Research Priorities in Plant Nutrition and Soil Fertility: Challenges and Opportunities

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Topical Outline

- Mega-trends
  - Food supply and demand projections for a human population of 9 billion
  - Availability of good arable land and crop yields
  - Fossil fuel costs and renewable biofuels
  - Society's growing concern about agriculture and the environment
- Research priorities in plant nutrition and soil fertility

Determinants of future food demand, supply, and cost

- Food demand depends on population growth and economic development
  - Higher incomes means more varied diets and greater consumption of livestock products (eating higher up the food chain)
- Food supply capacity depends on:
  - Arable land currently producing crops and trends in soil quality
  - Amount of uncultivated land with potential to support crop production and its soil quality
  - Current crop yields and yield trends into the future
- Food costs will depend on global and local food supply—demand balance and income levels

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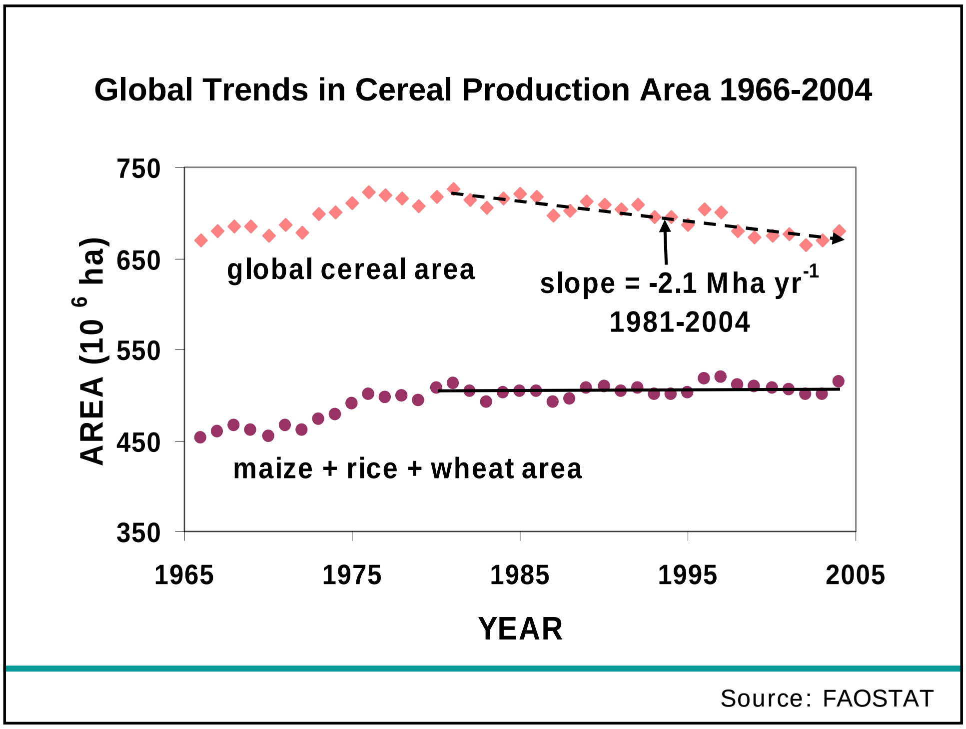
IFPRI-IMPACT model: Projected changes in population, cereal demand, yields, area, and prices

Indices	1995	2025	Annual rate of change (%)
Global population (billion)	5.66	7.90	1.12
Global demand for rice, wheat, and maize (10^6 Mg)	1657	2436	1.29
Total rice, wheat, and maize area (10^6 ha)	506	556	0.31 ?
Mean rice, wheat, maize yield (Mg ha^{-1}) [1]	3.27	4.38	0.98
World rice price (US$ Mg^{-1}, milled rice)	285	221	-0.84
World wheat price (US$ Mg^{-1})	133	119	-0.37
World maize price (US$ Mg^{-1})	103	104	0.03

Population projections: medium scenario of the UN 1998 projection.
Food projections: 'business-as-usual' scenario of food and water demand and supply, IMPACT model, International Food Policy Research Institute.

Source: Rosegrant et al. 2002. IFPRI

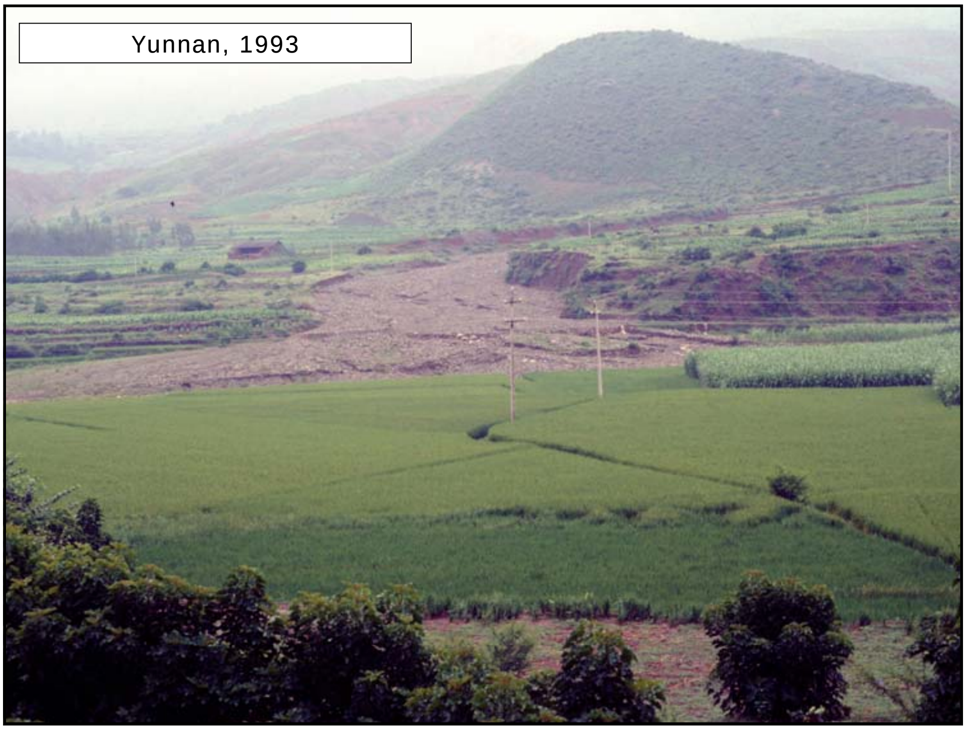

Global Trends in Cereal Production Area 1966-2004
750
650
550
450
350
AREA (10 6 ha)
global cereal area
slope = -2.1 Mha yr-1
1981-2004
maize + rice + wheat area
1965
1975
1985
1995
2005
YEAR
Source: FAOSTAT

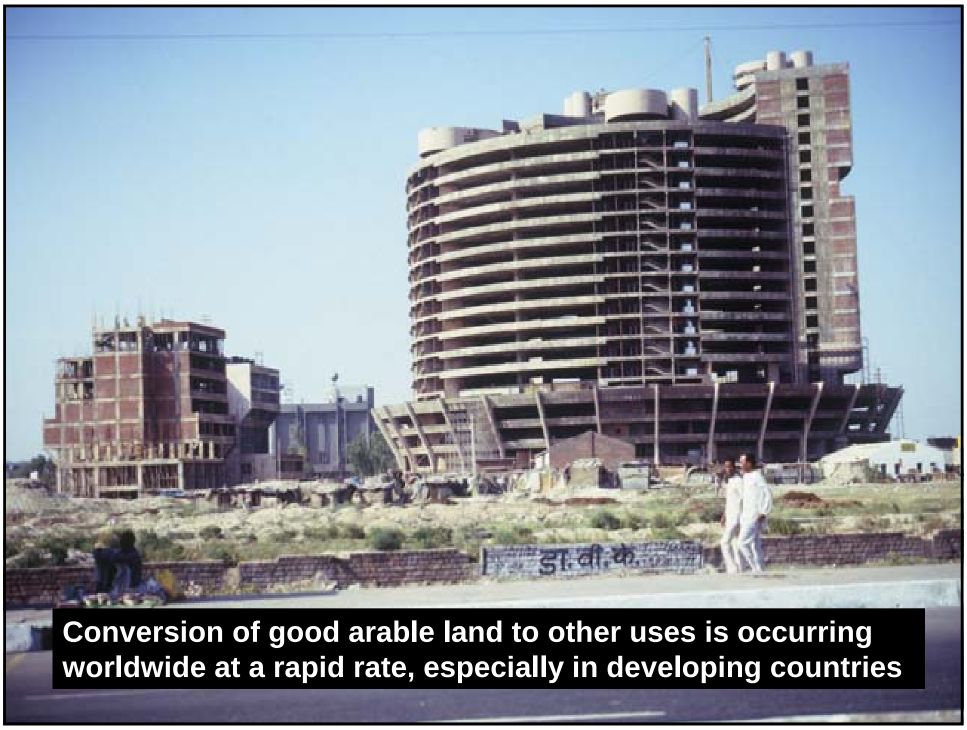

Sub-Saharan Africa


Sub-Saharan Africa


Sumatra, Indonesia


Yunnan, 1993


Yunnan, 1993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Conversion of good arable land to other uses is occurring worldwide at a rapid rate, especially in developing countries

Reality versus projections in arable land resources

- Cereal area has decreased by 0.3% annually since the early 1980s
- Cereal land being lost to urbanization and shifts to higher value crops in peri-urban areas
- Quality of remaining land reserve is much lower than land going out of production

Projected changes in population, cereal demand, yields, area, and prices (Source: Rosegrant et al. 2002. IFPRI)

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Total rice, wheat, and maize area (10^6 ha)	506	556	~~0.31~~ -0.10
Mean rice, wheat, maize yield (Mg ha^{-1}) [1]	3.27	4.38	~~0.98~~ +1.39
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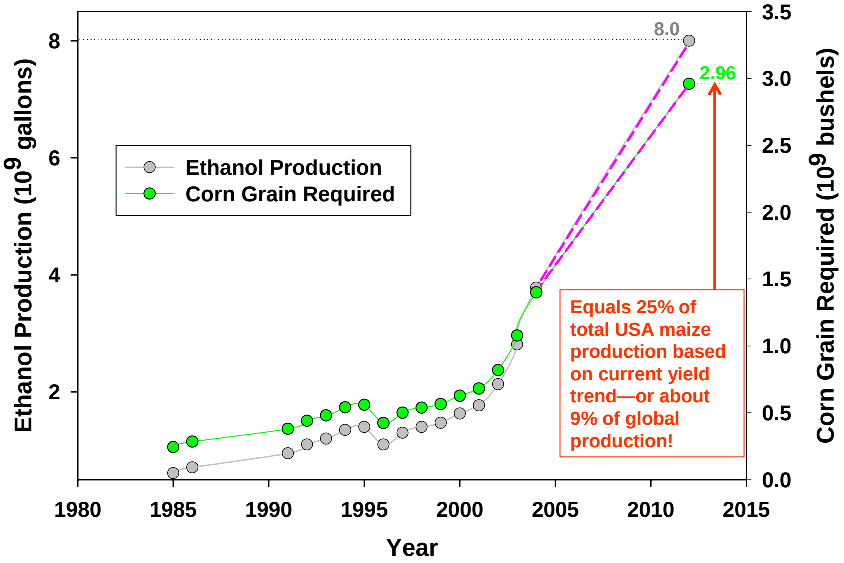
New development: rising energy costs and increased biofuel production from grain: USA Ethanol Production



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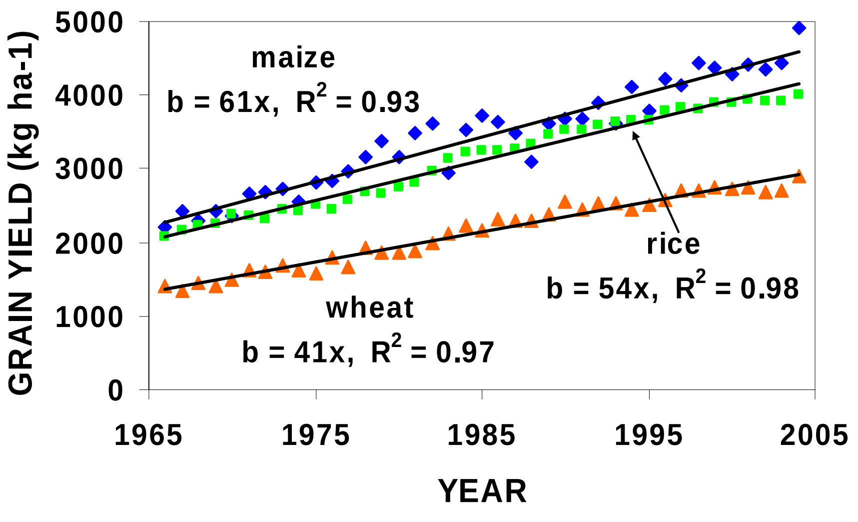
Prediction of global demand, supply, and yield of the three major cereals (maize, rice, and wheat) from 1995 to 2025 by the IFPRI—IMPACT model‡, and a modified prediction based on updated trends in land use.

	1995	2025	Annual rate of change (%)	Modified 2025 prediction¶	Modified annual rate change (%)
Population (10^9)	5.66	7.90	1.12	same	1.12
Demand (MMT)	1657	2436	1.29	2558	1.46
Production Area (Mha)	506	556	0.31	491	-0.10
Mean grain yield† (kg ha^{-1})	3.27	4.38	0.98	5.21	1.56

‡Rosegrant et al., 2002, International Food Policy Research Institute.
¶While the IFPRI-IMPACT prediction accounts for grain demand for human food and livestock feed, it does not consider grain used for biofuel or bio-based industrial feedstock production; the modified prediction assumes that 5% of global grain supply in 2025 is used for production of biofuel and bio-based industrial feedstocks
†Weighted average for the three major cereals.

So, what are the prospects for sustaining >1.5% annual rate of increase in cereal yields given available land reserves suitable for intensive cereal production, and trends in crop area devoted to cereals?

Global Yield Trends, 1966-2004



Global rate of increase in yield of maize, rice, and wheat, 1966-2004.

Crop	Mean yield (kg ha-1) 1966	2004	Rate of gain (kg ha^{-1} yr^{-1})	Proportional rate of gain (%) 1966	2004
Maize	2210	4907	61.0	2.76	1.24
Rice	2076	4004	54.4	2.62	1.36
Wheat	1408	2907	41.2	2.93	1.42

Global rate of increase in cereal yields is linear, and is falling well below the rate of >1.5% per annum that is required to meet demand for food and renewable biofuel energy on available crop land

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Producing sufficient food for 9 billion people who are much richer than average people are today is necessary, but not sufficient, to meet society's expectations of agriculture.

Agriculture must also contribute to improving environmental quality, conserving natural resources, and slowing climate change trends.

Society's environmental concerns about fertilizers

- Pollution of water resources—focus on nitrogen and phosphorus
  - Anoxia zones at river mouths; negative impact on fisheries
  - Loss of recreational value and "natural" beauty
  - Loss of biodiversity
  - Human health effects
- Greenhouse gas emissions (N_2O)
- Soil acidification from N fertilizers

Organic agriculture is not the answer—insufficient land and water to produce organic nutrients in sufficient quantities

	Nitrogen inputs in agriculture (10^6 Mg/yr)		
Region	Biological N fixation[1]	Mineral Fertilizers	Manure[2]
Africa	1.8	2.1	1.7
Asia	13.7	44.2	17.0
Europe+FSU	3.9	12.9	8.1
Latin America	5.0	5.1	3.0
North America	6.0	12.6	3.8
Oceania	1.1	0.7	0.7
Total	**31.5**	**77.6**	**34.3**

[1] Includes legumes, forage and other crops with N fixation

Mega-trend summary

- Cultivated land area for major staple crops will continue a slow, steady decline
- Current yield growth rates will not meet future demand for food and bioenergy without large expansion of cultivated area or accelerated yield gain
- Increasing concerns about negative impact of fertilizers on the environment
- Ecological intensification of crop production is needed to meet food demand, protect the environment, conserve natural resources
- Are researchers and industry up to the challenge?

What is Ecological Intensification?

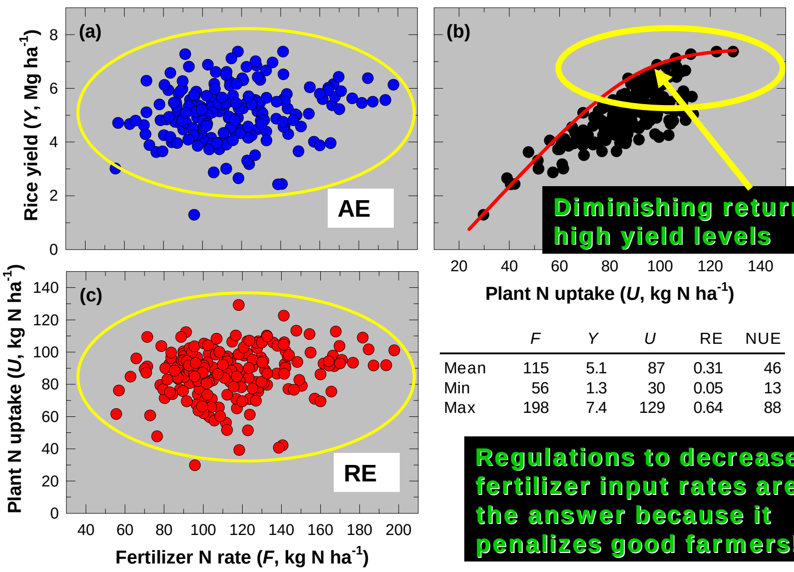
- Development of high-yield crop production systems that protect soil and environmental quality and conserve natural resources
- Characteristics of EI systems:
  - Average farm yields that are 85-90% of genetic yield potential
  - Achieve >70% N fertilizer uptake efficiency
  - Improve soil quality (nutrient stocks, SOM)
  - Rely on Integrated pest management (IPM)
  - Result in net reduction in atmospheric [GHG]
  - Have a net positive energy balance
  - In irrigated systems: 90-95% water use efficiency

N fertilizer uptake efficiency measured in farmer's fields—currently very low!

Crop	Country	Number	Mean N Rate (kg/ha)	N Fertilizer Efficiency (% applied)
Maize (after soy)	USA	55	103	37%
Rice (rice-rice)	Asia	179 179**	117 112	31% 40%
Wheat (rice-wheat)	India	23(1997)+ 21(1998)+	145 123	18% 49%

*Dobermann et al., 2002, Field Crops Res. **Improved N management.
+1997—low yielding year (2.3 t/ha); 1998—high yield year (4.8 t/ha).

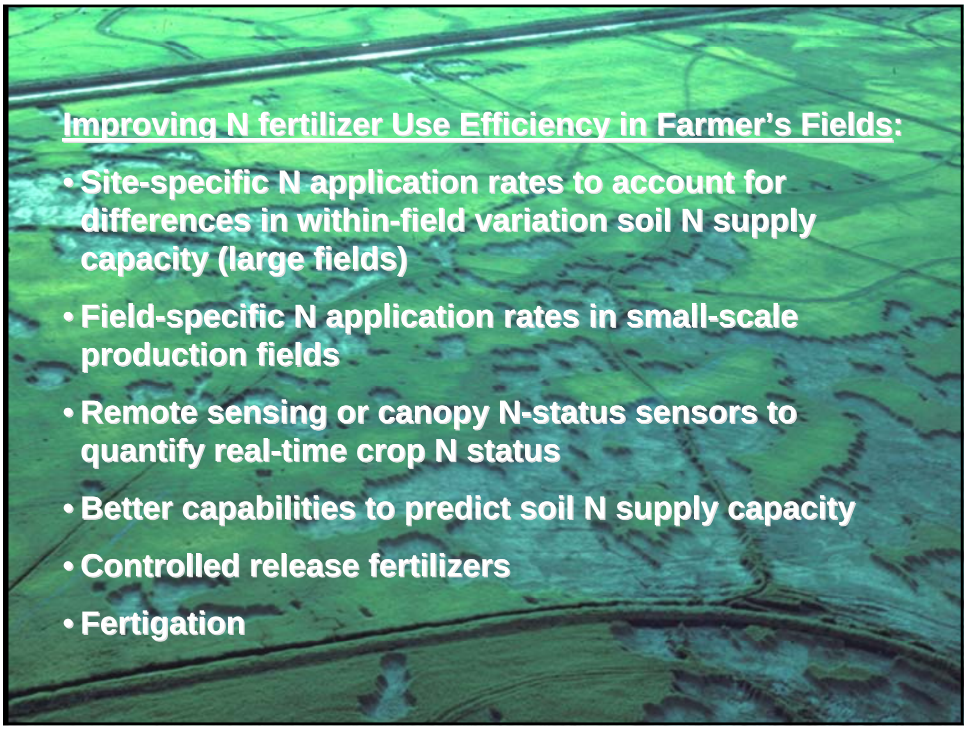
Disconnection between N fertilizer efficiency and N fertilizer rate in farmer's fields



	F	Y	U	RE	NUE
Mean	115	5.1	87	0.31	46
Min	56	1.3	30	0.05	13
Max	198	7.4	129	0.64	88

Regulations to decrease N fertilizer input rates are not the answer because it penalizes good farmers!

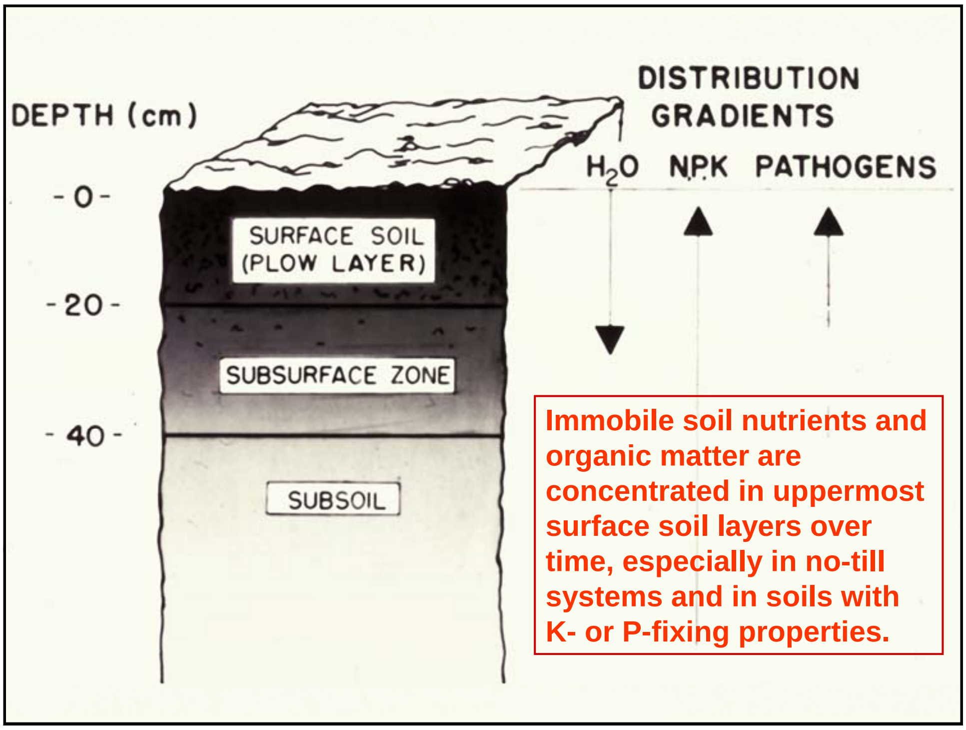
Irrigated rice, 179 farmers' fields in China, India, Indonesia, the Philippines, Thailand, and Vietnam, 1997-1999. From Dobermann et al, 2002

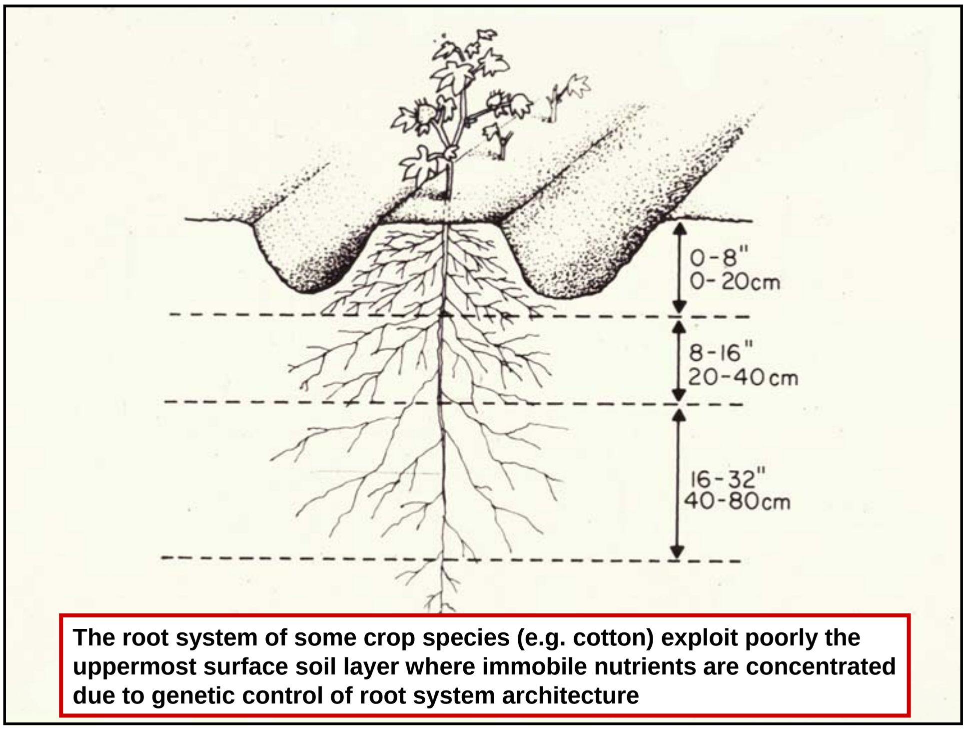


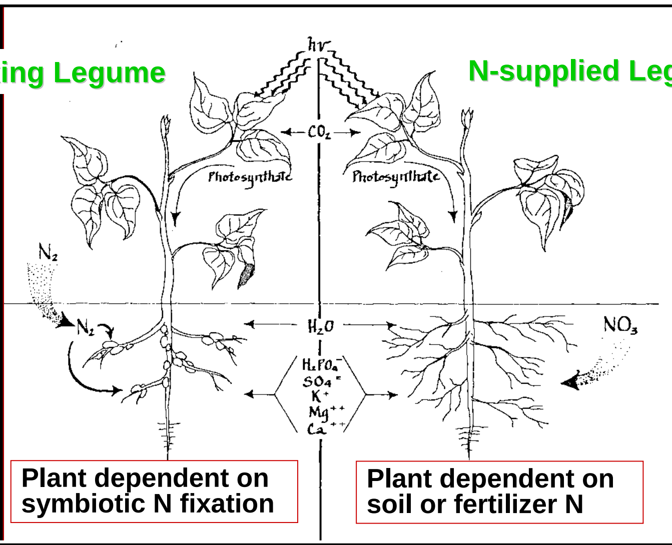
Dynamic N management: improved formulations, placement, timing -- synchronous with crop demand and soil N supply in time and space

Potassium, phosphorus, and micronutrients requirements increase at higher yield levels; nutrient balance more difficult to maintain

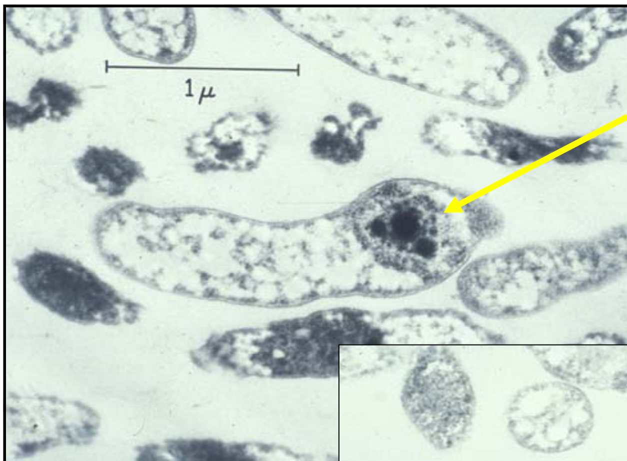
- Major gaps in fundamental knowledge:
  - Why requirements for K sometimes increase more than proportional increase in yield (e.g. cotton, maize)?
  - Why P requirements of legumes increase when crops depend on biological N fixation?
  - Nutrient x disease interactions not well understood especially for K and micronutrients—why are “subclinical” deficient plants more susceptible to disease?
  - Why parasitic weed (orabanche, striga) pressure decreases in soils with greater fertility levels—especially for phosphorus


DEPTH (cm)
- 0 -
- 20 -
- 40 -
SURFACE SOIL (PLOW LAYER)
SUBSURFACE ZONE
SUBSOIL
DISTRIBUTION GRADIENTS
H_2O NPK PATHOGENS
Immobile soil nutrients and organic matter are concentrated in uppermost surface soil layers over time, especially in no-till systems and in soils with K- or P-fixing properties.

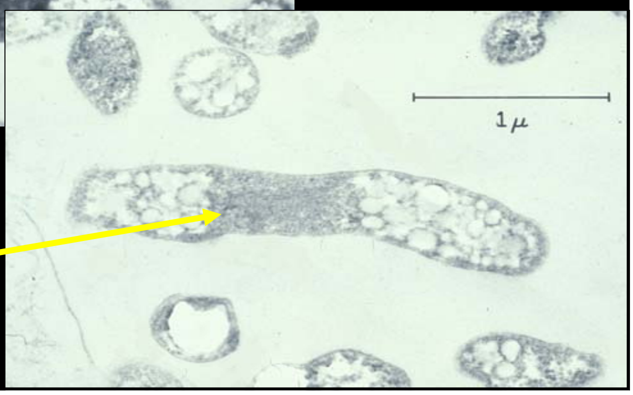

0-8"
0-20cm
8-16"
20-40cm
16-32"
40-80cm
The root system of some crop species (e.g. cotton) exploit poorly the uppermost surface soil layer where immobile nutrients are concentrated due to genetic control of root system architecture



N-fixing root nodules form at the expense of root lateral formation. Hence, legumes that depend on BNF for the majority of their N supply have reduced root development, which reduces ability to acquire nutrients—especially immobile nutrients such as P and micronutrients



Soybean rhizobium cell grown with adequate phosphorus supply store P in polyphosphorus granules.



Soybean rhizobium grown with deficient phosphorus supply similar to the root rhizosphere do not store P.

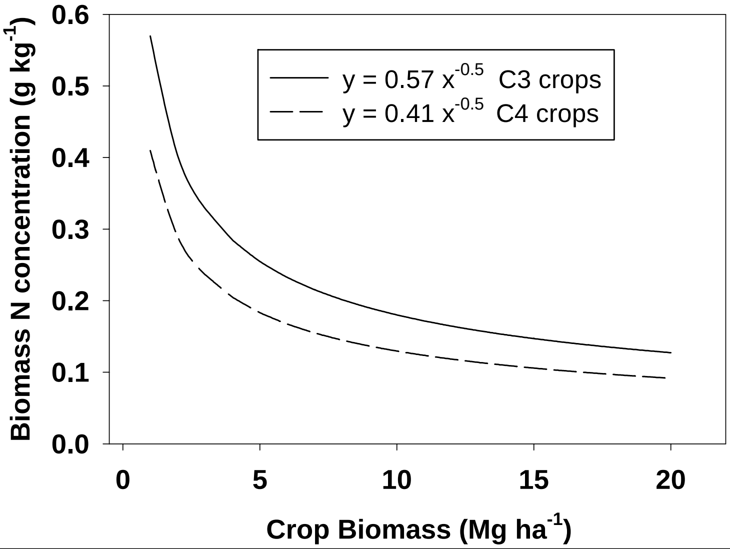
The challenge unmet:

- Meeting nutrient requirements of high-yield cropping systems while protecting environmental quality and conserving natural resources
  - Average farm yields at 85-90% of yield potential
  - Net positive environmental impact
- Who is currently leading research in this critical area and how much funding is it receiving?
  - Universities?
  - CGIAR Centers (IRRI, CIMMYT, etc)?
  - National agricultural research institutions (USDA, INRA, IARI, EMBRAPA, etc)?
  - Seed companies?
  - Fertilizer industry?
  - NGOs?

Are genomics and GMOs silver bullets?

- The tremendous increase in public- and private- sector research in these areas, at the expense of crop and soil management research, indicates that research leaders believe they are a panecea
- Poor prospects for improving N efficiency of major food crops via biotechnology (perhaps in some secondary crops that have not received much crop improvement attention?)
- Root system architecture is most promising target for biotech manipulation; only marginal improvements possible without mproving crop and soil management
- Are we over-investing in biotech solutions given decreasing overall investment in agric research?

The relationship between plant biomass yield and N content is tightly conserved when N is the primary limiting growth factor: Greenwood et al, *Ann. Bot.* 1990. Implication—little scope for genetic improvement of N use efficiency.



Conclusions

- **The scientific challenge of achieving global food security and protection of natural resources has been grossly underestimated:**
  - **Cereal demand is expanding rapidly because of population growth, robust economic growth, increasing use of grain for livestock, biofuels and bio-based feedstock**
  - **Land area suitable for intensive cereal production is decreasing**
  - **The rate of increase in cereal yields is falling below the rate of increase in demand**
  - **Genetic yield potential of rice and maize has not increased for over 30 years**
  - **Net effect on yield of increasing temperature and higher atmospheric [CO_2] from climate change is negative**
- **Average farm yields must reach 85-90% of genetic yield potential in the major cereal cropping systems—especially on irrigated land**
- **Dynamic, robust, efficient, profitable nutrient management approaches should be high priority!**

Related citations*

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