

Nutrient Management Decision Support Systems for Tree Crops

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ABSTRACT

*Decision support systems can help improving nutrient management in agricultural and forest ecosystems. We suggest that the practical components of nutrient management are 1) Diagnosis, 2) Prediction, 3) Economic analysis, and 4) Recommendations. Nutrient management and agronomic information for perennial crops such as peach palm (*Bactris gasipaes* Kunth) revealed important differences from annual crops because of differences in growth phases and in dominant nutrient processes in each of the phases. We recognize four phases in perennial crops 1) Nursery, 2) Establishment, 3) Fast-growth, and 4) Mature. In the Establishment phase, plant growth is highly dependent on soil properties, and there is more concern for soil nutrient intensity rather than quantity. Instead, large soil nutrient stores are needed in the Fast-growth phase not just high nutrient intensity. The nutrient status in the Mature phase is characterized by extensive recycling of nutrients already in the biomass and less dependence on soil nutrients. A decision support system for koa (*Acacia koa* A. Gray) would aid new koa stand establishment, and would be important to identify stands that are in need of management or in decline.*

KEYWORDS: decision steps, growth phases, soil nutrients, peach palm, koa.

INTRODUCTION TO DECISION SUPPORT SYSTEMS

Decision support systems mean many things to different people and the expression has become jargon in the decision-science field (Sprague, 1975; Jones, 1998). Decision support systems have represented diverse computer-based programs ranging from simple spreadsheets to complex simulation models. A useful definition is that such systems or procedures should improve the timeliness and ease of obtaining quality information needed to make a decision. A decision-support system should evaluate the implications and predict the results of alternative decisions leaving to the user to choose the alternative with desirable outcomes. One example is a system designed to evaluate management options for improved short-rotation tree biomass production (Philips et al., 1997). It combined growth and yield models, a short-rotation culture system model, GIS, and a linear programming model. The decision-aid systems that we will describe in this manuscript are somewhat different in that we expect extension personnel and scientists in other disciplines to be able to use them. Such decision-support systems should be helpful in exploring options and alternatives in support of improved management for tree crops.

Concepts. We suggest that nutrient management has an inherent structure and that it would be useful to explicitly recognize that structure and develop information pertinent to it. The structure that we propose is 1) Diagnosis, 2) Prediction, 3) Economic analysis, and 4) Recommendations. In our view, this structure represents the practical components of nutrient management. We suggest that this structure calls for an interdisciplinary team ranging from the

day-to-day manager to the extension scientist, to the research scientist, to the economist, and back to the extension scientist and field manager in a sometimes circular, iterative process.

Scenario. In the course of developing a decision-aid for upland rice farmers in the Philippines and neighboring southeastern Asian countries, we illustrate the structure in nutrient management with the following scenario. Imagine that an upland rice farmer in San Antonio, the Philippines, decides to lease some of the acid upland soils to expand the rice growing area. He/she plants the first crop but notices that the rice plants look different from usual. The plants also grow more slowly than usual. At harvest, rice yields from the new field are much lower than from other neighboring fields planted at the same time. The farmer knows something is wrong and discusses the problem with a neighbor farmer or contacts the local advisor who asks whether there were “bagiing” or manganiferous nodules in the soils. The advisor concludes that there may be a problem, and collects samples of plant tissue and soil, obtains an analysis and determines that the Mn levels in plant tissues are too high. The advisor compares expected yield increases with the cost of remedying the situation (probably by liming and change to a more acid tolerant rice variety) and decides that it is worthwhile and recommends the change to the grower. The grower changes the management and the crop grows well.

This scenario illustrates a successful detection and resolution of a nutrient management problem. We believe that good nutrient management often mimics this pattern. When the grower notices that the rice plants on the new land have a different color and when yields will be substantially less, a “Diagnosis” has been made that something is wrong and action is needed. The grower may or may not have the experience or technical help to determine a precise diagnosis or the necessary solution. If the grower can only conclude that something is wrong and calls for the help the process still succeeds. He/she may call on a neighbor, an advisor, or other source of expertise for assistance. The advisor, for example, knows that in order to develop a good solution a precise diagnosis is needed, soil nutrient pools should be measured, and the amount of remedial material needs to be estimated. This is the “Prediction” step. The advisors can also assist in the diagnosis because they know that where the “bagiing” occur there is a likelihood of Mn toxicity. The advisor knows, however, that the predicted solution must be cost-effective so a partial-budget analysis is conducted, and it is determined that the change in management such as a lime application and a variety change are profitable, i.e., have a benefit/cost ratio greater than 2 to 4. This is the “Economic analysis” component of the process. With the favorable economic analysis in hand the advisor explains and discusses the results of the Diagnosis, Prediction, and Economic analysis with the grower and together they consider changes in management. This is the ideal “Recommendation” section of the process.

NUTRIENT MANAGEMENT IN TREE PERENNIAL CROPS

We have organized and developed nutrient management information for perennial crops with peach palm (*Bactris gasipaes* Kunth) as the example. We find that there are some important differences from annual crops, in part related to the different phases of growth and the differences in nutrient processes in each of the phases (Deenik et al., 2000; Ares et al., 2002; Ares et al., 2003). We recognize four phases in perennial crops because the nutrient requirements, processes, and management alternatives are quite different in each of them. These are: 1) *Nursery*, 2) *Establishment*, 3) *Fast-growth*, and 4) *Mature*.

1) In the *Nursery Phase*, the seeds are germinated and grown up to individual seedlings. Normally, this takes place under controlled conditions to ensure a high survival. Plants usually grow in a small container of specified growth media with a well-known distribution of nutrients – much as done with preparing potting mixes. There is little need for soil analysis and diagnosis at this stage. Usually a nutrient recipe is prepared and added prior to planting.

2) The *Establishment Phase* is the phase during which the seedlings are placed in their final location for growth to productive specimens. Growth during this phase is highly dependent on soil properties and, thus, critical levels of soil pH and nutrients including Ca, Mg, K, and P are important. Often, young plants have exceedingly high requirements in terms of nutrient intensity (i.e., high levels of extractable or soil solution nutrient concentrations), although not particularly large quantities of nutrients are required. Also, during this time the seedling must establish and develop a thorough, extensive root system not only for nutritional support but for water, resistance to adverse conditions, and structural support. Clearly, this is the period for which the nursery phase is intended to adequately prepare the seedlings. This phase is dominated by concern for soil nutrient intensity, in contrast to high quantities of nutrients in moderately available pools. During this phase, aboveground growth is frequently slow, perhaps because there is proportionately more growth of roots and supporting tissue.

3) The *Fast-Growth Phase* differs from the *Establishment Phase* in that during this stage the aboveground biomass accumulates rapidly. There is clearly a high demand for nutrients to sustain the rapid, possibly exponential growth of aboveground biomass, and relatively little recycling is occurring because new tissue is being developed. Large soil stores of nutrients are needed in this case, that is, greater amounts of nutrients not just high nutrient intensity as may be required during the *Establishment Phase*. Large amounts of nutrients are actually mobilized to the aboveground biomass during this period.

4) In the *Mature Phase*, there is essentially no substantial net biomass increase or it is very small relative to that occurring during the *Fast-growth Phase*. The nutrient status during this stage is characterized by extensive recycling of nutrients already in the biomass. During this stage there is relatively less dependence of soil nutrients and much greater emphasis on nutrient recycling and nutrient content already in the biomass. We propose that measurement of soil pools may not be critical during this stage because of the extensive recycling that is occurring. The nutrient pools most relevant to the new tissue are the nutrients already in the plant, perhaps stored in older tissue.

The proposed phases growth and the nutrient management decisions that must be made during each step are shown in Table 2.

Diagnosis. The diagnosis section (Yost et al., 2000), is critically important because the people who can best perform this step are the forest managers that visit and monitor the stands the most often as there is no substitute for being observant and frequenting the site. This, in our view, reflects the crucial role that monitoring and observing plays in the team management of natural resources. Because it is essentially impossible to predict what pests, diseases, weather effects, and natural disasters will occur and when they will occur, close monitoring is required. Consequently, it seems that we have no choice but to be constantly on the vigil in order to react with management adjustments in a timely fashion.

There are several categories of information that we have found useful for diagnosis of nutrient deficiency and excesses: 1) Plant observations, 2) Location history and experience,

particularly if the region is known to be nutrient deficient, 3) Soil characteristics and taxonomy, and inferences related thereto, 4) Requirements of the trees existing or to be planted, 5) Indicator plants such as ferns or *Melastoma* that usually indicate acid soils in the area being evaluated, 6) Symptoms, growth, and yield of the previous stand, and 7) Soil and plant analysis data from the site. We have combined this qualitative and quantitative information using a cumulative probability framework (Bayesian method) described by Pearl (1988).

Nursery Phase: During this phase, it is clear that conditions must be tailored to provide good growing conditions for the young seedlings. Often ensuring that the amount of shade is sufficient but not too much is important, as is proper irrigation and general protection from extremes that would harm the seedlings. Management might include inoculation with Mycorrhizae, and Rhizobia for leguminous seedlings. Diagnosis during this phase is often a reflection of the amount and intensity of management.

Establishment Phase: The diagnosis of potential problem situations during this phase concentrates somewhat more on the soils and soil preparation into which the seedlings were transplanted. This includes ensuring adequate nutrient status. We propose that measurements that assess nutrient intensity are probably most important. For example, estimates of soil solution P may be better predictors of establishment success than measures of labile or solid phase nutrients.

Fast-growth Phase: Diagnosis during this phase is likely to take place using soil and foliar analysis. During this phase there is a large import of nutrients, thus we suggest that measures of soil nutrient stores would be more useful. Also, because of the large transfer of nutrients, there is an opportunity for deficiency symptoms but this is usually only useful in extreme cases. Also, the absence of symptoms does not ensure nutrient adequacy. Certainly, other diagnostic methods are preferred so that the deficiency can be anticipated and corrected before yield and quality are compromised. In most cases, growth would already be impaired before the appearance of deficiency symptoms.

Mature Phase: Nutrient diagnosis during this period seems to be most effective with plant analysis. Some studies indicate that the majority of nutrient P for new growth comes from recycled nutrients rather than from soil pools, at least in some *Metrosideros* stands (Herbert, 1995). It seems clear that if soil samples are taken too deep, they may be irrelevant to the effective nutrient cycle. Consequently, we are currently recommending soil analysis of the 0-5 cm zone in order to best estimate the critical soil nutrient pools.

Prediction. During the *Nursery Phase*, we expect that the prediction of nutrient requirements will be relatively simple. As suggested before, nutrient requirements can largely be provided as standard mixes of required nutrients. Therefore, there is little need for plant and soil analysis as diagnostic tools for this phase. Consequently, decision-aid predictions for this stage may be limited to text presentation of the standard nutrient mixes and methods to properly prepare the mixes, alternative growth containers, and the typical management needed to ensure seedling growth and survival.

During the *Establishment* and *Fast-growth Phases*, we expect that prediction will likely focus on providing sufficient nutrients in the soil, but only in the potential rooting zone, such that nutrient placement is important. Differences might occur between the *Establishment Phase* and the *Fast-growth Phase* in terms of prediction because during establishment it is likely that a high nutrient intensity is of primary importance, while during the *Fast-growth Phase*, large amounts

of nutrients would need to be supplied. Consequently, it may be that these two phases are sometimes supplied from slightly different soil nutrient pools (solution nutrients in the *Establishment Phase*, and labile pools in the case of the *Fast-growth Phase*). Nevertheless, a standard method may be useful in estimating the amounts of nutrient that should be added in both phases.

The prediction section differs from the diagnosis section in that the purpose is to determine not only that something is wrong, but what is wrong and what it takes to replace or restore it. These remedies for whatever is wrong are usually biophysical and chemical predictions. Often the remedy is a specific amount of a nutrient fertilizer. In the case of N, the prediction is often related to the estimates obtained by the Stanford approach (Stanford, 1973) that estimates the total nutrient N requirement and then subtracts for the amounts that are in the soil, crop residues, green manures, and animal manures.

Calculations of N needs can be estimated from an adaptation of the Stanford equation:

$$N_{fert} = (Yld \times N_{Yld}) - [N_{soil} + (N_{gm} \times C_{gm}) + (N_m \times C_m)] / E_{fert} \quad (1)$$

where:

N_{fert} = Predicted N fertilizer requirement (kg N/ha)

Yld = Dry matter yield, vegetative and reproductive (kg/ha)

N_{Yld} = Mean concentration of N in vegetative and reproductive tissues (%N/100)

N_{soil} = Nitrogen from soil organic matter and previous crop residue mineralization and from soil atmospheric deposition during growing season (kg N/ha)

N_{gm} = Nitrogen mineralized from green manure in current growing season (%N/100)

C_{gm} = Proportion of N mineralized from green manure that is absorbed by plant (0-1)

N_m = Nitrogen mineralized from manure (kg N/ha)

C_m = Proportion of N mineralized from manure that plant absorbs (0-1)

E_{fert} = Fertilizer efficiency (0-1)

In the case of P, we have predicted requirements based on the following simple equations:

$$P_{fert} = (b_c - b_0 / a_2) \times depth / 10 \times placement\ factor \quad (2)$$

where:

P_{fert} = Amount of P fertilizer (kg P/ha)

b_c = Target critical level in the soil (mg P/kg)

b_0 = Measured level of extractable P in the soil (5 cm depth is recommended) (mg P/kg)

a_2 = Buffer coefficient (the extractable P increase per unit applied P) (mg P/kg)/(kg P/ha)

In the case of K, we propose a combination of the N and P methods. We begin by estimating how much fertilizer K is needed to raise the soil K level (K_0) to the critical soil K level (K_c), also based as in the case with P on a “buffer coefficient”. In addition, the amount of K that is likely to be removed or taken up by the plant biomass is estimated and the amount of K fertilizer needed to provide that quantity of K is estimated and divided by the appropriate efficiency factor of K fertilizer uptake and utilization. Written out it becomes:

$$K_{fert} = (K_c - K_0) / K_{bc} \times depth / 10 \times placement\ factor + K_{uptake} / K_{eff} \quad (3)$$

where:

K_{fert} = Amount of K fertilizer (kg K/ha)

K_c = Target critical level in the soil (mg K/kg)

K_0 = Measured level of extractable K in the soil (5 cm depth is recommended) (mg K/kg)

K_{uptake} = Amount of K absorption (kg K/ha)

K_{eff} = Efficiency factor for K fertilizer absorption and utilization, fraction (0-1)

The requirement is usually greater than 0.15 cmol/kg for K or the amount of K needed to replace that removed in the crop biomass and harvested products. This requirement, then, is adjusted by a buffering coefficient not unlike that used in the case of P.

In the *Mature Phase*, estimating the amounts of nutrients to supply during this phase is difficult, but we suggest that there may be a way of extending the concept of a soil buffer coefficient to include the plant - soil buffer coefficient that would serve a relatively similar purpose. That purpose is to estimate how much nutrient should be added in order to increase the foliar level of nutrient from the existing level (presumably deficient) to an adequate level. It might be argued that to develop a coefficient that would describe such a relationship is impossible given the complexity of the soil - plant nutrient cycling that occurs. Perhaps that is true, but very complex systems have been apparently successfully handled in the soil pool - extractable pool system that is described by the current “buffer coefficients” (Cox, 1994).

Economic analysis. Our previous decision-aids have all consider economic analysis as an integral part, this is because of the need for a decision-aid to span the entire process of decision-making. Our experiences have reinforced this view by illustrating the importance of being able to evaluate the economic consequences of changing species, soils, interest rates, and costs of both inputs and outputs all as part of a single, integrated unit. Seldom are such broad, yet detailed consequences examined outside of the use of decision-aids where the individual implications of a change in any of the components of the decision-making process can be reliably changed and rerun. Our economic analyses to date have been relatively simple, usually being partial budget analyses, producing an expected benefit/cost ratio. The advantage of a partial budget analysis is that data inputs are few – usually within ready access of extension agents and growers. The disadvantages are that the approach assumes that there is no interaction among the variable costs and production prices. Also, the overall enterprise may be losing money, yet a partial budget analysis of any subset of factors may be positive. Our choice of a relatively simple analysis is consistent with the overall approach in developing decision-aids, for which is better to assemble the information available at the moment to support decisions that cannot wait. Decision-making actuality is that decisions must be made at a particular time and place and one cannot wait for perfect information.

Recommendation. The last module of the decision-aids is the *Recommendation*. This is a summary of the diagnosis, the prediction of what is needed to resolve the problem, and the expected benefits and costs of what is needed to remedy the problem. This information needs to be assembled, organized and presented to land managers in ways that they can use it to improve their decision-making. Seldom do we intend for the users to be the growers and farmers, but our goal should be so. We constantly need to be seeking ways to simplify and directly present the information for those who will pass it on to the growers as well as others who may be able to use it, providing it is adequately explained and sufficiently intuitive.

ENVISIONING A DECISION SUPPORT SYSTEM FOR KOA

We will illustrate the development of a decision-aid by outlining what one might look like for koa (*Acacia koa* Gray), which is a very important tree species for the State of Hawaii and the Hawaiian culture. The process would be similar for other species such as *Eucalyptus*. Firstly, we should consider the goals of a koa decision-aid, for example:

- Improving koa yields, wood quality and tree form
- Protecting the environment
- Preserving native biodiversity

While it would be useful to develop a tool that would aid new koa stand establishment, it also would be important to have a tool that would assist in identifying the characteristics of stands that are in need of management or which are on the verge of decline for various reasons. For the purposes of this exercise, we shall take the case of the koa system that is designed to assist the preparation and outplanting of a new stand. We briefly look at the various phases:

Nursery Phase: Research has shown that koa, as an “undomesticated” tree species, has high genetic variability in growth rates, tree form and disease tolerance (Brewbaker, 1996; Sun et al., 1996), as well as in morphological (Daehler et al., 1999) and physiological characteristics (Ares et al., 2000a). Provenance selection is, therefore, crucial for a successful establishment of a koa stand. At a trial in Waiawa, island of Oahu, the Kaumana provenance grew only 0.1 m/yr in height, while the height growth rate for the Pacific Palisades was 1.5 m/yr (Cole et al., 1996). Also, growth of the Pacific Palisades provenance in a nearby study was much higher than that of the Kukaiau provenance (Silva and Scowcroft, 1996). Rainfall, elevation and mean annual temperature of the area where the Pacific Palisades provenance naturally grows, are very similar to those in Waiawa. This suggests that foresters should select local seed sources for koa afforestation, at least until more information on provenance selection become available, and, that koa populations should be protected from genetic pollution.

Once an appropriate provenance is selected, the standard nurseries procedures are to be carried out. These include to provide adequate growth conditions, supply needed nutrients in a mix, and ensure rhizobia and mycorrhizae colonization. Evidence for the importance of rhizobia and mycorrhizae in koa, are not unequivocal; however, it seems to be the best strategy to assure adequate colonization before outplanting.

Establishment Phase: Responses of koa to additions of P and other nutrients during the establishment phase have already been documented on Oxisols and Ultisols in Hawaii (Silva and Scowcroft, 1996). Koa increased in height and diameter with increasing doses of P (from 0 to 1400 kg/ha) applied in the planting hole. Unfortunately, soil and foliar P data were not available to determine P critical levels. Soil-genotype interactions were evident; growth of the Pacific Palisades provenance, for instance, was higher on Oxisol (Wahiawa) than on Ultisol (Leilehua). In another study, addition of 150 kg P/ha increased basal diameter of koa seedlings from local Oahu seeds but seedlings of a koa provenance from a more fertile site in Hawaii did not respond to fertilization (Scowcrof and Silva, 2005).

Ensuring an adequate establishment requires good site preparation, although precisely what preparation is most critical remains to be developed in research studies. A study examined growth response of koa after extensive site preparation which included tillage to 20-cm soil depth with the addition of lime throughout and an application of basal fertilizer for each planting hill. This extensive site preparation was required in order to example the genetic potential of 12

Acacia accessions. It is unlikely that such an extensive preparation is needed in all cases, but it is interesting to compare the average annual growth with such preparation with growth without it. This was possible with adjoining studies at Waiawa Correctional Facility, Oahu. Growth of koa, admittedly not the best provenance, with the preparation that included plowing, rhizobia, mycorrhizae, 20-220-20 fertilizer, and 8 t/h lime, was about 2.2 m/yr in height, while growth with plowing, rhizobia, mycorrhizae, 20-20-20 fertilizer and no lime, was about 0.9 m ht/yr (Cole et al., 1996). This contrasted with growth of 1.0 m ht/yr where there was no preparation and 300 kg P/ha was applied at planting. Many factors were involved in the superior growth, but it does indicate at least a growth potential of the species during the first year after outplanting in perhaps ideal conditions.

Fast-growth Phase: Soil nutrient levels are likely still important, especially in the “quantity” aspect such as extractable P levels. Again, we believe that foliar analysis will become more important during this phase, and its use will be useful if standards and critical levels can be determined. Certainly, an issue is what tissue should be measured for proper nutrient diagnosis. It is not certain that it should be the same as that used during the *Mature phase*. During the early part of this phase, it is possible that little nutrient recycling will occur, while during the latter stages recycling through internal redistribution and litter fall will become important.

Clearly, some diagnostic and predictive information is needed for the *Fast-growth Phase*. Allometric measurements will be useful to assess biomass accumulation and nutrient demand (Ares et al., 2000b). This non-destructive technique should be useful for assessing koa growth and in developing a comprehensive inventory of koa stands with different genotypes and across diverse sites in Hawaii. Because koa fixes N through biological means (Pearson and Vitousek, 2001), we expect that some assessment of the success and variation with stand age and soil type of the symbiotic process should be monitored to record its effectiveness.

Mature Phase: Little information is available on nutrient requirements of koa during the *Mature Phase*. Mean annual stem diameter increment of a 24-year-old koa stand increased after P fertilization in combination with thinning and vegetation control (Scowcroft et al., 2007). Based on nutrient requirements and responses of other species (Herbert, 1995), we anticipate that there are likely stands that would be responsive to nutrient amendment, but the diagnostic criteria for this stage are not available. We would expect extensive recycling of nutrients and a higher dependence on foliar analysis during this phase. There is, for example, very scanty research on response to nutrient additions of koa in the *Fast-growth* and *Mature Phases*. And even for the *Establishment Phase*, most research has been conducted on Oxisols and Ultisols which are “atypical” soils within koa’s native range. Research should be performed on Andisols, Histosols and Inceptisols, which are the most prevalent soils in the koa belt. Fertilization studies that can be combined with thinning and control of exotic grasses appear appropriate for areas in the island of Hawaii where there are koa stands of different age regenerated by soil scarification. In addition to measuring growth, other responses such as changes in tree form and wood quality, and in the composition of understory plant communities should be monitored.

The envisioned decision support system for koa should integrate, from early stages of development, responses to other growth factors in addition to nutrients. Research has shown that koa is limited by water availability either in its native range (Harrington et al, 1995; Ares and Fownes, 1999), and in plantations (Meinzer et al., 1996). At least, amount and distribution of rainfall, and soil water-holding capacity, should be incorporated as predictors of koa yield into

the decision support system. Because the decision-aid will likely target the Hawaiian islands as the geographical setting for the simulations, there would be an excellent opportunity to incorporate the already substantial (and currently improving) GIS data base on biophysical features to the decision aids (<http://www.state.hi.us/dbedt/gis/index.html>). Refined allometric models would provide less biased estimates of tree components and of total biomass aggregates, and would allow more precise estimates of other processes besides wood yield such as nutrient accumulation and carbon storage (Thornley and Cannell, 2000).

Modeling efforts with Acacia koa. Previous research (Grace, 1995) developed a koa growth model that can be useful to drive growth simulations in the decision-aid. The model that predicts stand dynamics under the following influences:

- Grazing - effects on tree growth, leaf area index, and harvestable volume
- Competition from larger trees
- Stochastic birth and mortality

Basal area was a relatively easily measured parameter that represented stand dynamics and might be a diagnostic feature in a decision-aid. In addition, use of allometric equations would be useful in documenting growth.

Summary of a preliminary decision-aid. The above results give hints at management requirements of *Acacia koa* but also point out the major gaps in knowledge needed to manage the species. It is suggested that further specification of the decision-aid would assist in identifying and suggesting critical research in order to provide the necessary data to properly manage this important species.

CONCLUSION

Decision-aids are practical tools that, when well-prepared, implement knowledge and provide good advice for potential tree growers. Our experience is that frequent users of such systems actually learn the information and often can soon perform almost as well as the decision-aids after a certain period of time. Consequently, this can be a learning and teaching tool as well as a method of generating quality recommendations.

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Table 1. Theoretical outline of decision-making structure in nutrient management.

Steps	Diagnosis	Prediction	Economics	Recommendation
Type of information	Is nutrient management action needed?	How much nutrient to add, changes in plant, soil?	Is the bio-chemical physical prediction feasible and cost-effective?	Craft the conclusions for proper presentation to the grower or manager

Table 2. Theoretical outline of decision-making structure in nutrient management in perennial tree crops.

Phase	Diagnosis	Prediction	Economics	Recommendation
Nursery	Detecting problems in the nursery: shade limitations, water, disease, others	Simple, use potting mixes of pre-made nutrients	Suggestions of ways to reduce labor costs, low-cost potting materials	Experience suggested guidelines for good nursery management
Establishment	Detecting if the soil nutrients are sufficient. Plant analysis is a secondary tool	Predict amounts of nutrients to increase soil levels. Perhaps nutrient intensity a primary factor?	Evaluate costs of the fertilization (likely localized placement becomes important)	Presenting alternatives for establishment in a user-friendly way
Fast-growth	Detecting if the soil nutrient status is sufficient. Plant analysis is a secondary tool	Predict amounts of nutrients to increase soil levels, perhaps nutrient supply rather than nutrient intensity?	Evaluate costs of the fertilization (likely localized placement becomes important) versus benefits of increased productivity	Presenting alternatives for the fast-growth phase in a user-friendly way
Mature	Detection of nutrient status – plant analysis as the primary tool	Predict amounts of nutrients necessary to increase foliar levels (soil-plant buffer coefficient)	Evaluate costs versus benefits of increased productivity	Present the summary of analysis of the mature phase and of all the phases to inform the grower or manager of options

Table 3. Comparison of early growth of *Acacia koa* under differing initial levels of inputs and preparation (Cole et al. 1996).

Site preparation	Initial liming	Rhizobia inoculation	Mycorrhizae inoculation	Starter fertilizer	Follow-up	Height growth (m/yr)
Land clearing	None	None	None	300 kg P/ha	0	1.0
Disk (20 cm)	None	Yes	Yes	20/20/20 kg/ha	0	0.9
Disk (20 cm)	8 t/ha	Yes	Yes	20/20/20 kg/ha	200 kg P/ha	2.2