHING
- nitrate (NO_3^-)
- soluble organic N



Components of N Fertilizer Efficiency at the Field-Level: Maize in Nebraska

From: Cassman et al., 2003. Ann. Rev. Resources and Environ.

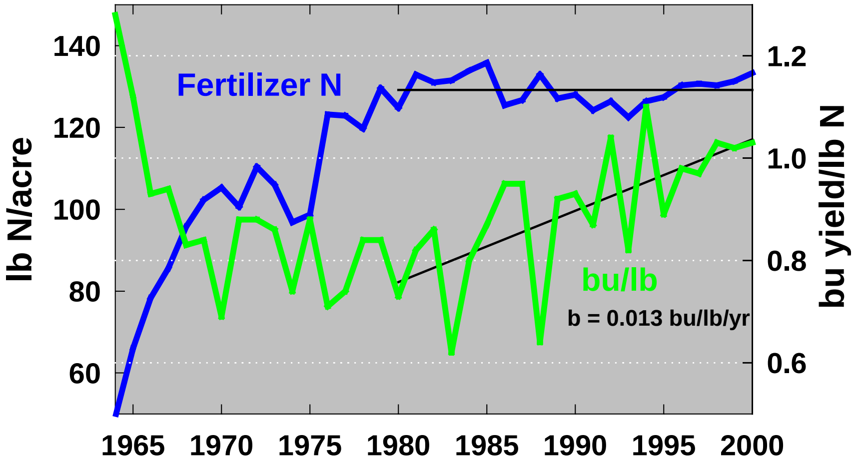
Best current estimates of average on-farm N fertilizer uptake efficiency for the major cereals in the world's most productive cropping systems based on direct measurements in farmers fields.

Crop	Region	N Fertilizer (kg N ha^{-1})	Efficiency (% of applied N)
Maize*	USA	103	37
Rice**	Asia	117	31
Wheat*	India	123	18 (poor climate)
		146	49 (good climate)

* Cassman et al., 2002. AMBIO 31: 132-140.

**Dobermann et al., 2002. Field Crops Res. 74:37-66.

Fertilizer N Use on Corn, 1964 - 2000



Source: Annual USDA cropping practices surveys of >2000 farms

➢Are substantial increases in N fertilizer efficiency possible as crop yields continue to increase? The answer depends on:

- **Detailed understanding of the biophysical controls on N efficiency and using this knowledge to develop improved crop and soil management systems**
- **Adequate investment in research to ensure knowledge development, and in extension to ensure adoption of improved technologies by farmers**

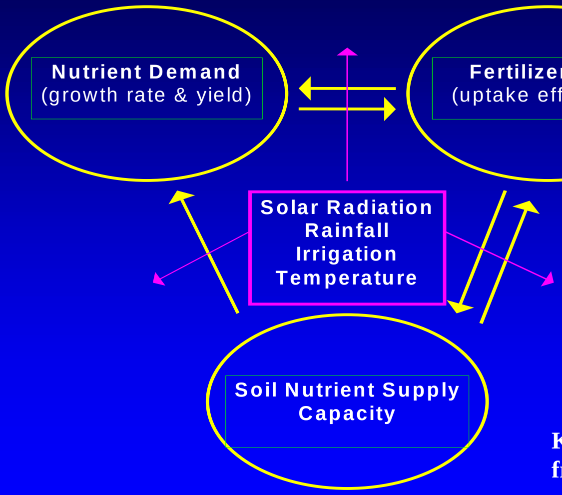
High yields and high N fertilzer efficiency are possible at a production scale!

CSP 2001 results based on combine harvest

System	Yield	N fertilizer	Yield/N fert
	bu/ac	lb N/ac	bu/lb N
Irrigated			
Maize (soy)	217	136.5	1.59
Maize (maize)	209	174.5	1.20
Rainfed (various)	142	114.0	1.25
USA maize (mean)	135	140.0	1.03

Univ. of Nebraska, CSP project, unpublished data

Optimal management of N fertilizer to achieves maximum profit while protecting environmental quality depends on the dynamic interactions among crop nutrient requirements, soil properties, and climate.



Nutrient Demand
(growth rate & yield)

Fertilizer Rate
(uptake efficiency)

Solar Radiation
Rainfall
Irrigation
Temperature

Soil Nutrient Supply Capacity

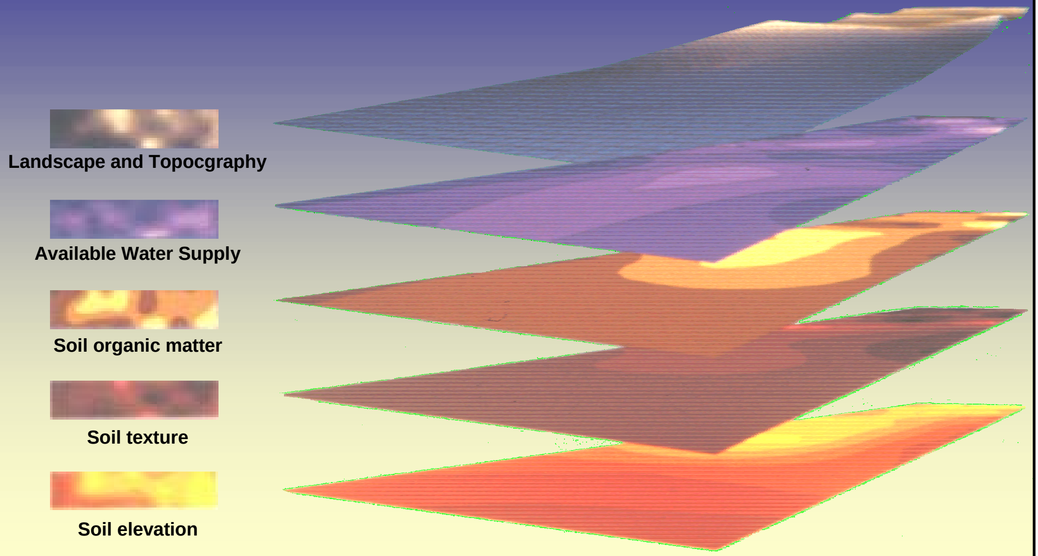
K.G. Cassman: Conceptual framework of dynamic N management. 2003 IFA Conference.

Precision Agriculture

- **Exact implementation of all management operations uniformly applied to a single field**
- **Site-specific management within a field to account for spatial variation in soil and pests**
- **Variety/hybrid selection; tillage; planting date, density and row spacing; nutrient amount, formulation, and placement, integrated pest management; irrigation amount and timing**

From: Cassman, 1999. Proc Natl Acad. Sci. (USA) 96: 5952-5959.

Precision Farming: Field Geographic Information



Landscape and Topocgraphy

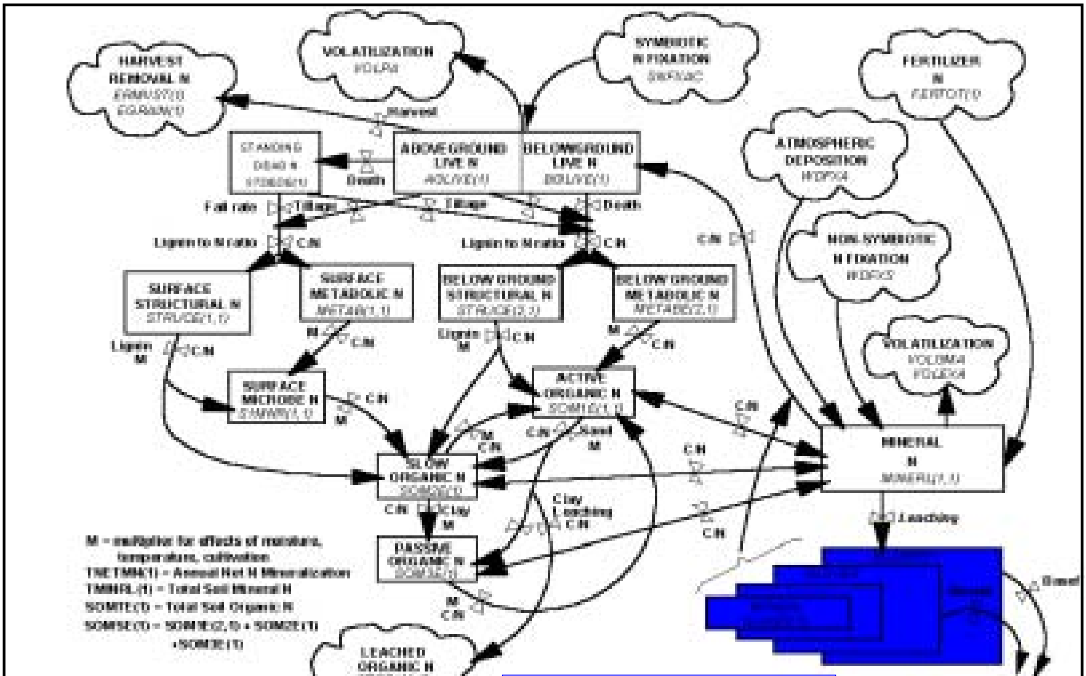
Available Water Supply

Soil organic matter

Soil texture

Soil elevation

Crop simulation models are needed to predict key development stages, growth rates, and N demand throughout the crop growth period



Century N Module

Take Home Message

- High fertilizer N efficiency can be achieved at high yield levels and high rates of N fertilizer application only when applied N fertilizer is congruent with crop N demand and the indigenous N supply
  - Matches in-season pattern of crop N demand
  - Matches spatial variability within large production fields (large-scale, mechanized agriculture)
  - Matches field-specific requirements in small production fields (small-scale, labor-intensive)

The same principles apply for implementing precision N management in large- and small-scale agriculture:

- Accurate estimates of crop N demand and the indigenous soil N supply throughout crop growth
- Must account for field-specific and site-specific variation
- Simulation models and user-friendly decision-support tools needed
- Weather forecasting

Concluding Remarks

- The good news
  - Both sustained increases in yield and substantial increases in N fertilizer efficiency are possible with information-intensive crop and soil management
  - A substantial increase in N efficiency will reduce the Nr load from agriculture significantly
- The bad news
  - Investment in research and extension in both developed and developing countries is woefully inadequate to achieve the needed improvements in yield and N fertilizer efficiency

THANK YOU