Molecular plant physiology: the significance of plant nutrition in supporting human nutrition

Plant Nutrition

- **Molecular biology** allows us to identify the genes responsible for nutrient uptake, transport and utilization in plants.
- Ultimately it will be possible to **'design'** plants with specific traits to ensure optimal productivity in a given environment or to use these genes as molecular markers for conventional breeding.
- The challenge is to identify the most logical targets and to integrate these transgenic plants into the **food production** system.

Outline

- Problems associated with human nutrition.
- Target Processes
- Current Status of Research

Food Systems, Diet and Disease

- Global food systems are **failing to provide adequate quantities of essential nutrients** and other factors needed for good health, productivity and well being in many developing nations,
- Green revolution cropping systems have resulted in reduced food-crop diversity and **decreased availability of micronutrients**.

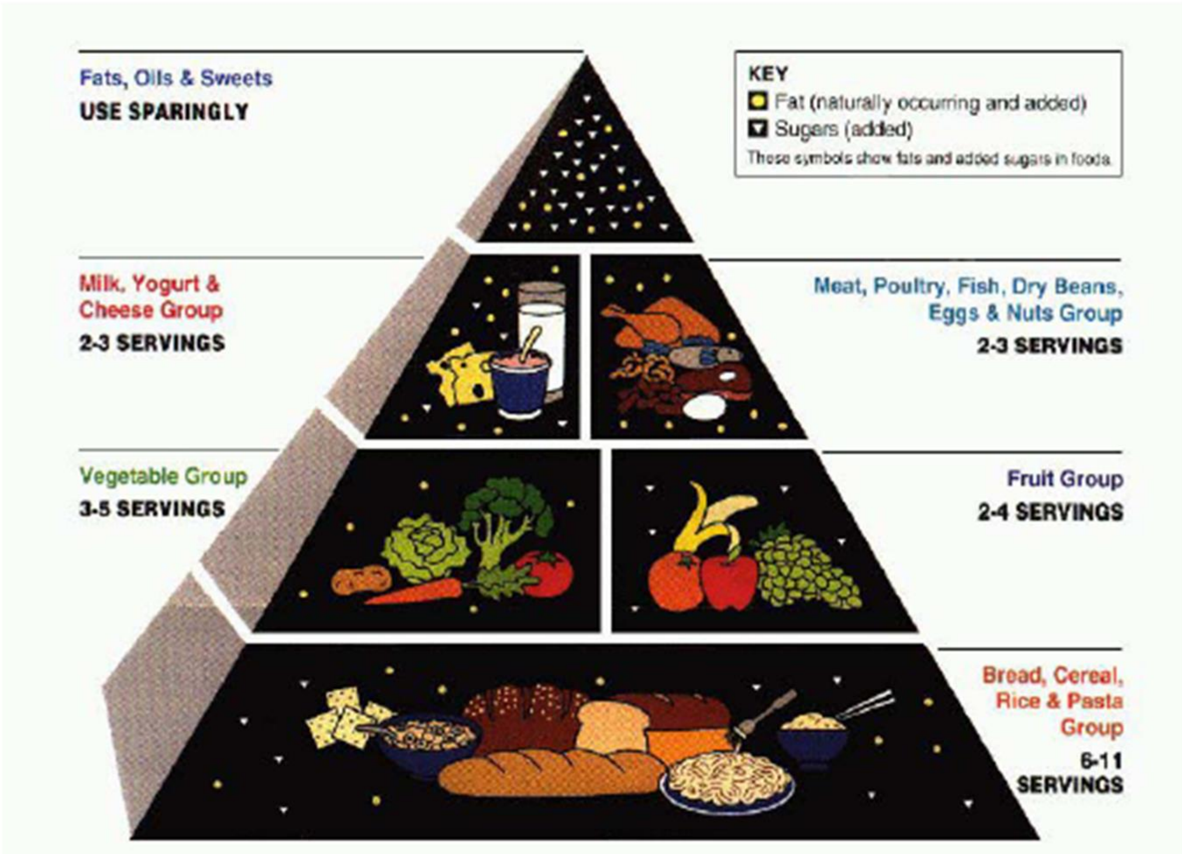
Food Systems, Diet and Disease

- Nutrition transitions are causing increased rates of **chronic diseases (cancer, heart disease, stroke, diabetes, osteoporosis)**
- Holistic, sustainable improvements in the **entire food system** are required to solve the massive problem of malnutrition and increasing chronic disease rates in developed and developing countries.
- How can agriculture & molecular technologies contribute?

Global Food Systems' Problems

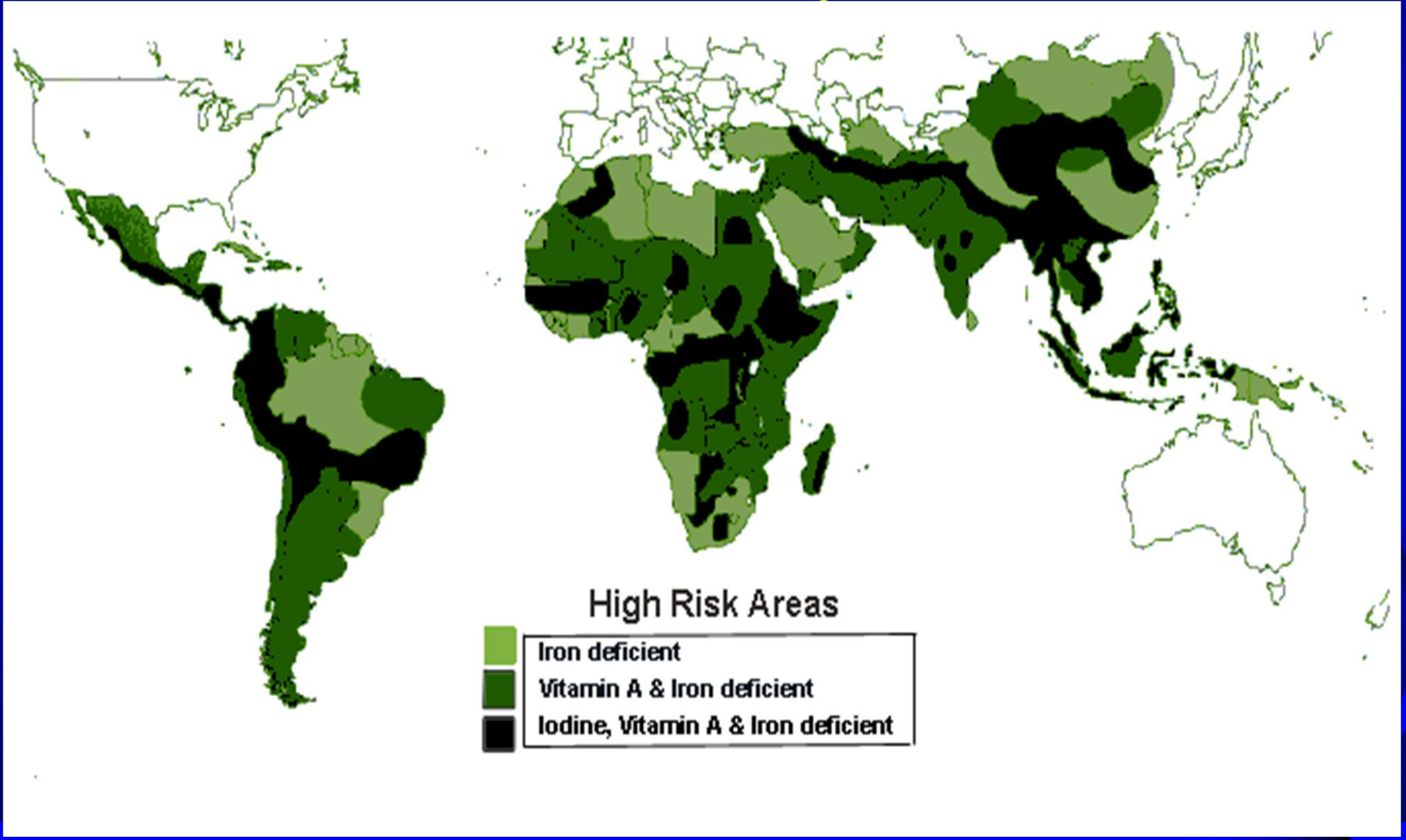
- Agriculture's primary focus is on production alone, with **little concern for nutritional** or health-promoting qualities.
- Nutritionists tend to emphasize unsustainable **medical approaches** to solve malnutrition problems
  - supplements
  - food fortificants
- Simplistic views are the norm – looking for **"silver bullet"** approaches for solutions

Improving nutrient output of agricultural systems to meet human needs



Food Guide Pyramid – Diversity the Key

Global Prevalence of Iron, Vitamin A and Iodine Deficiencies (>3 billion are affected)



Global Malnutrition & Nutrition-related Diseases (WHO, 2000)

Protein-energy malnutrition - 149.6 million under-five children - slowly decreasing

Iodine deficiency disorders - 740 million - rapid progress towards elimination in some sectors in some countries

Vitamin A deficiency blindness - 2.8 million under-five children - slowly decreasing

Iron deficiency anemia – 1.48 billion women, children and men

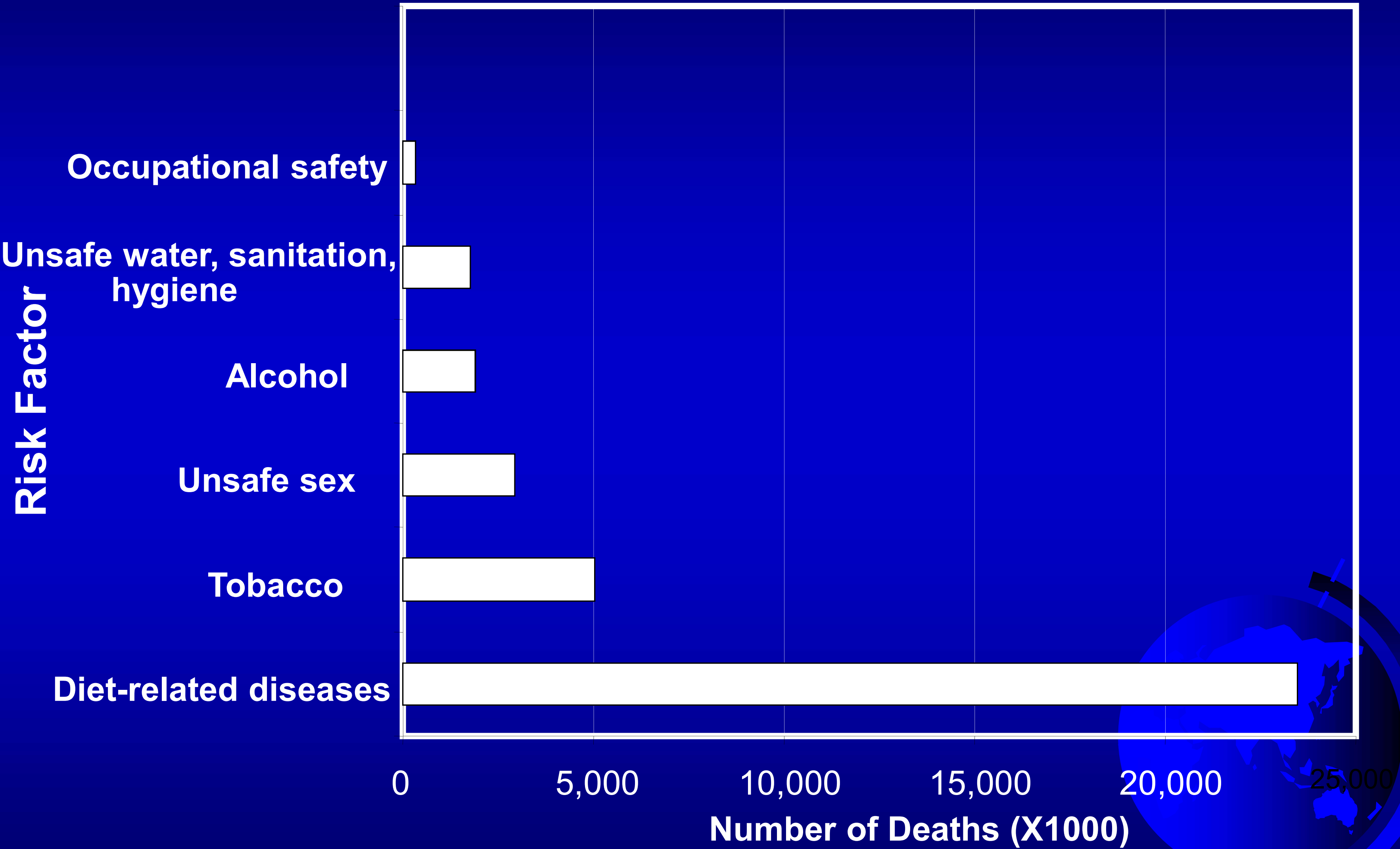
Global Malnutrition & Nutrition-related Diseases (WHO, 2000)

- **Cancer (diet-related) -** Of 10.3 million cases of cancer per year, 3-4 million (30-40%) are preventable by feasible appropriate diets and exercise.
- **Malnutrition of the elderly -** 540 million elderly - well over half - have some diet/nutrition-related degenerative disease - cardiovascular, diabetes, osteoporosis, cancer.
- **Osteoporosis -** Around 2 million hip/spine fractures per year (80% in women).
- **Also:** Scurvy (vitamin C), beriberi (thiamine, B1), rickets (vitamin D & Ca), folate, Zn, & Se deficiencies are causing deaths of millions worldwide.

The Known 50 Essential Nutrients for Sustaining Human Life

Water & Energy (2)	Protein (amino acids) (9)	Lipids-Fat (fatty acids) (2)	Macro-Minerals (7)	Micro-Elements (17)	Vitamins (13)
Water	Histidine	Linoleic acid	Na	Fe	A
Carbohydrates	Isoleucine		K	Zn	D
	Leucine		Ca	Cu	E
	Lysine	Linolenic acid	Mg	Mn	K
	Methionine		S	I	C (Ascorbic acid)
	Phenylalanine		P	F	B_1 (Thiamin)
	Threonine		Cl	B	B_2 (Riboflavin)
	Tryptophan			Se	B_3 (Pantothenic acid)
	Valine			Mo	Niacin
				Ni	B_6 (Pyridoxal)
				Cr	Folate
				V	Biotin
				Si	B_{12} (Cobalamin)
				As	
				Li	
				Sn	
				Co (in B_{12})	

Some WHO Major Risk Factors Causing World Deaths in 2000



(World Health Report, 2002)

Malnutrition -

will be responsible for 3,000 deaths globally, mostly women, infants and children, during this lecture!

- Globally, one in three people are malnourished
- This global crisis is happening now!
- These deaths are preventable!
- What is the root cause of these deaths?
- What can we do to prevent them from happening in a sustainable way?

Calcium Deficiency

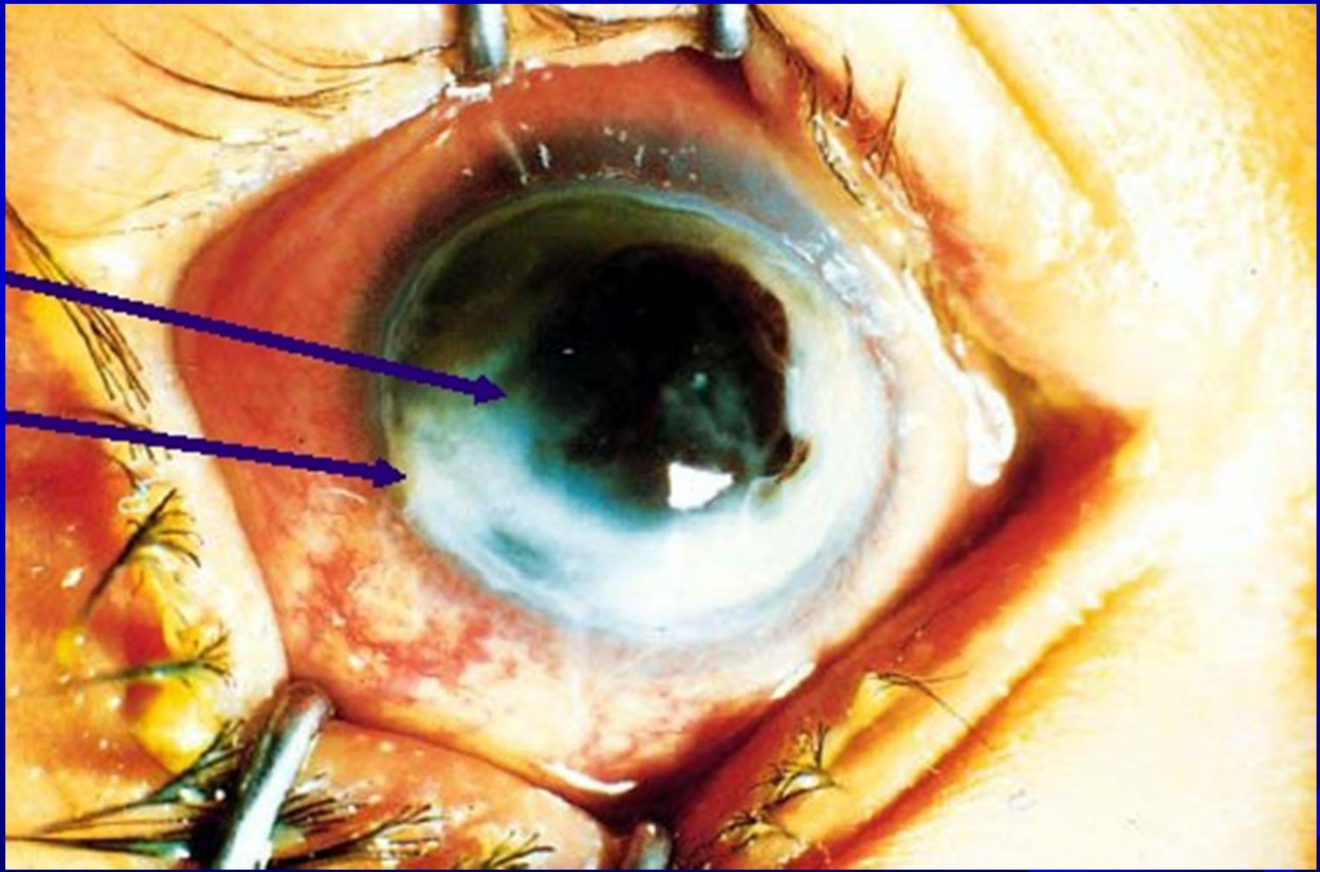
Zn deficiency

Fe deficiency

Vitamin A Deficiency in a 3 year-old Indonesian Child

Dissolved cornia

Buldging iris with whitish material

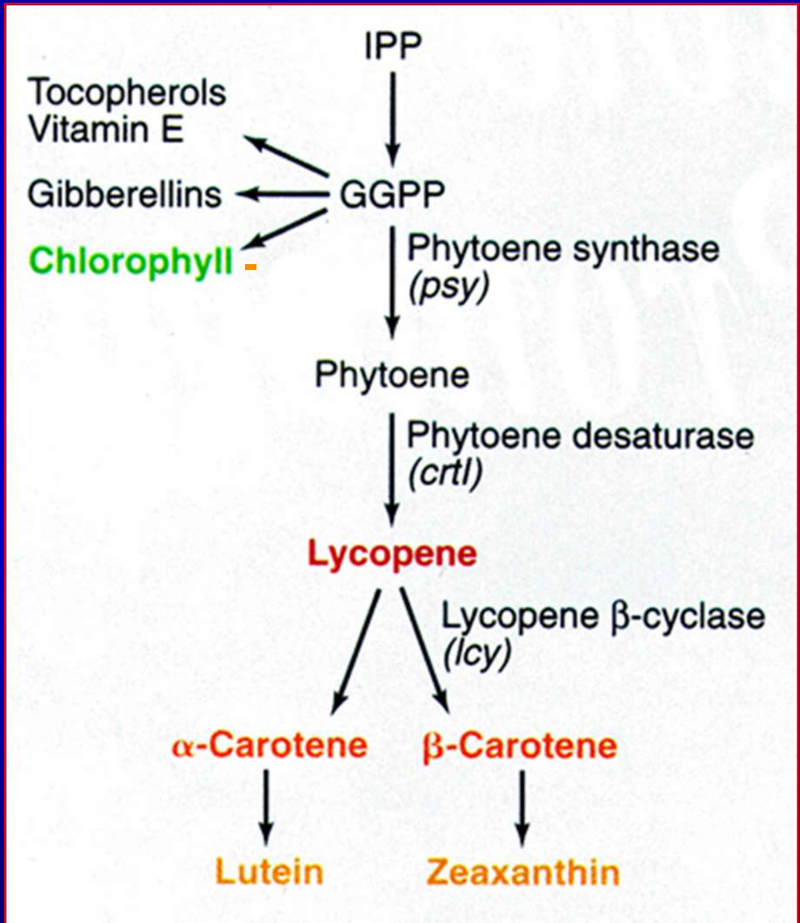


Iodine Deficiency Goiter

IMPROVEMENT OF THE NUTRITIONAL QUALITY OF FOODS

- Increase density of trace minerals
  - increased uptake
  - increased allocation to edible portion of crop
- Decrease density of anti-nutrients
  - phytates
  - tannins
- Increase density of substances that promote bioavailability of trace minerals
  - hemoglobin
  - ferritin

Golden Rice



Introduced enzyme (source)

(daffodil)

(bacteria)

(daffodil)

Normal rice

"Golden" rice

Ye et al. (2000) Science 287: 303 - 305.

Increase in Iron absorption by heme.

Source of Iron	Normal men	Normal women
Heme	20	31
Non heme	2.5	7.5

HEMOGLOBIN

- Presence of different hemoglobins in plants has long been known but not exploited. [Kubo, 1939; Appleby, 1984; Gibson et al., 1989; Bogusz et al., 1990]
- Introduction of hemoglobin in tobacco has been successfully completed but not tested for nutritional value. [Bogusz et al., 1990; Holmberg et al., 1997]
- Other high-Fe proteins have also been incorporated (Ferritin from soy expressed in Rice).

PHYTATE

- Major antinutrient in grain seeds dramatically reduces Fe and Zn bioavailability. [Combs et al., 1996]
- Mutants with 50-80% reduced phytate, unaffected agronomically. [Raboy, 1997]
- However, phytate is a highly conserved molecule and is thought to be important for seed viability and vigor of the seedling. [Welch, 1996]

Enhanced content of health promoting phytochemicals

- Composition of many ‘secondary’ products is influenced by nutritional status and agronomic practices.
- Improved processing and storage characteristics.
    - Influenced by Overall Nutrient Balance.

Agricultural Approaches to "Healthier" Plant Foods

- Field Site Selection
- Agronomic Practices
  - macronutrient fertilizers
  - nitrogen, phosphorus, potassium, sulfur, calcium, magnesium
  - affects protein, fats, vitamins, antinutrients, etc.
  - micronutrient & trace element fertilizers
  - Zn, Se, Co, Ni, I, Mo, Li, Cl - effective in increasing amount in plant seeds and grains
  - Fe, Cu, Mn, B - not effective in increasing seed or grain levels

Agricultural Approaches to "Healthier" Plant Foods

- Cropping systems
  - **legume-cereal** rotations -affects micronutrient content
  - use **micronutrient-dense varieties** of food crops
  - increase production of **vegetables, fruits, & legumes**
- Utilize **indigenous plant foods** and **diversify food** systems
- Genetically modify food crops to improve nutrient output of farming systems

Large Genetic Potential to Improve the Micronutrient Efficiency of Crops

- Historically, plant breeders did not select for micronutrient efficient traits in food crops
  - used most fertile soils in selection process
  - resulted in high yielding varieties that require high inputs to maximize yields
- Within "wild" relatives and land races of crop plants large variation exists to improve micronutrient efficiencies in crop plants
- Limitation to breeders is the ability to screen genotypes for micronutrient efficiency traits

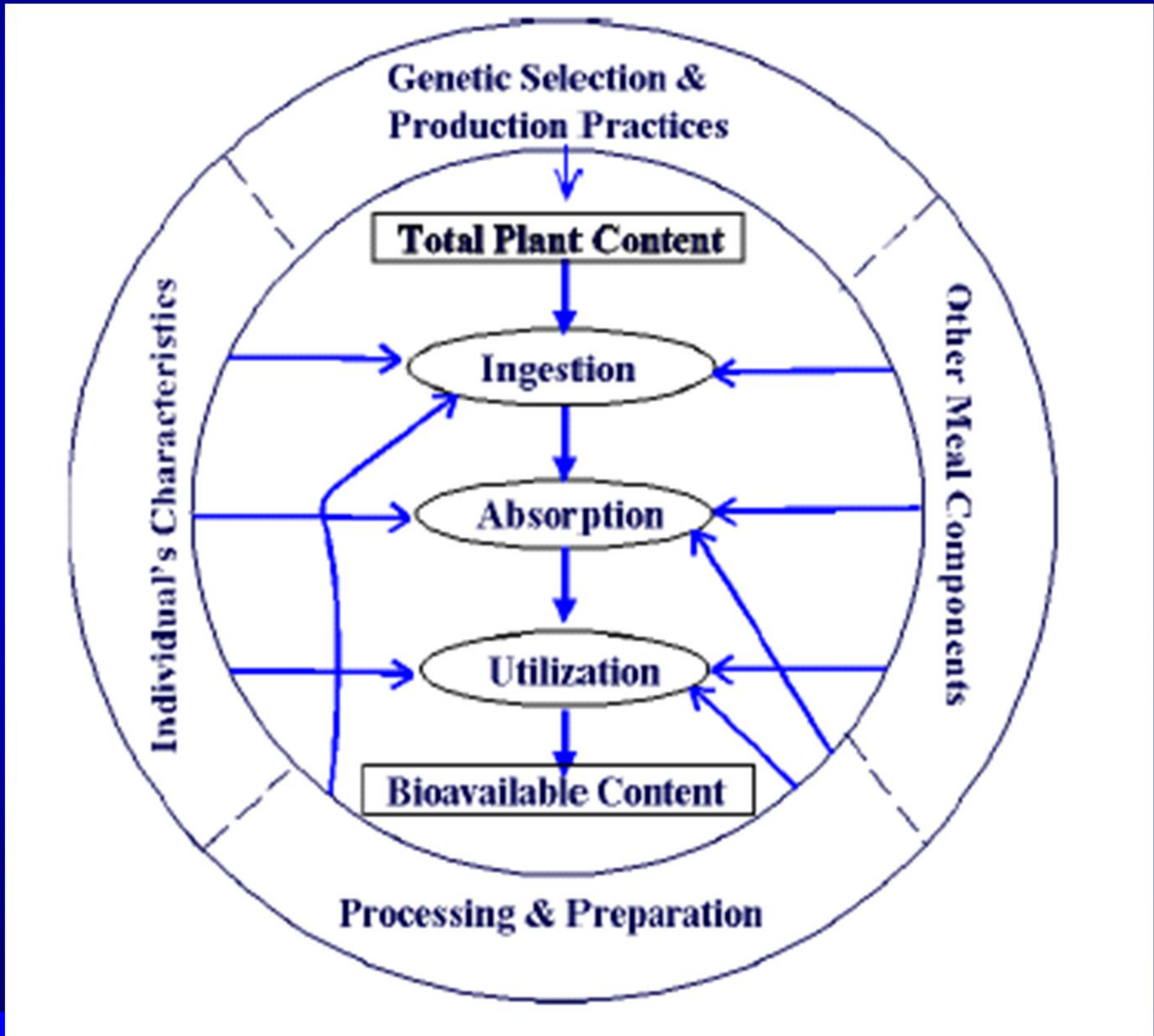
Agronomic Benefits of Micronutrient Element-Enriched Seeds (e.g. Zn)

- Better seed viability
- Greater seedling vigor
- Denser stands (less soil erosion)
- Lower seeding rates (lower cost to farmers)
- Larger root absorptive surface (better water & nutrient use efficiency)
- Better resistance to disease
- Better plant survival
- Increased plant & seed yield

The Importance of Bioavailability

- **Bioavailable** amount of a micronutrient in a meal, not the total amount, is the critical factor for human health
- Definition – the amount of a nutrient in a food that can be **absorbed** from a typical diet and utilized in the body
- Most staple plant foods (cereal grains and legume seeds) fed alone contain **very low levels** of bioavailable **Fe** and **Zn** (e.g., about 5%) because of the **antinutrients** they contain (phytate, polyphenols, etc.)
- Increasing the bioavailability of micronutrients from **5% to 30%** would have the same effect as increasing their total amounts in staples by **6 fold**

Complexities of Bioavailability



Agriculture's
Agenda for Better Health

- Make **human health** and well being an explicit goal of agricultural systems in addition to productivity & environmental goals
- **Re-diversify** cropping systems & design for maximum nutrient output.
- Make more use of **indigenous micronutrient-dense** edible plant species, small livestock, & fish
- Use agricultural practices (e.g., fertilizers) that increase the **bioavailable micronutrient** output of farming systems
- Breed for and select for **bioavailable** micronutrient-dense **staple food crops** with micronutrient efficiencies
- **Genetically modify** plants to increase nutritional & health promoting factors
- Redefine sustainable agriculture to include adequate nutrient output for healthy & productive lives.

Role of plant nutrition to increasing productivity

Target Processes

- Overcoming limitations to productivity
  - Deficiencies
  - Toxicities
  - Problem soils (pH, salt, nutrient imbalance, heavy metals)
  - Efficiency of nutrient usage,
  - Emphasis on preventing, correcting and tolerating pollution.
  - Improved effectiveness of fertilizers

Target Processes

- Enhancing crop quality and food value
  - Increased micronutrients density and availability in consumed product (grain)
  - Improved food quality (nutritional value, health promoting characteristics) and processing characteristics
  - Improved expression of transgenes through optimization of plant nutrition.

Approaches to Overcoming Deficiencies and Toxicities

- MANIPULATION OF UPTAKE
- Identification of genes responsible for nutrient uptake, i.e. Protein ‘Carriers’ or ‘Channels’ and their regulation.
- Identification of genes responsible for solubilizing nutrients in the soil. Relevant for sparingly soluble nutrients such as Fe, P, Zn, Cu, Mn.

Transporter proteins involved in nutrient uptake

NO_3^--N	NH_4^+-N	Potassium	Phosphorus
NRT1(1-2)	AMT1	ATK1	ATP1
NRT2(1-2)		SKOR	ATP2
NRT3		HvHAK1-2	AtPT4
CHL1		AtKUP1-4	StPT1
CHL8(?)		AtKUP1	AtPT2
PTR2B		HKT1	StPT2
			GvPT
			LePT1
			MtPT1

Potential Opportunities to Manipulate Uptake

- All species contain a suite of channels and carriers. To date no particular carrier has been shown to be uniquely superior, there has been no improvement of nutrient uptake through transfer of overexpression of any of these genes in an engineered plant.
- Down regulation of uptake genes may help tolerance of toxic soils and reduce uptake of contaminant metals (i.e. Cd)

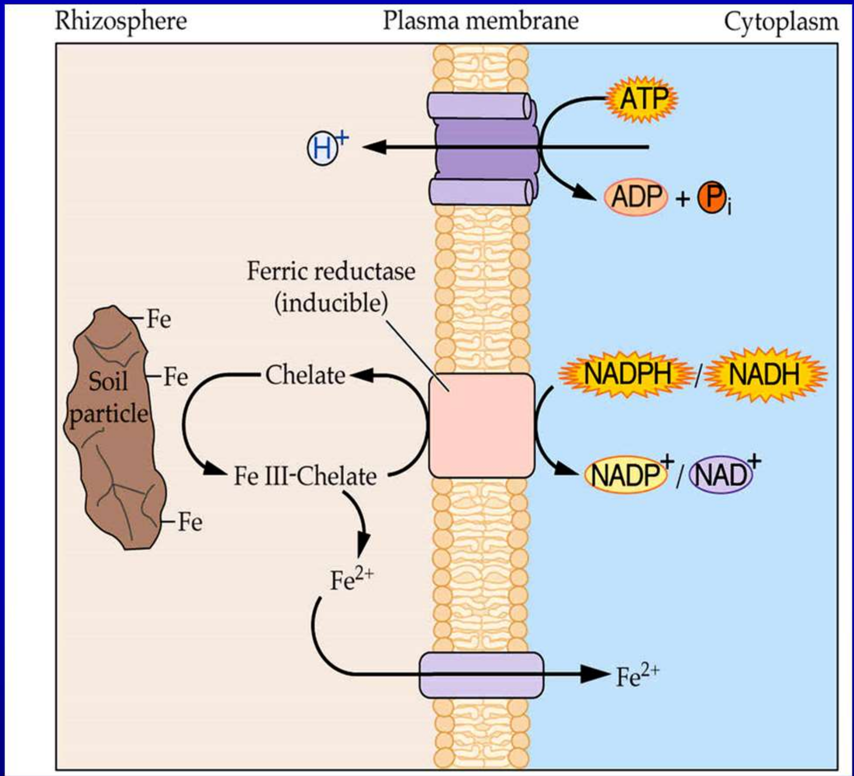
Potential Opportunities to Manipulate Uptake

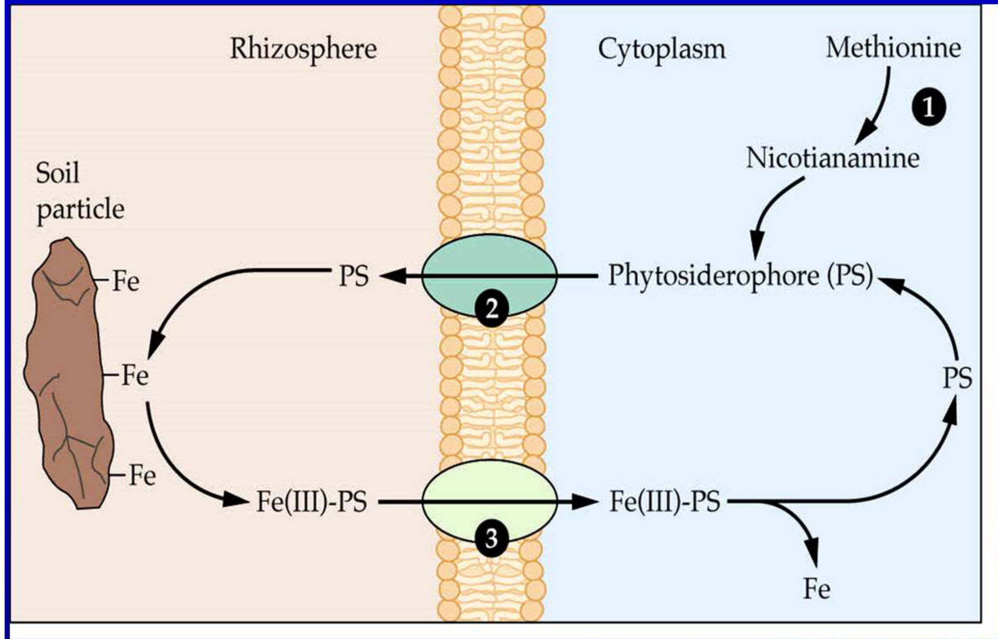
- Limitations include:
  - Multiple levels of redundancy
  - Integrated regulation of nutrient status
  - Irrespective of uptake characteristics the demand for nutrient remains yield dependent.
  - In a well managed field fertilization is a more effective solution.

Enhancing Adaptive mechanisms to problem soils

- Limited solubility of certain elements in the soil due to soil properties (notably Fe and P) can result in deficiencies that cannot be readily corrected through fertilization.
- Excesses of nutrients can substantially limit productivity in certain soils (notably Na, Al, Fe)

Rhizosphere Changes





Manipulation of Adaptive Mechanisms to Problem Soils has Considerable Potential

- Biosynthetic pathway for phytosiderophore production has not been fully determined. Multi-gene character.
- Manipulation of production of excreted organic acids, reductants and protons is clearly achievable.

Conclusion

- There are many mechanisms that can be modified
- Molecular biology offers many tools to solve nutrition problems and use conventional breeding for finding the best genotype.

What can you do?

- Become informed
- Promote food-based system approaches to finding sustainable solutions to malnutrition
- Advocate for a food systems program at Cornell University and at other universities
- Tell a friend/student/colleague about the critical role agriculture plays in human health
- Advocate for more nutrition education in elementary schools, high schools & medical schools
- Advocate for close ties between nutrition and agriculture, agriculture and health, health and nutrition at all levels in global food systems
- Advocate to include human nutrition & health as part of sustainable agriculture goals