**SOIL TESTING AND PLANT ANALYSIS RELATIONSHIPS FOR IRRIGATED
CHILE PRODUCTION**

By

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ABSTRACT

In a field study of irrigated chile (*Capsicum annum* L.) production in southeastern Arizona and southwestern New Mexico from 2008 through 2009, soil and tissue test samples were analyzed for a spectrum of nutrients at 16 different sites, including nitrogen (N) phosphorus (P), potassium (K), zinc (Zn), iron (Fe), and boron (B), with the objective of evaluating soil and tissue nutrient testing procedures and establishing basic testing guidelines and recommendations with respect to yield potentials. Soil samples were collected each year before planting. Plant tissue samples from all plots were collected at the following four stages of growth: first bloom (FB), early bloom (EB), peak bloom (PB), and physiological maturity (PM). All fertilizer and nutrient inputs were monitored, managed, and recorded within current Extension guidelines for irrigated chiles.

Results for soil and tissue analysis were compared to yield results. The results provide estimates for baselines which can be tested through subsequent calibration experiments for the development of recommendations for critical soil and tissue test values. Absolute minimum soil test nutrient values were identified as 10 ppm P, 110 ppm K, 0.3 ppm Zn, 2.0 ppm Fe, and 0.25 ppm B. Absolute minimum FB tissue test values were 0.2% P, 4.5% K, 10 ppm Zn, 80 ppm Fe, and 30 ppm B. These soil test and plant nutrients values will be evaluated in subsequent experiments in an effort to better define fertilizer nutrient inputs and to obtain better nutrient management efficiencies in irrigated chile production systems.

INTRODUCTION AND LITERATURE REVIEW

Globally, pepper (*Capsicum annum* L.) represents a huge market, with over 3 million hectares cultivated annually (Bosland and Votava, 2000). China is the leading global producer (Wein, 1997). In the United States, chile peppers are grown primarily in southern California, Arizona, and New Mexico (Bosland and Votava, 2000). U.S. chile production is a multi-million dollar industry, with almost 25,000 acres planted in 2007 with a production value of close to \$120 million (NASS 2007). Chile peppers are a valuable source of nutrients and vitamins, and are traditionally used as both fresh and dried pods and in a variety of spices and sauces. In the previous century, fertilizer was cheap and environmental repercussions of over-fertilization were not fully understood (Brown, 1987). However, as profit margins shrink and environmental standards increase, growers are increasingly aware of fertilizer needs and costs. Very few studies have been conducted on chile peppers to correlate and calibrate nutrient levels and to identify critical tissue and soil test values. Furthermore, growers may be hesitant to implement nutrient standards which, to them, seem low or conservative, especially when their livelihood depends on the outcome.

This field experiment was conducted at field sites in cooperation with two growers in Arizona and New Mexico in an effort to evaluate current soil and nutrient testing procedures. By conducting the experiments in the field in cooperation with growers, we can begin to establish verifiable and reliable testing guidelines and

recommendations with respect to yield potentials. This study compared soil test values and tissue test values for nitrogen (N), phosphorus (P), potassium (K), iron (Fe), zinc (Zn), and boron (B) at selected stages of growth to dry weight chile pod yield on a kilogram per hectare basis (kg ha^{-1}). We did analyze all soil and tissue samples for a wide range of nutrients, including those listed above as well as magnesium (Mg), calcium (Ca), sodium (Na), sulfur (S), copper (Cu), and manganese (Mn). However, for the sake of limiting the scope of this research we only used N, P, K, Fe, Zn, and B for analysis. We feel these are the most important nutrients to chile and therefore the most relevant towards beginning to establish nutrient relationships.

Knowledge of the effects of macro- and micronutrients allow us to optimize the yield potential of agricultural systems. However, when seeking to optimize yield potential of cropping systems, a primary consideration is the soil itself. Soil type, texture, and pH all impact plant growth and nutrient availability. Soil fertility is defined as “the ability of the soil to supply nutrients in adequate amounts and proper ratios for the growth of crops” (Marschner, 1995). Conducting soil fertility field experiments can generate new information for methods, timing, and rates of fertilizer application that can be specific for crop type. By comparing soil nutrient test values to yield results for a particular crop, we can begin to relate production to levels of nutrients in soils. Further experiments and analyses can lead to soil test calibration and the development of nutrient critical values or ranges.

The ability to increase yield potential by increasing soil nutrient availability must be approached in a sustainable manner in fertilizer form (Fageria, 2007). As such,

nutrient recommendations that result in over-fertilization may be just as detrimental as those that result in under-fertilization. While over-fertilization may appear more sound for the grower in the short-term, long-term environmental and economic considerations may be just as detrimental as immediate yield reductions experienced with under-fertilization. For many years, laboratory recommendations to growers in the United States erred on the conservative side, that is, they knowingly recommended fertilizer results that were higher than necessary (Brown, 1987). This strategy was implemented under the assumption that it would be preferable to “build up” a base level of soil nutrient levels. However, this doctrine proved unsound in many ways and was unwise for the environment long-term. Even knowing this and with new data increasingly available, convincing growers to lower fertilizer applications may be difficult (Rayment, 2005).

With current knowledge of nutrient dynamics and movement in soil, and considering the costs of fertilizer inputs, previous soil test standards and nutrient recommendations should be re-examined. Some studies have focused on N, P, and K recommendations in pepper cultivars as those nutrients are known to have a large effect on crop response and plant yield (Xu et al., 2001, Ruiz et al., 2000, Castorena et al., 2003).

In conjunction with a soil testing program, analyzing nutrient levels in plant tissues, primarily leaves and petioles, is an important tool for determining plant nutrient status. We can analyze tissue nutrient values and then correlate test values with plant

yield. These tissue test values can be used as a basis for fertilizer recommendations, especially when used in combination with soil testing (Walsh, 1973).

Standardized sampling is very important for obtaining useable results. Different amounts of nutrients concentrate in different areas of the plant; leaf test values may be quite different from petiole test values. Choosing standard leaves at each sampling is one method. Most tissue testing programs use the most-recently-matured leaves and petioles for mobile nutrients, although younger leaves are sometimes used for micronutrient analysis (Hochmuth, 1996). Leaves must be washed, rinsed, dried, and ground before analysis (Fageria, 2007). One commonly used tool for plant tissue analysis is inductively-couple plasma optical emission spectroscopy (ICP-OES). This method involves dissolving the samples in an acid solution to bring all the components into solution. The liquid is then aerolized and decomposed by the plasma. This decomposition causes photons to be emitted. The instrument measures these photons and correlates those energy levels to specific atomic components (Benton Jones, 1977).

A notable effect in plant tissue analysis is that of dilution, which is a decrease in nutrient concentration in plant tissue. Dilution effects in nutrient analysis are common as the plant matures. Since nutrient concentration is the relationship between the nutrient of interest and the plant dry matter, concentrations will change if the rate of nutrient absorption changes in relationship to the rate of production of plant materials. Nutrient concentration will increase if plant uptake of nutrients is faster than plant matter formation. Conversely, nutrient concentration will decrease if nutrient uptake remains the same but the rate of plant dry matter formation increases (Wolf 1982).

Many nutrients typically show dilution effects with age, such as N, P, and Fe. One exception is B, which will often concentrate in tissue over time.

The ultimate goal of an agricultural tissue testing program is to identify critical nutrient concentrations and correlate those concentrations to fertilizer response and plant yield. Critical nutrient concentration is defined as “the nutrient concentration which is just deficient for maximum growth” (Ulrich, 1952). Generally, critical nutrient concentration may be estimated for maximum yield. Since nutrient concentrations can and will vary between soils depending on texture, pH, cultivar, temperature, and a host of other factors, critical nutrient ranges have been suggested instead (Dow, 1982). As a general guideline, if nutrient recommendations were broad enough, growers could use them in conjunction with a soil testing program as a good baseline analysis of the cropping system and as a starting point for a fertilization program. However, it is important to note that a fertilizer rate which may maximize plant dry matter yield may not in fact maximize marketable crop yield (Moreno et al., 1996). This biological phenomenon is obvious in many plant species including pepper. The goal is to maximize marketable yield, not plant material, and our field experiments compared nutrient results solely with marketable yield without regard for total dry plant material. Current target levels for pepper tissue analysis are listed in Table 3 (see Appendix B).

One part of a soil and nutrient testing experiment is the statistical analysis of the results. Statistical analysis of soil and tissue test values includes mean, standard deviation, and coefficient of variation (CV). We can also test for a significance level with respect to the difference between nutrient values and their impacts on yield results,

generally done at $p=0.01$ or $p=0.05$ level of significance. Standard deviations and CV can also give some indication of the accuracy of the mean. CV indicates the error as a percent of the mean value, and thus CVs can be compared to one another regardless of the absolute value of the mean in question. The CV generally increases rapidly as nutrient concentrations decrease, implying that lower nutrient values are more susceptible to errors in analysis. Since any errors in analysis or discrepancies in sample collection and handling will add to the uncertainty, it is imperative to maintain standards of collection and analysis. Since the CV is a normalized measure of the distribution of the data set, it is possible to evaluate the theoretical dispersion of a data set with a given mean. By using this theory, we can determine that mean concentrations of 100, 1, 0.1, and 0.01 mg kg^{-1} have theoretical CVs of 8%, 16%, 23% and 32% respectively (Rayment, 2005).

Many different techniques have been proposed for analysis of soil and tissue testing results. For a detailed review, see Walworth and Sumner (1986). Cate and Nelson (1971) proposed a visual method that involves graphing yield versus the nutrient values of interest; the data are then partitioned into different quadrants visually in order to estimate a critical nutrient value. This method has obvious limitations: it requires expert knowledge to determine visual segmentation of the data; it involves no quantifiable analysis; it only produces one value for a result; and finally, it can easily overlook key components of the data. However, this method does give a reasonable “first look” at the data.

Another useful method for data analysis of soil and tissue test values is establishment of boundary lines (Walworth and Sumner, 1986). Boundary line analysis can give a peak nutrient level for maximum yield. However, for the results to be meaningful, a very large data set must be used; for example, Walworth and Sumner compiled over 8000 data points for a boundary line analysis of maize and N. This method is also visual instead of mathematical.

Other methods include a nutrient response curve and critical nutrient ranges instead of critical nutrient values (Dow and Roberts, 1982). Kenworthy (1973) proposed a balance index for an analysis tool. This mathematical analysis relates the nutrient of interest to the mean and standard deviation of the data set and show the difference between that specific value and the optimum concentration (Walworth and Sumner, 1986). The Diagnosis and Recommendation Integrated System (DRIS) is another analysis tool that has been less commonly used in recent years (Walworth and Sumner, 1986). The DRIS systems compares yield to nutrient ratios, such as Leaf N/Leaf P. This technique is validated by known nutrient interactions in plants.

Another important distinction with regard to soil test K is the difference between a water extractable K test and a test such as NH_4OAc . Water extractable soil K tests only evaluate the soil K that is present within the soil solution. Of course, soil dynamics dictate that K sorbed to soil colloids may also become plant available, and especially will become plant available as the soil solution K decreases. Therefore, water extractable K tests do not correlate well with K uptake and crop response such as yield. However, NH_4OAc extractable K measures both the soil solution K and the K that is sorbed to soil

colloids. Therefore, NH_4OAc extractable K is best correlated to plant status including yield results.

In summary, many different methods exist to analysis soil and leaf nutrient values obtained in a sampling regime. The method chosen often depends on the research goals. The chile research presented in Appendix A uses the Cate and Nelson (1971) method and Kenworthy (1973) balance index approach as good starting points for further experimentation on nutrient critical values in irrigated chile production.

There are several elements known to be essential for plant growth and development: carbon (C), hydrogen (H), oxygen (O), N, P, K, calcium (Ca), magnesium (Mg), sulfur (S), copper (Cu), Fe, Zn, manganese (Mn), B, molybdenum (Mo), nickel (Ni) and chlorine (Cl) (Fageria, 2007). The primary macronutrients are N, P, and K. Plants require these nutrients in large amounts. The micronutrients, including Cu, Fe, Zn, Mn, and B are required in smaller amounts but are still necessary for plant growth. While the micronutrients have specific deficiency symptoms, overabundance of the micronutrients can lead to toxicity symptoms and reduced yield in agricultural crops (Benton Jones et al., 1991).

Besides sunlight and water, plant available N is probably the most limiting factor in plant growth and yield. Nitrogen may indeed be the key component in yield potential of modern agricultural systems (Ruiz et al., 2000). Availability and uptake of N affects both the fruiting and the yield of many crops including sweet pepper (Xu, 2001). In many non-irrigated systems, fertilizer N is the most costly input for agricultural systems

(Wilson, 1995). Plant demand for N and corresponding fertilizer inputs have been extensively studied for many crops.

Nitrogen uptake is dependent on a variety of factors, including available forms of N in the soil, stage of crop development, crop variety, and environmental conditions such as temperature and soil moisture. Nitrogen is available to plants in both the NH_4^+ and NO_3^- form. Factors such as climate, soil drainage, and soil aeration determine which species dominates in the soil, and therefore which species is plant available at any given time. Nitrogen uptake in warm temperatures may be higher than uptake in colder temperatures. Plant uptake changes as the plant matures and depends on the specific crop. For example, corn may have highest rates of N uptake between 20 and 90 days after planting as compared to rate of N uptake before 20 days or past 90 days after planting (Fageria et al., 2007).

Nitrogen not only plays an important part in crop yield and quality but also is a significant source of surface water pollution (Sisson et al., 1991). The ability to quantify fertilizer inputs necessary for optimal yield without being excessive has become particularly important in recent years as the detrimental environmental effects of surplus N have become known. Nitrogen not taken up by plants can cause surface water pollution since N is often present in anionic form, not strongly sorbed to soil colloids but instead readily transported into surface waters or leached into ground waters (Shepherd et al., 1993). Optimal yields may be obtained with moderate rates of N, leaving less N in the system at the end of the growing season that could potentially have negative environmental consequences. Nitrogen management techniques can further improve

efficiency while improving crop production, including managing the time, rate, and method of fertilizer application (Fageria et al., 2007).

Research on pepper (*Capsicum annuum* L.) indicates that plant uptake of N affects fruit set, and that pepper plants take up different forms of N at different stages of growth (Xu et al., 2001). Research on hot pepper (*Capsicum* spp.) showed that a moderate rate of N application (150 kg N ha^{-1}) resulted in the best plant yields, while increasing N rates could actually contribute to disease susceptibility (Vos and Frinking, 1997). Target levels of N for sweet pepper tissue analysis have been stated as 3.5-5.5%, without stating whether those values were based on leaves or petioles (Bosland and Votava, 2003). Optimum levels of N in chili pepper using the youngest fully mature leaves have been recorded as 3.0-5.0%, although they did not specify stage of growth (Wein, 1997). From first bloom to final 1/3 of plant development, N sufficiency levels in bell pepper (*Capsicum annuum*, Grossum group) are as 4.0-6.0%. For the final 1/3 growth stages, the sufficiency levels of N decrease to 3.5-5.0% (Benton Jones et al., 1991). For chili pepper, based on the N sufficiency levels of youngest mature leaves at first bloom and early fruit set are 2000 ppm and 800 ppm respectively (Lorenz and Tyler, 1983). Sufficiency levels for petiole N at first bloom are 7000 ppm and at early fruit set 2000 ppm (Lorenz and Tyler, 1983). A summary of sufficiency levels for leaf blade and petiole test N in chili pepper is found in Table 3 in Appendix B.

Phosphorus (P) is an essential nutrient for plant growth and crop production and is especially critical during vegetative development (Jeshke et al., 1996). Phosphorus is needed for synthesis of many cellular components including nucleotides and

phospholipids. Plant growth slows if P is not present in amounts necessary for cell synthesis and division (Benton-Jones et al., 1991). Symptoms of P deficiency are a reduction in number of plant leaves and a reduction in photosynthetic activity (Wein, 1997). Deficiency in P can also result in leaf senescence in the older leaves while the younger ones remain healthy (Rashid and Awan, 2005). Miller (1961) observed that pepper plants deficient in P are weak with narrow, grayish-green leaves. Fruits on P-deficient pepper plants may be shorter and narrower than those on plants supplied with adequate levels of P (Bosland and Votava, 2000).

Many plants can grow in low P conditions. However, N availability strongly influences P absorption. Research on eggplant growth showed that an increase of N fertilization, when combined with P, may cause the plants to be able to change inorganic P to organic P at higher rates, leading to higher yields (Lopez-Cantarero et al., 1998). Phosphorus acquisition is also a function of a healthy root system (Adalsteinsson and Jensen, 1989). Varietal differences in root systems such as root hair density may influence P uptake, especially in P-limiting conditions. In agricultural plants, efficiency of P uptake efficiency may be affected by plant and genotype characteristics such as root morphological factors, individual rates of nutrient release to xylem and rates of redistribution within the plant (Fageria et al., 2007).

Research has demonstrated that indiscriminate widespread use of P fertilizer may have negative consequences (Saxena, 1998). Vegetable crops may show toxicity symptoms if too much P is applied. Fertilizer P recommendations must be based upon the available soil P and the amount of soil P required for the particular crop (Kamprath

and Watson, 1980). A valid fertilizer recommendation requires calibration for the cropping system involved (Srivastava et al., 2006). A study in India showed a linear increase in rice (*Oryza sativa* L.), wheat (*Triticum aestivum* L.), and soybean (*Glycine max* L. Merr.) yield with increasing amounts of soil P up to an application of 26 kg P ha⁻¹. Increasing rates of application above this amount did not result in significantly higher yields. Of course, this numerical value for added P is site specific and would change if factors of the experiment changed, such as soil type, texture, and crop. However, over-fertilization is unnecessary, uneconomical, and possibly even detrimental to plant growth (Srivastava et al., 2006). Fertilizer application rates of 70 kg P ha⁻¹ have been shown to positively increase yield in irrigated chile (Lal and Pundrik, 1971), although literature values range from 30 to 80 kg P ha⁻¹ (Iruthayaraj and Kulandaivelu, 1973). Lal and Pundrik measured the initial soil P as 15 ppm P₂O₅, but Iruthayaraj and Kulandaivelu did not report initial soil test values.

In addition to plant attributes, rates of P uptake can also depend on soil characteristics. For example, phosphorus removal in barley (*Hordeum vulgare* L.) was greater in a silt loam soil than it was in other soil types (Sardi et al., 2009). Overall, P concentration in plants is probably a function of soil type, residual soil P, and rates of freshly applied P (Sardi et al., 2009). Perhaps the most important factor impacting P availability for plant growth is soil pH. Phosphorus is most available at moderate pH, approximately 6-7 (Brady and Weil, 2002). Plants use this fact to their advantage by using root exudates to change the characteristics of the rhizosphere as necessary. Root

exudates can make low-solubility P compounds available to the plant for growth (Fageria et al., 2007).

Phosphorus sufficiency levels in the most recent fully developed leaf of bell pepper (*Capsicum annum*, Grossup group) from first bloom to early 1/3 growth stages range from 0.35 to 1.0%. Deficiency in P for this growth stage is 0.23 -0.34% (Benton-Jones et al., 1991). Other sources show the sufficiency levels for mid growth from the youngest mature leaf is 0.3-0.7% for bell pepper (Reuter and Robinson, 1997).

Potassium is the third of the plant macronutrients. Potassium is the most abundant cationic component of plant cells. It can compose up to 10% of the total plant dry weight (Martinez-Cordero et al., 2005). Potassium is known to be linked to N uptake, and is also important for protein synthesis in plants (Marschner, 1995). In addition, K is essential for plant physiological functions such as photosynthesis, drought tolerance, and enzyme regulations. Potassium deficiency negatively impacts crop quality and may cause increased susceptibility to diseases (Valenzuela, 1996). Low levels of K may cause bronzing, necrosis, and leaf drop in pepper plants (Ozaki and Hamilton, 1954). In addition, K deficiency in peppers can cause necrotic lesions and defoliation (Miller, 1961). Pepper plants with excessive K levels, above 6.0% for the first bloom stage of growth, may exhibit toxicity symptoms and a corresponding decrease in fruit quality (Valenzuela, 1996; Reuter and Robinson, 1997).

It is important to note than an excess of sodium or ammonium in the soil may inhibit K uptake and therefore be detrimental to plant growth. Under K-limiting conditions some plants are still able to uptake K in a process known as high-affinity K⁺

uptake. Pepper plants in limiting K conditions have been shown to be able to uptake more K than would normally be expected (Martinez-Cordero et al., 2005). Other crops, notably cotton (*Gossypium hirsutum* L.), may show signs of K deficiency even when K is present in the soil at levels that would normally be sufficient for most crops (Fageria et al., 2007).

Recommended soil test K values for sweet pepper grown in a mulch culture were 26 ppm (Hochmuth et al., 1988). Research for irrigated chile production indicates increased K can significantly affect yield and has recommended fertilizer values as 60-90 kg K ha⁻¹ (Lal and Pundrik, 1971). Initial soil test values were reported as 72 ppm K₂O at pH 8.5 (Lal and Pundrik, 1971). Research for bell peppers showed optimum tissue nutrient levels as 3.0-6.0% K; stage of growth was not specified (Bosland and Votava, 2000). For the youngest fully mature leaves in chile plants, 3.0-5.5% has been stated as the optimum level (Wein, 1997). In bell pepper, sufficiency levels of the most recently mature leaf during the first bloom to final 1/3 growth were 4.0-6.0%, while in the final 1/3 the sufficiency levels decreased to 3.5-4.5% (Benton Jones et al., 1991). For chili pepper, the petiole levels and youngest mature leaf blade sufficiency levels of K for first bloom were both 5% (Lorenz and Tyler, 1983). A summary of tissue test values specific to chili pepper may be found in Table 4 and Table 6.

Of note, in a study on P and K rates of fertilization on pepper and other vegetable crops, Hanlon and Hochmuth (1992) concluded that yield response can be optimized well before the previously recommended rates of fertilization, which were crop specific. This response indicates that grower practices may result in rates of

fertilization that are higher than necessary, which not only reduces economic viability of the crop in question but also may contribute to pollution effects such as decline in surface water quality and eutrophication (Brown, 1987). The study established soil levels of soil K as 20-35 ppm as low, 36-60 ppm as medium, and 61-125 as for high. For P, the low values were 10-15 ppm, the medium values were 16-30 ppm, and the high values were 31-60 ppm.

In studies of soil K nutrition, research noted no significant differences in yield between prior established fertilizer rates and new, lower rates. However, K leaf concentration may increase with increased fertilization, but with no corresponding increase in plant yield. This increase in plant tissue concentration may lead growers to believe in the efficacy of fertilizer treatments even though no yield results are present. A study of irrigated pepper grown in a mulch culture also recommended a reduction in K fertilizer rates (Hochmuth et al., 1988). The initial K soil test values in this study were 26 mg/kg for both years, which corresponds to the mean value for our study of 24 ppm. With extractable levels of K from 20-35 ppm, the recommended fertilizer rate was modified from 160 to 130 lb/acre (Hochmuth et al., 1988).

The micronutrients essential for plant growth are Cu, Fe, Zn, Cl, Mo, Mn, Ni, and B. Of these, B deficiency is more widespread than any other micronutrient deficiency and may prove to be of particular importance to chile crops (Nabi et al., 2006). Major sources of B in the soil are borosilicates and borates. Physiologically, B is important in certain plant enzymes, for synthesis of nucleic acids, and for cell division and growth (Benton Jones et al., 1991). In addition, B plays a significant role in root growth and

development. Research shows that plants uptake B in the form of boric acid, H_3BO_4 . At high pH, boron will also be present in the soil solution in its anionic form, H_2BO_3^- (Brady and Weil, 2002). This form is less plant available, so plant uptake of B is known to decrease as pH increases and less boron is found in the plant available form, H_3BO_4 .

Boron is known to be important in a range of vegetable crops (Rashia et al., 2002). However, plant requirements for B can vary dramatically between different crops and may even differ between cultivars. This variation makes identification of optimal fertilizer rates for B problematic (Fageria et al., 2007). Boron toxicity is a common problem (Nabi et al., 2006), especially in arid and semiarid regions where soils usually have high pH and irrigation water may also be high in B (Hosseini et al., 2007). Symptoms of B deficiency in pepper plants include stunted growth and yellowing of the younger leaves (Nabi et al., 2006).

Accepted values for soil fertilizer rates for B range from 0.5 to 5 kg B ha⁻¹ (Brady and Weil, 2002). A study on pepper in greenhouse conditions found B application increased dry-matter yield of sweet pepper. Maximum dry-matter yield occurred when soil B ranged from 1.0 to 2.0 mg B kg⁻¹ soil. Levels of B above 2.0 mg B kg⁻¹ soil resulted in toxicity. In plant tissue, B concentration for 95% of maximum yield was 65 mg B kg⁻¹ in three-week old plants and 49 mg B kg⁻¹ in six week old plants. The decrease in tissue B with increase in plant age is a result of dilution effects. Overall, the experiment showed that measuring B in plant tissue is a good indication of the nutritional status of the crop (Nabi et al., 2006).

Levels of plant tissue B reported in the literature range from 20-118 ppm. For bell pepper plants, first bloom test levels of B in the youngest mature leaves range from 25-75 ppm, with values greater than 75 ppm being considered high. For mid-growth stages, the adequate range of B in the leaf tissue ranges from 40-100 ppm (Reuter and Robinson, 1997). Other research shows no changes with stage of growth and leaf tissue test B, with a recommended value of 25-75 ppm as sufficient (Benton Jones et al., 1991).

Pepper types exhibit varying responses to levels of applied B; the B nutrient demand of chile peppers may also be dependent on the specific cultivar (Sims and Johnson, 1991). Moreover, factors such as soil texture, pH, and irrigation water quality all affect B uptake (Sims and Johnson, 1991). The current field experiment included a range of chile cultivars in a range of field conditions. Thus the overall B measured and correlated to yield gives a good indication of general crop nutritional status, but may be hiding some effects of B on the different cultivars by consolidating them all together in one study.

Zinc also plays an important micronutrient role in cropping systems. Major sources of Zn in the soil are silicates, oxides, and carbonates (Brady and Weil, 2002). Zinc may increase a plant's drought tolerance, an important factor in the desert Southwest (Sultana et al., 2001). Zinc is instrumental in plant biomass production and is a cofactor for many enzymes (Grotz and Guerinot, 2006). It may be important in chlorophyll production, photosynthetic activity, and pollen function in plants (Kaya and Higgs, 2002). Zinc deficiency may decrease N metabolism in plants, which is important since, as discussed, N is vital and yield limiting in many cropping systems. Zinc deficiency

symptoms occur as interveinal chlorosis in younger leaves and “rosette-like” strands of small leaves (Fageria et al., 2007).

As with many other plant nutrients, soil chemical and physical conditions greatly affect Zn availability and plant uptake. Soil pH impacts the bioavailability of Zn; bioavailability increases as pH decreases (Benton Jones et al., 1991). Zinc deficiency may be even more noticeable in arid climates, as calcareous soil conditions, which are commonly found in desert-type soils, have been linked to lower plant availability. Zinc uptake may also be a function of P availability (Fageria et al., 2007), and available Zn may decrease when available P is very high (Benton Jones et al., 1991). There are no published critical nutrient values for Zn for soils used to produce chile pepper. Commonly accepted ranges for soil application for most crops ranges from 0.5-20 kg Zn ha⁻¹ (Brady and Weil 2002). Research on canola (*Brassica napus* L.) suggests that Zn availability and corresponding crop response may be increased more with foliar nutrient application than with soil fertilization. This trend is most relevant for cropping systems on calcareous soils (Bybordi and Mamedov, 2010).

Zinc tissue levels in bell pepper range from 20-100 ppm. For first bloom, adequate Zn levels for the youngest mature leaf blades range from 20-200 ppm, with values below 20 being deficient and above 200 being high. For early fruiting stages of growth in bell pepper, adequate tissue Zn levels range from 35-260 ppm (Reuter and Robinson, 1997).

Iron also plays an important role in plant physiology. As with Zn, Fe is especially important in the desert Southwest as it can affect the plant's drought tolerance (Sultana et al., 2001). Iron acts as an electron carrier and is important in oxidation-reduction reactions as well as chlorophyll formation (Brady and Weil, 2002). Iron deficiency is common for many crops in the United States, including corn (*Zea mays* L.), beans (*Phaseolus vulgaris* L.), and rice (*Oryza sativa* L.). Iron deficiency symptoms include interveinal chlorosis, similar to deficiency symptoms for Zn. The symptoms will appear first in new plant growth (Fageria et al., 2007).

Soil factors such as texture and pH are particularly important in determining the availability and plant uptake of Fe (Brady and Weil, 2002). High pH conditions reduce available Fe. Iron may be limiting in a cropping system due to the predominate chemical form of the micronutrient. If Fe is not soluble or plant available, plants will exhibit deficiency symptoms regardless of the amount of the nutrient actually present (Bybordi and Mamedov, 2010). Iron also interacts with P in plants, sometimes resulting in induced Fe deficiency where P is high. Genetic variation of cultivars of crops such as soybeans may result in micronutrient uptake occurring at differing rates, and the same may prove true of pepper (Fehr, 1982). Accepted fertilizer application ranges for most agricultural crops are 0.5-10 kg Fe ha⁻¹ (Brady and Weil, 2002). Adequate tissue Fe levels in bell pepper for first bloom and final 1/3 stages of growth range from 60-300 ppm for the youngest fully mature leaves (Reuter and Robinson, 1997).

In conclusion, the literature results regarding peppers for nutritional requirements often specify fertilizer rates as well as optimum leaf and petiole nutrient levels. However, the current guidelines specific to New Mexico cultivars of chile pepper from New Mexico State University (Guide A-122, Soil Test Interpretation, NMSU Cooperative Extension Service) are not based on research specific to irrigated chile pepper in the desert Southwest. The current project aims both to validate their nutrient levels and to identify potential critical points for further research.

APPENDIX A

SOIL TESTING AND PLANT ANALYSIS RELATIONSHIPS FOR IRRIGATED CHILE PRODUCTION

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Soil Testing and Plant Analysis Relationships for Irrigated Chile Production

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Abstract

In a field study of irrigated chile (*Capsicum annum* L.) production in southeastern Arizona and southwestern New Mexico from 2008 through 2009, soil and tissue test samples were analyzed for a spectrum of plant nutrients at 16 different sites, including nitrogen (N), phosphorus (P), potassium (K), zinc (Zn), iron (Fe), and boron (B). The objectives were to evaluate soil and tissue nutrient testing procedures and to establish basic soil and plant tissue testing guidelines and recommendations with respect to yield potentials. Soil samples were collected before planting. Plant tissue samples from plots at all sites were collected at the following four stages of growth: first bloom (FB), early bloom (EB), peak bloom (PB), and physiological maturity (PM). Fertilizer and nutrient inputs were monitored, managed, and recorded within current Extension guidelines for irrigated chiles.

Results for soil and tissue analyses were compared to yield results. The results provide estimates for baselines which can be tested through subsequent calibration experiments to establish recommendations for critical soil and tissue test values. Absolute minimum soil test nutrient values were identified as 10 ppm P, 110 ppm K, 0.3

ppm Zn, 2.0 ppm Fe, and 0.25 ppm B. Absolute minimum FB leaf tissue test values were 0.2% P, 4.5% K, 10 ppm Zn, 80 ppm Fe, and 30 ppm B. Complete data sets for leaf and petiole tissue test values for all stages of growth were collected. These soil test and plant nutrients values will be evaluated in subsequent experiments to better define fertilizer nutrient inputs and to gain better nutrient management efficiencies in irrigated chile production systems.

Introduction

Globally, pepper (*Capsicum annum* L.) represents a huge market, with over 3 million hectares cultivated annually (Bosland and Votava, 2000). Chile peppers are a valuable source of nutrients and vitamins, and are traditionally used as both fresh and dried pods and in a variety of spices and sauces. In the United States, chile peppers are grown primarily in southern California, Arizona, and New Mexico. (Bosland and Votava, 2000). Over 10,000 hectares of chile are produced in the U.S. annually with a production value of close to \$120 million (NASS 2007).

In the previous century, fertilizer was cheap and environmental repercussions of over-fertilization had not been studied extensively (Brown, 1987). However, as profit margins shrink and environmental standards increase, growers are increasingly aware of fertilizer needs and costs. Very few studies have been conducted specifically on chile peppers to correlate and calibrate nutrient levels and to identify critical soil and tissue test values. Furthermore, growers may be hesitant to implement soil and tissue test

values or fertilizer recommendations which, to them, can often seem low or too conservative.

There are 16 nutrients known to be essential for plant growth and development (Fageria, 2007). Of these, N is the most important essential nutrient for plant growth and crop yield. Furthermore, N is required in the greatest amounts. In the majority of cases, N is the most costly input for agricultural systems (Wilson, 1995). Plant demand for N and corresponding fertilizer inputs have been extensively studied for many crops including chile (Hochmuth and Hanlon, 1995). Target levels of N for sweet pepper tissue analysis have been stated as 3.5-5.5% (Bosland and Votava, 2003) and 4.0%-6.0% (Benton Jones et al., 1991). Optimum levels of N in chile pepper using the youngest fully mature leaves have been recorded as 3.0-5.0% (Wein, 1997). For chile pepper, based on the youngest fully mature leaf, sufficiency levels of N are 2000 ppm at first bloom and 800 ppm at early fruit set. Sufficiency levels for petiole test N at first bloom are 7000 ppm and 2000 ppm at early fruit set (Lorenz and Tyler, 1983). Surplus N inputs can result in excessive vegetative development and thereby reduce yield in irrigated red chile (Mahajan et al., 2007).

The next macronutrients essential for plant growth and development are P and K. Phosphorus is particularly important for vegetative growth (Jeshke et al., 1996). Indiscriminate P fertilization without using a soil and tissue testing basis will be ineffective at best (Saxena, 1998). Yield for rice (*Oryza sativa* L.), wheat (*Triticum aestivum* L.), and soybean (*Glycine max* L. Merr.) may be optimal at a fertilizer application of 26 kg P ha⁻¹. Of course this value is site and crop specific (Srivastava et al.,

2006). Fertilizer application rates of 70 kg P ha^{-1} can positively increase yield in irrigated chile (Lal and Pundrik, 1971), although literature values range from 30 to 80 kg P ha^{-1} (Iruthayaraj and Kulandaivelu, 1973). Optimum levels for P in the youngest fully mature leaves of pepper plants are 0.3-0.6% (Wein, 1997). Phosphorus sufficiency levels in bell pepper (*Capsicum annum*, Grossup group) taken from the most recent fully developed leaf blade for the first bloom to early 1/3 growth stages are 0.35 to 1.0%. Deficiency in P for this growth stage is 0.23 -0.34% (Benton-Jones et al., 1991). Research has demonstrated that indiscriminate widespread use of P fertilizer may in fact have negative consequences (Saxena, 1998). Vegetable crops such as chile may show toxicity symptoms if too much P is applied.

Potassium has been linked to N uptake and protein synthesis (Marschner, 1995). Recommended soil test K values for sweet pepper grown in a mulch culture were 26 ppm (Hochmuth et al., 1988). Lal and Pundrik (1971) found that increased K can significantly affect yield of irrigated chile and recommended fertilizer rates of $60\text{-}90 \text{ kg K ha}^{-1}$ (Lal and Pundrik, 1971). Research for bell peppers showed optimum tissue nutrient levels as 3.0-6.0% K; stage of growth was not differentiated (Bosland and Votava, 2003). Optimum K levels in the youngest fully mature leaves of chile plants has been reported as 3.0-5.5% K (Wein, 1997). The petiole levels and youngest mature leaf blade test levels of K in chile for first bloom were both 5% for sufficiency (Lorenz and Tyler, 1983).

Micronutrients are also essential for plant growth and crop yield, although in smaller quantities than macronutrients. Iron, Zn, and B all play important roles in plant

physiology. Both Zn and Fe are especially important in the desert Southwest as they can affect a plant's drought and salinity tolerance (Sultana et al., 2001). Zinc is a cofactor for many enzymes (Grotz and Guerinot, 2006). Iron may act in electron transport reactions and is important both in oxidation-reduction reactions and in chlorophyll formation. Functions of B include activation of some enzymes and translocation of sugars (Brady and Weil, 2002). Suryanarayana and Hariprasad (1985) demonstrated an increase in yield with foliar application of Zn and B in irrigated chile production, although tissue testing was not conducted as part of their research ().

Target tissue concentrations for these micronutrients in pepper have been reported as 80-200 ppm Fe, 40-100 ppm Zn, and 30-90 ppm B (Bosland and Votava, 2003). Other sources suggest optimum levels for these micronutrients as 20-100 ppm for Zn, 30-100 ppm for B, and 60-300 ppm for Fe (Wein, 1997). For bell pepper plants, first bloom test levels of B in the youngest mature leaves range from 25-75 ppm, with values greater than 75 ppm being considered high. For mid-growth stages, the adequate range of B in the leaf tissue ranges from 40-100 ppm (Reuter and Robinson, 1997). In a study on pepper tissue, B concentration for 95% of maximum yield was 65 mg B kg⁻¹ in three-week old plants and 49 mg B kg⁻¹ in six week old plants (Nabi et al., 2006). Adequate Zn levels in the youngest mature leaf blades at first bloom range from 20-200 ppm, with values below 20 being deficient and above 200 being high. Adequate tissue test values of iron in bell pepper for first bloom and final ¹/₃ stages of growth range from 60-300 ppm for the youngest fully mature leaves (Reuter and Robinson, 1997).

One goal of soil and nutrient testing is to establish a soil or tissue nutrient level at which a crop will exhibit a positive response to additional inputs through fertilization. Cate and Nelson (CN) (1971) identify this point visually by graphing a crop characteristic such as yield against nutrient value.

The CN methodology involves placing two lines on the data set that overlap and form four quadrants (see red lines in Figure 2 for an example). The goal of dividing the data is to maximize the data points in the upper right and lower left quadrants while simultaneously minimizing the data points in the other two quadrants. This specific data distribution and the corresponding critical point is estimated visually by moving the lines until the number of data points in each quadrant are maximized and minimized appropriately. (As previously stated, in all cases the nutrient of interest is graphed against dry yield on kg ha^{-1} basis.) Where the resulting vertical line placement crosses the x-axis becomes the critical point. For example, in Figure 2, the critical point for soil test P is 20 ppm. Below this “critical point,” additional fertilization should increase yield, all other factors being equal, and above this nutrient value little or no crop response is expected.

Kenworthy (1973) offers another approach to nutrient analysis by setting nutrient optima. These optima are usually based on mean data from healthy, high-yielding plants. These optima, when combined with the coefficient of variation (cv), produce a Balance Index (BI) that easily interprets crop nutrient status.

In general, the CN method seeks to set a critical value that is lower than the Kenworthy method. Use of a CN critical point in a cropping system would theoretically result in lower fertilizer inputs. A Kenworthy approach might be more conservative from a grower perspective as it results in a higher optima nutrient value for the cropping system. Theoretically, this nutrient value is “safer” since there is less chance of the plant becoming deficient if a higher nutrient status is maintained. However, maintaining such a nutrient status may often result in excess fertilizer inputs with the possibility for little or no increase in yield.

This field project was conducted in cooperation with growers in Arizona and New Mexico in an effort to evaluate current soil and nutrient testing procedures and guidelines for irrigated chile production. By conducting the experiments in the field in cooperation with growers, we strove to establish reliable basic testing guidelines and to begin to develop nutrient testing recommendations with respect to yield potentials. This study correlated soil test values and tissue test values for each stage of growth for P, K, Fe, Zn, and B to dry weight yield on a kilogram per hectare basis (kg ha^{-1}).

The objectives of this study were to evaluate current soil and tissue testing procedures to produce basic testing guidelines and critical levels for soil, leaf blade, and petiole tissue with respect to chile yield, and to compare the results with current guidelines for soil and tissue test values for N, P, K, Fe, Zn, and B. In particular, two different soil testing methods for K are compared to determine which method is suitable for irrigated chile production. The critical values estimated in this study can be further evaluated in later calibration studies in an attempt to better define fertilizer inputs. By

establishing valid testing criteria, we seek better nutrient management efficiencies in irrigated chile production.

Materials and Methods

Field experiments were conducted in 2008 and 2009 on growers's fields in New Mexico and Arizona. The experimental program included multiple field sites, each containing individual subunits that were used for discrete soil and tissue sample evaluation. In 2008, five field sites were established in southwestern New Mexico (NM) (2008NM1 through 2008NM5) and five more were established in southeastern Arizona (AZ) (2008AZ1 through 2008AZ5). Each field site had five plots, resulting in 50 different sample locations from the 2008 growing season. Each plot measured 12 meters by 12 meters. Within each plot, row spacing was one meter and plant spacing was 30-40 centimeters. In 2009, three field sites were established both in southwestern NM (2009NM1 through 2009NM3) and southeastern AZ (2009AZ 1 through 2009AZ3), with each plot size in each field identical to those of 2008. Collectively, a total of 16 fields and 80 plots were evaluated in 2008 and 2009.

The plots contained different cultivars; including red and green chile varieties. Differences in yield or nutrient test results between varieties were not analyzed. The research specifically did not attempt to develop cultivar-specific recommendations for irrigated chile production in the desert Southwest. Cultivars included 1904, Cayenne 603, PHB 345, BN-14, LB-25 in 2008, and BN-16, AZ-20, AZ-2011-5918, and AZ 2011-5940 in 2009.

The fields were managed by the grower-cooperators and all crop inputs were provided on an as-needed basis in full coordination with the project director. Water, nutrient, and pest-management practices were conducted in accordance with current recommendations and guidelines published by New Mexico State University. Pivot irrigation was used in Arizona and drip irrigation in New Mexico. Water quality samples were taken and analyzed for a full range of nutrients. Growers fertilized with 41 kg N acre⁻¹ and 8 kg P acre⁻¹ prior to planting. Thereafter, 3.8 kg N acre⁻¹ was applied on approximately 10 day intervals.

Chile stands were established with seed at planting dates ranging from 18 March to 28 April for the two seasons. Plant populations were approximately 25,000-34000 plants per hectare. Composite soil samples from each plot were taken at planting. Soil P values were determined using NaHCO₃ extraction (Olsen *et al.*, 1954). Soil K values were determined using both 1:5 (soil:water) extraction and NH₄OAc extraction for comparison purposes. Soil Fe and Zn were extracted with pentetic acid (DTPA) (Lindsay and Norvell, 1978; Soltanpour *et al.*, 1979) and soil B analysis was based on hot water soluble B (Gupta, 1967; Nabi *et al.*, 2006).

The physiological stages of growth were based on a heat unit (HU) 30/13° C threshold crop phenology model developed by Soto-Ortiz and Silvertooth (2007), and field observations of actual crop conditions in each site. Climate data were gathered daily from the Arizona Meteorological Network (AZMET) using the weather stations nearest the growing locations for the AZ field, and from a grower manager temperature

recorder near the NM sites. The AZMET stations report temperature values hourly and the temperature data are used to calculate heat unit (HU) accumulation using the 30/13°C thresholds which are commonly used to model warm season crops according to Baskerville and Emin (1969) and Brown (1989). Heat unit accumulation after planting (HUAP) was recorded and matched to the stage of growth and field observations of crop conditions (see Fig 1). Tables 1 and 2 show sampling dates and HUAP for all samples in both 2008 and 2009.

Table 1: Sampling dates and HUAP (2008) listed by stage of growth.*

<u>Site</u>	<u>FB_Sampled</u>	<u>HUAP</u>	<u>EB_Sampled</u>	<u>HUAP</u>	<u>PB_Sampled</u>	<u>HUAP</u>	<u>PM_Sampled</u>	<u>HUAP</u>	<u>Harvest</u>	<u>HUAP</u>
2008NM1	7.17.08	2359	7.31.08	2634	8.13.08	2919	8.31.08	2942	10.04.08	3901
2008NM2	7.02.08	1967	7.17.08	2336	7.31.08	2611	8.14.08	2919	10.04.08	3878
2008NM3	7.02.08	1949	7.17.08	2297	7.31.08	2572	8.14.08	2880	10.04.08	3840
2008NM4	6.18.08	1674	7.03.08	2035	7.16.08	2332	7.31.08	2685	10.04.08	3925
2008NM5	6.18.08	1658	7.03.08	2018	7.17.08	2366	8.07.08	2793	10.04.08	3908
2008AZ1	7.03.08	1211	7.18.08	1489	8.01.08	1785	8.14.08	2087	9.20.08	2713
2008AZ2	7.18.08	1436	7.25.08	1650	8.06.08	1944	8.22.08	2234	9.20.08	2867
2008AZ3	7.03.08	1227	7.15.08	1465	8.01.08	1826	8.07.08	1973	9.20.08	2580
2008AZ4	7.11.08	1301	7.25.08	1588	8.07.08	1882	8.22.08	2172	9.25.08	2809

* All plots in a field were sampled on the same day (HUAP); wide range of HUAP demonstrates variability in HUAP model depending on other environmental characteristics, cultivar, etc.

Table 2: Sampling dates and HUAP (2009) listed by stage of growth. *

<u>Site</u>	<u>FB_Sampled</u>	<u>HUAP</u>	<u>EB_Sampled</u>	<u>HUAP</u>	<u>PB_Sampled</u>	<u>HUAP</u>	<u>PM_Sampled</u>	<u>HUAP</u>	<u>Harvest</u>	<u>HUAP</u>
2009NM1	7.1.09	1559	7.13.09	1854	7.28.09	2240	8.11.09	2580	9.26.09	3484
2009NM2	7.1.10	1578	7.13.10	1873	7.28.10	2258	7.28.09	2599	9.26.10	3502
2009NM3	6.17.09	1299	1.01.09	1621	7.13.09	1916	8.11.11	2302	9.26.11	3546
2009AZ1	6.30.12	1150	7.13.12	1430	7.29.09	1770	8.11.12	2069	9.18.09	2665
2009AZ2	6.30.13	1140	7.13.13	1420	7.28.13	1782	8.11.13	2059	9.12.13	2752
2009AZ3	7.7.09	1277	7.21.09	1588	8.04.09	1900	8.18.09	2178	10.02.09	2934

* All plots in a field were sampled on the same day (HUAP); wide range of HUAP demonstrates variability in HUAP model depending on other environmental characteristics, cultivar, etc.

After planting, all plots were monitored for plant growth and development and the total number of fruiting positions. Tissue samples were collected at physiological stages of growth corresponding to first bloom (FB), early bloom (EB), peak bloom (PB), and physiological maturity (PM). Leaf tissue analyses for P, K, Fe, Zn, and B were conducted using optical emission spectroscopy (ICP-OES) (Benton Jones *et al.*, 1991). Petiole analysis for NO₃-N and PO₄-P was accomplished with acetic acid extraction and analyzed with ICP-OES (Baker, 1971).

At each stage of growth, plant samples were randomly collected from each plot. Approximately 60-75 leaf blades and petioles were collected from each plot of the uppermost recently-matured leaves. Tissue samples were hand-washed in distilled water and dried at 110° C. Leaves and petioles were then separated and mechanically ground before storage at 20 °C. All soil and tissue samples were analyzed at a commercial laboratory for a complete range of nutrients, including N, P, K, Fe, Zn, B, Mg, Ca, Na, S, Cu, Mn, and Mo, in accordance with the methods referenced in the preceding paragraphs.

Samples from each plot were harvested manually at crop maturity. Harvest dates ranged from mid-September to late October and were based on crop maturity. At harvest, fresh pod weight was recorded for three, one m² sample areas within each plot area. After drying, the dry pod weights were recorded and used to calculate percent moisture. Yield results from each sample area were averaged and converted to project

wet and dry harvest weights per hectare for each complete plot area. Yield estimates from each plot were also compared to the commercial chile yields in the surrounding

Figure 1. Chile Physiological Model Check (Development as a function of Heat Units)

fields. Nutrient analysis results were plotted versus dry weight yield for P, K, Zn, Fe, and B for both the soil samples and the tissue samples from each stage of growth. Analysis for N was only evaluated for petiole $\text{NO}_3\text{-N}$, since petiole $\text{NO}_3\text{-N}$ is most commonly used as an indicator of plant N status.

Soil and tissue test values were plotted against dry yield data on a kg ha^{-1} basis. Initially, regression analysis was performed in an attempt to produce statistical correlation between nutrients and yield. Examination of these results showed the low validity of regression analysis on the data set, so the data were then evaluated using two other methods in order to present legitimate conclusions for future researchers and for grower fertilizer inputs.

For critical point derivations to be used in future calibration research, soil and plant tissue data were evaluated using the CN (1971) method. Literature supports the use of this method for tissue data as well as soil data (Walworth and Sumner, 1986; Olaleye *et al.*, 2010; Srivastava *et al.*, 2008). It is important to note that other methods are available for determination of critical points, including a proposal of critical ranges by Dow and Roberts (1982) and modeling techniques (Waugh *et al.*, 1973). Diagnosis and recommendation integrated systems (DRIS) generally use nutrient ratios and have been commonly applied to crops such as maize (Beaufils, 1973; Walworth and Sumner, 1987).

Walworth and Summer (1988) discuss several variations of boundary line determination for evaluation of critical points. These methods may also be suitable for

this data set and would result in slightly different values for critical points. However, the CN technique allows us a viable starting point with commonly accepted methodology for determining potential critical points that merit further calibration in continuing experiments.

Data were also analyzed using Kenworthy's (1973) approach to nutrient balance indices (BI). The Kenworthy analysis is advantageous because, through BIs, the researchers can provide nutrient status guidelines for grower samples based on their relative effect on yield.

We used the Kenworthy BI approach to evaluate the data set for nutrient optima by using all data points having a dry yield higher than 4500 kg ha⁻¹. All points corresponding to lower yields were dropped from the data set, and the mean and cv of the remaining data were calculated. This cut-off point for dry yield was chosen because it corresponds to a yield that a grower would accept as a minimally good yield. The resultant mean value was used as the optima for the Kenworthy analysis, and can be used in Equations 1 and 2 in conjunction with the cv to define BIs.

Results are summarized for the identified nutrient optima and coefficient of variation (cv). The nutrient optima and the cv derive from a known data set for the crop of interest; the optima is the mean value. A BI can then be calculated for any soil or tissue sample based on the following system of equations:

$$BI = \frac{x}{n} \cdot 100 + \left(1 - \frac{x}{n}\right) \cdot cv \quad \text{all } x < n \quad (\text{Equation 1})$$

$$BI = \frac{x}{n} \cdot 100 - \left(1 - \frac{x}{n}\right) \cdot cv \quad \text{all } x > n \quad (\text{Equation 2})$$

where BI is the balance index, x is the nutrient value, n is the nutrient optima, and cv is the coefficient of variation of the data set. The balance index will therefore range from 1 to 100. The lower the index, related to another nutrient index in the same sample, the higher the possible effect of a change in nutrient status, accomplished through fertilization or some other change in plant uptake, on plant performance.

Results and Discussion

Summaries are provided for soil and tissue test values for N, P, K, Zn, Fe, and B in Tables 3-14. Soil test results show ranges for each nutrient and potential critical points compared to current guidelines (Table 3). Tissue test data are given by stage of growth and show range for each nutrient as well as potential critical values and current recommended guidelines.

The results for soil nutrient critical level estimate a baseline for future grower management and fertilizer inputs. These data provide a platform for further calibration experiments to develop recommendations for critical soil test values. Potential critical values for future study and calibration are 20 ppm P, 240 ppm K (based on NH_4OAc extraction), 4.0 ppm Fe, 0.75 ppm Zn, and 0.9 ppm B (Figures 2 and 3; Table 3).

Table 3: Comparison of soil test results with current sufficiency guidelines published by New Mexico State University (NMSU) with potential critical points

Soil Nutrient	Current Guidelines *	Experiment Results	CN Critical Point
P	15-22 ppm	9.9-65 ppm	20 ppm
K	230 ppm** 30-60 ppm ***	110-1900 ppm** 52-177 ppm***	240 ppm***
Fe	2.5-4.5 ppm	1.9-9.5 ppm	4.0 ppm
Zn	0.5-1.0 ppm	0.3-2.26 ppm	0.75 ppm
B	0.5-1.0 ppm	0.25-2.72 ppm	0.9 ppm

*Guide A-122, Soil Test Interpretation, NMSU Cooperative Extensions Service

** Water soluble K ***NH₄OAc K

Figure 2: Chile dry yield versus soil test P with Cate and Nelson (1971) lines of best fit (red) and green line showing Kenworthy (1973) optima.

Soil test results for K need further experimentation as the range for soil K was very large, 110-1900 ppm. This range is in part due to the variations in soil textures across the field sites. At the New Mexico field sites, soils were dominated by sands and

by silt loams. At the Arizona field sites, the soils were dominated by clays and by clay loams. Also, sandy loams and sandy clays were seen at both sites in both years. The New Mexico soil classification was Typic Torrifuvent, and the Arizona soil classification was Typic Haploargid. In addition, it is important to note that results for soil test B show a decrease in dry yield at soil test levels above 2.0 ppm. Growers should avoid excessive soil B by monitoring their B application (see Figure 3).

Figure 3: Chile dry yield versus soil test B with Cate and Nelson (1971) lines of best fit (red) and green line showing Kenworthy (1973) optima.

Table 4 shows data for the Kenworthy (1973) approach for the soil test results, and lists standard deviation (s) and CN critical points for comparison purposes. The data may be used to calculate BI in accordance with the equations previously presented. Note that Figures 2 and 3 show both the CN critical points and the Kenworthy optima.

Inspection of the graphs and the data in the table shows that the Kenworthy optima is approximately one standard deviation higher than the CN critical point.

Table 4: Soil test data optima for use in the Kenworthy (1973) BI system*

Nutrient	CN Critical Point	Kenworthy Optima	<i>s</i>	<i>cv</i> (%)
P	20 ppm	27.3	8.7	35.6
K	240 ppm	790	459.9	58.2
Zn	0.75 ppm	0.86	0.45	51.7
Fe	4.0 ppm	4.7	2.2	47.5
B	0.9 ppm	1.6	0.64	40.9

***Data derived by averaging data from plant dry yields higher than 4500 kg ha⁻¹ ;
s – standard deviation, cv –coefficient of variation**

Tables 5 gives leaf test values for P, K, Fe, Zn, and B at FB. For the FB stage of growth, leaf test values for CN critical points are 0.31% P, 35 ppm Zn, 135 ppm Fe, and 35 ppm B (see Table 5). (These graphs are not shown.) As previously explained, all leaf blade and petiole critical points are based on CN (1971) graphical analysis of dry yield (kg ha⁻¹) plotted against the corresponding tissue test values. These potential critical points should be investigated with further calibration experiments.

Table 5: FB Leaf blade test results compared to current sufficiency guidelines published by NMSU with potential critical points

Leaf Nutrient	Current Guidelines *	Experiment Results	CN Critical Point
P	0.35-1.0%	0.19-0.48 %	0.31%
K	4-6%	4.24-11.6%	4.5%
Fe	60-300 ppm	77-445 ppm	135 ppm
Zn	50-200 ppm	7.8-53.3 ppm	35 ppm
B	25-75 ppm	31.6-106 ppm	35 ppm

***Guide A-122, Soil Test Interpretation, NMSU Cooperative Extensions Service**

Table 6 shows the statistics to be used in calculating BI for FB leaf blade tissue tests. The table shows the data and optima for the Kenworthy (1973) approach, and lists standard deviation (*s*) and CN critical points for comparison purposes. As with soil test data, the leaf blade statistics may be used to calculate BI in accordance with the equations previously presented.

Table 6: FB Leaf blade test data optima for use in the Kenworthy (1973) BI system*

Nutrient	CN Critical Point	Kenworthy Optima	<i>s</i>	<i>cv</i> (%)
P	0.31%	0.32	0.06	20.2
K	4.50%	4.9	0.50	9.1
Zn	35 ppm	32.8	11.9	36.1
Fe	135 ppm	234	101.9	43.5
B	35 ppm	56.4	13.7	24.3

***Data derived by averaging data from plant dry yields higher than 4500 kg ha⁻¹ ;
s – standard deviation, *cv* –coefficient of variation**

At the EB stage of growth, possible critical points for further calibration are 0.22% P, 4.8% K, 31 ppm Zn, 80 ppm Fe, and 35 ppm B (see Table 7). Very high Fe levels, up to 466 ppm, were observed at FB and EB with negligible decreases in yield (see Figure 4). Although samples were thoroughly washed, contamination from handling and grinding is one possible reason for these high Fe levels. These values merit consideration in further calibration experiments to verify acceptable Fe levels in irrigated chile production. Table 8 shows the data and optima for the Kenworthy (1973) approach, and lists standard deviation and CN critical points for comparison purposes.

Figure 4: Chile dry yield versus leaf blade Fe at EB with Cate and Nelson (1971) lines of best fit (red) and green line showing Kenworthy (1973) optima.

Table 7: EB Leaf blade test results compared to current sufficiency guidelines published by NMSU with potential critical points

Leaf Nutrient	Current Guidelines *	Experiment Results	CN Critical Point
P	0.22-0.7%	0.2-0.44%	0.22%
K	3.5-4.5%	3.1-7.4%	4.80%
Fe	60-300 ppm	66-466 ppm	80 ppm
Zn	50-200 ppm	4.8-50 ppm	31 ppm
B	25-75 ppm	30-204 ppm	35 ppm

***Guide A-122, Soil Test Interpretation, NMSU Cooperative Extensions Service**

Table 8: EB Leaf blade test data optima for use in the Kenworthy (1973) BI system*

Nutrient	CN Critical Point	Kenworthy Optima	s	cv (%)
P	0.22%	30.5	0.05	18.1
K	4.80%	5.4	0.88	17.2
Zn	31 ppm	32.6	11.5	37.5
Fe	80 ppm	217	80.8	49.9
B	35 ppm	59.3	37.0	62.3

***Data derived by averaging data from plant dry yields higher than 4500 kg ha⁻¹ ;
s – standard deviation, cv –coefficient of variation**

For PB chile tissue test analyses, possible critical points are 0.23% P, 4.5 % K, 75 ppm Fe, 25 ppm Zn, and 45 ppm B (see Table 9). Table 10 shows the data and optima for the Kenworthy (1973) approach, and lists standard deviation (s) and CN critical points for comparison purposes.

Table 9: PB Leaf blade test results compared to current sufficiency guidelines published by NMSU with potential critical points

Leaf Nutrient	Current Guidelines *	Experiment Results	CN Critical Point
P	0.25-0.3%	0.14-0.44%	0.23%
K	5.0-6.0%	2.8-6.9%	4.50%
Fe	60-300 ppm	58-172 ppm	75 ppm
Zn	20-200 ppm	5-46 ppm	25 ppm
B	24-118 ppm	28-277 ppm	45 ppm

***Guide A-122, Soil Test Interpretation, NMSU Cooperative Extensions Service**

Table 10: PB Leaf blade test data optima for use in the Kenworthy (1973) BI system*

Nutrient	CN Critical Point	Kenworthy Optima	s.	cv (%)
P	0.23%	28.3	0.05	18.1
K	4.50%	5.4	0.72	17.2
Zn	25 ppm	26.3	10.9	41.5
Fe	75 ppm	88.5	20.2	22.9
B	45 ppm	46.1	25.1	44.9

***Data derived by averaging data from plant dry yields higher than 4500 kg ha⁻¹ ;
s – standard deviation, cv –coefficient of variation**

The results for PM leaf test values are given in Table 11. However, application of the CN methodology showed no critical values for the nutrients analyzed in the research, and current grower guidelines do not recommend leaf blade test values for this stage of growth. Table 12 shows the data and optima for the Kenworthy (1973) approach, and lists standard deviation (s) and CN critical points for comparison purposes.

Table 11: Leaf Blade Test Values for PM

	P [%]	K [%]	Fe [ppm]	Zn [ppm]	B [ppm]
Mean	0.26	4.5	70.7	22.8	87.7
St. Dev	0.04	0.85	12.9	8.1	73.9
C.V.	17%	19%	18%	36%	84%
Range	0.14-0.35	2.1-6.0	52-118	5.4-39	32-381

Table 12: PM Leaf blade test data optima for use in the Kenworthy (1973) BI system*

Nutrient	Kenworthy Optima	<i>s</i>	<i>cv</i> (%)
P	0.24	0.04	16.2
K	4.9	0.83	18.2
Zn	30.2	8.8	39.9
Fe	71.9	13.6	18.9
B	55.1	26.5	37.6

***Data derived by averaging data from plant dry yields higher than 4500 kg ha⁻¹ ;
s – standard deviation, *cv* –coefficient of variation**

Overall, with the exception of B, all nutrient concentrations decreased over time, as would be expected due to general dilution effects with increasing plant dry matter production.

It is worth noting that leaf test B at all stages of growth included some very high values, >100 ppm B, only at the AZ field sites. Irrigation water was sampled and averaged less than 0.05 ppm B. The B source is undoubtedly excessive grower application. As a result, dry yield declined in all stages of growth with leaf test B above approximately 100 ppm. In many cases the decrease in yield was quite dramatic. At FB, for example, above 100 ppm B, dry yield decreased almost 3000 kg ha⁻¹ from peak yield with B levels at 50 ppm (see Figure 5). Very high leaf test B was also observed at PB and PM, and in both cases coincided with dramatic decreases in yield. At PM, low yields of around 3000 kg ha⁻¹ at 300-350 ppm B. Growers should avoid excessive B applications in order to obtain optimum yields. This finding serves to reinforce the basic objectives of the research.

Figure 5: Chile dry yield versus leaf blade B at PB with possible toxicity effects noted.

Table 13 provides the petiole data for $\text{NO}_3\text{-N}$ and $\text{PO}_4\text{-P}$. No critical values seem evident for petiole test N. This result suggests that maintaining petiole test N within the levels seen in the tables below is sufficient for near-maximum yield. At FB and EB, petiole test N of 1000 ppm and higher was sufficient for optimum yield. These values are worth confirming in an effort to avoid over fertilization, as previously discussed. As seen in Table 14 and 15, these values are lower than the established baselines for $\text{NO}_3\text{-N}$ in Chile petioles that are commonly used in regional production systems. Possible critical values for P are 1200 ppm at the FB stage of growth and 1000 ppm at the EB stage of growth. Tables 14 and 15 give balance index statistics for petiole tests.

Table 13: Petiole test results compared to current sufficiency guidelines published by NMSU with CN potential critical points

Petiole Nutrient	Current Guidelines*	Experiment Results	CN Critical Point
NO ₃ -N	10000 ppm	2000-13,200 ppm	--
PO ₄ -P	2000 ppm	4000-7300 ppm	1000 ppm EB 1200 ppm FB

***Guide A-122, Soil Test Interpretation, NMSU Cooperative Extensions Service**

Table 14: Petiole test data optima for NO₃-N given by stage of growth for use in the Kenworthy (1973) BI system*

Stage of Growth	Kenworthy Optima	<i>s</i>	<i>cv</i> (%)
EB	5700	3250	56.5
FB	6800	2980	50.4
PB	4300	2430	56.8
PM	2900	1500	50.6

***Data derived by averaging data from plant dry yields higher that 4500 kg ha⁻¹**

Table 15: Petiole test data optima for PO₄-P given by stage of growth for use in the Kenworthy (1973) BI system*

Stage of Growth	CN Critical Point	Kenworthy Optima	<i>s</i>	<i>cv</i> (%)
EB	100 ppm	1300	566	35.5
FB	1200 ppm	1200	522	35.4
PB	--	1300	424	31.8
PM	--	1000	418	36.6

***Data derived by averaging data from plant dry yields higher than 4500 kg ha⁻¹**

Results and Discussion for Soil K Extraction Comparison

For soil K testing, all 2008 soil samples were analyzed using both 1:5 (soil:water) extraction and NH_4OAc extraction. As one would expect, the results from the two different extraction methods varied dramatically, in some cases more than one order of magnitude. Figure 6 shows a comparison of the two methods graphically for the soil test values. The 1:5 extraction is likely only measuring the K in the soil solution, while the NH_4OAc extraction should measure both the soil solution K and the exchangeable K. The soil exchangeable K is relevant to plant nutrition and the NH_4OAc extractions are the values used in the soil test K discussion and analysis. The 1:5 extractions do not indicate sensitivity to soil K variation and show no relationship to plant yield.

Previous research has confirmed that the measurement of K in the soil solutions has little relevance to exchangeable K (Thomas, 1967). This difference in laboratory results for differing methods of K extraction highlights the care that must be taken in choosing an analysis method for both tissue samples and soil samples that correspond to guidelines and critical values.

Figure 6: Comparison of K soil test values for two different extraction methods

Conclusions

Both the CN (1971) methodology and the Kenworthy (1973) BI approach give useful information about crop nutrient status to the growers. By graphically breaking the data set into lower and high yielding groups with a quadrant sectorization, the CN approach produces lower critical points than, for example, the Kenworthy BI approach. As fertilizers grow more expensive and environmental concerns take hold, setting lower fertilizer standards that still produce optimum yields is most advantageous to the grower in the long term. Thus, the CN critical points are valid starting points for future calibration work in order to eventually produce optimum yields with minimum inputs.

On the other hand, the Kenworthy approach has been presented here, and comparison shows that, in all cases, Kenworthy optima are higher than CN critical

points. Although these higher optima feel “safer,” they do not necessarily provide by themselves a complete evaluation or estimate of critical value to manage nutrient inputs. Growers may still achieve the same optimum yields, but may end up using more fertilization when following the BI system.

The Kenworthy optima values are consistently shown to identify a nutrient level where sufficient nutrient status has been realized to support optimal yields. The CN values tend to identify a point below which nutrient levels are apparently deficient in terms of supporting optimal yields. Thus, the interval between the CN values and the Kenworthy optima points identify the range for marginal crop response to increasing nutrient content. This range in nutrient content needs to be the target zone for future calibration work in the field.

Finally, this experiment established baseline references for soil and tissue test nutrient values for irrigated chile production in the desert Southwest. Relating these values to yield results over the two-year study show several possible nutrient test values which can be used for further calibration in an effort to better define appropriate fertilizer inputs in relation to critical values. These results can then be combined to gain better nutrient management efficiencies in irrigated chile production systems.

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APPENDIX B: FIGURES AND TABLES

The explanation outlines the tables and figures that follow in this Appendix. Tables 3-12 give information on previous nutrient test values in chile as well as the values derived from this research. Tables 13-19 give a comparison of the research results to the guidelines published by New Mexico State University for chile growers.

Figures 2-6 show soil test values plotted against dry yield for 5 nutrients: P, K, Zn, ZnFe and B. The following set of figures (7-11) plot dry yield against the environmental mean value of the soil test value for the five plots within each field. The error bars show the standard deviation for each environmental mean soil test value. All yields both in the soil test data and the tissue test data are on a kg ha^{-1} basis.

Figures 14-18 show leaf blade test P plotted against dry yield for each stage of growth. The first figure for each stage of growth shows each data point, while the second figure shows the leaf blade test values averaged within each field with the standard deviation error bars plotted on the graph as for soil test values. This pattern repeats itself for each set of figures; the figures are grouped by nutrient.

Following the figures associated with leaf blade B, figures 52-56 show leaf blade test results for each nutrient plotted against HUAP. A regression line and the associated r^2 value is presented with each nutrient to show the change in nutrient levels over time.

The next grouping of figures present the petiole test values for $\text{NO}_3\text{-N}$ and $\text{PO}_4\text{-P}$ for each stage of growth. As with the nutrient test values, the first figure for each stage of growth shows each nutrient value, while the second figure shows the petiole test

values averaged within each field with the standard deviation error bars plotted on the graph as for soil test values. The final figure compares the two extraction methods for soil test K.

Figure 1. Chile Physiological Model Check (Development as a function of Heat Units)

Table 1: Sampling dates and HUAP (2008) listed by stage of growth. All plots in a field were sampled on the same day (HUAP); wide range of HUAP demonstrates variability in HUAP model depending on other environmental characteristics, cultivar, etc.

<u>Site</u>	<u>FB Sampled</u>	<u>HUAP</u>	<u>EB Sampled</u>	<u>HUAP</u>	<u>PB Sampled</u>	<u>HUAP</u>	<u>PM Sampled</u>	<u>HUAP</u>	<u>Harvest</u>	<u>HUAP</u>
2008NM1	7.17.08	2359	7.31.08	2634	8.13.08	2919	8.31.08	2942	10.04.08	3901
2008NM2	7.02.08	1967	7.17.08	2336	7.31.08	2611	8.14.08	2919	10.04.08	3878
2008NM3	7.02.08	1949	7.17.08	2297	7.31.08	2572	8.14.08	2880	10.04.08	3840
2008NM4	6.18.08	1674	7.03.08	2035	7.16.08	2332	7.31.08	2685	10.04.08	3925
2008NM5	6.18.08	1658	7.03.08	2018	7.17.08	2366	8.07.08	2793	10.04.08	3908
2008AZ1	7.03.08	1211	7.18.08	1489	8.01.08	1785	8.14.08	2087	9.20.08	2713
2008AZ2	7.18.08	1436	7.25.08	1650	8.06.08	1944	8.22.08	2234	9.20.08	2867
2008AZ3	7.03.08	1227	7.15.08	1465	8.01.08	1826	8.07.08	1973	9.20.08	2580
2008AZ4	7.11.08	1301	7.25.08	1588	8.07.08	1882	8.22.08	2172	9.25.08	2809

Table 2: Sampling dates and HUAP (2009) listed by stage of growth. All plots in a field were sampled on the same day (HUAP); wide range of HUAP demonstrates variability in HUAP model depending on other environmental characteristics, cultivar, etc.

<u>Site</u>	<u>FB Sampled</u>	<u>HUAP</u>	<u>EB Sampled</u>	<u>HUAP</u>	<u>PB Sampled</u>	<u>HUAP</u>	<u>PM Sampled</u>	<u>HUAP</u>	<u>Harvest</u>	<u>HUAP</u>
2009NM1	7.1.09	1559	7.13.09	1854	7.28.09	2240	8.11.09	2580	9.26.09	3484
2009NM2	7.1.10	1578	7.13.10	1873	7.28.10	2258	7.28.09	2599	9.26.10	3502
2009NM3	6.17.09	1299	1.01.09	1621	7.13.09	1916	8.11.11	2302	9.26.11	3546
2009AZ1	6.30.12	1150	7.13.12	1430	7.29.09	1770	8.11.12	2069	9.18.09	2665
2009AZ2	6.30.13	1140	7.13.13	1420	7.28.13	1782	8.11.13	2059	9.12.13	2752
2009AZ3	7.7.09	1277	7.21.09	1588	8.04.09	1900	8.18.09	2178	10.02.09	2934

Table 3. Optimum nutrient levels in pepper leaf tissue

Nutrient	Bell Pepper Sufficiency (Plant Part/Stage of Growth not Specified (Wein, 1997)	Pepper Leaf Sufficiency Levels (Lorenz and Tyler, 1983)	Pepper Petiole Sufficiency Levels (Lorenz and Tyler, 1983)
N	3.0-5.0%	0.2% EB 0.8% PB	.7% EB 1.5% PB
P	0.3-0.6%	0.2%	.25%
K	3.0-5.5%	5.0% EB 4.0% PB	5.0% EB 4.0% PB 3.0% PM
Fe	60-300 ppm		
Zn	20-100 ppm		
B	30-100 ppm		

Table 4: Range of sufficiency tissue test levels for K in peppers

	K [%]	Pepper Type	Stage of Growth	Source
Most recently mature leaves	3.0-5.5	chile	first bloom	Wein, 1997
Most recently mature leaves	4.0-6.0	bell	first bloom	Benton Jones et al., 1991
Most recently mature leaves	3.5-4.5	bell	final 1/3	Benton Jones et al., 1991
Most recently mature leaves	5.0	chile	first bloom	Lorenz and Tyler, 1983
Petiole	5.0	chile	first bloom	Lorenz and Tyler, 1983

Table 5: Soil Nutrient Test Statistics

	P [ppm]	K [ppm]	Fe [ppm]	Zn [ppm]	B [ppm]
Mean	24.3	749	4.89	0.935	1.46
St. Dev	9.3	450	2.2	0.45	0.67
C.V.	38%	60%	45%	48%	46%
Range	9.9-65	110-1900	1.9-9.5	0.3-2.26	0.25-2.72

Table 6: FB Leaf Test Values

	P [%]	K [%]	Fe [ppm]	Zn [ppm]	B [ppm]
Mean	0.32	5.8	225	33.6	55.3
St. Dev	0.06	1.03	102	11.4	15.7
C.V.	19%	18%	45%	34%	28%
Range	0.19-0.48	4.34-11.6	77-455	7.8-53.5	31.6-106

Table 7: EB Leaf Test Values

	P [%]	K [%]	Fe [ppm]	Zn [ppm]	B [ppm]
Mean	0.3	5.1	148	30.8	61.6
St. Dev	0.05	0.89	79	10.5	37.1
C.V.	17%	17%	53%	34%	60%
Range	0.2-0.44	3.1-7.4	66-446	4.8-50	30-204

Table 8: PB Leaf Test Values

	P [%]	K [%]	Fe [ppm]	Zn [ppm]	B [ppm]
Mean	0.28	4.7	89	26.1	70.3
St. Dev	0.05	0.76	21.5	10.1	56.8
C.V.	19%	16%	24%	39%	81%
Range	0.14-0.44	2.8-6.9	58-172	4.8-45.6	28-277

Table 9: PM Leaf Test Values

	P [%]	K [%]	Fe [ppm]	Zn [ppm]	B [ppm]
Mean	0.26	4.5	70.7	22.8	87.7
St. Dev	0.04	0.85	12.9	8.1	73.9
C.V.	17%	19%	18%	36%	84%
Range	0.14-0.35	2.1-6.0	52-118	5.4-39	32-381

Table 10: Petiole Test Values

	FB		EB		PB		PM	
	P [ppm]	N [ppm]	P [ppm]	N [ppm]	P [ppm]	N [ppm]	P [ppm]	N [ppm]
Mean	1600	6407	1400	6200	1300	4400	1100	3200
St. Dev	500	3500	500	3000	400	2400	400	1700
C.V.	33%	55%	37%	48%	32%	55%	37%	53%
Range	800-3300	1400-13,200	400-3200	500-11500	400-2600	200-10100	100-2600	1000-7300

Table 11: Comparison of soil test results with current sufficiency guidelines published by New Mexico State University with potential critical points (*Guide A-122, Soil Test Interpretation, Cooperative Extensions Service) (Water soluble K, ***NH₄OAc K)**

Soil Nutrient	Current Guidelines *	Experiment Results	Potential Critical Pt
P	15-22 ppm	9.9-65 ppm	20 ppm
K	230 ppm** 30-60 ppm ***	110-1900 ppm** 52-177 ppm***	240 ppm***
Fe	2.5-4.5 ppm	1.9-9.5 ppm	--
Zn	0.5-1.0	0.3-2.26 ppm	0.75 ppm
B	0.5-1.0	0.25-2.72 ppm	0.9 ppm

Table 12: Leaf blade test results for FB compared to current sufficiency guidelines published by New Mexico State University with potential critical points (*Guide A-122, Soil Test Interpretation, Cooperative Extensions Service)

Leaf Nutrient	Current Guidelines *	Experiment Results	Potential Critical Pt
P	0.35-1.0%	0.19-0.48 %	0.31%
K	4-6%	4.24-11.6%	--
Fe	60-300 ppm	77-445 ppm	135 ppm
Zn	50-200 ppm	7.8-53.3 ppm	35 ppm
B	25-75 ppm	31.6-106 ppm	35 ppm

Table 13: Leaf blade test results for EB compared to current sufficiency guidelines published by New Mexico State University with potential critical points (*Guide A-122, Soil Test Interpretation, Cooperative Extensions Service)

Leaf Nutrient	Current Guidelines *	Experiment Results	Potential Critical Pt
P	0.22-0.7%	0.2-0.44%	0.22%
K	3.5-4.5%	3.1-7.4%	4.80%
Fe	60-300 ppm	66-466 ppm	80 ppm
Zn	50-200 ppm	4.8-50 ppm	31 ppm
B	25-75 ppm	30-204 ppm	35 ppm

Table 14: Leaf blade test results for PB compared to current sufficiency guidelines published by New Mexico State University with potential critical points (*Guide A-122, Soil Test Interpretation, Cooperative Extensions Service)

Leaf Nutrient	Current Guidelines *	Experiment Results	Potential Critical Pt
P	0.25-0.3%	0.14-0.44%	0.23%
K	5.0-6.0%	2.8-6.9%	4.50%
Fe	60-300 ppm	58-172 ppm	75 ppm
Zn	20-200 ppm	5-46 ppm	25 ppm
B	24-118 ppm	28-277 ppm	45 ppm

Table 15: Petiole test results compared to current sufficiency guidelines published by New Mexico State University with potential critical points (*Guide A-122, Soil Test Interpretation, Cooperative Extensions Service)

Petiole Nutrient	Current Guidelines*	Experiment Results	Potential Critical Pt
NO ₃ -N	10000 ppm	2000-13,200 ppm	--
PO ₄ -P	2000 ppm	4000-7300 ppm	1000 ppm EB 1200 ppm FB

Yield vs Soil Test P

Figure 2: Chile dry yield versus soil test P.

Yield vs Soil Test K

Figure 3: Chile dry yield versus soil test K using NH_4OAc extraction.

Yield vs Soil Test Zn

Figure 4: Chile dry yield versus soil test Zn.

Yield vs Soil Test Fe

Figure 5: Chile dry yield versus soil test Fe.

Yield vs Soil Test B

Figure 6: Chile dry yield versus soil test B.

Yield vs Mean Soil Test P

Figure 7: Chile dry yield versus mean soil test P with standard deviation error.

Yield vs Mean Soil Test K

Figure 8: Chile dry yield versus mean soil test K with standard deviation error.

Yield vs Mean Soil Test Zn

Figure 9: Chile dry yield versus mean soil test Zn with standard deviation error.

Yield vs Mean Soil Test Fe

Figure 10: Chile dry yield versus mean soil test Fe with standard deviation error.

Yield vs Mean Soil Test B

Figure 11: Chile dry yield versus mean soil test B with standard deviation error.

Yield vs FB Leaf P

Figure 12: Chile dry yield versus leaf test P for FB stage of growth.

Yield vs Mean FB Leaf P

Figure 13: Chile dry yield versus mean leaf test P for FB stage of growth with standard deviation error.

Yield vs EB Leaf P

Figure 14: Chile dry yield versus tissue leaf P for EB stage of growth.

Yield vs Mean EB Leaf P

Figure 15: Chile dry yield versus mean leaf test P for EB stage of growth with standard deviation error.

Yield vs PB Leaf P

Figure 16: Chile dry yield versus leaf test P for PB stage of growth.

Yield vs Mean PB Leaf P

Figure 17: Chile dry yield versus mean leaf test P for PB stage of growth with standard deviation error.

Yield vs PM Leaf P

Figure 18: Chile dry yield versus leaf test P for PM stage of growth.

Yield vs Mean PM Leaf P

Figure 19: Chile dry yield versus mean leaf test P for PM stage of growth with standard deviation error.

Yield vs FB Leaf K

Figure 20: Chile dry yield versus leaf test K for FB stage of growth.

Yield vs Mean FB Leaf K

Figure 21: Chile dry yield versus mean leaf test K for FB stage of growth with standard deviation error.

Yield vs EB Leaf K

Figure 22: Chile dry yield versus leaf test K for EB stage of growth.

Yield vs Mean EB Leaf K

Figure 23: Chile dry yield versus mean leaf test K for EB stage of growth with standard deviation error.

Yield vs PB Leaf K

Figure 24: Chile dry yield versus leaf test K for PB stage of growth.

Yield vs Mean PB Leaf K

Figure 25: Chile dry yield versus mean leaf test K for PB stage of growth with standard deviation error.

Yield vs PM Leaf K

Figure 26: Chile dry yield versus leaf test K for PM stage of growth.

Yield vs Mean PM Leaf K

Figure 27: Chile dry yield versus mean leaf test K for PM stage of growth with standard deviation error.

Yield vs FB Leaf Zn

Figure 28: Chile dry yield versus leaf test Zn for FB stage of growth.

Yield vs Mean FB Leaf Zn

Figure 29: Chile dry yield versus mean leaf test Zn for FB stage of growth with standard deviation error.

Yield vs EB Leaf Zn

Figure 30: Chile dry yield versus leaf test Zn for EB stage of growth.

Yield vs Mean EB Leaf Zn

Figure 31: Chile dry yield versus mean leaf test Zn for EB stage of growth with standard deviation error.

Yield vs PB Leaf Zn

Figure 32: Chile dry yield versus leaf test Zn for PB stage of growth.

Yield vs Mean PB Leaf Zn

Figure 33: Chile dry yield versus mean leaf test Zn for PB stage of growth with standard deviation error.

Yield vs PM Leaf Zn

Figure 34: Chile dry yield versus leaf test Zn for PM stage of growth.

Yield vs Mean PM Leaf Zn

Figure 35: Chile dry yield versus mean leaf test Zn for PM stage of growth with standard deviation error.

Yield vs FB Leaf Fe

Figure 36: Chile dry yield versus leaf test Fe for FB stage of growth.

Yield vs Mean FB Leaf Fe

Figure 37: Chile dry yield versus mean leaf test Fe for FB stage of growth with standard deviation error.

Yield vs EB Leaf Fe

Figure 38: Chile dry yield versus leaf test Fe for EB stage of growth.

Yield vs Mean EB Leaf Fe

Figure 39: Chile dry yield versus mean leaf test Fe for EB stage of growth with standard deviation error.

Yield vs PB Leaf Fe

Figure 40: Chile dry yield versus leaf test Fe for PB stage of growth.

Yield vs Mean PB Leaf Fe

Figure 41: Chile dry yield versus mean leaf test Fe for PB stage of growth with standard deviation error.

Yield vs PM Leaf Fe

Figure 42: Chile dry yield versus leaf test Fe for PM stage of growth.

Yield vs Mean PM Leaf Fe

Figure 43: Chile dry yield versus mean leaf test Fe for PM stage of growth with standard deviation error.

Yield vs FB Leaf B

Figure 44: Chile dry yield versus leaf test B for FB stage of growth.

Yield vs Mean FB Leaf B

Figure 45: Chile dry yield versus mean leaf test B for FB stage of growth with standard deviation error.

Yield vs EB Leaf B

Figure 46: Chile dry yield versus leaf test B for EB stage of growth.

Yield vs Mean EB Leaf B

Figure 47: Chile dry yield versus mean leaf test B for EB stage of growth with standard deviation error.

Yield vs PB Leaf B

Figure 48: Chile dry yield versus leaf test B for PB stage of growth.

Yield vs Mean PB Leaf B

Figure 49: Chile dry yield versus mean leaf test B for PB stage of growth with standard deviation error.

Yield vs PM Leaf B

Figure 50: Chile dry yield versus leaf test B for PM stage of Growth

Yield vs Mean PM Leaf B

Figure 51: Chile dry yield versus mean leaf test B for PM stage of growth with standard deviation error.

P Leaf Test Values Over Time

Figure 52: Leaf test values for P plotted against HUAP

K Leaf Test Values Over Time

Figure 53: Leaf test values for K plotted against HUAP

Zn Leaf Test Values Over Time

Figure 54: Leaf test values for Zn plotted against HUAP

Fe Leaf Test Values Over Time

Figure 55: Leaf test values for Fe plotted against HUAP

B Leaf Test Values Over Time

Figure 56: Leaf test values for B plotted against HUAP

Yield vs FB Petiole N

Figure 57: Chile dry yield versus petiole test N for FB stage of growth.

Yield vs Mean FB Petiole N

Figure 58: Chile dry yield versus mean petiole test N for FB stage of growth with standard deviation error.

Yield vs EB Petiole N

Figure 59: Chile dry yield versus petiole test N for EB stage of growth.

Yield vs Mean EB Petiole N

Figure 60: Chile dry yield versus mean petiole test N for EB stage of growth with standard deviation error.

Yield vs PB Petiole N

Figure 61: Chile dry yield versus petiole test N for PB stage of growth.

Yield vs Mean PB Petiole N

Figure 62: Chile dry yield versus mean petiole test N for PB stage of growth with standard deviation error.

Yield vs PM Petiole N

Figure 63: Chile dry yield versus petiole test N for PM stage of growth.

Yield vs Mean PM Petiole N

Figure 64: Chile dry yield versus mean petiole test N for PM stage of growth with standard deviation error.

Yield vs FB Petiole P

Figure 65: Chile dry yield versus petiole test P for FB stage of growth.

Yield vs Mean FB Petiole P

Figure 66: Chile dry yield versus mean petiole test P for FB stage of growth with standard deviation error.

Yield vs EB Petiole P

Figure 67: Chile dry yield versus petiole test P for EB stage of growth.

Yield vs Mean EB Petiole P

Figure 68: Chile dry yield versus mean petiole test P for EB stage of growth with standard deviation error.

Yield vs PB Petiole P

Figure 69: Chile dry yield versus petiole test P for PB stage of growth.

Yield vs Mean PB Petiole P

Figure 70: Chile dry yield versus mean petiole test P for PB stage of growth with standard deviation error.

Yield vs PM Petiole P

Figure 71: Chile dry yield versus petiole test P for PM stage of growth.

Yield vs Mean PM Petiole P

Figure 72: Chile dry yield versus mean petiole test P for PM stage of growth with standard deviation error.

Comparison of Soil K Extraction Methods

Figure 73: Comparison of soil test K results from 1:5 (Soil:Water) extraction versus using NH₄OAc extraction

Yield vs Water Extractable Soil Test K

Figure 74: Chile dry yield plotted against 1:5 (Soil:Water) K extraction

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