Nickel and Plant Disease

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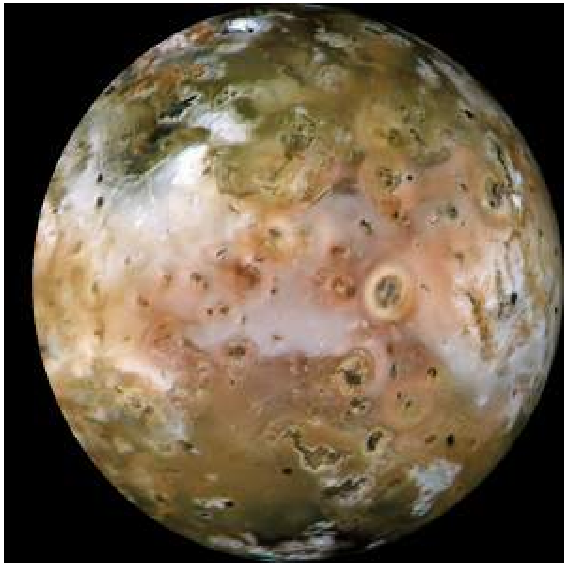
USDA ARS

Part I:
General Perspective

- Relatively little is known compared to other trace nutrients:
  - Agricultural significance?
  - Roles in plant metabolism, growth, and development?
  - *Disease resistance???*

Nickel as an *Essential* Trace Nutrient: A Diminishing Role



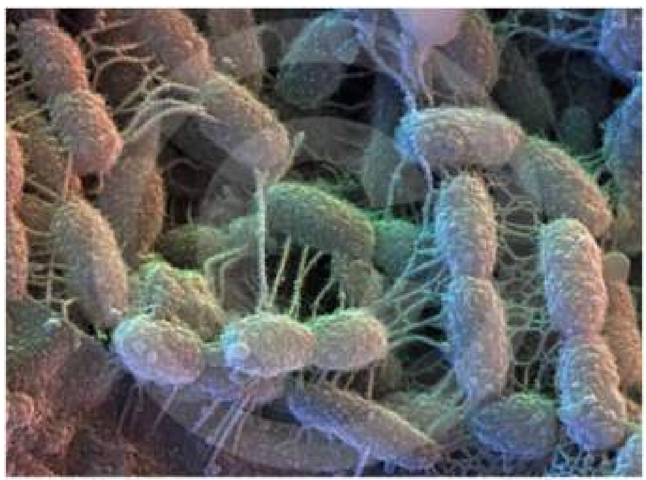
Early Earth Atmosphere:

-2.7 billion-years (60% of history)
-CH_4, H_2, CO, H_2S, NH_4
-Electron-rich gases
-*Reducing atmosphere*
-Nickel is a primary catalyst
-Ni, Co, Ti, V act as major catalysts

Late Earth Atmosphere:

-1.8 billion years (40% of history)
-0.6 billion year-ago (proliferation of complex organisms)
-CO_2, N_2, O_2
-Electron-poor gases
-*Oxidizing atmosphere*
-Nickel plays a relatively minor role
-Mn, Fe, Cu, Zn act as major catalysts

Today's Earth: Nickel's Role is Diminished but Still Critical



Low Nickel
(ppb--most plants)

Medium Nickel
(ppm--tropical legumes)

High Nickel
(ppm—
certain hydrophiles)

High Nickel

Early Earth

Now: ~248,000 known species of higher plants;
~69,000 known species of fungi

Now

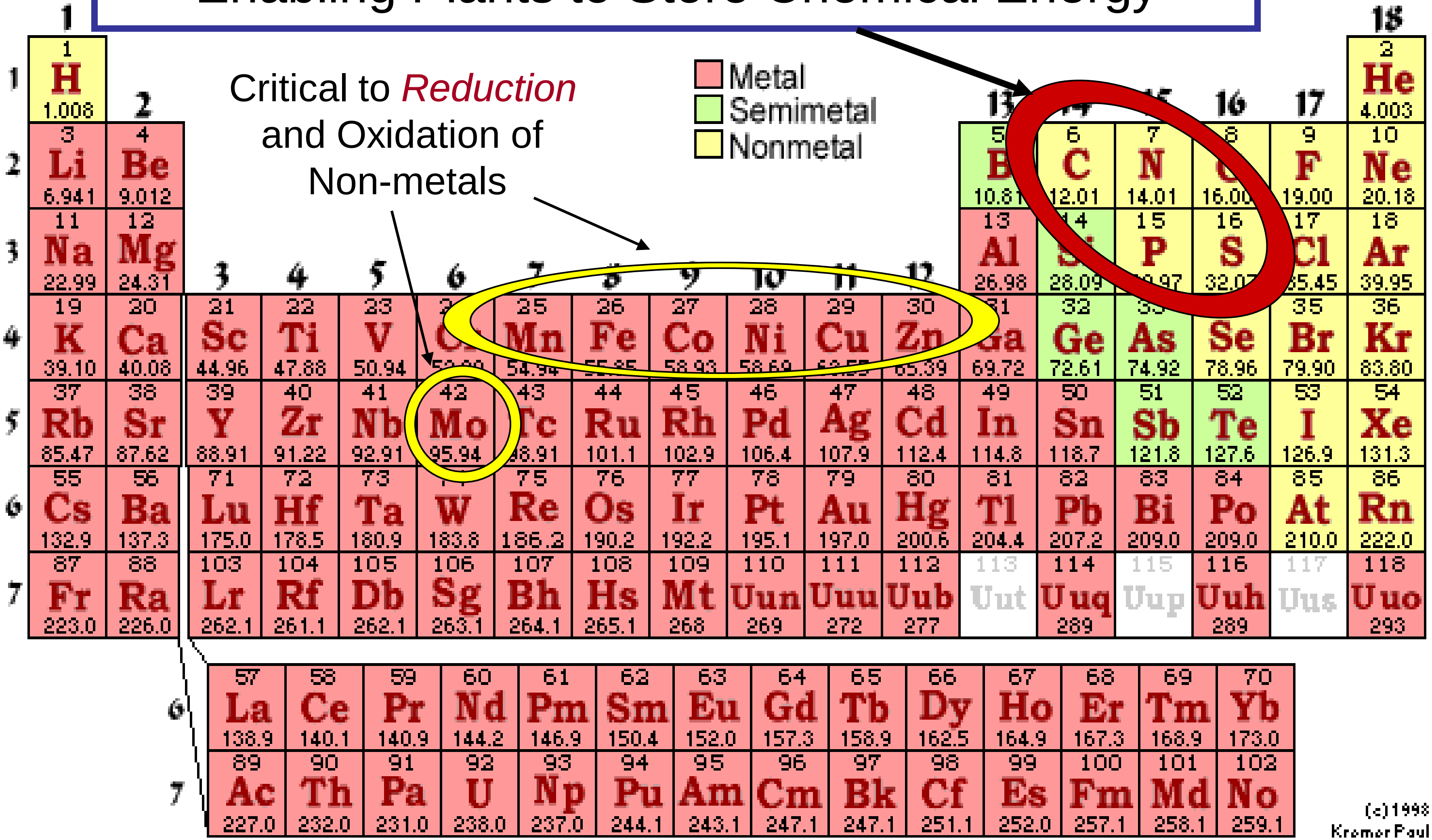
Part II:
Nickel's Relevance to Key Non-metals Involved in Disease Resistance

“The Big Five”!!!



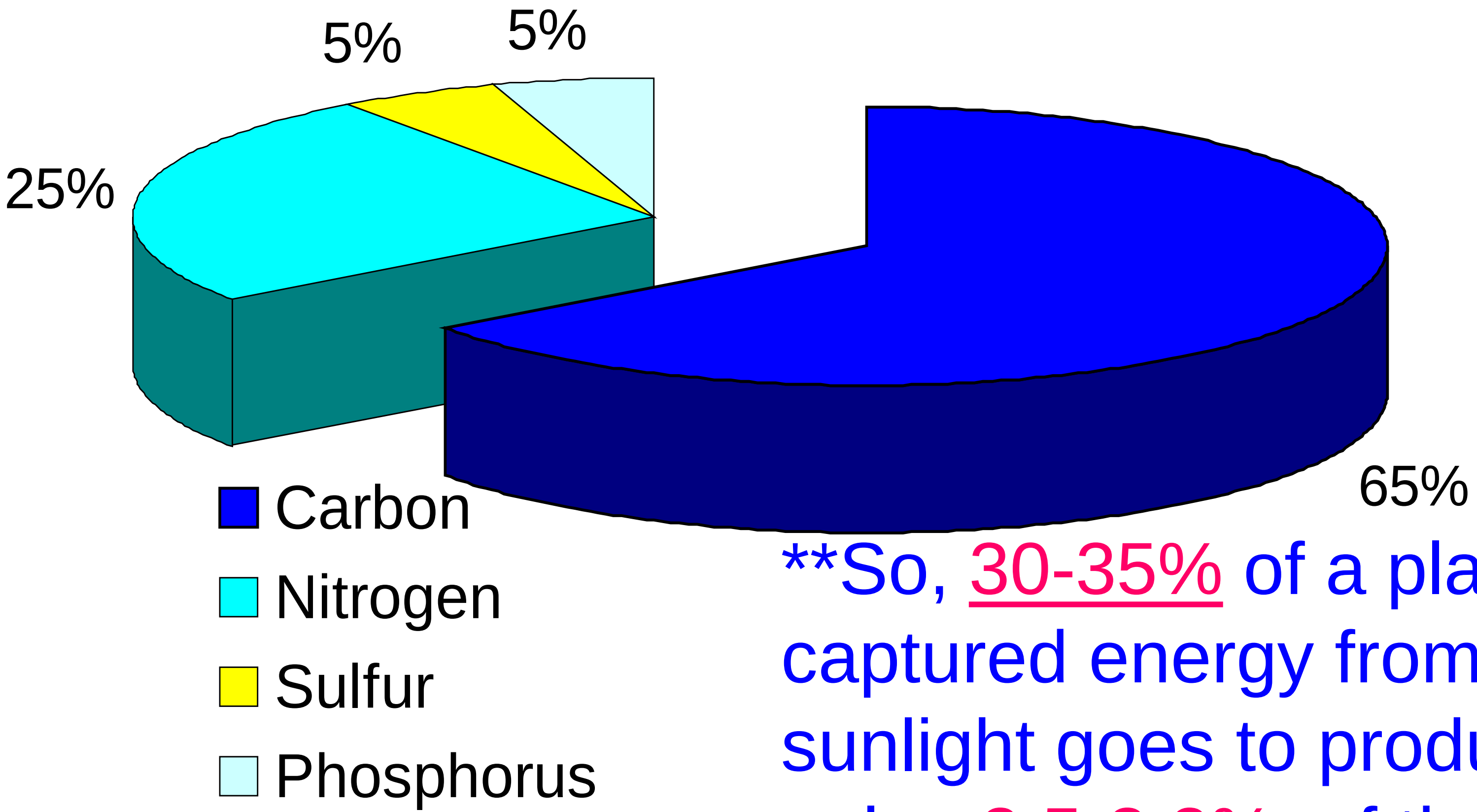


The "Big 4" Non-metals Are Key Elements Enabling Plants to Store Chemical Energy



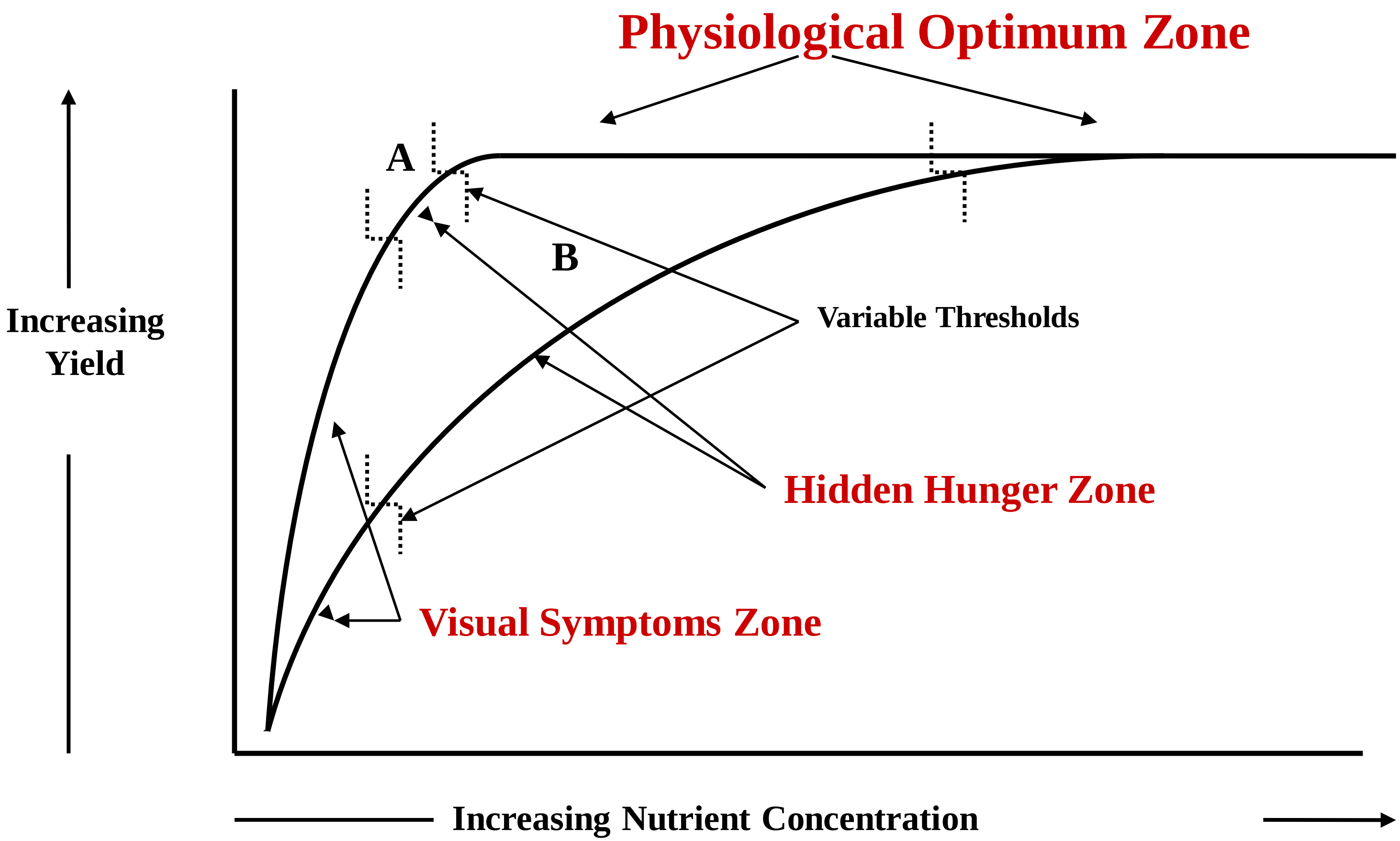
Non-metals are "critical" for storage of chemical energy!!!

Photoassimilation of Non-metals Consume a Disproportionably Large Amount of the Total Energy Expended by Higher Plants



**So, 30-35% of a plant's captured energy from sunlight goes to produce only ~2.5-3.2% of the plant's dry weight!!!

General Relationship Between Yield and Mineral Nutrition



Fundamental Role of Nickel in Crops

- The following major enzymes, in either lower or higher plants, require Ni for catalysis:
  - ***"Urease"***
  - Superoxide dismutase
  - NiFe hydrogenases
  - Methyl coenzyme M reductase
  - Carbon monoxide dehydrogenase
  - Acetyl coenzyme-A synthase
  - Hydrogenases
  - RNase-A
  - *Probably several others!!!*

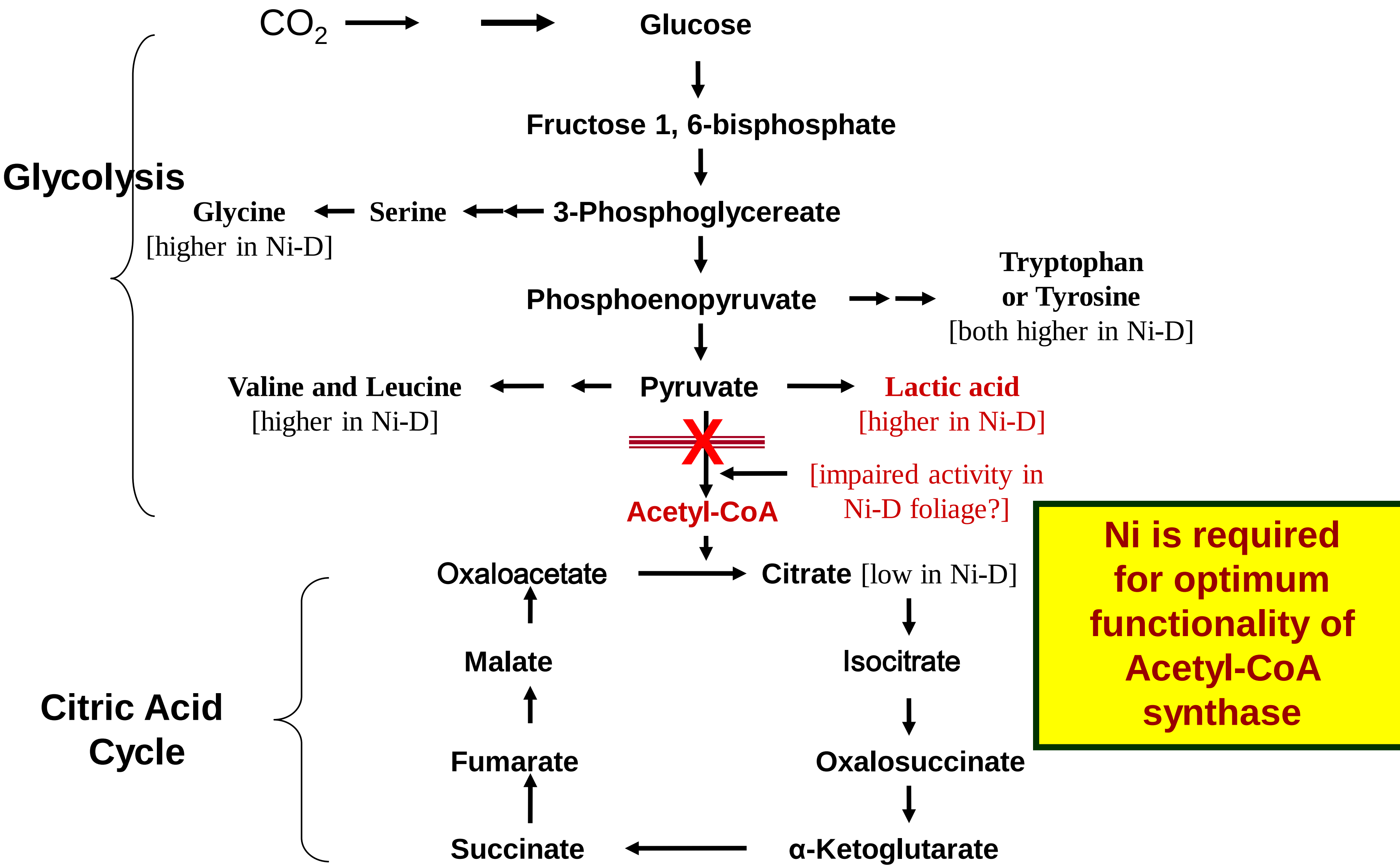
- Also, it is estimated that ~500 proteins and peptides *bind* Ni

Urease Is Not Just for Breakdown of Urea

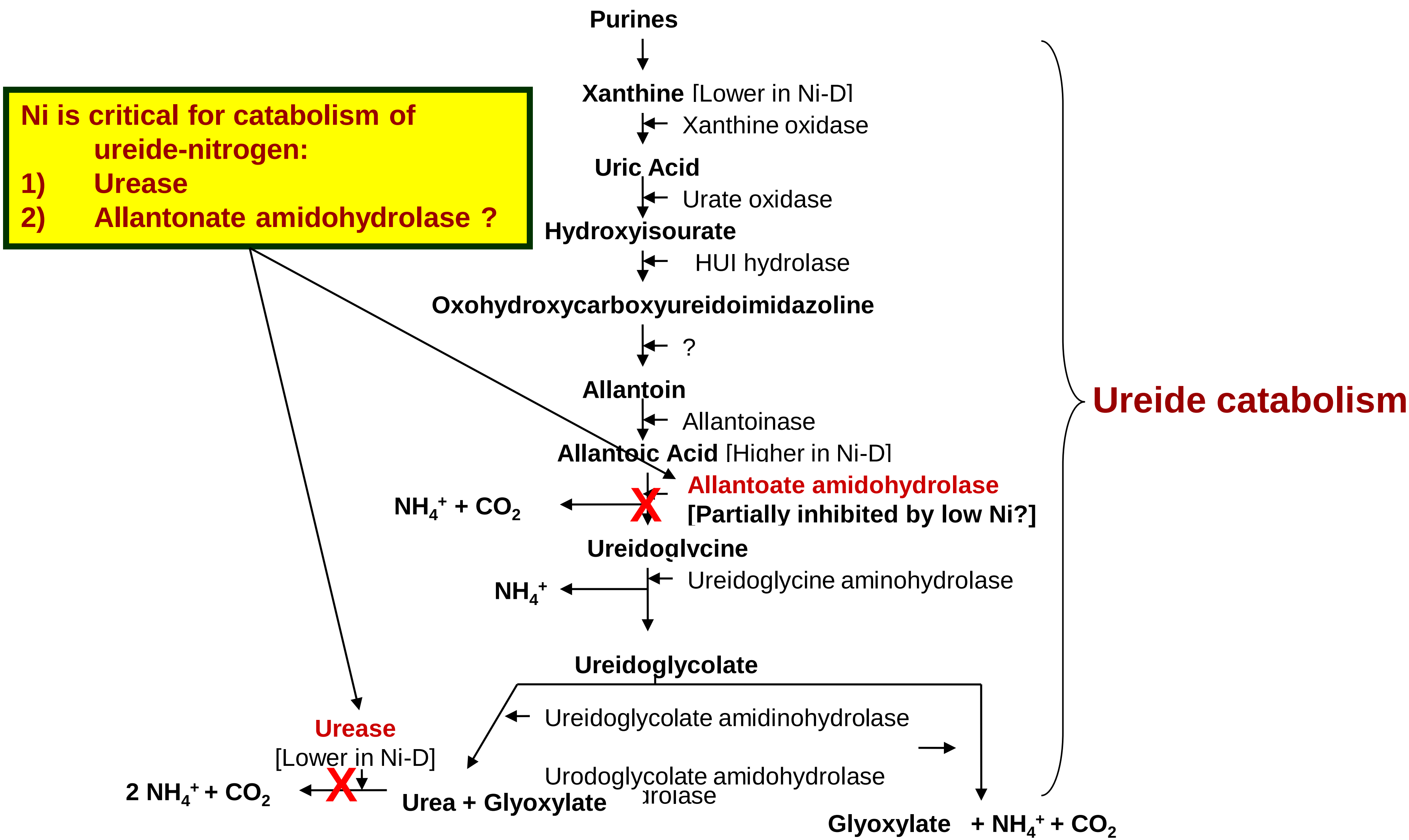
- Substrates of urease :
  - *Urea*
  - Formamide
  - Acetamide
  - N-methylurea
  - N-hydroxyurea
  - N,N’-dihydrosyurea,
  - Semicarbazide
  - Phosphoric acid amides

K_{cat} of alternative substrates are ~10^2 to 10^3 fold lower than observed for urea

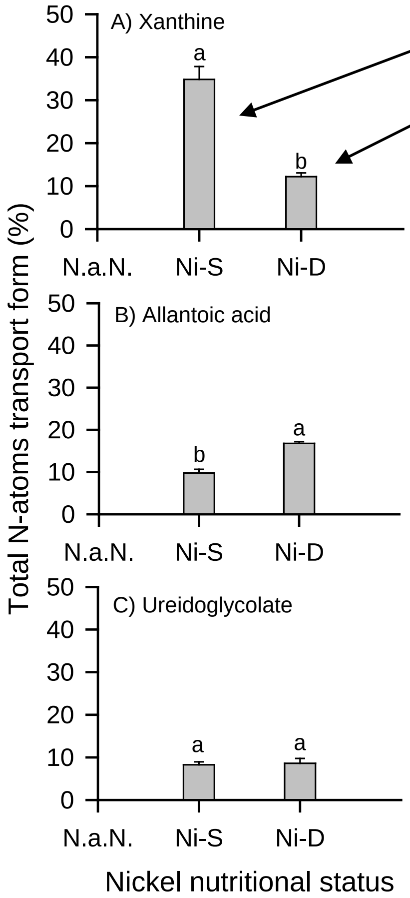
Nickel Deficiency Disrupts Metabolism of Photoassimilated Carbon



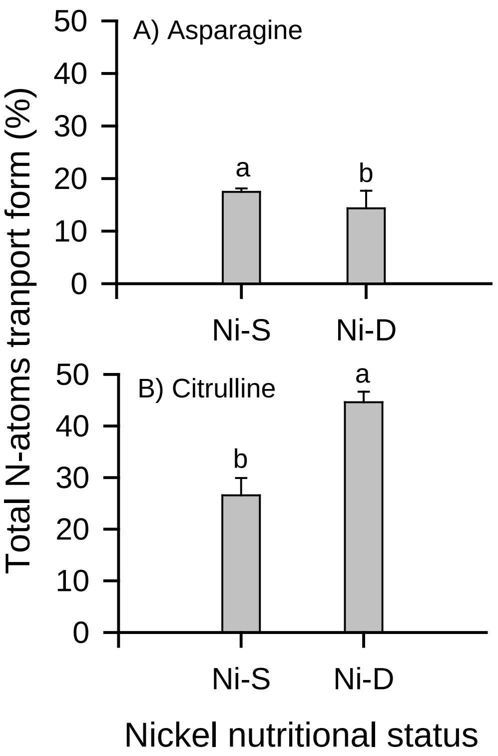
Nickel Deficiency Disrupts Metabolism of Organic Nitrogen



Nickel Status Appears to Affect Breakdown and Forms of Translocated Organic Nitrogenous Compounds From Dormant Season Storage Pools in Perennials



Ni-S = Nickel sufficient
Ni-D = Nickel deficient

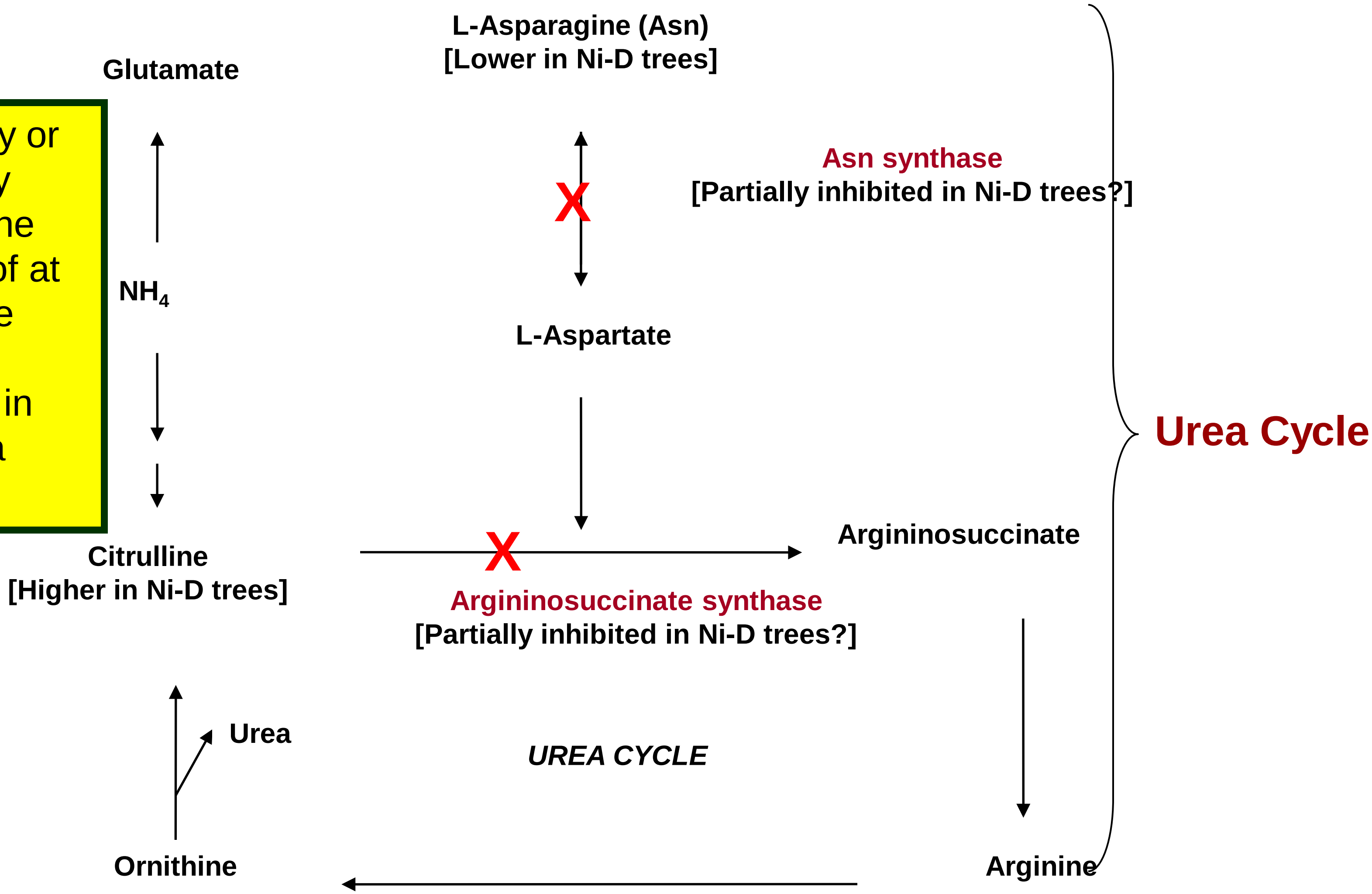


Ni deficiency alters:

a) the form of N translocated and
b) the economy of N and C translocation

Nickel Deficiency Appears to Potentially Disrupt the Urea Cycle

Ni directly or indirectly affects the activity of at least one critical enzyme in the Urea Cycle



Part III:
Nickel's Relevance to Plant Defense

- Plants are surrounded by an enormous number of potential enemies (e.g., fungi, bacteria, viruses, nematodes, mites, insects, mammals, etc.).
- They cannot move away from enemies!
- How do they protect themselves?

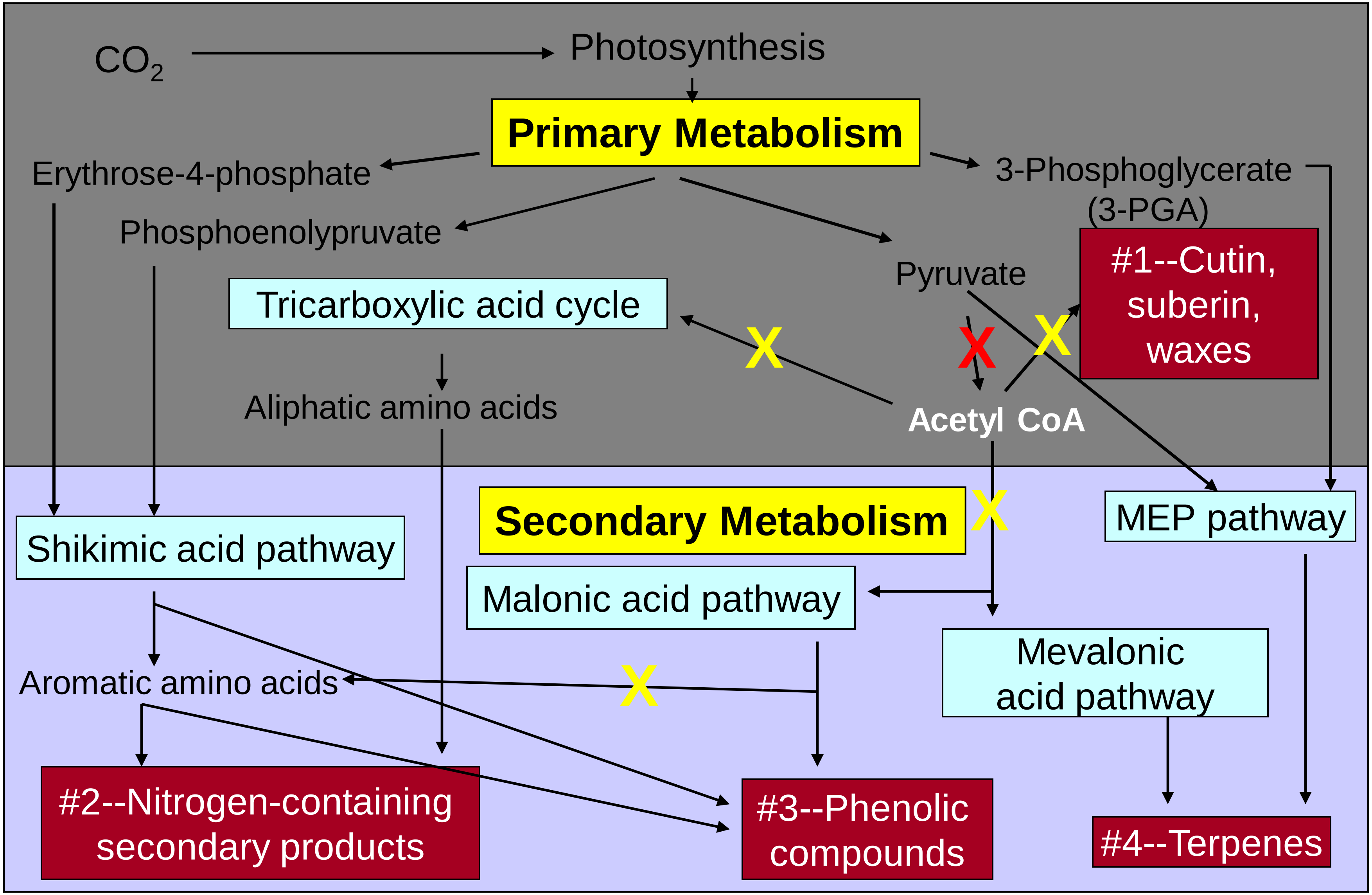
1) Physical barriers:

-Lipids (e.g., waxes, cutin, suberin)

2) Harmful chemicals (chemical weapons):

-Secondary metabolites (e.g., classes of terpenes, phenolics, nitrogen-containing compounds)

Plant Disease Defense: Four Key Strategies



Nutrient Imbalances: Absolute vs. Ratio

In terms of organ or tissue composition, the concentration *ratio* of the various nutrients can be more important than the *absolute* concentration of each element!!!

Examples:

Ni/Zn—Little leaf & replant disease of pecan

Ni/Cu—Little leaf & replant disease of pecan

Ni/(Zn+Cu)—Little leaf & replant disease of pecan

K/Mg—Fusarium in cotton

Ca/K—Rot gummosis of orange

N/K—Late potato blight

Cl/NO_3-Stalk rot of wheat

Plant Nutrition and Disease: Basic Principals

- #1:
  - In the case of *coevolved* hosts and disease pathogens, their interaction exist in an approximate equilibrium that slightly shifts to favor one or the other as the nutrient element environment changes. A similar relationship exists for exotic pathogens if the host possesses some degree of natural resistance.

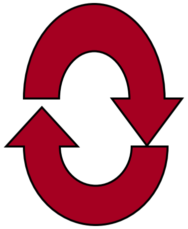
Plant Nutrition and Disease: Basic Principals

- #2:
  - "Host plant resistance" is the main method of control for most diseases; thus, enhancement of disease resistance and/or tolerance is potentially a major component of control.
    - An often overlooked aspect of disease control strategies is management to enhancement the natural resistance mechanisms already operating within in the plant.
    - One major factor affecting enhancement is mineral nutrition status!!!

Plant Nutrition and Disease: Basic Principals

- #3:
  - Plant diseases ***impair*** crop mineral element nutrition and associated basic plant processes.

- #4:
  - Nutrient deficiency can ***predispose*** crops to infection that, once established, stress crops further by ***impairing*** nutrient acquisition and/or utilization.



Plant Nutrition and Disease: Basic Principals

- #5:
  - Plants with optimal nutritional status possess the highest resistance to diseases; thus, expressed resistance generally decreases as nutritional status increasingly deviates from the optimum.

Plant Nutrition and Disease: Basic Principals

- #6:
  - The influence of mineral nutrition on plant *resistance* is:
    - Relatively small in “highly susceptible” or “highly resistant” cultivars/varieties
    - Often substantial in “moderately susceptible” or “partially resistant” cultivars/varieties.
    - Must be corrected during early stages of plant growth.

Plant Nutrition and Disease: Basic Principals

- #7:
  - Typically, the germination of fungal conidia, or spores, on plant surfaces, and the development of the *appressorium* (i.e., a root-like structure) that penetrates host tissue, is *stimulated* or suppressed by the presence of plant *exudates*.
    - Thus, the *"flow of cellular exudates through walls and membranes"* greatly affects the success or failure of infection by most fungal disease pathogens.
      - *The flow of these exudates depends on:*
        - » *cellular concentration key elements (e.g., N, K, B, Ni, Cu…)*
        - » *permeability of membranes (e.g., Ca, B, Si, Ln^{3+})*
        - » *and the corresponding diffusion gradient (e.g., evapotranspiration).*

Part IV:
Species with Higher than Normal Nickel Requirement

Today:

~248,000 known species of higher plants

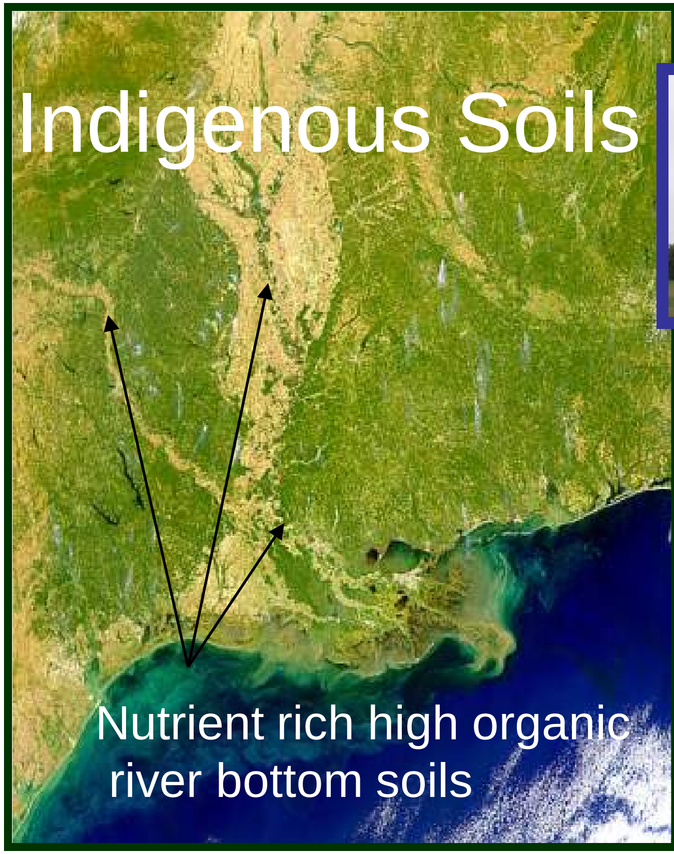
~ 69,000 known species of fungi

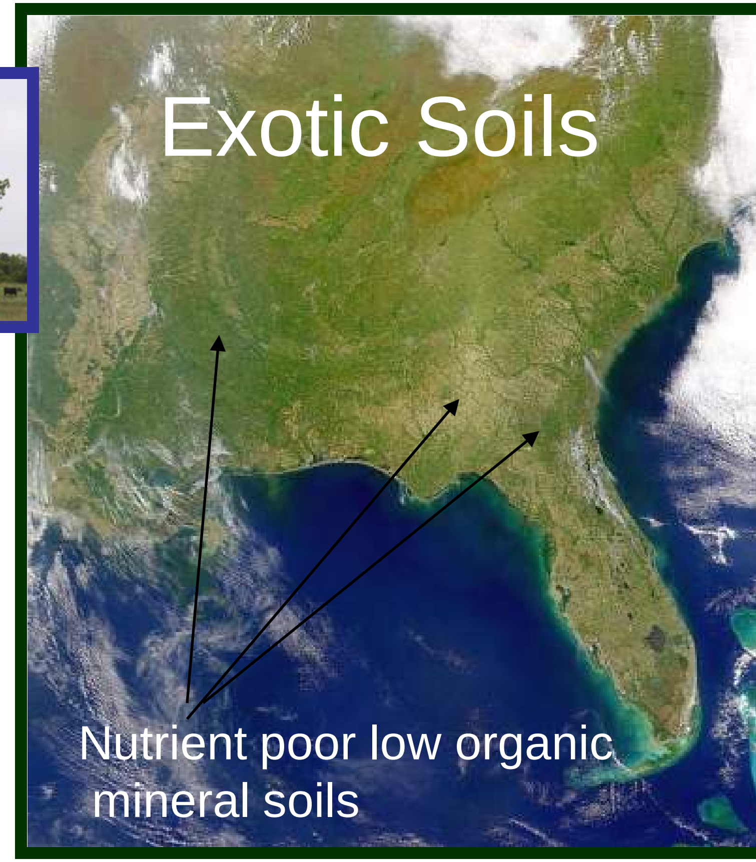
Hydrophilic Species:
Many Transport Nitrogen as Ureides*

- Tropical legumes (e.g., peanut, soybean, pigonpeas, many bean species)
- Hydrophiles: Many plant genera that evolved from river-bottom habitats characterized by moist, high organic, well drained soils and relativley low sunlight. (e.g., *Alnus, Annona, Betula,Carpinus, Juglans, Carya, Nothfagus, Ostrya, Plananus, Populus, Pterocarya, Salix, Vitis, and many others---likely also coffee*)

* **Uredides are nitrogen forms build on urea-like structures.**

Pecan—A Hydrophilic Species





Native rive-bottom soil environment:
(moist, slightly acid, deep, high organic, high fertility soils)

Alien mineral soil environment:
(dryer, low organic matter, lower CEC, lower nutrient availability)

Nickel Deficiency in U.S. Agriculture
(i.e. Ni application corrects harmful symptoms)

-1st reported in 1917!!!

-Has gradually become more common and more severe from 1917 until recently!!!

Nickel Deficiency in U.S. Agriculture

-Putative causes:

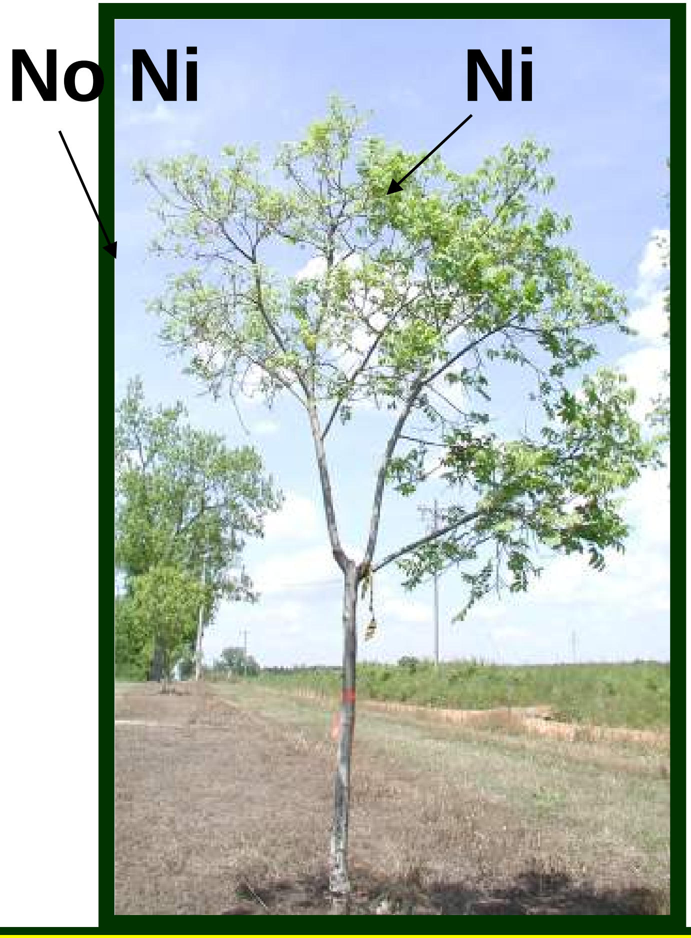
- -viruses
- -cold injury
- -insect injury
- -Mn deficiency (1960-1990)
- -Cu deficiency (1991-2002)

Nickel Deficiency in U.S. Agriculture

-Mn deficiency
(1960-1990)

-Cu deficiency
(1991-2002)

-Ni was later proved to be the limiting bioactive *contaminate* of both Mn and Cu fertilizers!!!



Pecan—a hydrophilic species:

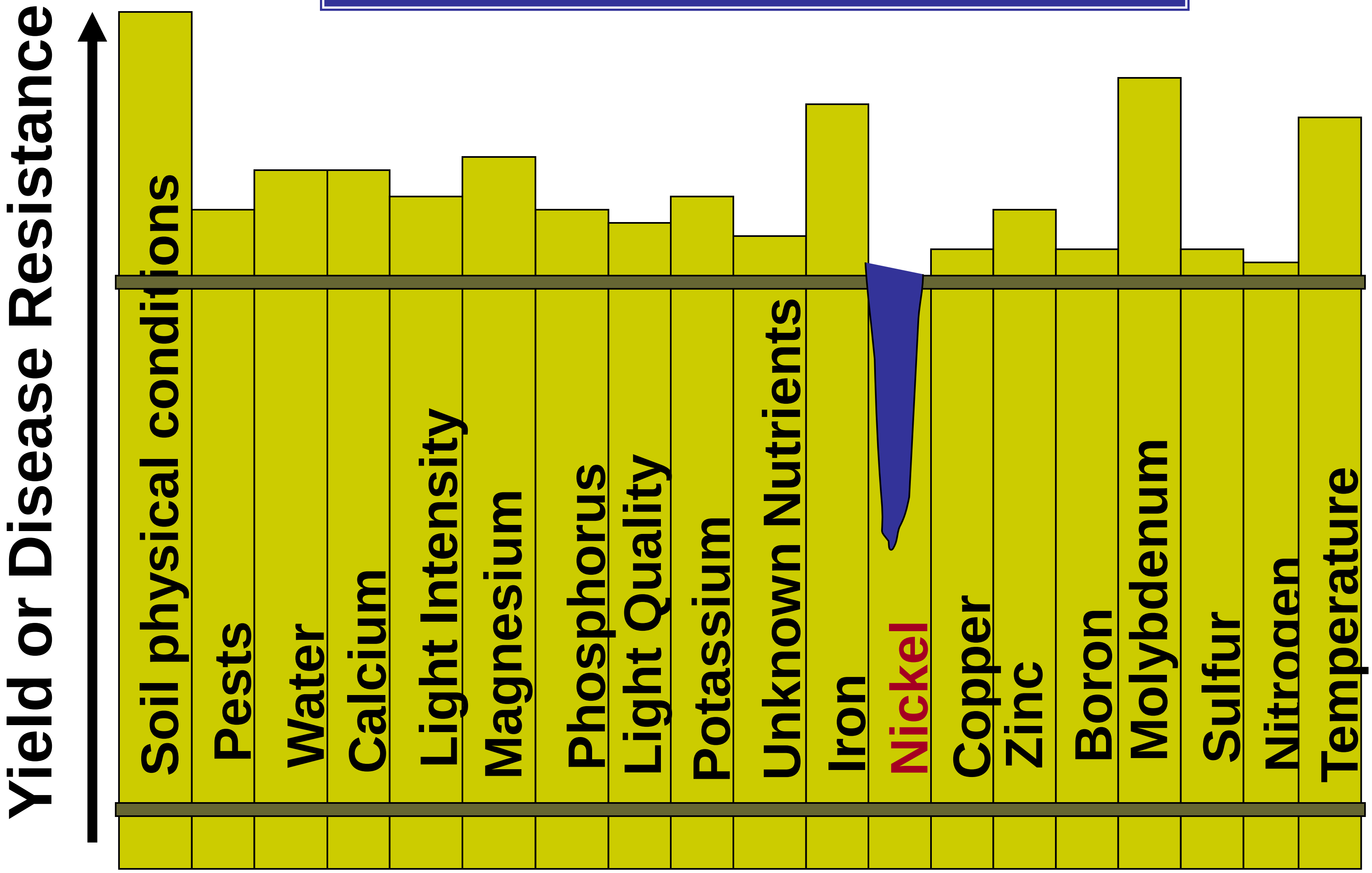
1) Ni enables normal spring growth upon application to foliage soon after budbreak, and

2) There is relatively little phloem mobility or mobilization.

Sufficiency Ranges

Species type	*Approximate sufficiency range* (*u*g/g dry weight)
Amide-N transporting annual and perennials	0.001-0.200
Ureide-N transporting woody perennials	3-30?
Tropical legumes	1-30?
Grasses	0.001-0.200
Pecan (*Carya illinoinensis*)	3-30

The Law of Minimum



Part V:
Nickel Disorders & Plant Disease

- I – Nutritional maladies: Acute Ni deficiency symptoms—usually non-pathological
- II - Pathogen induced Ni deficiency
- III- Ni disorders and crop resistance to disease pathogens
  - –Scab disease
  - –Rust diseases

Ni Deficiency: *Severe Form*

Orchard Replant Disease:

- 2nd generation orchards
- Has been observed to be induced by excessive Zn, Cu, Ca, and nematodes

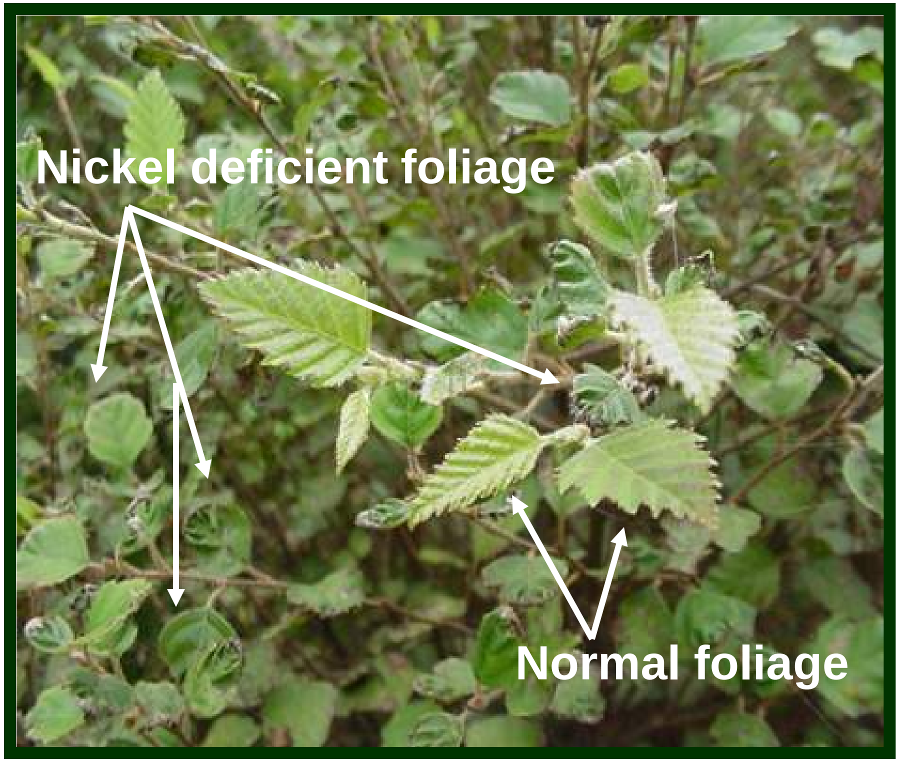
Ni Deficiency:
Moderate Form



Mouse-ear or Little-leaf Disease (Malady):

- Most common in 2nd generation orchards
- Usually inducible by excessive soil Zn, Cu or Ca
- Can be triggered by excessively dry and/or cool soil in early spring

Example #2: "Little Leaf" of Containerized River Birch Trees



Symptoms Associated With Nickel Deficiency

- -blunted tips of leaves or leaflets (consistent with urea toxicity and possibly lactic acid and oxalic acid)
- -thickening of leaves or leaflets, and curling of leaf or leaflet margins
- -necrosis of leaf or leaflet tips with dark green zone adjacent to necrotic zone
- -brittle wood and limbs (likely reduced lignification)
- -reduced growth vigor and flowering

Symptoms Potentially Associated With Nickel Deficiency

-dwarfed internodes, <u>"bonsai"</u> form

-weak shoot growth, failure to survive dormant season (looks like <u>cold injury</u>)

-abnormally sharp pointed buds

-rosetting, loss of apical dominance

-death of shoots and limbs

- plant death

Nickel Deficiency

- Severe symptoms are ***rarely*** observed in the field
- Evidence with pecan, birch, Scots pine, daylilys, barley, potatoes, mint, etc. indicate that field deficiency in many crops is far ***more common*** than previously thought!
- Only trace amounts of Ni are needed for normal metabolism, but ***timing of bioavailability is critical***!
- Ni is substantially ***less toxic*** to plants than many other important trace elements (i.e., Mo, Cu, Co, Cr)

II: Pathogen Induced Nickel Deficiency Disease

Example #1:
Rootknot Nematodes (*Meloidogyne partityla*) Greatly Affects Nickel Uptake by Roots

-Presence of rootknot (*Meloidogyne partityla)* or ring nematodes (*Criconemoides xenoplax*) can *trigger* or *enhance* Ni deficiency symptoms

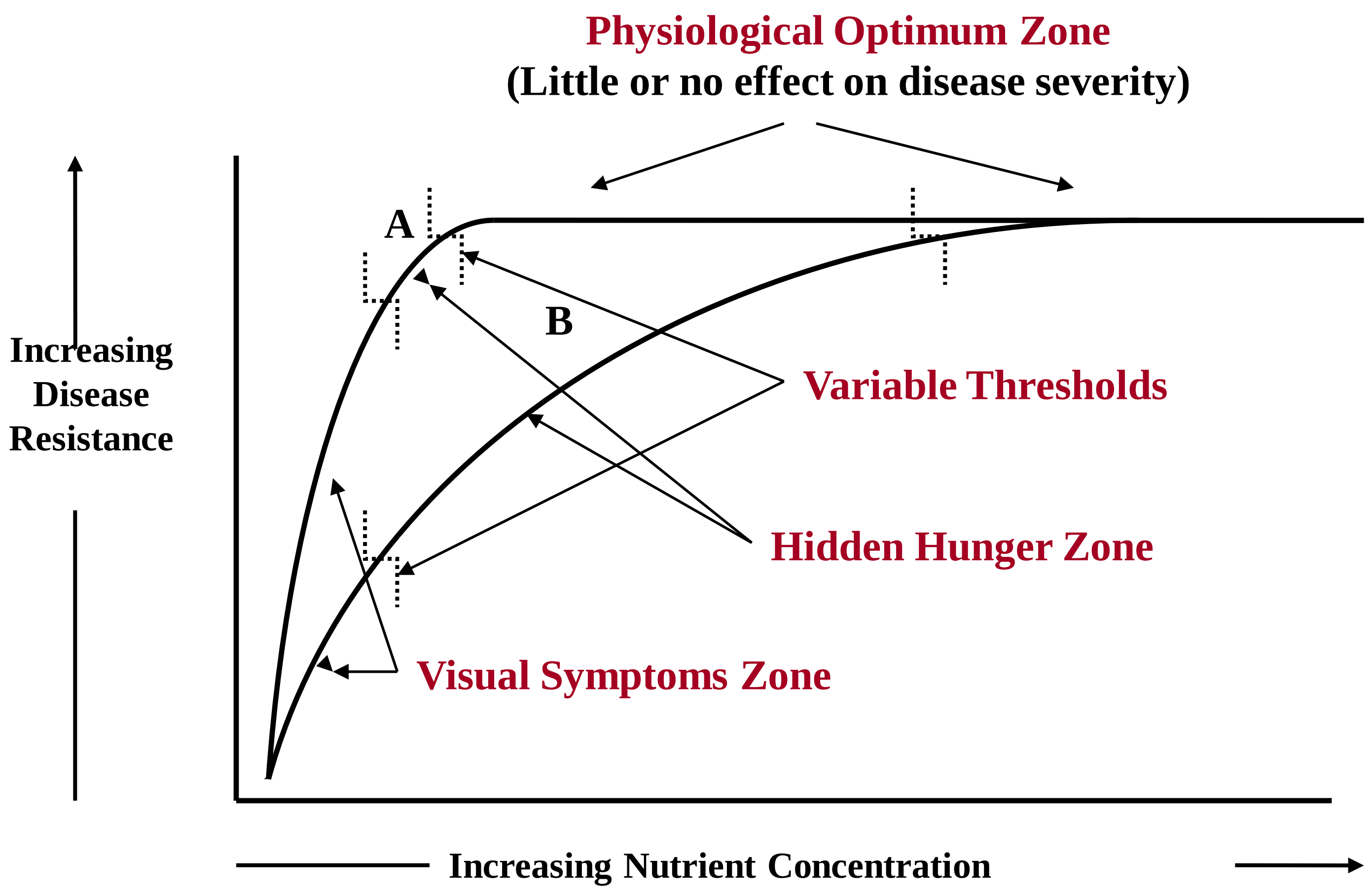
Correction of Nematode Induced Ni Deficiency!

Spring growth after foliar $NiSO_4$ or $NiCl_2$ applied the previous October.

Hidden Hunger: Bouganvilla

"Hidden hunger" appears to be fairly common in certain ornamental species growing in artificial soil media.

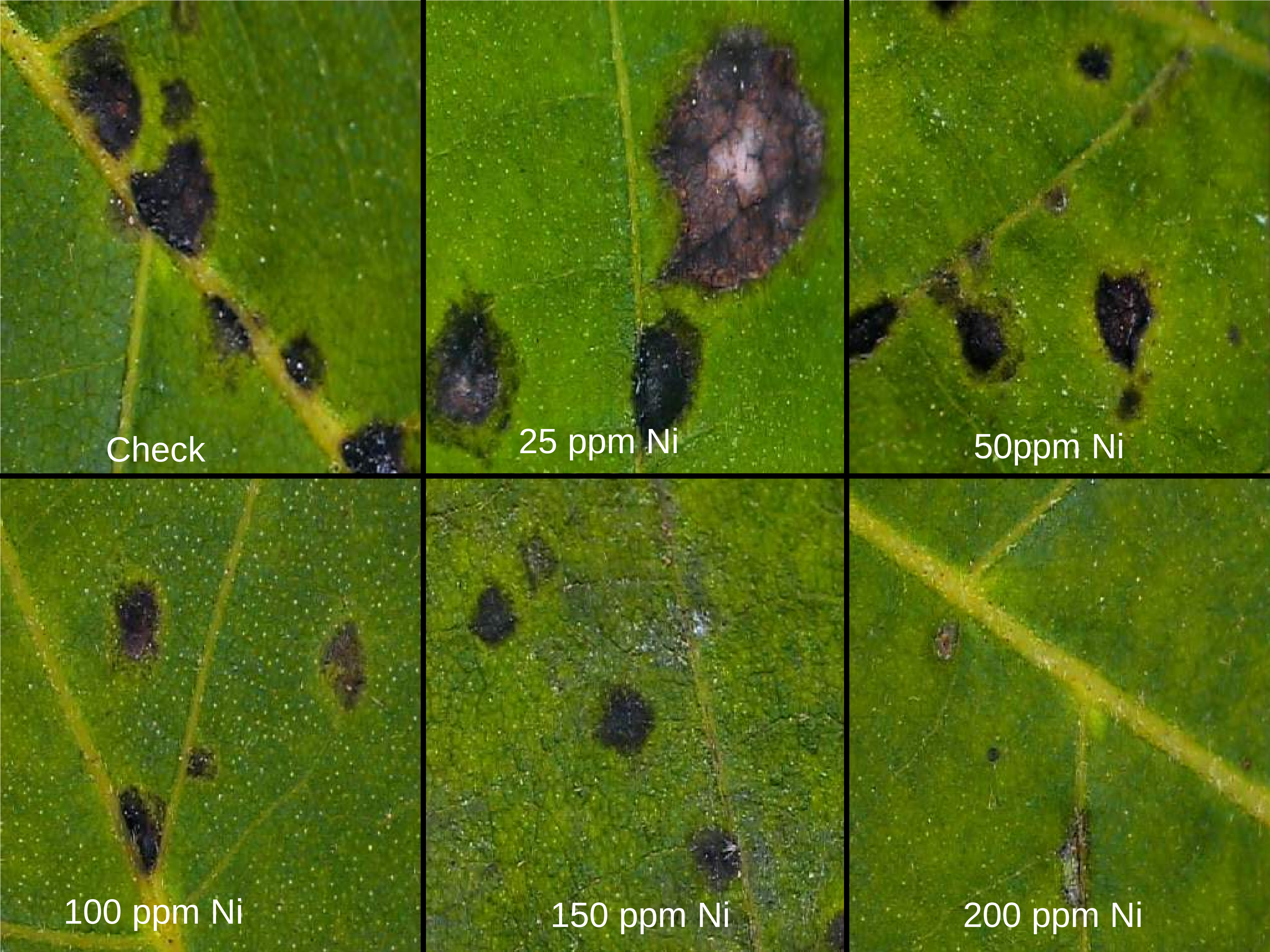
Hidden Hunger Form of Nickel Deficiency & Plant Disease



Effects of Nickel on Plant Diseases

- 1950's:
  - There were several patents by agrichemical companies for use of Ni to control diseases!!!

Example #1:
Pecan Scab Disease
(*Fusicladosporium caryigenum*)


Check
25 ppm Ni
50ppm Ni
100 ppm Ni
150 ppm Ni
200 ppm Ni

Effect of Ni on scab spore germination.

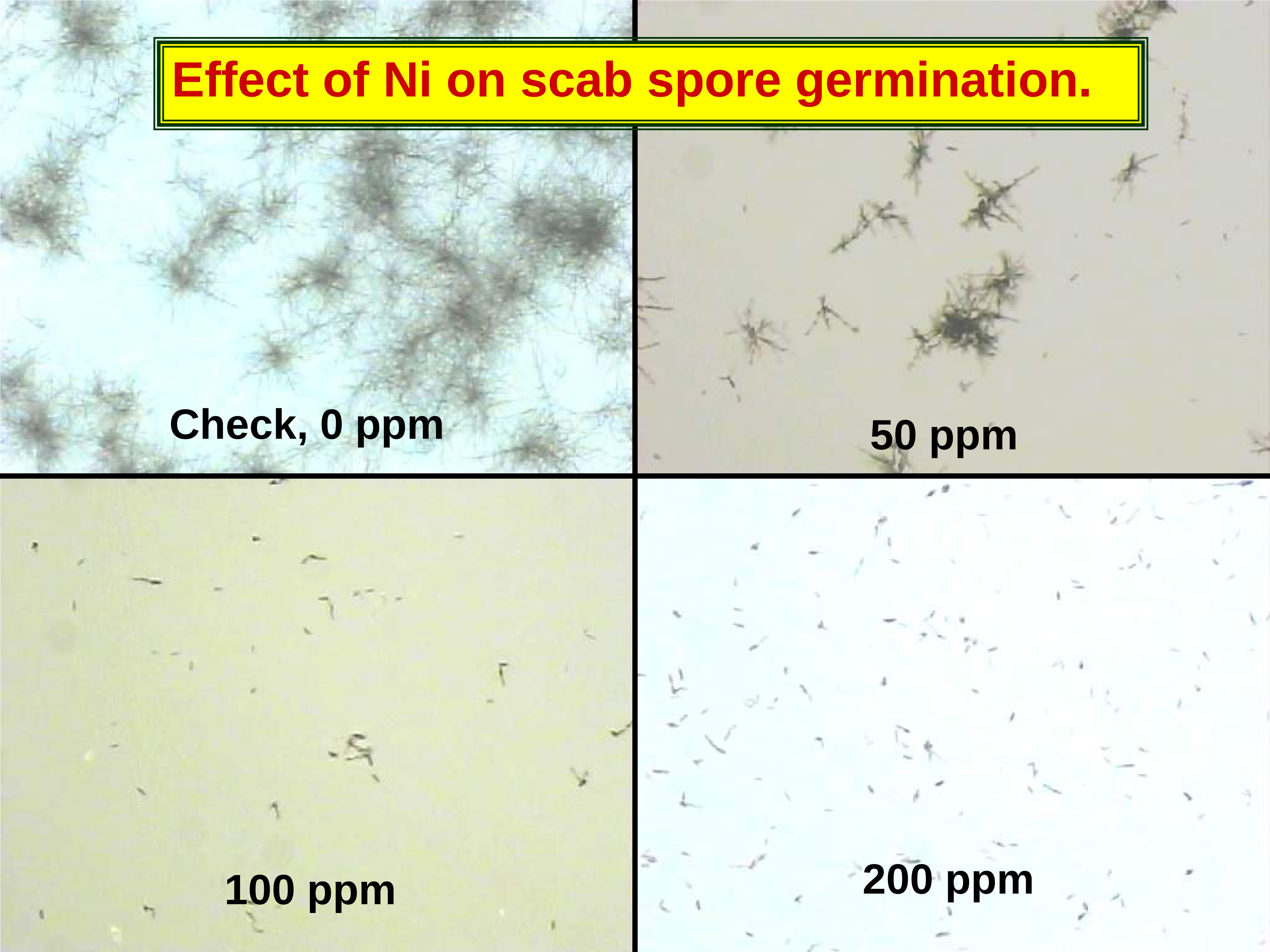


Table 2. Influence of nickel mixed with fungicides on percentage of fruit surface covered by pecan scab fungus

Cultivar (degree of resistance to pecan scab)	SuperTin fungicide (% disease)	SuperTin fungicide plus nickel (% disease)
Wichita (low resistance)	81 b	75 a
Apache (moderate resistance)	54 b	26 a
Desirable (moderate resistance)	30 b	16 a

Table 1. Influence of foliar sprays of nickel on pecan scab severity of developing fruit and on resulting nut size of 'Desirable' pecan. "Farm Treatment Fungicide" and "Farm Treatment Fungicide + Ni" was applied twice, early June and mid July. Spray treatments were applied at 700 L per ha. Nickel was 1000 ml of Nickel Plus per ha and applied concurrently with the fungicide sprays.

Scab control treatment	Nut scab severity rating (%)	Nuts per kg
Farm treatment check	30 a	120 a
Farm treatment plus nickel	26 b	114 b

The different letters following the treatment means reflects statistical significance at *a* = 0.02 (i.e., 98% probability that the treatments are indeed different) via ANOVA testing.

Table 1. Influence of foliar sprays of nickel on pecan scab severity of developing fruit and on resulting nut size of ‘Desirable’ pecan. “Farm Treatment Fungicide” and “Farm Treatment Fungicide + Ni” was applied twice, early June and mid July. Spray treatments were applied at 700 L per ha. Nickel was 1000 ml of Nickel Plus per ha and applied concurrently with the fungicide sprays.

Scab control treatment	Kernel percentage
Farm treatment check	51a
Farm treatment plus nickel	55b

The different letters following the treatment means reflects statistical significance at *a* = 0.02 (i.e., 98% probability that the treatments are indeed different) via ANOVA testing.

Example #2: Rust Diseases

Rust Diseases:
Daylilly Rust (*Puccinia hemerocallidis*)

Nickel Treatments

Ni @ 0 ppm

Ni @ 100 ppm

Ni @ 200 ppm

Nickel and Daylily Rust

- Nickel treatment to either *soil* or *foliage* results in >95% protection against daylily rust in commercial settings:
  - If the variety *possesses resistance* to begin with!!!
  - But, has *no effect* if the variety is *highly susceptible* to rust!!!

Other Crops Where Nickel Affects Rust Diseases

- Brown spot of rice (*Helmenthosporium oryzae*)
- Rice seedling blast (*Pyricularia oryzae*)
- Groundnut rust (*Puccinia arachidis*)
- Leaf spot of wheat

Soybean Rust Diseases:
Enhanced Resistance?

Circumstantial evidence indicates that, in certain situations, Ni has the potential to reduce soybean rust in varieties *already possessing resistance*, but is unlikely to influence resistance in highly susceptible varieties.

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Soybean Yields:
Can Nickel Improved Bean Yields?

Influence of 2 foliar sprays of nickel (50 ppm Ni as Ni-liganosulfonate) on bean yield of soybean.

Nickel treatment	Indexed yield in 2005	Indexed yield in 2006
No Nickel	100a*	100a
Nickel	111a	115a

* Statistically analysis at a $P = 0.10$

Evidence indicates that Ni likely has potentially for improving bean yield in specific situations.

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Part VI:
Factors Influencing Bioavailability
Availability of Nickel

Average* Metal Concentration (mg/kg) in U.S. soils:

-US Surface Soils:

Ni = 19
Cu = 25
Zn = 60

*excluding serpentine soils (very high Ni content)

-**Florida Surface Soils:**

Ni = 6
Cu = 5
Zn = 12

Almost all Soils Contain Plenty of Nickel!!!

Soil Factors Reducing Bioavailability of Nickel

- Soil:
  - Cool soil during early spring
  - Dry soil during early spring
  - High pH
  - Exceedingly high Ca and/or Mg in soil solution
  - Exceedingly high transition trace metals (Fe, Mn, Co, Cu, Zn)
  - Low cation exchange capacity (CEC)
  - High soil P

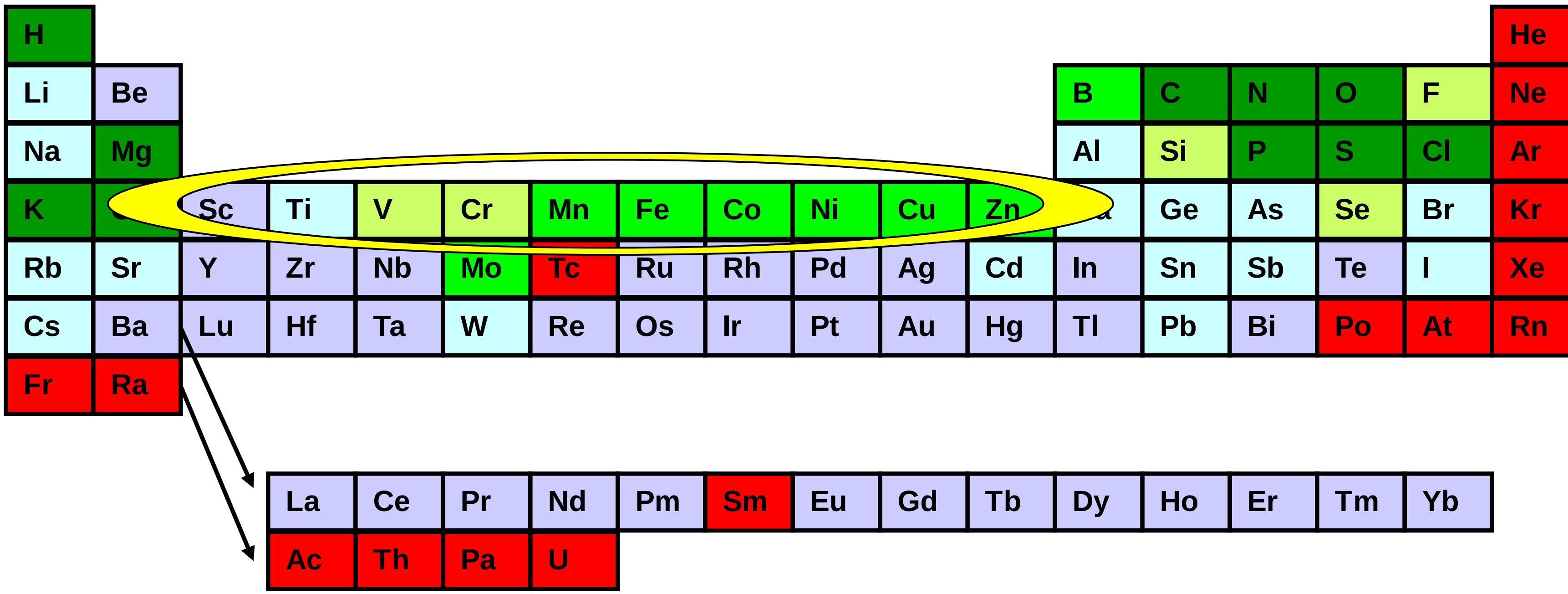
Bioavailability of Nickel in Soils

- Soil chemistry:
  - $Ni_3(PO_4)_2$: very low Ni^{2+} solubility
  - Co-precipitates with aluminum and iron oxyhydroxides, especially in neutral to alkaline soils
  - In organic-rich acidic soils Ni is relatively bioavailable because of complexation by organic ligands

Competition Among Transition Trace Elements for Movement Through Uptake Channels:

“Competitive Inhibition” Among Transition Elements

Essential micro nutrients	10
Essential trace nutrients	7-8
Probable essential trace nutrients	5-6
Beneficial trace nutrients	~`17
Possible beneficial nutrients*	~36
Unlikely essential or beneficial **	16

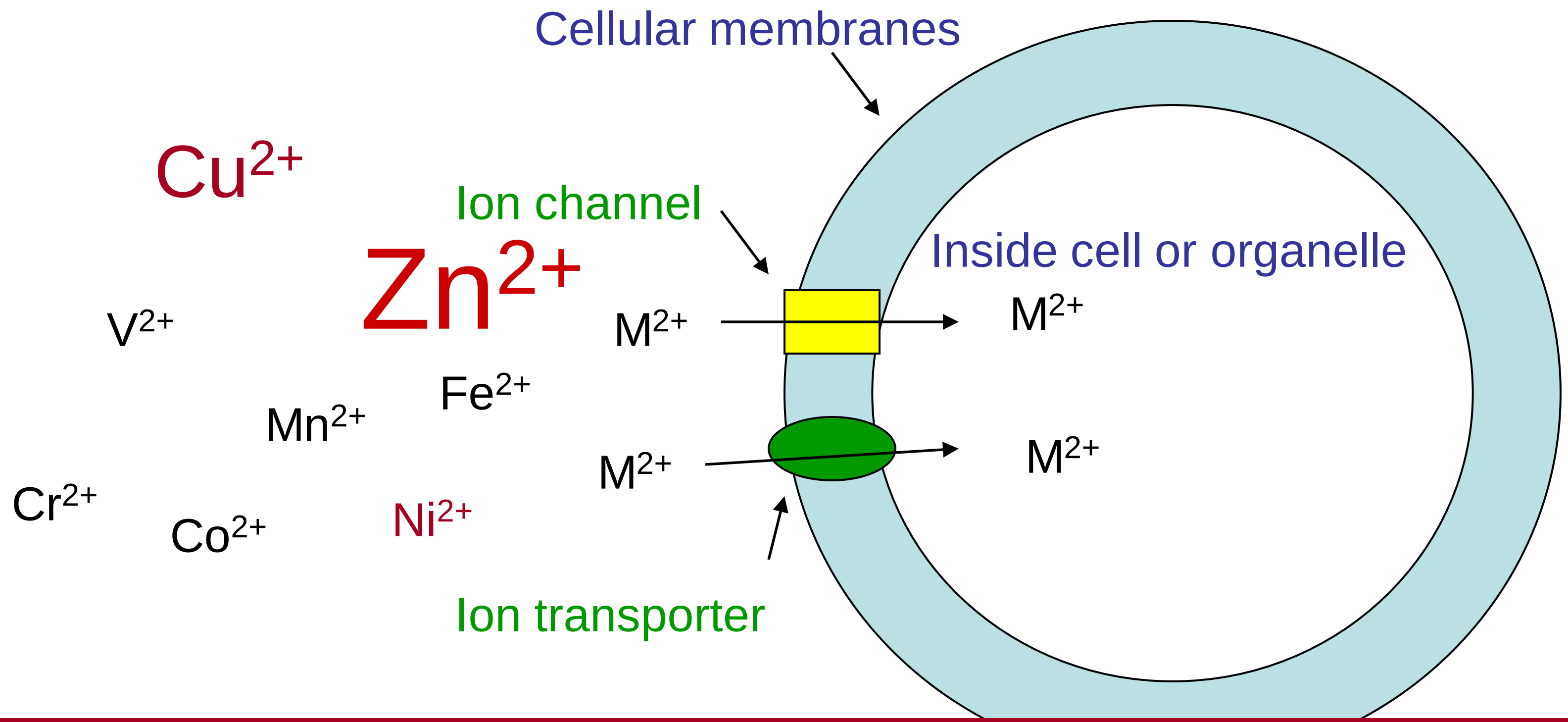


* Under special circumstances for specific species

**Strong radioactive elements or noble gases

Competitive Inhibition Among Transition Metal Trace Nutrients

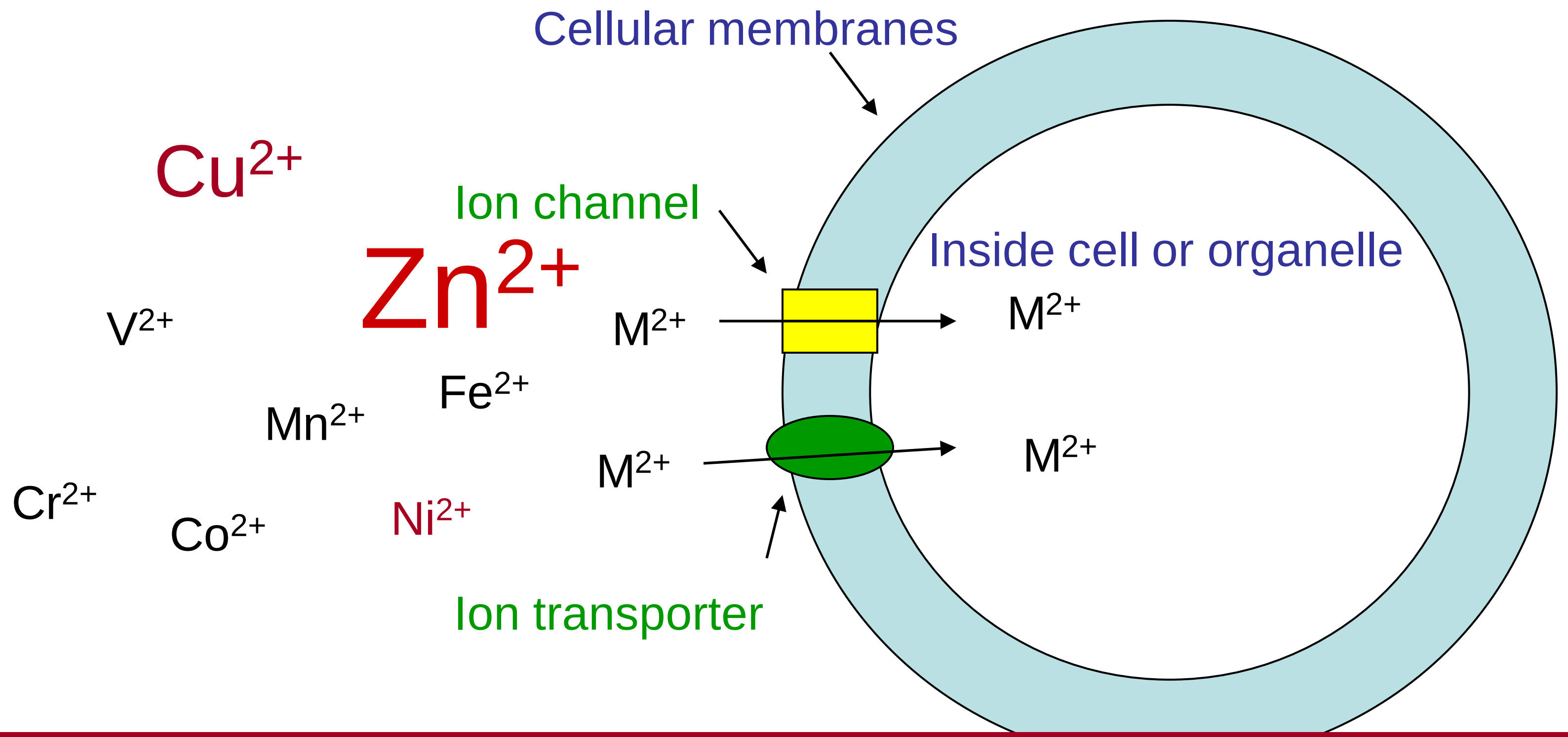
M^{2+} = Divalent transition metal ion



If concentration of a competing trace element is abnormally high relative to the element of interest, then a physiological imbalance can occur through *competitive inhibition* of uptake or movement across cell walls or membranes!

Competitive Inhibition Among Transition Metal Trace Elements

M^{2+} = Divalent transition metal ion



Result can be *competitive displacement* of a key transition metal ion in an enzyme by another metal of lower affinity, but in much greater abundance; thus *limiting or eliminating enzyme functionality*.

Factors Affecting Bioavailability of Nickel

- Biological:
  - Nematodes (i.e., rootknot)
  - Fungi?
- Genetic:
  - Ureide vs. Amide transporting species
  - Genotypic variation

Factors Inducing Deficiency

- Other:
  - *Herbicide* damage to roots and/or mycorrhizae
  - A high probability of a potential adverse impact of glyphosate herbicide on Ni bioavailability!!!
  - Exceedingly high concentrations of phosphorus or transition metals in plant cells

Anecdotal Evidence Indicates that the Hidden Hunger Form of Nickel Deficiency May be Common in Many Crops During Early Spring Canopy Growth

- Mid summer *leaf analysis does not necessarily* provide a satisfactory measure of Ni nutritional status of the plant during early spring!!! (note Ni/Zn ratio effect)
- Soil Ni levels also *relate poorly* to early season Ni content of above ground plant organs

Common Field Factors Contributing to Nickel Deficiency

- High soil pH (>7; especially >8)
- Soils that are sandy or with low cation exchange capacity
- Exceedingly high soil Zn, Cu, Mn, Fe, Ca, Mg, P
- Exceedingly high levels of Zn, Cu, Mn, Fe, and P, or combination of these, within cells
- Dry and/or cool soils in early spring
- Heavy early spring application of nitrogen
- Rootknot nematodes
- Combinations of the above

Nickel Toxicity
(necrotic spots on foliage)

- ~≥65 ppm dw in leaf tissue of most woody perennials (can greatly vary depending on relative concentration of other metals and crop species)

- Foliar sprays on several woody perennials indicate that ~≥400 ppm Ni solutions, depending on leaf age, can be phytotoxic; [can be >50 ppm in certain Ni sensitive species (e.g., tomato)].

Apparent Nickel Nutritional Range for Ni Loving Species (~3-30 ppm dw)*

- For deficiency symptoms:
  - Visual: ~ <0.5-0.9 ppm **
  - Hidden hunger: ~0.9 - ~3 ppm? **
- For toxicity symptoms:
  - Visual: ~$\geq$ 65 ppm
  - Hidden harm: ~ $\geq$60 ppm?

* Excluding hyperaccumulators (Ni @ 3-4% dry wt.)

** <u>Depending on leaf concentration</u> of Zn, Cu, Fe, Mn, and P (e.g., Ni/Zn Ratio)

Anecdotal Evidence Indicates that the Hidden Hunger Form of Nickel Deficiency May be Common in Many Crops During Early Spring Canopy Growth

- "Hidden Hunger" deficiency often a appears to occur for a duration of a few days to *3-6 weeks* during canopy deployment.
- Potential great impact on *early season* nitrogen utilization, growth, and disease resistance.

Influence of Nickel on Seeds

- Pecan: The greater the seed Ni concentration the greater the degree of:
  - kernel filling,
  - uniform seed germination,
  - early growth vigor of resulting seedlings,
  - and potential for improved seedling resistance to certain diseases

Part VII:
Some General Guidelines on Nickel Management

Nickel Management Considerations

A) Are there visible symptoms of Ni deficiency?

-- if slight to moderate deficiency, then 1 or 2 foliar applications of Ni
(applied at parachute stage of bud break and 2 weeks later; 50-100 ppm Ni spray).

-- if severe deficiency, then for perennials treat in late autumn with 100 ppm Ni foliar spray—remobilization.

B) Is there evidence of “hidden hunger”?

--1 or 2 foliar applications of Ni about 10 days and 24 days after bud break or sprouting (25-100 ppm Ni spray—will depend on the crop).

Nickel Management

C) Ask, why is the crop Ni deficient?

--Low bioavailability is most likely a symptom of another problem; e.g., dry soil, cold soil, high pH, excessive divalent metals, rootknot nematodes, *and circumstantial evidence indicates that glyphosate herbicide is likely an inducer of Ni deficiency in certain crops.*

D) Will Ni affect disease resistance or tolerance?

--A good chance if the species transports nitrogen as ureides , but efficacy will likely require foliar treatment during *early* stages of canopy expansion.

E) Is the subject crop likely to have Ni problems?

--A distinct possibility if the crop transports ureido-N, but is unlikely if it transports almost exclusively amide-N or amino-N.

Conclusion

Nickel, *the forgotten essential nutrient element:*

-potentially plays a key role in enhancement of disease resistance in certain plants; especially in crops transporting nitrogen as ureides (vs. amides, or amino acids).

Greater knowledge of the relationship of nickel's interaction with plant nutrition provides a basis for modifying certain current agricultural practices to reduce disease severity in Ni sensitive crops and their integrated crop production systems.