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Are Critical Values For Nutrient Management In Almond And Pistachio Orchards Invalid?

Or has there been a systematic misuse of sampling methodology and an industry- (and university-) wide misinterpretation of results?

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***Summary:** Ninety percent of growers and consultants participating in recent grower and consultant focus groups on nutrient management in tree crops, and the majority of respondents to an industry-wide survey, felt that the University of California (UC) "critical values" (CVs) for nutrient management in almond and pistachio were inadequate for modern production levels based on 1) current CVs are limited in application or 2) there are systematic errors in use of critical values. Review of current and historic data, however, indicates that the University of California established CVs for almond and pistachio production were reasonable and unlikely to be sufficiently incorrect to warrant the largely negative industry perceptions. It is apparent, however, that there has been a systematic misuse of sampling methodology and industry- (and university-) wide misinterpretation of results. Discussions with plant nutritionists working in high-value crops in the U.S. and in the international community suggest that this 'simple' misinterpretation of the use and interpretation of tissue samples is widespread.*

The large variability in leaf nutrient concentrations seen in tree crops has resulted in the development of standardized sampling techniques that strive to limit variability from sample to sample. While it is true that the use of a standardized sampling protocol is essential if you are to contrast results with a predetermined standard, this does not necessarily imply that such leaf samples are either the most sensitive or the most relevant indicators of tree nutrient status or potential for response. The choice of a July, non-fruiting, exposed spur leaf for nutrient analysis in almond is clearly a compromise selected to ensure low variability. There has been no study (to our knowledge) that specifically attempts to determine the relative sensitivity of this standard leaf in California almonds with any other leaf type or time of sampling.

In addition to within-tree variability in leaf nutrient status, there is also a great deal of within-orchard and between-orchard variability that occurs as a consequence of variability between trees, changes in soil conditions, and local microclimate. Typically, this within-field variability is not considered in sampling and, as a consequence, can lead to incorrect interpretation

This principle is illustrated in the following graph of 50 independent single-tree nutrient samples taken, one per row, across a mature almond orchard (Figure 1). In this example, leaf K concentrations vary greatly in the 50 sampled trees in this highly productive orchard. The average leaf K of this orchard is 2 percent, which is significantly greater than the University of California (UC)-recommended 1.4 percent K. Current UC recommendations would suggest this field is over-fertilized. The grower, however, is convinced, and has good yield records to verify it, that he obtains his highest yield when he targets a field average K concentration of 2 percent. The reason for this apparent

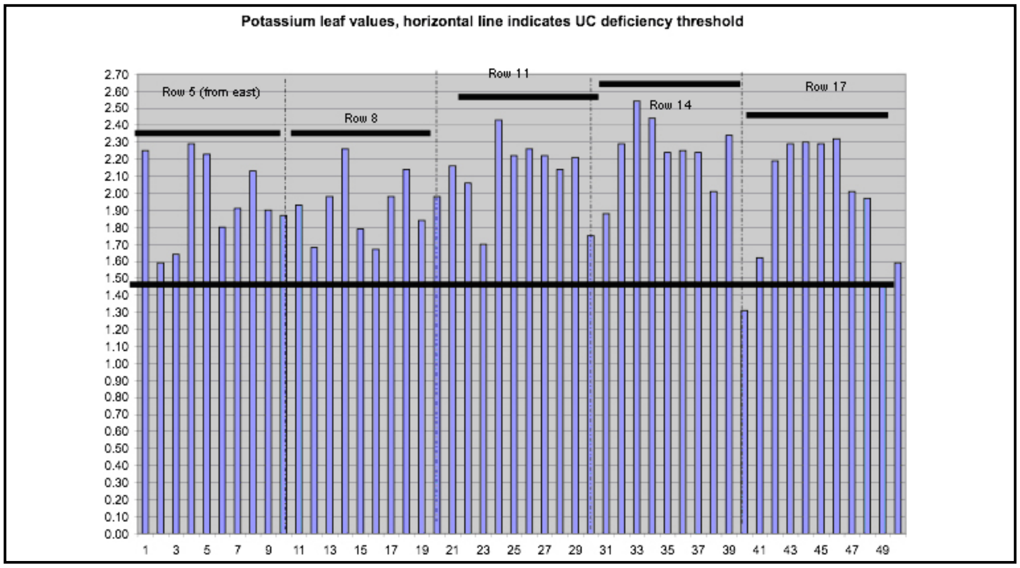


Figure 1. Leaf K values were determined in 50 individuals (1 per row) across a 50-acre orchard. The current CV for K in almond is 1.5%. Here the grower has targeted a field CV of 1.9% with the resultant effect that yield response to K has been maximized and 95% of all individuals have a tissue K value exceeding 1.5%.

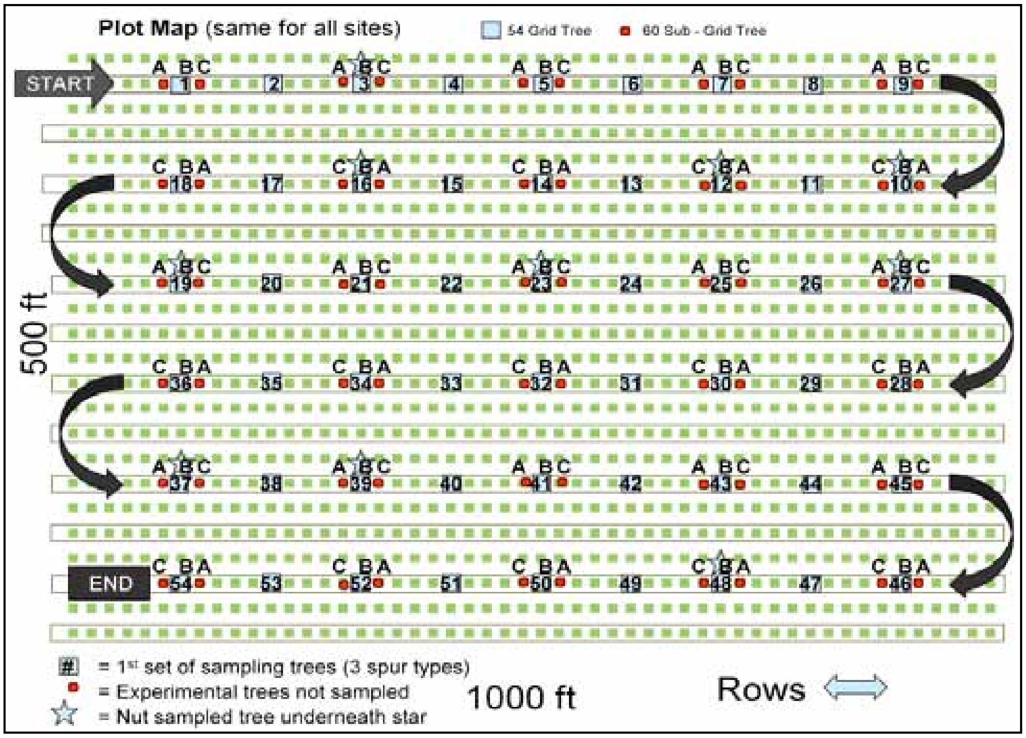


Figure 2. Field sampling strategy to partition components of yield and nutrient variability in almond. This experiment I repeated at 5 sites spanning the almond production areas of California.

disagreement is clear: by targeting a field mean of 2 percent, the grower is ensuring that all trees in the orchard are above the critically required K concentration of 1.4 percent. Maintenance of the field at the UC recommended 1.4 percent mean value would result in 50 percent of all trees being deficient in K. In this instance, the growers' perception of the critical value was more appropriate for yield optimization than the researchers'.

These results highlight a point that has been overlooked: for an individual plant the CV represents the minimum nutrient concentration in that individual plant that is required to attain 95 percent full yield. In a population of plants, however, the CV is the nutrient concentration of the population that results in 95 percent of all individual plants attaining full yield. This population CV will always be greater than the CV of the individual plant by an amount determined by the variability in the population. Estimating field variability is, therefore, essential if the true field CV is to be determined. None of the current texts or guidelines on nutrient management in tree species recognizes this issue and, as a consequence, many researchers have been misusing the single most trusted tool for nutrient management in tree crops.

To further examine and illustrate the extent and nature of errors in the use of tissue sampling we have initiated a series of experiments in which the yields and nutrient-use in large numbers of trees have been examined. Estimates of spatial, temporal, environmental, and genetic components of nutrient variability are under way and will be used to develop new approaches to sampling methodology and nutrient management in high-value crops.

Experimentation

Field variability. In agronomic crops derived from genetically uniform material, field variability in yields and nutrient status is largely the result of changes in the local environment (soil, water, micro-climate). In perennial crops, field variability not only is a result of this local environmental effect but is also a consequence of significant variability in genetics of the rootstock, the life history of the plant (grafting, pruning, and harvesting effects) as well as prior yield and growth of neighboring trees. The resulting complexity is therefore far greater. To address this, an extensive grid sampling protocol was established at each of five separate sites transecting Californian almond production regions, using techniques developed for GIS. In each orchard at 54 grid points, uniformly distributed across a 10- to 15-acre block of trees, May and July leaf nutrient status, light interception, truck diameter, and tree yield were determined in each tree (Figure 2). At 30 of these grid points, the nutrient status and yield of two neighboring NP trees were also collected as independent data points. Initially, non-fruiting spur leaves in exposed positions were selected for these samples. However, depending on early results, sampling protocols may be adjusted. Two statistical techniques--nugget sampling and modified Mantel--were used. These approaches allow for partitioning of variance in nutrient status due to environment, genetic variability, and random variability, plus allow for determination of interactions and dependencies between nutrition and yield and the nature of spatial variability within an orchard.

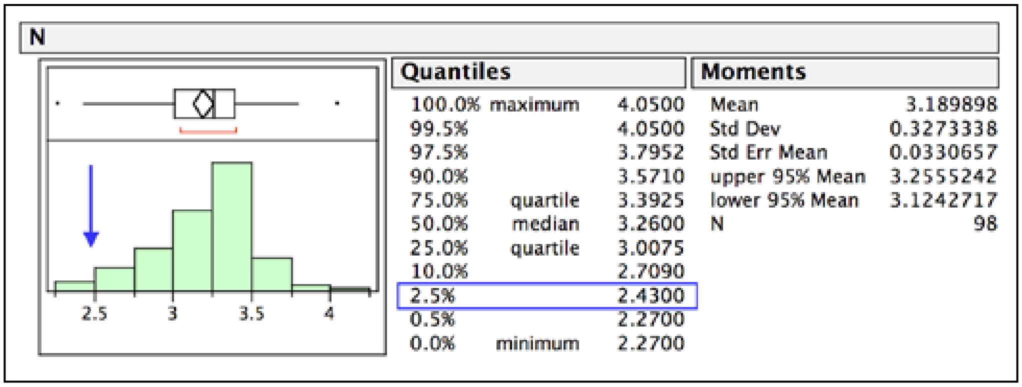
Yield collection. Individual tree yields were determined on 4,288 trees for six years in a single, highly productive orchard. Tree yields were gathered by a precision harvester. A pistachio yield monitor was developed by UC Davis in collaboration with Paramount Farming Company. To allow tree yields to be discretely determined, a standard commercial pistachio harvester was retrofitted with a weighing system. Tree location in the field was simultaneously determined with a number of redundant mechanisms, including differential GPS for row identification, physical markings, and an odometrical encoder wheel.

Nutrient-use efficiency. Leaf and nut samples have been collected across all experimental sites at five stages of crop growth. Sampling intensity averaged 20 discrete samples from each acre across each 50 acres at each of five experimental sites over five dates. Data will be presented as histograms to illustrate field variability and surface maps. Overall, this experiment will collect far more samples (2,672 samples from 456 trees), analyze far more nutrients (N, K, P, S, Ca, Mg, B, Zn, Mn, Fe) than ever performed before, and will collect individual tree yields associated with each of these samples. This detailed approach is designed to provide the foundation for statistical information needed to guide fertilizer practices for the foreseeable future. Nutrient-use efficiency (NUE) is calculated as N-removed-in-crop/N-input-annually over an eight-year period. In these orchards, no significant N is present in the irrigation water, irrigation water does not move below the root zone, and all pruning residue and leaves remain in the orchard.

Results

We predict that the adoption by growers of fertilization regimes, aimed to ensure that 95 percent of all individual trees in an orchard are above the established critical value, will result in a field mean nutrient concentration at least two standard deviations above the established CV. Figure 3 illustrates that this is indeed the case. The grower in this example precisely targeted the optimal economic fertilization rate.

While the results illustrated in Figure 3 verify that growers are fertilizing the majority of their orchards to ensure



Quantiles

100.0%	maximum	4.0500
99.5%		4.0500
97.5%		3.7952
90.0%		3.5710
75.0%	quartile	3.3925
50.0%	median	3.2600
25.0%	quartile	3.0075
10.0%		2.7090
2.5%		2.4300
0.5%		2.2700
0.0%	minimum	2.2700

Moments

Mean	3.189898
Std Dev	0.3273338
Std Err Mean	0.0330657
upper 95% Mean	3.2555242
lower 95% Mean	3.1242717
N	98

Figure 3. Leaf samples were collected using standard practice (10 pairs of leaves pooled from each tree) from 100 individual pistachio trees across a 10-acre orchard containing 1,250 individuals. Leaf tissue N was analyzed. Established critical values for pistachio are marked with a blue arrow and the corresponding blue box outlines the percentages of trees that are below this value.

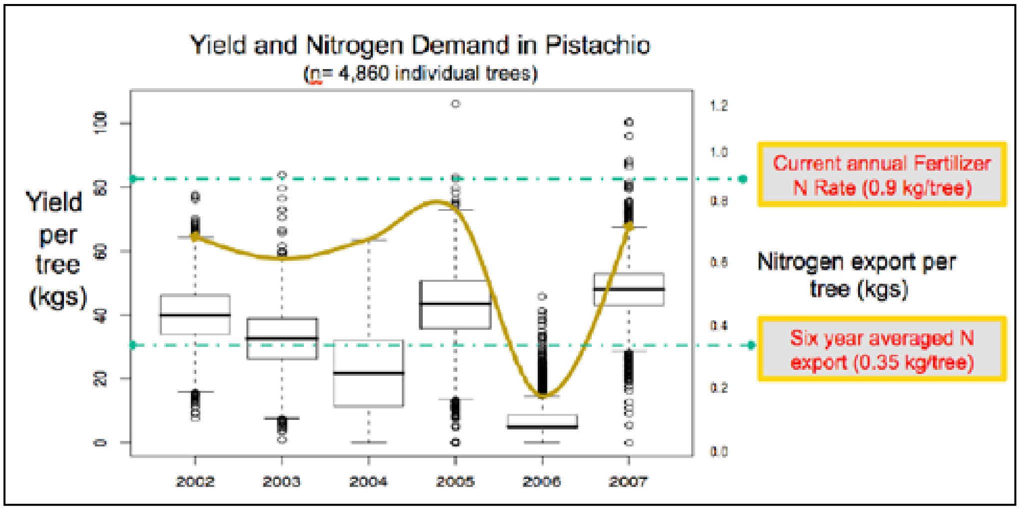


Figure 4. Nutrient demand was calculated as the product of yield x nutrient content of the exported crop. Yield was measured in every individual tree over the six-year experimental period. Box and whisker plots show mean (25th, 75th and 95th percentiles) of yield and N removal in each year. Dashed lines represent current N fertilization rate and calculated N removal in each year. The solid line represents a theoretical annual fertilization regime that would maintain fertilization of 95% of individuals based upon real yield in that year.

every tree is satisfied, this approach is economically viable only because fertilizer costs are a small part of operating expenses. This approach to fertilization is also a consequence of the lack of technology available for variable rate fertilization in orchards that are managed as a single uniform fertigated unit.

The impact of this approach to fertilization can be further exacerbated in crops that vary unpredictably in their yield. Pistachio undergoes strong yield fluctuations and growers currently have neither the means to predict the current year's yield, monitor in-season nutrient status, nor apply variable-rate fertilization within a single management unit (typically an orchard 40 to 100 acres in size). As a consequence there is a tendency over time to select a fertilization regime that ensures that every tree receives adequate fertilization every year. The outcome of this approach is highlighted in Figure 4. In this example, the grower established a fertilization rate of 0.9 kg per tree, ensuring that >95 percent of all trees received adequate N in all years. This level of fertilization takes into account the variability within and between years, and has been developed as a means of removing uncertainty. This rate of application, however, represents 2.5 times the six-year average tree N export (0.35 kg/tree), and an overall NUE of less that 33 percent across 6 years. This apparent gross inefficiency can be traced to 1) the marginal cost of additional N, 2) the inability to predict or measure field variability, and 3) lack of adequate tools to measure and monitor nutrient status. In the absence of any alternative approach, the logic behind grower decisions to fertilize in this manner is both clear and reasonable. However, if a grower were provided with the tools to predict and fertilize to meet actual demand (solid line), NUE could immediately be increased from 33 to 45 percent. However, even this simple tool does not currently exist.

What to do

In high value crops, it is concluded that tissue sampling strategies that only provide knowledge of 'mean' field nutrient status are of limited value unless they also provide an estimate of field variability. The constraints of tissue sampling are further exacerbated by the perennial nature of tree crops and the inability to effectively predict yield or to conduct early-season tissue sampling and fertilizer adjustment for which standards of practice have not been established. The limitations of current sampling strategy are further exacerbated by the constraints to nutrient management (which is now largely applied through fertigation) which limit the ability of growers to manage within field variability. This, coupled with the relatively low cost of fertilizer as a component of overall production costs, has resulted in the adoption of fertilizer regimes that are inefficient.

To address these issues, several new initiatives are:

1) Tissue sampling strategies that must provide information of in-field variability. This will require:

   a. Development of new sampling strategies

   b. Development of low-cost handheld, remote, or *in situ* probes to monitor plant and/or soil nutrient status

   c. Research into modeling approaches to nutrient demand and nutrient status determination

2) Required yield prediction models. For most high-value crops, extractive yield represents the primary determinant of nutrient application. Yield prediction models that allow for early-season adjustment of fertilization strategies will be required. This will require:

a) Development of yield monitors and predictive technologies

b) Research into yield determinants and model development

3) Variable rate application technologies will be required for high value species. It is counterintuitive that precision technologies have not been applied to high-value crops and that the adoption of fertigation as the primary source of nutrition has reduced the ability to conduct variable-rate fertilization. We recommend:

   a) Development of engineering approaches to provide differential with field fertilizer delivery

   b) Research into the effects of timing and product form on crop response.

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