Rethinking the principles and practices of nutrient monitoring and field testing in horticultural crops.

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Constraints
- Low input, low economic margin, high variability
- Multiple stresses
- Poor resource availability/affordability (Nutrient management = ‘0’, though typically 50% of production costs)
- Risk aversion (cultural and economic - food/income security)

Approaches and Solutions
- Political/commercial
  - Resource availability (nutrients, improved cultivars, advice)
- Biological/Agronomic
  - Optimized growth potential (Improved Genetics and Stress Tolerance)
  - Synchrony of N availability and N demand (Agronomy, Soil Sci)
  - Better NUE (uptake, utilization, root characteristics) under low and critical nutrient conditions.
- Technological (?)
  - Improved formulations, sensing, site specific management will not be adopted unless technologically ‘accessible’ and of clear economic benefit
  - Google maps, mobile phones, text messages and remote decision systems have great unmet potential for even the poorest farmers.
Contrasting Agricultural Systems:
Contrasting Challenges.
Strawberry production in California.

**Constraints/Opportunities**
- Per Ha production cost $73,000, fertilization costs $600 (<1%), returns of $30,000 Ha (1000 ha average size)
- Raised covered bed, sprinkler and drip fertigated
- High runoff, very low NUE (<25% \( R_{EN} \) – fertilizer N recovery kg N applied/kg N recovered in exported crop)
- Published information is very limited, poorly adapted to modern production and rarely used. (Survey data)

**Approaches and Solutions**
- Knowledge (real time, site specific models of plant growth and N demand)
- Technological (tools in place – fertigation, defined root volume)
  - Formulations (Slow release), fertigation, modeled demand based applications.
  - Sound information and approachable technology
  - Benefits will be extremely hard to show, adoption will NOT be driven by economics or yield, only ease of use.
    - Limited adoption of Site Specific management in high value crops
- Biological?
  - Root nutrient uptake is non-limiting, productivity is aggressively managed (breeding and inputs)
  - Disease and stress tolerance remain important.

http://coststudies.ucdavis.edu
Managing the Nutrition of Horticultural Crops

Relevance:

- 500,000 Ha of bearing acreage
- >7,000 growers
- $3.2 billion crop value (2008)
- California’s largest export crop, USA 4th largest export crop (tree and vine crops collectively)
- Californian practices are representative of most tree and vine crops in the US, and much of the world.
- Scale of industry, perennial nature, and introduction of precision harvesting provides unique research opportunities.
- Very nitrogen use efficiency is possible
What do we know and how do we manage?

Leaf Sampling and Critical Value Analysis in Orchard crops
(based on Ulrich @ U Calif in 1950-70’s)

- Carefully defined sampling protocols
  - Defined position in tree
  - Single time of year
  - Contrast with standard Critical Values
    - Yield trials (N, K, B)
    - Leaf symptoms (P, S, Mg, Ca, Mn, Zn, Fe, Cu)
    - Unknown (Ni, Cl, Mo)

- Australia: Standard protocol for determining deficiencies. Limited use for management.

- Chile/Canada: Historically important for routine management, being replaced by consultant ‘experience’ and company ‘knowledge’.

- Asia: Cornerstone of citrus and large plantation management. Growing utilization.

- Mediterranean Region: Primary means of nutrient management.

- EU: ‘Commonly collected though rarely used for decision making, only for deficiency correction.’
Focus Group Activity

- 45 leading growers, private consultants, university extension, govt. agencies

Random, balanced selection of 1,650 Almond Growers

- 34 questions on demographics, practices, constraints and perceptions
- 558 responses (33% of industry ±5% margin of error)

Recent farmer surveys on nutritional practice.

**Australia:**

*Key crop nutrient management issues in the Western Australia grains industry: a review*


*Australian Journal of Soil Research, 2009, 47, 1–18*

**China:**

*Reducing environmental risk by improving N management in intensive Chinese agricultural systems*

Xiao-Tang Ju, Guang-Yi Xing, Xin-Ping Chen, Shao-Lin Zhang, Li-Juan Zhang, Xue-Jun Liu, Zhen-Ling Cai, Bin Yin, Peter Christen, Zha-Liang Yue, and Hu-Xiao Zhang

*PNAS | March 3, 2009 | vol. 106 | no. 9 | 3041–3046*
Are tissue samples collected and if so how often?

On one of your typical almond orchards, how often are plant tissue samples collected? (Choose all that apply)

- Never: 40 respondents
- Less than once/year: 43 respondents
- Once/year: 307 respondents
- More than once/year: 98 respondents
- When problems are detected: 32 respondents
- I don't know: 5 respondents

>80% compliance
Are tissue samples being used to guide fertilizer management?

Do you think the University of California critical values are adequate to ensure maximal productivity in almonds?

>70% have little to no faith in the results or their use.

> Subsequent informal surveys suggest these issues are pervasive in tree crops globally.
Apparently tissue sampling is not trusted—Why?

Is the use of Plant Samples and the Critical Value or Critical Range appropriate for Trees/Vines?

Development of the Critical Value concept

  - analytical techniques have developed, principles/practices remain unchanged or have been diminished with time.

- originally defined as a means to identify when a crop is ‘.just deficient..rather than just sufficient.. to define if, but not how much, fertilizer should be added.’ (paraphrased from Ulrich, 1952)
  - thus, soil depletion to sub-optimal levels is a pre-requisite to fertilization
  - however, in high value crops allowing crops to become ‘just deficient’ is untenable.
  - von Liebig originally postulated that the intent of tissue analysis was ‘maintain soil fertility by replacing nutrients removed in harvests.’

- the complexity of tissue sampling was recognized, but never adequately optimized for trees.
  - within tree and within field variability is extreme, access to fully sunlight leaves is difficult, relevance of lower canopy leaves to tree productivity is poorly defined.

- limitations of the method and the utility of the data have been mostly forgotten.
  - Lawes and Gilbert-Rothamsted (1851) emphasized that tissue testing cannot predict quantitative demand for fertilizer, a conclusion reiterated emphatically by early writers but overlooked in most modern texts.
Variability in Plant Tissue Response to Nutrient Supply
Effect of K on Yield in Almond

Above the critical value, tissue analysis is unreliable.

Ulrich 1947

Secondary deficiencies (Liebig's law)
Shading and changes in leaf phenology
Luxury consumption
Problem with leaf sampling: Sampling challenges.

Shoot Zn Distribution Through A Dormant Peach Tree (ppm)

- 19.1 - sun exposed
- 28.5 - sun exposed
- 47.9 - shaded
- 39.7 - sun exposed
- 70.3 - shaded
- 16.3

Standard Sample: Fully Exposed non-fruiting leaves in late summer
Problem: Collecting representative samples in very difficult.

- Wallace (1953) collected 100 pairs of leaves from a single Valencia orange tree and analyzed for macronutrients.

<table>
<thead>
<tr>
<th></th>
<th>Mean ± s.d. (%)</th>
<th>Range (%)</th>
<th>CV (%)</th>
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<tbody>
<tr>
<td>Nitrogen</td>
<td>2.09 ± 0.247</td>
<td>1.61–2.65</td>
<td>11.8</td>
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<tr>
<td>Phosphorus</td>
<td>0.119 ± 0.010</td>
<td>0.089–0.145</td>
<td>8.4</td>
</tr>
<tr>
<td>Potassium</td>
<td>1.24 ± 0.194</td>
<td>0.63–1.68</td>
<td>15.6</td>
</tr>
<tr>
<td>Calcium</td>
<td>3.92 ± 0.589</td>
<td>2.42–6.35</td>
<td>15.0</td>
</tr>
<tr>
<td>Magnesium</td>
<td>0.22 ± 0.045</td>
<td>0.10–0.34</td>
<td>20.6</td>
</tr>
</tbody>
</table>

Conclusion: Collecting a ‘representative’ sample is exceedingly difficult without extreme care to ensure uniformity.
Strong Yield Interactions
High Nutrition is essential for High Yield
High Yield however depresses Leaf Nutrients
Leaves near fruit are not collected – Valid?
Proximity to Fruit Influences Leaf Nutrient Status

NF = Non fruiting spur leaf : F1 = Leaf on spur with 1 fruit : F2 = Leaf on spur with 2 fruit

Current CV > 2.3

% N in NF spur leaf in July/Aug is Deficient

Sufficient N to maximal light saturated Ps

Saa et al Poster 1434
Shade and Sun Leaves have Identical N Response Curves (peach)

Light Saturated Photosynthesis

$A_{\text{max},W}$ (μmol CO$_2$ g$^{-1}$ s$^{-1}$)

$N_W$ (%)

- High N - Sun
- High N - Shade
- Low N - Sun
- Low N - Shade

Preliminary

Almond 2.3%
Peach 3%
Leaf Health Influences return Bloom in Spur Bearing Species

The relationship of ‘Nonpareil’ almond spur fruiting status in 2003 to spur Winter survival and return bloom in Spring 2004

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<tr>
<td>Single-Fruited (F1)</td>
<td>86.5</td>
<td>18.9</td>
<td>1.67 ± 0.10</td>
</tr>
<tr>
<td>Non-Fruiting (NF)</td>
<td>99.2</td>
<td>56.6</td>
<td>1.92 ± 0.06</td>
</tr>
</tbody>
</table>

Carbon or nutrient effect?
Making Sense (?) of Complexity.

6 year study in Navel Orange
Yield x Tissue Nutrient Status

CV of 23 g kg\(^{-1}\) is associated with maximal yield +/- 50%!

- difficulty in tissue sampling,
- yield determination difficulties,
- inadequate physiological rationale etc.
Variability, Economics and Incorrect Interpretations

Incorrect!
if field average K Concentration = 1.7%, then 50% of the field is, by definition, deficient.

*UC Critical Value = 1.7%
**Field average K = 1.7%
Therefore current K program is optimum????

Average = 1.7%
Growers worldwide invariably target higher tissue levels than supported by data. Why?

Leaf samples collected from an excellent grower and critic of UC critical values.

Grower target CV = 2.0% K (95% of trees are above 1.4% K)

University of California recommended CV = 1.4% K
Survey of leaf N distributions in Californian Orchards

![Histogram showing July N concentration (%) with critical value and percentage of trees.]

- Percentage of trees
- July N concentration (%)
- Critical Value
- n=114
Improved sampling techniques, remote or handheld testing, re-education, regulation will all fail if the rationale for grower behavior is ignored.

\[ \text{Yield lost} \times \text{Yield saved} < 1 \]

![Graph showing the relationship between July N concentration and percentage of trees, with a critical value and cost implications.](image)
Managing Nutrition of High Value Crops

Avoid over-fertilization without under-fertilizing any. How?

Correct deficiencies
Spatial distribution of leaf N
Identification – Management - Economics

Safe area for fertilizer reduction
Summary: Tissue Testing for Horticultural Crops

- An inappropriate technology for well managed high value crops.
  - Difficult to practice and hard to interpret (except in deficiency range – rare)
  - Does not inform management practice
  - Not suitable for detection of supra optimal fertilization (insensitive, uptake and NUE decrease with application in excess of needs and induces interactions)
  - Rigorous adherence to sampling protocols may increase reproducibility, but not relevance.
  - Expensive (?) or simply a waste of money.

- Grower dissatisfaction with approach is understandable
  - ‘Over’ fertilization is a logical response to uncertainty and lack of viable tools.
  - Improved tools or lower cost (remote sensing, hand held meters, increased sampling and testing, better standards) do not address the problem.

Alternatives?
Alternate Approaches to Nutrient Management in Horticulture

Nutrient Budgeting

Nutrient Replacement
von Liebig\(^1\) (1840): the ‘fertility of the soil could be maintained through the simple expedient of returning to the soil as fertilizers the nutrients contained in the crops removed from the field’.

Nutrient Use Efficiency
(Cassman et al\(^2\), 2002) ‘We define the NUE of a cropping system as the proportion of all N inputs that are removed in harvested crop biomass, contained in recycled crop residues, and incorporated into soil organic matter and inorganic N pools.’

Essential Components and Challenges:

- Estimate demand (Direct measurement or crop growth simulation to determine seasonal patterns of uptake and partitioning)
  - Numerous models in agronomic crops (Manage-N, APSIM, INFO-crop etc)
  - Initial modeling efforts in Prunus species (DeJong and collaborators, UCD)
- Measure and control inputs and losses (soil, fertilizer, irrigation, leaching, volatilization)
- Manage efficiencies and interactions
  - Synchronization and synlocation of nutrient applications
  - Monitoring crop response

*Horticultural crops are ideally suited to this approach. (4 R’s)*

\(^1\)Chemistry and its application to agriculture.  \(^2\)Ambio Vol. 31 No. 2, March 2002
Demand: Predicting Yield Potential in Almond and Walnut

Bruce Lampinen, UCD
Nutrient Demand: Whole tree

Harvesting:
5 mature trees x 5 times in a year
Whole Tree N Contents by Organ in Almond.

The scale of nutrient demand is determined by Yield.
The ability to predict yield and fertilize accordingly would greatly improve management.
Nutrient Demand and Seasonal Dynamics in Almond Export from Orchard in Crop (3,200 kg. ha\(^{-1}\))

Nutrient Export per 1000 kg harvested crop: N=56-60 kg, K=51-54 kg, P=6-8 kg
Almond

NUE (RE$_N$), 118 individual Tree NUE estimations
(N removed in harvested fruit / applied)

Fertigated: 5 in-season demand matched applications

Soil or plant reserve depletion

Standard Practice (250-275 kg N ha)$^{-1}$
NUE$^{-1}$$_{3500}$ kg ha) = 0.82
Fertigated, low rainfall, neutral low OM soils.
Results: Yield Maps
(4,280 to > 10,000 trees harvested each year)

2002 89lbs

2003
1424: Spatial Patterns Confound Experiments in Orchard Crops (Rosenstock et al)

2004 49lbs

2005 95lbs

2006 15lbs

2007 105 lbs
Nutrient Use Efficiency and Variability in Pistachio.

4850-9650 individual Tree NUE estimations
(N removed in harvested fruit / applied)

12 year Mean NUE  = 0.72 (0.82-2006)

60,000 kg total 6yr N application (40 ha).
41,000 kg exported in yield.
7,000 est kg pruning, leaf loss and growth
12,000 kg 'lost'
50 kg ha⁻¹ yr⁻¹

24 yo Pistachio 115 mm rainfall zone, no deep percolation.
Silt loam, pH 6.7-7.0, OM 0.6%, 2 ppm NO₃N (100cm). Fertigated with five in-seasons split apps.
10 yr ave yield = 4,000 kg ha = 180 kg N ha in exported fruit
Mean N application 250.
Influence of Precision Management on Fertilizer Losses – first steps.

Nitrogen unaccounted for in yield (60,000 kg N applied)

Can we further increase precision by modeling individual tree behavior in time and space?

Adjust fertilizer application rate to annual demand. 65% reduction in N loss

Adjust fertilizer application rate for spatial demand. (-45%)

Spatial and annual (-72%)

Management regime

- Overfertilized
- Underfertilized

- Current practice
- Year
- Halves
- Year + Halves
- Current practice
- Year
- Halves
- Year + Halves

2002 - 2007
Yield and hence N demand and ‘Residual’ is not uniform in any field.

Yield of 768 individual trees (100 acre)
Nitrogen Fertigation and N$_2$O fluxes in Time & Space (Smart et al, UCD)

Fertigation 0:600am

Three dimensional model of N$_2$O flux from the drip zone.

(1.296 kg N$_2$O-N ha$^{-1}$ y$^{-1}$)
Pattern Recognition and Yield Estimation in Pistachio.

Whole field yield could be successfully modeled (+/- 30%) based on:
- Historic yield
- Climate
  - Chilling hours, heat units, weather anomalies.
- Early season predictors
  - Sampling procedures
  - Remote sensing

Individual tree determination remains more challenging:
- Sub populations of trees clearly exist
- Biological basis for yield fluctuation is not well understood.
Chaos Dynamics, non linear modeling and the Prediction of Yield in Satsuma Mandarin

Kenshi Sakai, Tokyo University of Agriculture and Technology

Off year tree

On year tree
Estimation of Jaccobian dynamics from ensemble data set of 96 individuals over 5 years.
One Year Forward Prediction

Time series mathematical modeling resulted in >90% one year forward prediction accuracy. (96 trees/4 years)

Model does not utilize any biological principles or environmental variables.

Pistachio data set is 10,000 individuals for 6 years with information on plant biology and environment.

Almond trial initiated 2008. 1,500 individuals at 4 sites with extensive measurement of biological and environmental variables.

Yield prediction is challenging but possible but can only be implemented with new engineering and orchard design.

- Variability within a tree and orchard is substantial. Rigorous standardization increases reproducibility but not relevance.
- Leaf sampling is not adequately sensitive at supra optimal nutrient concentrations.
- Sampling protocols and interpretation have been misused.
- As a consequence, orchard level critical values are difficult to interpret.
Alternate Practices: Nutrient Budgeting and Spatial and Temporal Fertilization

- Acceptable yield prediction, and hence nutrient demand, can be achieved with existing technologies and could be improved significantly.

- Variability within an orchard and over time is substantial, but poorly documented and understood.

- Under growth and production conditions used here, high NUE’s are observed in Almond and Pistachio orchards.

- Managing nutrients by managing for spatial and temporal variability is critical to efficiency.

Modeled and measured yield prediction is viable

Biological basis for variable production remains poorly understood.

Temporal and spatial variability is significant. Overall NUE can be very high.

Site specific management is promising and viable.
Rethinking the principles and practices of nutrient monitoring and field testing in horticultural crops.

The high value and long life of perennial systems, the inadequacy of current practices, the willingness of industry to adopt technology and environmental and market demands, represents an ideal opportunity to re-invent our approach to nutrient management.

This requires: Technology, engineering,

• Yield Measurement and Prediction – Integrated mathematical, biological, engineering and ecological approaches.

• Determination of Spatial Variability - Statistical and geo-statistical tools, sampling and sensing technologies, improved experimental designs.

• New Management Tools – Rapid yield and nutrient measurement techniques. New approaches to precision application -sub sector fertigation to single tree fertigation; VR devices and materials (surface/liquid).

Adoption will require development of sound information, packaged with an approachable technology that simplifies management. Yield and economic benefits will not drive acceptance.
Financial support:

USDA, CDFA, Almond Board, Pistachio Research Committee, Yara, GSL Compass, Mosaic, TKS.

Paramount Farming and numerous growers.

Students, Faculty, Staff:

Eike Luedeling, Sebastian Saa, Jeremy Nunes, Ismail Siddiqui, Saiful Muhammad, Todd Rosenstock, Maria Paz Santibanez, Sara Lopus, Blake Sanden, Mike Whiting.
Thank You
Managing for Spatial Variability

Introduces greater complexity in yield prediction

Yield Monitoring: Site specific Fertilization

>5,000 lbs

<2000 lbs

40 ha = 3,200 kg N

40 ha = 1,500 kg N

Difference in real N demand = 1,700 kg N

Difference in profit = $240,000
ONGOING RESEARCH

• More Rapid, Sensitive and Spatially Integrative Tissue Analysis.
• Yield Prediction and Monitoring

Ground and Aerial Imagery: In season nutrient status and yield prediction.

Handheld Monitors
Rapid nutrient measurements

Performance of an 8 PLS factor NIR model developed to predict the individual leaf N level on a dry weight basis in almond.

Aerial Image April 29 2009
Yield 2008