Foliar Fertilization: Principles and Practices.

Patrick Brown
University of California, Davis
Outline

• Why Bother with ‘expensive’ foliars (or targeted fertilization strategy)
  – Biological Rationale for Foliar Fertilization
• Scientific Principles of Foliar Fertilization
  – Pathways and Processes
  – Physiology
• Laboratory Trials and Field Practice
  – Lessons from Studies with Zinc (if time permits)
The Role of Foliar Fertilizers

Foliar Fertilizers are widely used to enhance both productivity and quality. In many ‘high-value’ crops a significant percentage of total fertilizer $$’ s are spent on foliar fertilizers.

RATIONALE:

1) To overcome soil limitations that restrict element solubility or mobility
   
   \[ (pH, \text{ carbonate, toxic ions, structural problems etc.)} \]
   
   - Fe deficiencies in calcareous soils
   - Zn/Cu deficiencies in high OM/High P soils
   - Unfavorable root zones (cold, wet, dry etc.)

2) To correct short-term or ‘\textit{Transient Nutrient Deficiencies}’
   
   - \textit{During times of high nutrient demand, compromised root activity or compromised transport}
     
     - High demand for specific nutrients during periods of high growth
     - Demand during periods of restricted root growth
     - Restricted delivery to fruiting and storage organs (Ca and B deficiency in apple)
   
   - \textit{To address nutrient demand during critical developmental stages}
     
     - Zn, B, Cu, Mo demand at flowering etc.
Soil pH and Minerology determines Nutrient Solubility

(knowledge of solubility characteristics of your soils is important.)

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<th>Very Slightly Acid</th>
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<td>COPPER AND ZINC</td>
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</tbody>
</table>

4.0 4.5 5.0 5.5 6.0 6.5 7.0 7.5 8.0 8.5 9.0 9.5 10.0
pH 8.4, 70% Free Lime
Transient Nutrient Deficiencies

Demand exceeds Supply

French prune (Prunus domestica L.)

- High yields can remove >300 kg K/ha/year
- Majority of K demand occurs over 50 days (4-8 kg K/ha/day)
- Very high demand for sugars to fill fruit results in severe carbon deprivation in roots.
- Soil K > 300 ppm (extractable)
- Beneficial use of foliar K nitrate.
Knowledge of Nutrient Accumulation Patterns and Integration with Environmental Constraints helps Predict Demand for Supplemental Foliar Fertilization.

Figure 5.2. Patterns of nutrient accumulation as a percentage of total seasonal accumulation over the growing season for six field crops (Adapted from Jones et al., 2009).
Right Rate and Time: Plant Nutrient Demand

Nitrogen Aerial Accumulation Wheat - California

K/N: 4 – 10 Kg/ha/day

Yield 142 bu/ac

14 ton Ha

Cool weather

Warm weather

Uptake decreases or stops at flowering

GDU

N lbs kg/ha

*above ground

Miller, 1990
Localized Nutrient Demand Can Exceed Uptake and Transport Capacity, even in a Well fertilized Soil.
Table 5.4. Influence of foliar-applied N at boll filling stage on boll load, leaf N and yield of cotton (Oosterhuis and Bondada, 2001).

<table>
<thead>
<tr>
<th>Fertilizer (kg N ha⁻¹)</th>
<th>Boll load</th>
<th>Foliar nitrogen (kg N ha⁻¹)</th>
<th>Yield (kg seed cotton ha⁻¹)</th>
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</thead>
<tbody>
<tr>
<td>50</td>
<td>Low boll load</td>
<td>0</td>
<td>783 cd¹</td>
</tr>
<tr>
<td>50</td>
<td>Low boll load</td>
<td>50</td>
<td>970 bc</td>
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<td>50</td>
<td>High boll load</td>
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<td>1035 b</td>
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<td>50</td>
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<td>50</td>
<td>1258 a</td>
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<td>100</td>
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<td>0</td>
<td>776 d</td>
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<tr>
<td>100</td>
<td>Low boll load</td>
<td>10</td>
<td>782 bcd</td>
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<tr>
<td>100</td>
<td>High boll load</td>
<td>0</td>
<td>884 b</td>
</tr>
<tr>
<td>100</td>
<td>High boll load</td>
<td>20</td>
<td>1170 a</td>
</tr>
</tbody>
</table>

¹ Means within a column followed by the same letter are not significantly different at P ≤ 0.05.
Periods of Demand Exceeding Soil Supply may Exist and may Justify Foliar Fertilization:

Q? Can the need be predicted?

Q? Can adequate nutrient be applied foliarly?

Q? What materials are best and how should they be applied

Q? Are they cost effective and more environmentally sound than ‘extra’ soil fertilization?
Transient Nutrient Deficiencies

Short term increases in nutrient demand for critical phenological processes.

Zinc

(Fe, B, Mo, Ni, Cu, Mn)

• Spring Fever – Characterized by late bud emergence, erratic flowering, small leaves with reduced internode length (little leaf and rosette)

• Most prevalent in cold wet springs as a consequence of reduced soil Zn uptake
Zinc Deficiency

Rice is sensitive to Zn deficiency which occurs in reduced soils, organic soils and as a consequence of Fe-co-precipitation.

Little-leaf is a classic Zn deficiency symptom seen in actively growing plants. Chlorosis is more typical in non-growing tissues.

Cotton
Impact of Zn Deficiency on Flowering in Prunus.

Soil Zn Application: Zn Deficient

Foliar Zn Application: Zn Sufficient

Courtesy of Scott Johnson
Zinc dependent molecular mechanisms are involved in dormancy, flowering and cell cycle processes.

Expression of ENY a C2H2 zinc finger increases during flowering, and seedling development.


Arabidopsis zinc-finger protein 2 is a negative regulator of ABA signaling during seed germination

Gabriele Drechsel, Sabine Raab, Stefan Hoth

Does This Imply A critical need For Zn During Flowering and is there active mobilization of Zn during this period?
Research Challenges

How do you measure and image nutrient distribution and concentrations at an organ and cellular level?

Goal:

• Improve our understanding of physiological basis for use of foliar fertilizers
• Improve our understanding of the mechanisms of transport of nutrients through leaf surfaces
μ Xray Florescence are conducted at Stanford and Argonne National Labs. (nano, confocal and 3D XRF are in development)
SR-XRF typical energy
Selective Uptake of Fe by Root Hairs
Impact of Zn Deficiency on Flowering in Peach.

Soil Zn Application: Zn Deficient

Foliar Zn Application: Zn Sufficient

Courtesy of Scott Johnson
Zn localization in anther of almond flower

Localized accumulation of Zn in pollen

μ XRF analysis

Tian and Brown (unpublished)
Spatial imaging of Zn, Ca and K in Stigma of Almond Flower indicates Strong Zn Mobilization at Pollination

µ XRF analysis

Tian and Brown (unpublished)
Direct imaging of Zn, K, Mn in developing buds, flowers and embryo in Almond Wheat and Pistachio.

μ-XRF and nano-XRF in freeze sectioned bud pre-opening (March)

(Tian and Brown, unpublished)
Zinc dependent molecular mechanisms are involved in dormancy, flowering and cell cycle processes.

Expression of ENY a C2H2 zinc finger increases during flowering, and seedling development.

There is a critical need for Zn during flowering and meristematic growth.

..and is there active remobilization of Zn during this period

..suggesting that targeted foliar Zn applications could benefit many cropping systems
Boron Deficiency in Wheat at Flowering

(high demand, low transpiration - deficiency most prevalent during humid weather at flowering)

Bernie Dell, Longbin Huang and Richard Bell

No Vegetative Deficiency

Strong Reproductive Deficiency

Pollen formation is most B sensitive phase of life cycle.
Boron Deficiencies in Corn
Iron Deficiency Peppers
Boron deficiency in rapidly growing tissue with poor vascular connections.
Causes of Transient Deficiencies

Zinc dependent molecular mechanisms are involved in dormancy, flowering and cell cycle processes.

Expression of ENY a C2H2 zinc finger increases during flowering, and seedling development.


Arabidopsis zinc-finger protein 2 is a negative regulator of ABA signaling during seed germination

Gabriele Drechsel, Sabine Raab, Stefan Hoff
Transient deficiencies are more likely with immobile elements

<table>
<thead>
<tr>
<th>TABLE 3.9 Mobility of nutrients in the phloem</th>
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<tbody>
<tr>
<td>Mobility</td>
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<tr>
<td>High</td>
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<td>S</td>
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<td>B</td>
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<tr>
<td>Mo</td>
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<td>N (amino-N)</td>
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<td>Mo</td>
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<tr>
<td>Cl</td>
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<tr>
<td>(Na)</td>
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</table>
B Mobility affects Foliar Response.

No Phloem B transport = Sensitive to fluctuations in soil B

High B

Low B

GMO - With Phloem B Transport:
Phloem Mobile B, tolerant of short term deficiency, foliar B easily transported.

Molecular introduction of Apple B transport gene

Brown et al 2000
Causes of Transient Deficiencies

Demand

Function

Mobility

Environmental Interactions
Function: Mobility: Environment Interactions

Molybdenum Foliar Sprays and Other Nutrient Strategies to Improve Fruit Set and Reduce Green Berries

Dr Christopher Williams
SARDI 2003-7
Molybdenum Deficiency in Grape

Seedless Fruit

Molybdenum deficiency (Live green ovaries)

Mo, Fruit Set and Uniformity

Table 4. Effect of foliar application of molybdenum and rootstock on number of flowers per inflorescence, % fruit set per vine, and number of green and coloured berries per bunch at site 4 in 2003/04.

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Flowers per inflorescence</th>
<th>Fruit set (%)</th>
<th>Green berries per bunch</th>
<th>Coloured berries Per bunch</th>
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</thead>
<tbody>
<tr>
<td>Unsprayed</td>
<td>394</td>
<td>22.8</td>
<td>51.2</td>
<td>77.4</td>
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<td>Sprayed</td>
<td>385</td>
<td>30.0</td>
<td>31.0</td>
<td>92.2</td>
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<td>Significance</td>
<td>ns</td>
<td>**</td>
<td>*</td>
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<td>LSD</td>
<td>1.9</td>
<td>13.3</td>
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<td>4.8</td>
</tr>
</tbody>
</table>

Dr Christopher Williams
SARDI 2003-7
Large Environmental Interaction: Foliar Benefit Does Not Always Occur (Climate, nutrient status etc. all interact)

Dr Christopher Williams SARDI 2003-7

Climate Affects:
- Rate of growth/metabolism
- Nutrient Remobilization and Uptake
- Nutrient Mobility

Figure 1. Average yield of unsprayed (○) and sprayed (●) grapevines over five years at Site 1 (a) and Site 3 (c), and over four years at Site 2 (b). Bars represent standard error of the mean.
Boron deficiency can be transient, dependent upon changes in the growing environment (water).
Drought Induced B Deficiency in Sunflower
Drought Induced B Deficiency in Sunflower
Boron Deficiency Induced Meristematic Death in Pinus radiata Following brief Drought.
B Deficiency: Flower Abortion in Walnut

Soil B 1999-01
Zero Soil B
Control B-Deficient

400ppm Foliar B
14 days pre-flowering

Relative Yield
45% 100% 25%

1 inch

Flower Death
Optimizing N use efficiency requires Optimal Management of all Inputs: e.g. Manganese Deficiency can limit crop response to N

- Manganese deficient section

Optimizing N use requires identifying and optimizing all production factors:

GNDVI 29 April 2009: SmartImage (B,G, NIR only) 1 m pixel (Britz Fert. Com.)
Summary: The Role of Foliar Fertilizers

BIOLOGICAL RATIONALE:
1) To overcome soil limitations that restrict element solubility or mobility
2) To correct short-term or ‘Transient Nutrient Deficiencies’
   1) LIMITED BY QUANTITY OF NUTRIENT THAT CAN BE APPLIED
   2) COMPLICATED BY UNCERTAINTY AND ENVIRONMENTAL INTERACTIONS
   3) MOBILITY OF THE ELEMENT MAKES A DIFFERENCE

ECONOMIC RATIONALE AND PRACTICAL CONSIDERATIONS:
1) Relative costs and benefits (requires a measure of efficacy and consistency)
2) Can the need for foliar fertilizers be predicted and the treatment implemented (requires an understanding of plant physiology and a measure of efficacy and consistency and an opportunity)

MECHANISTIC CONSIDERATIONS:
1) How do nutrients enter the leaf and what chemical and biological factors influence efficacy
2) How do foliar nutrients behave once in the apoplast and symplast
3) How effectively can they be transported and utilized and hence improve productivity
The Leaf is Well Designed to Prevent the Movement of Ions or Water Trying to get a hydrophilic ion through a hydrophobic surface.

Uncharged Molecules – Urea, Boron move freely

Table 1. Calculated urea retention and leaf absorption after 5 days

<table>
<thead>
<tr>
<th>Leaf number</th>
<th>Leaf area (mm$^2$)</th>
<th>Calculated retention urea (mg)</th>
<th>Observed wash (mg)</th>
<th>% urea absorbed$^a$</th>
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<tr>
<td>1</td>
<td>25928</td>
<td>9.4</td>
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<td>2</td>
<td>15297</td>
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<td>8</td>
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<td>90.4</td>
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<tr>
<td>9</td>
<td>12864</td>
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<td>0.6</td>
<td>87.5</td>
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<td>10</td>
<td>15041</td>
<td>5.5</td>
<td>0.9</td>
<td>83.6</td>
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<tr>
<td>11</td>
<td>14151</td>
<td>5.2</td>
<td>0.5</td>
<td>90.4</td>
</tr>
</tbody>
</table>

$^a$ % urea absorption = (calculated retention – observed wash) / (calculated retention).
Relative Permeability of Charged Elements– Zn$^{2+}$ (Zn salt)

Absorption is 0-6%. It is typical, even though this is very low, it is still greater than predicted.
Direct Penetration of Charged Solutions (Zn^{2+}) Through Intact Cuticles* is Theoretically Improbable

Mineral nutrient salts have an extremely low solubility in the lipophilic cuticle

Example: \( \text{NH}_4\text{NO}_3 \) solution

\[
\begin{align*}
c &= 0.1 \text{ mol/L} \\
c &= 4 \text{ nmol/L} \\
\text{fraction solubility} &= 0.000004\%
\end{align*}
\]

Courtesy Thomas Eichert
Polar Pores or Cracks?

Purely theoretical: Are these discrete genetically determined structures, or just regions of differential cuticle composition, cracks or defects?

Schönherr 2006

Courtesy Thomas Eichert
**Movement of charged ions/molecules through the cuticle layer**

**Transport is determined by volume of wetted surface and concentration gradient across cuticle.**


\( C_s - C_i \times J_c \)
What Determines the Rate of Uptake?

Cuticular penetration

• Lipophilic compounds (Urea, B) exhibit some solubility in cuticle and penetrate directly based on concentration gradients.

• $\text{H}_2\text{O}$ & electrolytes pass through discontinuities (cracks and imperfections):
  - Size of the pore/ion
  - Solubility and Concentration (free ion activity) of the applied salt – DRH/POD

($\text{DRH} = \text{Deliquescence relative humidity (POD)}$)
Point of Deliquescence (POD) or Deliquescence Relative Humidity (DRH)

<table>
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<tr>
<th>Compound</th>
<th>POD (%)</th>
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<tr>
<td>CaCl₂ · 6H₂O</td>
<td>33</td>
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<tr>
<td>Ca(NO₃)₂ · 4H₂O</td>
<td>56</td>
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<tr>
<td>MgCl₂ · 6H₂O</td>
<td>33</td>
</tr>
<tr>
<td>Mg(NO₃)₂ · 6H₂O</td>
<td>56</td>
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<tr>
<td>MgSO₄</td>
<td>90</td>
</tr>
<tr>
<td>Zn(NO₃)₂ · 6H₂O</td>
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<tr>
<td>ZnSO₄</td>
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<td>NH₄NO₃</td>
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<td>Ca-propionate · H₂O</td>
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<td>Ca-lactate · 5H₂O</td>
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<td>Ca-acetate</td>
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<td>FeCl₃ · 6H₂O</td>
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<tr>
<td>Fe(NO₃)₃ · 9H₂O</td>
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</tr>
<tr>
<td>Mn(NO₃)₂ · 4H₂O</td>
<td>42</td>
</tr>
<tr>
<td>MnCl₂ · 4H₂O</td>
<td>60</td>
</tr>
</tbody>
</table>

Relative humidity below which a salt will crystallize
POD/DRH of Table Salt (NaCl) is 75%

Below a relative humidity of 75% NaCl is a solid, above 75% it absorbs moisture and becomes a liquid. Only liquids can penetrate cuticles.
Role of Humidity in Foliar Nutrient Uptake. Concentration Effects

The driving force for nutrient movement into the leaf is the concentration gradient between leaf surface and internal leaf spaces.

Water vapor can be absorbed or lost from the droplet based upon RH and the *Deliquescence Relative Humidity* of the nutrient compound (DRH).

- If RH < DRH solution droplet will evaporate, increasing concentration until crystalization.
- If RH > DRH solution droplet will gain moisture, decreasing concentration and risking wash off.

## Adjuvants

<table>
<thead>
<tr>
<th>Adjuvant name on label</th>
<th>Proposed mode of action</th>
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</thead>
<tbody>
<tr>
<td>surfactant</td>
<td>lowering surface tension</td>
</tr>
<tr>
<td>wetting agent</td>
<td>equivalent to “surfactant”</td>
</tr>
<tr>
<td>detergent</td>
<td>equivalent to “surfactant”</td>
</tr>
<tr>
<td>spreader</td>
<td>equivalent to “surfactant”</td>
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<tr>
<td>sticker</td>
<td>increasing solution retention; rainfastness</td>
</tr>
<tr>
<td>retention aid</td>
<td>increasing solution retention; rainfastness</td>
</tr>
<tr>
<td>buffering agent</td>
<td>pH buffering</td>
</tr>
<tr>
<td>neutraliser</td>
<td>pH buffering</td>
</tr>
<tr>
<td>acidifier</td>
<td>lowering pH</td>
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<tr>
<td>penetrator</td>
<td>increasing the rate of foliar penetration (e.g. by ‘solubilizing’ cuticular components)</td>
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<tr>
<td>synergist</td>
<td>increasing the rate of foliar penetration</td>
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<tr>
<td>activator</td>
<td>increasing the rate of foliar penetration</td>
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<tr>
<td>compatibility agent</td>
<td>improving formulation compatibility</td>
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<tr>
<td>humectant</td>
<td>retarding solution drying by lowering the formulation’s point of deliquescence (POD)</td>
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<tr>
<td>drift retardant</td>
<td>better spray targeting and deposition on foliage</td>
</tr>
<tr>
<td>bounce and shatter minimizer</td>
<td>better spray targeting and deposition on foliage</td>
</tr>
</tbody>
</table>
Factors Affecting the Cuticular Penetration of Foliar Formulations

• POD – is the Formulation in solution?
  • Relative Humidity
    • which varies through day
    • Altered by canopy

• Is the molecule lipophilic (Urea, Boron etc)

• Charge, Size, Concentration ………

• Adjuvants
Environmental, physiological and biological factors affecting plant response to foliar fertilization
QUANTITATIVE AND PHYSIOLOGICAL ASPECTS OF FOLIAR FERTILIZATION

*Predicting the Effectiveness of an Application.*

1. Cuticle Characteristics and Penetration
2. Nutrient concentration in the solution applied (POD, charge, threshold of phytotoxicity).
3. Solution retention (per unit leaf area).
4. Leaf area per plant (per acre).
5. Leaf nutrient uptake (per unit leaf area, per tree, per acre).
6. Mobility of absorbed nutrient(s).
Leaf Surface Composition and Structure are Highly Varied.

- Species
- Leaf Surface
- Age
- Environment
- Nutrient Status

Epicuticular wax in Apple leaves varies with environment (Hellman and Stosser, 1992)

Growth Chamber
= 10 µg cm\(^{-2}\)

Field Grown
= 280 µg cm\(^{-2}\)

Epicuticular wax in Walnut varies with leaf age (Zhang and Brown, 1994)

40 Days Old
= 38 µg cm\(^{-2}\)

120 Days Old
= 430 µg cm\(^{-1}\)
QUANTITATIVE AND PHYSIOLOGICAL ASPECTS OF FOLIAR FERTILIZATION

Predicting the Effectiveness of an Application.

1. Cuticle Characteristics and Penetration
2. Nutrient concentration in the solution applied (threshold of phytotoxicity).
3. Solution retention (per unit leaf area).
4. Leaf area per tree (per acre).
5. Leaf nutrient uptake (per unit leaf area, per tree, per acre).
6. Mobility of absorbed nutrient(s).
Transport of Foliar Fertilizers Within Leaf and Plant.

**TABLE 3.9 Mobility of nutrients in the phloem**

<table>
<thead>
<tr>
<th>Mobility</th>
<th>High</th>
<th>Intermediate</th>
<th>Low</th>
</tr>
</thead>
<tbody>
<tr>
<td>K</td>
<td>Fe</td>
<td>Ca</td>
<td></td>
</tr>
<tr>
<td>Mg</td>
<td>Zn</td>
<td>Mn</td>
<td></td>
</tr>
<tr>
<td>P</td>
<td>Cu</td>
<td></td>
<td></td>
</tr>
<tr>
<td>S</td>
<td>B</td>
<td></td>
<td></td>
</tr>
<tr>
<td>N (amino-N)</td>
<td></td>
<td>Mo</td>
<td></td>
</tr>
<tr>
<td>Cl</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(Na)</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Even Mobile Elements will Not be Exported from Immature Leaves

Radioactive P applied to Leaves of Differing Age

Old

Young

Figure 4.1. $^{32}$P was applied to the indicated leaf (arrow) by immersion. 24 hours after exposure, plants were placed on X-ray film and the distribution of the labelled P was illustrated.
Mobility is Sometimes not Required

e.g. Foliar Zn, B, Mo at flowering.

Good spray coverage matters more than mobility
Factors Affecting the Efficacy of Foliar Fertilizers

PATHWAYS
1) Direct penetration through cuticle is possible for non-charged molecules (Urea, boron…)
2) Charged elements penetrate through cracks and pores.
3) Penetration through stomata, lenticels, bark, buds also occurs.

RATES OF UPTAKE DEPENDS ON:
1) Concentration of spray solution
   1) POD, Humidity, Rate.
   2) Surfactants, humectants
   3) Toxicity

AGRONOMIC & SPECIES CONSIDERATIONS:
1) Canopy Size, Leaf Retention
2) Plant Growth Stage
3) Species Differences in Cuticles
Summary: The Role of Foliar Fertilizers

BIOLOGICAL RATIONALE:
1) To overcome soil limitations that restrict element solubility or mobility
2) To correct short-term or ‘Transient Nutrient Deficiencies’

ECONOMIC RATIONALE AND PRACTICAL CONSIDERATIONS:
1) Relative costs and benefits (requires a measure of efficacy and consistency)
2) Can the need for foliar fertilizers be predicted and the treatment implemented (requires an understanding of plant physiology and a measure of efficacy and consistency and an opportunity)

Examples:
• Correct soil induced problems (Fe, Mn, Cu deficiency in high pH soils; Ca, K deficiency in some soils)
• Ensure optimal nutrition for flowering (Mo, Zn, B for flowering and fruit set)
  – ENVIRONMENTAL INTERACTIONS
• Supplementing nutrition at specific developmental stages (N for protein increase, Ca for fruits etc)
Secrets to Good Foliar Fertilization

• Understand why a foliar/fertilizer might be needed
  – soil limitations, root limitations, demand, plant phenology, environment, mobility)

• Pay attention to the really critical stages of development
  – flowering, ripening, bud development

• Use products and programs that have science behind them
  – Understand your crop/environment
  – Foliars: Soluble, suitable POD/humidity, crop specific, physiologically relevant, well-tested
  – Field Test and Optimize, but do it properly!
    • Apply test to 10 test plots, repeat a minimum of 4 times scattered across orchard.
    • Harvest/sample all plots separately.

• Sometimes, biological realities, economic risk and environmental uncertainty = Fertilize!
Thank You