From: *Plant Nutrient Management in Hawaii's Soils, Approaches for Tropical and Subtropical Agriculture*
J. A. Silva and R. Uchida, eds. College of Tropical Agriculture and Human Resources, University of Hawaii at Manoa, ©2000

Chapter 6

How Fertilizer Recommendations Are Made

R. S. Yost, Y. N. Tamimi, J. A. Silva, N. V. Hue, and C. I. Evensen

Recommendation, as we use the word here, means advice from a soil or crop specialist to those deciding *how much* of, *what form* of, and *when* to apply a fertilizer to a soil to benefit growth of a plant or crop. Recommendations of fertilizers and soil amendments must consider the interactions of all the factors discussed in this manual, including the soil, the crop, the climate, the beneficial effects of soil organisms such as rhizobia and mycorrhizal fungi, and the harmful effects of plant diseases, insects, and nematodes.

The relations among factors affecting plant growth are dynamic and complex. Any of them can become growth-limiting at any time, necessitating a specific remedy to permit the crop to achieve its genetic potential. The major tasks of the diagnosis and recommendation effort are to (1) identify growth-limiting (or yield-limiting) factors and (2) suggest economical, environmentally sound, and practical management alternatives.

In the process of modifying the amounts of nutrients in the soil, fertilizer applications have broad effects on the existing soil physical, chemical, and biological properties. Careful consideration of these impacts is needed, because unanticipated effects can limit plant growth and yield.

For example, achieving sufficiency of phosphorus (P) is not solely a question of increasing the amount of "available" P (see box at right). If the soil has been fumigated and the crop is one that is highly dependent on symbiotic associations with soil fungi (arbuscular mycorrhizal fungi), the crop—lacking aid from the fungi—will not obtain sufficient P even when soil analyses show high levels of extractable P, or when large amounts of P fertilizer have been added. In such cases, the most practical solution is to ensure that the crop is adequately colonized by the appropriate fungi. Similarly, even adequate fungal colonization of the plant roots will not ensure good yields if nematode infestation is severe. These examples illustrate how all parts of the soil-plant system are potentially growth-limiting. Consequently, a critical part of plant nutrient management is noticing suboptimal plant performance, identifying the cause (or causes), and devising a remedy.

In the overall diagnosis process that leads to a recommendation, individual soil and plant tissue samples are just part of the evidence that must be considered. It is a common misconception that the soil analysis or the plant tissue analysis is the only diagnostic informa-

Available nutrients are those nutrients that plants can absorb.

Extractable nutrients are those that are removed from the soil and measured during laboratory analyses. The extractant solutions may remove more or less of a nutrient than is actually available to a plant, so measurements of extractable nutrients are only a "best guess" of the levels of nutrient that a plant's roots can absorb.

tion that really matters. Equally important is the "background" information about the soil and plant. The form to be filled out for samples submitted to the CTAHR Agricultural Diagnostic Service Center (see Chapter 2) requests some of this useful information. The more complete and detailed the description of the background crop conditions, the better informed will be the diagnosis and the more likely it will be correct.

Because of the complexity of plant growth systems and the frequent uniqueness of growth environments, useful nutrient management strategies usually combine scientific principles with site-specific data and observations, seasoned with personal experience of the specific plant and production system. But there are some useful similarities among effective nutrient management plans. One such similarity is that nutrient recommendations are often developed in two steps:

- Diagnosis—Are yields or quality substandard? If so, what is the cause? If the cause is nutritional, is it due to deficiency or to excessive (possibly toxic) levels of the nutrient?
- Recommendation—What to do to correct the problem.

The preliminary diagnosis may begin with the grower observing an abnormal condition, or suspecting that growth is suboptimal. This leads to taking soil and/or plant tissue samples for analysis.

The next stage of diagnosis, after obtaining the analysis results, involves identifying potentially harmful soil conditions, or nutrient levels that are insufficient, excessive, or somehow out of balance. This stage requires some scientific knowledge of soils and plants and is often based on data from prior experiments with the specific types of soils and plants involved.

The recommendation (or what to do to correct the problem) often requires considerable knowledge of how soil-plant systems operate. This knowledge is at once broad (based on wide-ranging experience with various soils and plants) and specialized (in its depth of detailed scientific knowledge of specific soils and plants).

People who grow plants as a hobby or a business often are very good observers of the condition of their crops. With some scientific training and the help of literature on the subject (such as this book), they may be able to proceed through the diagnosis process and, based on their own experience, they may be able to develop their own strategies to correct the problem observed. However, we strongly suggest that consulting with professional experts on soils and plants is of value and can help to avoid mistakes. Although this book is designed to provide basic scientific information and stimulate learning about soil conditions and plant growth, growers in Hawaii are urged to take full advantage of the services of the Agricultural Diagnostic Service Center and the expert knowledge of the faculty of the University of Hawaii's College of Tropical Agriculture and Human Resources.

Diagnosis

Diverse kinds of information can contribute to a diagnosis by pointing to nutrient deficiencies or excesses and suggesting which nutrient is involved. These general indications include:

- visual symptoms of a deficiency
- yield reductions
- cropping history
- previous experience with the specific soil or soil family

More specific information about the crop and the soil-nutrient system is required to arrive at a recommendation to remedy the condition.

Diagnosis is the "front line" in nutrient management. If no one suspects a deficiency or an excess, then it is likely that the problem will go undetected and production will suffer. For this reason, we think it is important that all those involved in plant, soil, and nutrient management should be aware of the principles of diagnosis described in this manual. Those in the field who are closest to the production system on a day-to-day basis should know some aspects of the diagnostic process. The tools of diagnosis are discussed in the following paragraphs.

- ***Visual symptoms*** can suggest the presence of nutrient deficiencies but can be misleading (see Chapter 3 for descriptions of nutrient deficiency symptoms). Similar symptoms may not mean the same thing in all plants or all situations. Often, only a special combination of circumstances results in a distinctive color. Experience suggests that the *presence* of a symptom or symptoms can be more useful than the description of the particular symptom. Often, plants are deficient in a nutrient or nutrients but do not show symptoms. Even the presence of symptoms, however, is not definitive evidence of deficiency. Many causes—including disease, insect, and pesticide damage—can mimic nutritional deficiency symptoms. Soil and plant analyses are usually required to confirm that symptoms have a nutritional cause.

- ***Tissue analysis,*** the total nutrient content of a plant tissue, can be a precise tool for nutrient diagnosis. The particular tissue chosen is usually the one that is the best indicator of the plant's overall nutrient status. With corn, for example, the leaf just below the ear, sampled when the ear is silking, has been found to be most effective in diagnosing nutrient conditions that can result in yield changes. In some other crops, the "indicator" or "index" tissue is the youngest leaf that has most recently reached full size. Suitable indicator tissues must be identified for each crop by carefully controlled experiments.

Tissue analysis can sometimes fail to identify the nutrient deficiency. In the case of iron (Fe), zinc (Zn), and manganese (Mn), the total quantity of nutrient in the tissue selected for analysis may not indicate the total amount of the nutrient that is physiologically available within the entire plant; that is, some nutrients can be present in forms the plant cannot utilize.

- ***Nutrient dilution*** is another factor that can lead to misinterpretation of tissue analysis data. Nutrient contents are expressed as *concentration*, an amount of nutrient per unit weight of plant tissue. However, if the plant's accumulation of a nutrient lags behind its rate of growth (increase in weight), then the concentration of that nutrient in the tissue will decrease. Conversely, if nutrient acquisition continues but the plant weight does not increase, the nutrient concentration can increase. These conditions confuse the identification of the growth-limiting factor and complicate diagnoses. Such complications emphasize the need to consider several lines of evidence when diagnosing plant nutrient deficiencies.
- ***Sap analysis*** is another type of tissue analysis routinely used for some crops. Rather than measuring the nutrient content of the entire tissue, it measures the nutrient content of the plant's sap, or the juice readily squeezed from an indicator tissue. Sap analysis has become more widely used with the development of relatively inexpensive, portable instruments that measure certain plant nutrients in their ionic forms, such as measuring sap nitrate (NO_3^-) as an indicator of plant nitrogen (N) content. Sap analysis can be quickly done in the field and repeated during the growth of the crop. Easy though it may be to get a measurement with these portable instruments, the interpretation of the results is subject to the same complications that attend the other analysis methods described in this book. Localized correlation and calibration experiments are needed to accurately predict responses to fertilizer input recommendations derived from diagnostic interpretations based on sap analysis.
- ***Soil analysis*** provides information about the potential of a growth medium (field soil or prepared potting mix) to provide the nutrients required for plant growth. Routine soil (or plant media) nutrient analysis commonly measures extractable calcium (Ca), magnesium (Mg), potassium (K), and phosphorus (P). In special cases, soils are analyzed for aluminum (Al), for nitrogen as total N, ammoniacal N (NH_4-N), or nitrate N (NO^3-N), and for micronutrients, most often including boron (B), copper (Cu), manganese (Mn), and zinc (Zn). Based on knowledge of the particular soil's characteristics in relation to supplying nutrients, levels of extractable nutrients are interpreted to arrive at estimations of total amounts of nutrients available to a crop in that soil. These levels are in turn compared to "critical" levels considered adequate for the crop to be grown; critical levels are established by planned experiments, and often by compiling results of many planned experiments.

Soil analysis data is often most useful when combined with plant tissue analysis data. The combination of soil and tissue analyses, considered in light of site-specific information about the soil-plant system, is our most powerful tool in diagnosing plant growth problems.

A reliable soil analysis requires a sample that is truly representative of the soil or medium in which the plant is grown. (For specific instructions on sampling soils, see Chapter 2.) Getting a representative sample requires thoughtful observation of the area being sampled and careful sampling procedure. Collecting a good soil sample from a‘a lava land can be difficult, and the meaning of the analyses of the small amount of soil material obtained from such collections is uncertain.

Soil analyses are not definitive—they can mislead. For example, the soil K level may be high, but the plant may be deficient in K because of soil compaction, nematode infestation, or other factors that limit nutrient absorption.

- ***Cultural practices*** that affect soil salinity levels, organic matter content, tilth, aeration, and other soil conditions should be considered in nutrient diagnoses and interpretations. These conditions influence nutrient sufficiency when they affect nutrient transformations in the soil or nutrient transport through the soil, into the plant, and within the plant. This nutrient absorption pathway is extremely complex. It begins with various types of movement and chemical transformation as nutrients migrate from soil minerals or organic matter into the soil solution. Encountering plant roots, the nutrients are further influenced by the root rhizosphere. At the root surface, they enter the plant by being transported across a plant membrane. Within the plant, the nutrients move in the xylem to sites of growth, where they are synthesized into plant material.

This complex process is subject to influence by many factors. For example, water stress rapidly affects uptake of most nutrients. After a few days of wilting, plants can display the same yellowing of lower leaves associated with nitrogen deficiency. Phosphorus absorption by plants is strongly reduced by water stress; conversely, phosphorus deficiency leads to wilting.

- ***Timing*** of nutrient applications in relation to plant tissue sample collection can be critical to obtaining a meaningful plant sample. There is a time gap after fertilizer application before the "flush" of nutrient uptake and the resulting growth response in the plant have occurred. This may be several weeks for herbaceous plants and a year or more for established tree crops.
- ***Nutrient ratios*** are sometimes helpful in interpreting soil analysis data. For example, plants' sulfur nutrition is affected by their nitrogen content, so an unusual N/S ratio can signal imbalances. High soil potassium (K) levels can induce magnesium (Mg) deficiency, so the K/Mg ratio in the soil should be considered before assuming that soil Mg levels are adequate.
- ***Other factors*** in addition to nutrient levels can affect interpretations of nutrient conditions. Applications of fungicides and fumigants to control harmful organisms can eliminate the beneficial AM fungi (see Chapter 14, *Mycorrhizal Fungi and Plant Nutrition*). Many plants are strongly dependent on AM fungi for help in taking up phosphorus, and plant growth will be limited when the fungi are killed.

Recommendation

Once a nutrient deficiency is diagnosed, a recommendation can be developed for an action to correct the situation. We have described a diagnostic approach that assembles a wide range of information from various sources. Recommendations, in contrast, are developed by narrowing the approach to focus on the particular problem: What is wrong with the usual nutrient supply system?

Keys to diagnosing soil nutrient problems

- Recognize the problem. Be alert to signs of abnormal plant growth and declines in yield or product quality.
- Measure the situation. Keep good records of inputs, growth conditions, and yields. Monitor soil nutrient levels and other soil factors affecting plant growth such as soil pH, salinity, and moisture tension. Monitor the crop's nutrient content.
- Consult knowledgeable people before problems become severe.

A frequent answer is that there is a simple deficiency—the available "pool" of a certain nutrient or group of nutrients in the soil is too small. Just as frequently, however, factors other than limited quantity have restricted the supply of the particular nutrient. In this latter case, solving the deficiency is not always merely a question of adding more nutrient as fertilizer. In fact, most growers have already tried this remedy before asking for help.

As we have described above, many factors can affect the adequacy of nutrient supply. In developing recommendations, specialists from other disciplines often must be consulted to confirm the diagnosis. These specialists include plant pathologists, entomologists, horticulturists, and plant physiologists.

Correcting soil nutrient deficiencies

Soil nutrients can be grouped into three general categories:

Nutrients that react extensively with the soil

- phosphorus (P)
- potassium (K)
- calcium (Ca) and magnesium (Mg) as supplied in limestone and dolomite.

Management of these nutrients is largely concerned with their amounts in the soil, which are managed by determining how much nutrient is necessary for good growth (the *critical level* of the nutrient) and how much fertilizer nutrient is required to bring the soil or media to the necessary level. Soil test calibration determines for a particular crop and soil how much fertilizer is required to bring the soil test level to the level necessary for good growth (see box at right).

Nutrients that react relatively little with the soil

. . . and the need for which, consequently, is determined largely by plant demand; examples are nitrogen (N) and, in some soils, potassium (K).

Nutrients that are required in small amounts

. . . and which can easily be either deficient or toxic; these include zinc (Zn), manganese (Mn), iron (Fe), boron (B), molybdenum (Mo), and copper (Cu).

The importance of developing nutrient management programs

The power to improve crop management using information obtained from a methodical program of nutrient monitoring was recognized several decades ago by Harry F. Clements and incorporated into his crop log system for sugarcane production. Today, similar techniques are applied in monitoring the nutrient status of many crops—for example, macadamia nuts.

To improve the accuracy of fertilizer recommendations, farm managers should keep records of their fertilization program and crops' responses to it. A good soil fertility management record would consist of:

- soil and plant tissue analyses at the beginning of the fertilization cycle
- measurements of crop yields
- records of fertilizer inputs (amounts and times) associated with the crop yields
- soil and plant tissue analyses after the cropping cycle.

These data permit estimation of the nutrient additions and removals and the resulting deficits or surpluses. After several years, such records will reveal trends in nutrient status that have resulted from the fertilization program. In addition, records of applications of other agricultural chemicals to the crops may be useful in the diagnosis of problems that occur. Monitoring nutrients in this way provides useful management information.

Regulations affecting agriculture are becoming more stringent when it comes to impacts of agricultural practices on the environment. Already, on-farm use of certain agricultural chemicals, such as pesticides, must be recorded to ensure that "best management" guidelines are being followed and that applications are done properly. In the future, records on use of fertilizers may also be required to help state and federal regulatory agencies protect the environment. Farmers who use sound recordkeeping and nutrient management practices to improve their profitability will be better prepared to comply with and meet the standards of any new regulations on agricultural chemicals.

Calibration

A soil test is calibrated in a two-step process:

- Identify the level of each nutrient that is adequate for good growth of the crop.
- Determine how much fertilizer is needed to increase soil test values to the level of adequacy for the nutrient and the crop.

The results of each of these steps vary with the soil type. For example, depending on the soil, the amount of phosphorus needed as fertilizer may range from 2 to 50 times the actual increase in soil-test P that will result from the fertilizer application.

Calibration research is expensive to conduct, and because of the numerous crops grown in Hawaii and the many different types of soils found in the state, development of calibration data has been limited. Therefore, field testing by growers cooperating with researchers is presently one of the few practical ways to obtain calibration data.

The CTAHR Agricultural Diagnostic Service Center

In recent years, CTAHR's Agricultural Diagnostic Service Center staff and other CTAHR faculty have focused much effort on transforming and improving the soil and plant tissue analysis service. The specific objectives of this effort have been to improve the handling and analysis of soil and plant tissue samples by accomplishing the following goals:

- change sample analysis procedures to more quantitative methods that have better supporting research (in the form of correlation and calibration studies

from other areas)
- shorten the time between soil sample submission and delivery of diagnostic and recommendation results to clients
- provide growers with an acceptable alternative to U.S. mainland laboratories, which often give recommendations that are irrelevant to Hawaii conditions
- develop, confirm, and standardize recommendations appropriate for Hawaii conditions
- improve the diagnosis and recommendation process by making it clearer to all the parties involved (growers and extension agents, extension specialists, and their supporting departments)
- provide supporting information (such as is contained in this book) to assist agents in explaining and interpreting diagnoses and recommendations
- promote interactive communication and facilitate information feedback from the parties involved to the CTAHR Nutrient Management Working Group that would permit the group to correct faulty diagnoses and recommendations and implement more appropriate new procedures
- develop a computerized system that would reduce the amount of time required by the specialist to generate quality recommendations.

These changes have resulted in more samples being received by the ADSC and increased awareness of nutrient management by specialists, extension agents, and their clients.

Fertilizer Advice and Consulting System for diagnosing nutrient status and recommending fertilizer applications

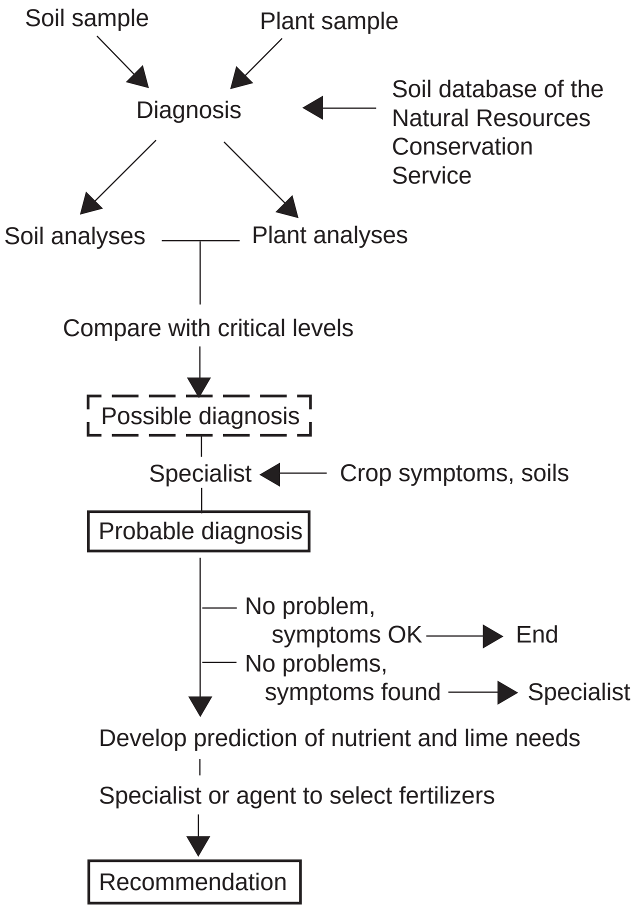
The last step in the preceeding list of objectives is a crucial one. It has led to the development of the Fertilizer Advice and Consulting System (FACS). This involved organizing the information that is already available on Hawaii's soils and crops. Also, it attempts to automate the process of comparing new information about a specific situation with the existing body of knowledge.

FACS is a computer program developed using an "expert systems" knowledge-capture strategy. Computers cannot mimic all of the human decision-making process, but they can store much of the information that experts need to make decisions, and they can make that information available to others. They can also do some of the preliminary analysis of the information by duplicating some of the considerations that an expert would apply to a problem.

The goal of soil and plant tissue analysis is to improve nutrient management for increased productivity and economic benefit and decreased negative effects on the environment, if not to improve environmental impact. The analysis is used to identify nutrient mismatches between crop, soil, and farmer needs and develop recommendations that correct the mismatches. The details of this process as used by ADSC are diagrammed in Figure 6.1.

An example of the type of information FACS uses for diagnosis is that contained in the table developed by the CTAHR Nutrient Management Working Group

Figure 6-1. Diagnosis sequence for soil and plant samples in the CTAHR Agricultural Diagnostic Service Center



(Tamimi et al., 1994), which gives broad target ranges of soil pH, phosphorus, potassium, calcium, magnesium, and salinity that have been established for some crops in Hawaii.

Wherever possible, FACS uses local data to interpret foliar analysis results, but at the present time the program is largely based on the plant nutrition book by Jones et al. (1991). The sufficiency ranges given in the Tamimi et al. (1994) fact sheet have been expanded in FACS to five categories of suggested interpretations for both soil and plant analysis: very low, low, sufficient, high, and very high. These ranges correspond to specific interpretations and actions. For example, if sample values were interpreted in the "very low" or "very high" ranges, it indicates that a change in the nutrient management program is needed, not just the addition of more or less nutrient.

Our current interpretations reflect a substantial change in the philosophy of nutrient management. No longer is excess fertilizer applied considered "money in the bank" or nutrient "insurance." Rather, it is wasteful, environmentally harmful, and could be the focus of regulatory action in the future.

Developing FACS has involved the use of logic, which is intended to make the diagnosis and recommendation process clear and open to scientific critique. FACS has also been developed to help its users learn principles of nutrient management. This knowledge can empower growers to improve their nutrient management programs by understanding the value of information used in diagnoses. They also can be more knowledgeable when implementing the recommendations for correcting crop, soil, and management mismatches.

If diagnosis identifies nutrient deficiencies or excesses, FACS proposes a recommendation. Often, nutrient deficiencies are found, because our tropical soils are highly weathered. The process by which recommendations are developed depends on the client. For example, recommendations for homeowners stress convenience and environmental concerns in the selection and application of nutrients, while recommendations for a rancher may focus more on productivity, economic, and environmental factors. The general sequence used in FACS for developing recommendations is as follows:

- Soils and soil series are grouped into three broad categories based on bulk density: heavy soils (bulk density 1 g/cc), light soils (bulk density 0.5 g/cc), and a'a lava soils.
- The crop to be grown will determine the target pH range, and the yield goal will determine the probable nitrogen demand.
- If needed, a recommendation for soil pH adjustment is determined to meet the crop needs, depending on acidity and alkalinity factors. In locations where rainfall is adequate for crop growth, soil acidity is often a problem. Buffer curves are used to calculate lime requirement, considering whether the limiting factor is Ca or Mg deficiency, Mn toxicity, Al toxicity, or extreme pH (see the chapter on soil acidity and liming for more detailed information).
- The phosphorus requirement is determined. Target soil levels are identified, and broad buffer coefficients (the change in extractable P per unit of applied phosphorus) are used for the three soil categories. The general formula is $[P_{target} – P_{actual}]$ divided by the buffer coefficient.
- The potassium need is considered using a similar calculation procedure (target minus actual divided by the buffer coefficient).
- Critical levels of calcium and magnesium are considered. Based on the initial levels and the expected changes due to lime and phosphorus applications, predicted levels are compared with minimum levels and, if they are still inadequate, additional nutrient applications are recommended.
- Micronutrients are added as a "blanket" application when foliar analysis indicates deficiency.

The development of the Fertilizer Advice and Consulting System is dynamic and ongoing. As more accurate and precise information becomes available, FACS will be improved. Continued review of literature and accumulation of local experience is necessary to improve recommendations. FACS also must be thoroughly tested by Cooperative Extension Service agents and specialists. The goal is to develop a "self-correcting" system that incorporates input from growers, researchers, extension agents, extension specialists, and the ADSC while moving cooperatively toward improved and proactive management of nutrients in Hawaii's agricultural and natural ecosystems.

References

Dahnke, W.C., and R.A. Olsen. 1990. Soil test correlation, calibration, and recommendation. In: Soil testing and plant analysis. 3rd ed. Soil Sci. Soc. Am., Madison, WI.

Fixen, P.E., and J.H. Grove. 1990. Testing soils for phosphorus. In: Soil testing and plant analysis. 3rd ed. Soil Sci. Soc. Am., Madison, WI.

Jones, J.B. Jr., B. Wolf, and H.A. Mills. 1991. Plant analysis handbook. Micro-macro Publishing Inc., Athens, GA.

Peck, T.R., and P.N. Soltanpour. 1990. The principles of soil testing. In: Soil testing and plant analysis. 3rd ed. Soil Sci. Soc. Am., Madison, WI.

Sims, J.T., B.V. Vasilas, K.L. Gartley, B. Milliken, and V. Green. 1995. Evaluation of soil and plant nitrogen tests for maize on manured soils of the Atlantic coastal plain. Agron. J. 87:213–222.

Tamimi, Y.N., J.A. Silva, R.S. Yost, and N.V. Hue. 1997. Adequate nutrient levels in soils and plants in Hawaii (general guide). CTAHR publication AS-3. University of Hawaii at Manoa. 2 pp.

Tindall, T., and D. Westermann. 1995. Proceedings, Western Regional Nutrient Management Conference, March 8–9, 1995.

TropSoils. 1992. Proceedings of the TropSoils Phosphorus Decision Support System Workshop, College Station, TX, March 11–12, 1992. TropSoils Bulletin no. 92-02. Department of Agronomy and Soil Science, University of Hawaii at Manoa.

Westerman, R.L. (ed). 1990. Soil testing and plant analysis. 3rd ed. Soil Sci. Soc. Am., Madison, WI.