Target Seedling Symposium

Chapter 10
Mineral Nutrition and the Target Seedling

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ABSTRACT

Containerized Douglas-fir seedlings were grown in a greenhouse for seven months. Treatments were started in June 1989 by modifying a standard nutrient solution to give three levels each of nitrogen and phosphorus in a complete factorial design. Both nutrients were supplied at one-third of control, control, and three times control. Foliar nitrogen, phosphorus, potassium, total dry weight, and root growth capacity after four weeks were measured in late December 1989. These data were used to compare three methods of assessing plant nutritional status: critical concentration, vector diagnosis, and DRIS (diagnosis and recommendation integrated system). Unlike critical concentration, both vector diagnosis and DRIS identify relative, not absolute, differences between treatments.

Both nitrogen and phosphorus were found to limit growth when compared to the standard nutrient solution. Dry weight was most influenced by nitrogen and RGC was most influenced by phosphorus. Data suggest that the level portion (luxury consumption) of a critical concentration curve is caused by deficiencies in other nutrients. Also, critical concentration was found to be of little value in making nutrient recommendations. Both vector diagnosis and DRIS were more useful in identifying and ranking limiting nutrients.

10.1 Introduction and Objectives

Good mineral nutrition is fundamental to producing the target seedling. It is as basic as light and water. And just like these other factors, mineral nutrition is more or less taken for granted. A mental picture of the ideal seedling is a summary statement of the effects of good mineral nutrition. Among other details, this picture includes good color, height, and caliper. It is equally easy to visualize a seedling that has a mineral nutrient deficiency. That mental picture can be as vivid as the first and is highlighted by poor growth and color.

Most forest nursery managers would acknowledge that good mineral nutrition is a basic part of producing the target seedling. In spite of this fact, many nursery managers do not have the tools needed to gather information about nutrient imbalances or deficiencies before damage has been done. Many managers find interpretation to be as difficult as gathering the information.

This primary goal of this chapter is to describe some relatively new methods of evaluating the nutrient status of plants. These methods will be compared with conventional methods. The focus will be on the practical application of these new methods and detail the technical aspects of the methods. The core of this paper will be principles and not specific prescriptions.

10.2 Basic Principles of Mineral Nutrition

10.2.1 Uses of mineral nutrients

The emphasis of this brief review of basic mineral nutrition is to place scientific facts into a practical perspective. It is beyond the scope of this chapter to enter a detailed discussion of the biochemical or cellular level actions and interactions of the different mineral nutrients. Discussions at this level can be found in several readily available textbooks. Among these are: Kramer and Kozlowski 1979, Epstein 1972, Hewitt and Smith 1974, and Gauch 1972. A recent publication by Landis et al. (1989) is a readable overview of mineral nutrition in forest nurseries.

In the mid part of the nineteenth century, agricultural chemists began to understand that mineral elements used by plants were taken up from the soil (Hall 1905). The obvious extension of this idea was to use the analysis of plant material to describe the nutrient supply of the soil. For many years plant analysis was seen as a biological method of soil analysis. Only in the past 30 years or so has the emphasis changed to using the analysis of plant material to evaluate the nutrient status of the plant (Bouma 1983).

It is important to emphasize the limitations of plant nutrient analysis. A thorough examination of a plant's nutrient content can show an imbalance, a deficiency, or an excess of certain nutrients. It cannot prescribe a particular amount of fertilizer to be added nor can it predict the response to a given amount of fertilizer. It must be remembered that the soil type, environmental conditions (temperature, humidity, etc.), and the plant itself will regulate uptake and utilization of a mineral nutrient. Knowledge of the nutrient content of a plant is useful because of the relationship between nutrients and physiological processes. For example, the analysis of nitrogen in a leaf is useful primarily because nitrogen in a leaf is correlated to the relative rate of photosynthesis. However, many other factors can change photosynthesis. Consequently, the measurement of nutrient content is only useful because the overall nutrient picture of a seedling is a reflection of the overall vigor of that seedling. Knowing something about an item that is relatively easy to measure (nutrient content) is valuable when that information is strongly related to something that is not as easy to measure (physiological condition).

Like all plants, tree seedlings have definite, well defined mineral nutrient requirements. There are 16 commonly

Table 10.1--*Elements essential to plant growth. Ranked by quantity found in oven dry tissue and listed by major role in plant tissue (Modified after Salisbury and Ross 1978).*

Element	Rank	%	Role in plant
Carbon	1	45.0	Carbohydrate
Oxygen	2	45.0	Carbohydrate
Hydrogen	3	6.0	Carbohydrate
MACRONUTRIENTS			
Nitrogen	4	1.5	Amino acids, protein, nucleic acids, chlorophyll
Potassium	5	1.0	Enzymes, osmotic control, pH balance
Calcium	6	0.5	Enzymes, membrane stability, middle lamella
Magnesium	7	0.2	Enzymes, chlorophyll
Phosphorus	8	0.2	Energy transfer, nucleic acids, phosphorylated sugars.
Sulfur	9	0.1	Amino acids, protein, Enzymes
MICRONUTRIENTS		ppm	
Iron	10	100	Enzymes, electron transport
Chlorine	11	100	Photosynthesis, non-essential role in osmotic control
Manganese	12	50	Enzymes, oxidation-reduction
Zinc	13	20	Enzymes
Boron	14	20	Carbohydrate translocation
Copper	15	6	Enzymes
Molybdenum	16	0.1	Enzymes

accepted elements that make up the essential mineral nutrients (Table 10.1). These elements are usually placed in broad groups based on relative concentration in the plant. Macronutrients are more abundant than micronutrients. It is a common mistake to believe that a macronutrient is more important to a plant than a micronutrient. While it is certainly true that macronutrients are required in greater quantity than micronutrients, all are required for the plant to function normally. An absence of any essential element will have serious consequences.

An element is judged essential if it meets three criteria (Arnon and Stout 1939):

1) Absence of the element will cause abnormal growth or in severe cases cause the plant to be unable to complete its life cycle.

2) It must be a part of some compound needed by the plant for normal metabolism. The effect of the element must come about by an internal function and not an external function.

3) The element cannot be completely replaced by another element.

These criteria are so basic that they have become a part of the litany and grown transparent. There are two basic principles involved that are worth restating. First, it would be unusual in a nursery situation for a plant to be grown long enough that problems with the life cycle would become apparent. In contrast, abnormal or poor growth is relatively common. Unfortunately the definition of poor growth is often subjective and hence is not always immediately apparent. Second, elements that are not essential can alter how a seedling grows. These elements can either be beneficial or toxic. An example of a beneficial element would be sodium which can partially replace potassium in some roles within the plant. Partial substitution can make a moderate deficiency less apparent at first. In conrast, lead is an example of an element which has a harmul effect and can stop some enzymes from functioning. By interacting with essential elements, some toxic eleents may mimic deficiencies.

10.2.2 Symptoms of deficiency

Nutrient deficiencies have been the subject of many studes. Two studies have been done on western conifers (Munson 1960, van den Driessche 1989). Both studies have color plates and descriptions of the deficiencies. Most deficiency studies are done by removing the element in question from a nutrient solution and then evaluating the appearance of the plants (Table 1 0.2). This produces a plant that would not usually be seen in an operational nursery. Even though a nursery may not supply enough nitrogen for optimum growth, it is unlikely that a nursery would not supply any nitrogen.

Table 10.2—*Generalized symptoms of mineral nutrient deficiency of selected elements. More detailed descriptions can be found in Landis et al. (1989) and van den Driessche (1989). Note: In conifer leaves, the symptoms will usually appear at the tips first. This may or may not be followed by the entire leaf.*

NITROGEN—Nitrogen is used as a constituent of chlorophyll and one of the first symptoms of nitrogen deficiency is pale green, short needles. Nitrogen is mobile within the plant and the symptoms may appear on older foliage first, but because nitrogen is used in so many important compounds (enzymes, nucleic acids), deficiency will cause plant-wide symptoms.
POTASSIUM—Potassium is used to balance osmotic potentials and help regulate pH. The symptoms are variable, but usually include browning of the leaves. Potassium is mobile so the symptoms are usually on the older leaves \first. Potassium is used throughout the plant so overall the plant will be stunted.
CALCIUM—Calcium is used in the middle lamella and cell walls. Calcium is not mobile within the plant. The usual symptoms include distorted leaves, poor meristem elongation and yellowing of newer leaves. A recent calcium deficiency will only be shown in the new leaves.
MAGNESIUM—Magnesium is used in chlorophyll. Leaves usually become yellow from a lack of chlorophyll.
PHOSPHORUS—Phosphorus deficiency will usually be shown as dull green-gray leaves. In some plants the leaves become dark green or purple. The leaf size tends to be normal, but the plant becomes stunted.
SULFUR—Sulfur is used in amino acids. Because nitrogen is also used in amino acid, the symptoms are similar. Pale green to yellow leaves that are stunted will usually be the first symptom. Most often appears in the younger leaves first.
IRON—Iron is used in the formation of chlorophyll. The first symptoms are yellowing foliage. Because iron is immobile the younger leaves are usually the first to show symptoms.

Consequently the symptoms, if any, are commonly less dramatic.

Ingestad has developed theories relating growth rate and nutrient concentration (Ingestad 1977, Ingestad 1982). These theories are explained in mathematical equations that relate growth rate, uptake rate, and other related processes. This work is important to discussion of deficiencies because it shows the relationship between nutrient

supply, growth rate, and development of deficiency symptoms.

Nutrients are consumed at a rate that is dependent on growth. Faster growing plants need, and consume, more nutrients. The problem faced by nurseries and those doing nutrient experiments is that the supply of nutrients is lumpy while growth is smooth. Nutrients are supplied in large, infrequent doses and growth is an ongoing process with a more or less constant rate. At the beginning of a growing season the plants are small and need relatively little nutrients. Plant growth is exponential and as the season progresses the addition of nutrients must greatly increase. If the nutrient supply is inadequate for the growth rate, then deficiency symptoms appear. This is often the case at the beginning of a new season when plants break bud and quickly add new growth. These deficiency symptoms are usually transient and disappear when the growth rate adjusts to the nutrient situation. Ingestad (1982) has shown that ". . . under natural conditions with marked nitrogen deficiency, vegetation is normally green, independent of plant species. It is to be expected that plants in their natural environment attain a steady state because growth adjusts to the nutritional resources of the site." This means the only dependable symptom of a nutrient deficiency will be a reduction in growth. Other visible symptoms may or may not appear. As a consequence, a nutrient analysis of the plant tissues will be required if a deficiency is to be detected and maximum growth maintained. It should be pointed out that maximum growth is not always the goal of the nursery. Inducing dormancy or relocating growth may be the goal at different times of the year.

10.3 Measuring Mineral Nutrient Content

10.3.1 Review of statistics

An understanding of five ideas from basic statistics will be useful in the following sections. Two of these are mathematically based (mean and variance) and three are conceptual (sample, normal distribution, and equality). Both mean and variance are easily determined with a hand calculator. In fact, many hand calculators have these functions preprogrammed and report the results at the push of a button. The textbook *Elementary Statistics* by Khazanie (1990) is recommended for a review of basic statistics. It is outside the scope of this paper to deal with statistical principles beyond this brief review.

Biological data, such as nutrient concentrations, will usually be more or less bell-shaped when it is plotted (Figure 10.1). Most commonly this kind of data will also be skewed to the right (Samuels 1989). Imagine a piece of graph paper with a horizontal line drawn across the bottom. This line represents the range of numbers that the data points have assumed and one square has been filled in each time a data point was measured. The more frequently occurring values form taller and taller stacks of filled in squares. If enough data points are measured and the population is normally distributed, then the curve will be perfectly bell-shaped.

If the data is normally distributed, then the mean will be at the top of the bell or the center of the distribution. The mean is the arithmetic average, or the sum of all data points divided by the number of data points (sum of X/n). The main use of the mean is to locate the center of the data distribution.

The variance determines the shape of the bell. The bell will be wide and flat (platykurtic) if the data is highly variable. In contrast, the bell will be tall and narrow (leptokurtic) if the data has little variation. Variance is calculated by subtracting each data point from the mean and squaring the result. All of these subtracted and squared numbers are added and divided by the number of data points minus 1 (sum of X minus mean of X squared divided by n-1). Variance does not have any hidden significance. It is simply one method of answering the question, "How variable is this data set?" The most common method of expressing variance is standard deviation. Standard deviation is the square root of variance and is used because it is in the same units as the mean variance is in units squared). After the mean and variance have been calculated it is possible to estimate the shape and middle of the normal curve.

The coefficient of variation is frequently used in nutrient analysis. The c.v. is the standard deviation divided by the

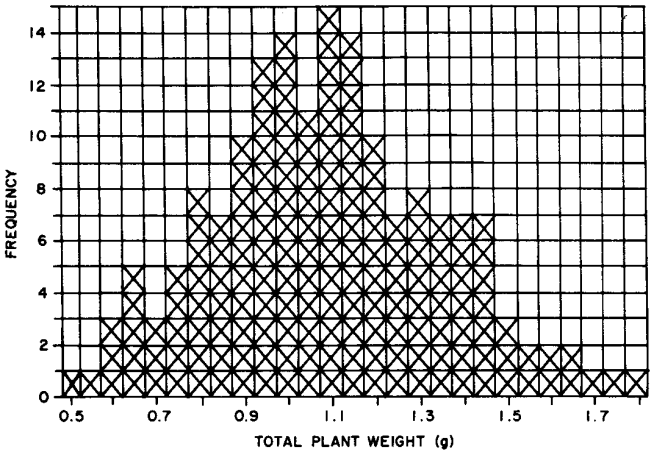

Figure 10.1—*Total weight of seedlings from the December harvest of the comparison experiment. Each X represents one plant. The distribution of the data approximates a normal distribution.*

mean times 100 and expresses variation as a percentage of the mean.

A sample is a part of a population. Without worrying about rigorous definitions, a sample is just a small part of a larger group. The major problem with a sample is it may not represent the population. The two most common errors are: 1) too few individuals are chosen for the sample or 2) the sample has been in some way biased. In this context, bias means that one part of the population has been over- or under-represented by the way in which the sample was chosen. An example would be choosing plants next to the road because they are easier to collect. The most important thing to understand about samples is that they are subsets of populations. From a practical viewpoint this means if the sample were to be repeated a second time, the mean and variance that were obtained the first time would be different from those of the second sample.

The final concept is that of equality. It is fairly straightforward that three does not equal four. However, in statistics three may well equal four. Mathematically equal means four equals four, but statistically equal does not. Much of inductive statistics is concerned with procedures to determine if the means of two or more samples are statistically equal. In general, it is more likely two samples will be judged statistically different if their means are far apart on the number line and their variances are small. The major difficulty in nutrient analysis is in determining when a value being compared to a standard is statistically equal or statistically different.

10.3.2 Sampling and determination of chemical composition

A few general ideas summarize some of the important aspects of sampling. First, the goals of sampling should reflect the goals of the experiment. Quite often the goals of an experiment done by a production nursery are more general than those for a scientific study. The major differences are usually seen in purpose, use of the information, and sampling intensity, If only general, record keeping information about the nutrient status of a stock type is desired, then infrequent samples may be taken on fewer populations. However, in all cases the sampling must encompass the full variation in the population being evaluated. This means that plants must be included from as many beds or benches as the stock type occupies. Many times a section of a nursery bed will show obvious reduced growth or other symptoms of difficulty. These areas can be identified and separated from other beds before sampling. Poor growth areas should still be sampled. In all cases the sample size should be large enough to identify meaningful, statistically significant differences. If the sample is too small, no significant differences will be detected. Procedures for determining sample size are detailed in virtually all statistic textbooks.

Second, plants should be randomly chosen. The easiest way to ensure a random sample is to use some form of a random starting point. A random number generator or table will help with this step of the process. From the starting point, some systematic pattern can be followed. Remember that, in general studies, the major problem is to overcome bias. A nursery manager needs to be careful to collect trees that are truly representative of their nursery. It is easy to systematically choose plants that are above average and not like most of the nursery. A truly unbiased sample will be valuable if the goal is to run an ongoing evaluation. In some of the following nutrient evaluation procedures it is useful to have samples from both the better trees and the cull trees.

When designing a nutrition experiment, a control group must be identified. In a bareroot nursery, an unfertilized plot may be used as a control treatment. Alternatively, a plot treated with a standard fertilizer system could be used. A container nursery may want to use a standard nutrient solution as a control and formulate different nutrient solutions for treatments.

The plant part sampled and timing of sampling can have a large effect on the usefulness of tissue analysis results. Plant tissue samples may be taken from whole plants, the shoot, or foliage only. The nutrient content of each plant part will be quite different. A review of Table 10.1 shows that some nutrients, like nitrogen, would be present in high quantities in the metabolically active parts of the plant. In contrast, calcium would be present in all parts of the plant. This is not unrelated to age. Consider the effect of the stem on an analysis. In very young seedlings the stem is a relatively small part of the whole plant. As the plant ages, the stem becomes more and more of the biomass. By the time a 2-0, 1-1, or 2-1 plant were sampled, the stem would be the major portion of the biomass. The most useful procedure is to use an easily identifiable part of the plant in the sample. Using the last fully expanded, mature leaves will solve the problems of physiological age, and identification of a plant part. Repeatable, useful information will be obtained if the same plant part is sampled at the same physiological time each year.

Collected samples should be clean and placed in plastic bags along with an identification tag. Samples cannot be over identified. If the sample cannot be quickly dried, it should be kept cold in an ice chest to slow metabolic activity. After collection, the samples are usually oxidized to remove carbon, hydrogen, and oxygen by the Kjeldahl acid digestion method. The nutrient content is then determined by titration, specific-ion electrode, atomic absorbtion or spectrophotometry. Many of these procedures are discussed more in depth by Landis (1985). A useful handbook for these and other procedures is Chemical Analysis of Ecological Materials (Allen 1974).

10.4 Description of Comparison Experiment

Non-mycorrhizal Douglas-fir seedlings were grown in a heated, ventilated greenhouse in 5-in^3 leach tubes with a standard nutrient solution (Ingestad and Lund 1986). After seven months, treatments designed to bring about a range of nutrient conditions were started. The nitrogen and phosphorus levels of the standard nutrient solution were modified. These nutrients were supplied at one-third of control, control, and three times control (Table 10.3). This created a two-way factorial design with nine treatments. Other nutrients continued to be supplied at the levels described by Ingestad and Lund.

The treatment that received nutrients with the original levels of nitrogen and phosphorus will be referred to as the control. The exception is in the DRIS section where the convention of other authors will be followed and the control treatment will be referred to as the norm. Throughout the paper this treatment will be abbreviated as Nn Pn (nitrogen normal-phosphorus normal). Similarly the treatment which had one-third the control nitrogen level and three times control phosphorus level would be referred to as N- P+.

This experiment had five harvests: June 5, July 2, July 31, August 28, and December 27, 1989. On each harvest date, ten seedlings per treatment were lifted. Among the variables measured on each tree were: root growth capacity at two weeks, root growth capacity at four weeks, height, caliper, leaf, stem and root dry weight, number of buds, number of branches, and net photosynthesis. A micro-Kjeldahl digest was done on the foliage. Phosphorus was determined with a spectrophotometer, while nitrogen and potassium levels were done by specific ion electrode.

Table 10.3—*Nitrogen and phosphorus levels in ppm in nutrient solution for each of the nine treatments. Minus* (-) *treatments are 1/3 of the normal (n) level, while the plus treatments are 3 times the normal level. The minus treatments were intended to induce deficiency and the plus treatments were intended to show the luxury consumption phase. All other essential nutrients were held constant at the normal level.*

	N_-	N_n	N_+
	N,P	N,P	N,P
P_-	8.3, 1.1	25, 1.1	75, 1.1
P_n	8.3, 3.25	25, 3.25	75, 3.25
P_+	8.3, 9.75	25, 9.75	75, 9.75

10.5 Interpretation of Values

10.5.1 Critical nutrient concentration/range

The most common method of diagnosing mineral nutrient problems is determining critical nutrient concentration. In practice the mineral nutrient content of a specific plant part is determined in the laboratory. These values are adjusted with experience and used as guides to compare how well other plants are supplied with the same mineral nutrients. This concept is based on a predictable and repeatable relationship between yield and the concentration of any single mineral nutrient. The dependability of the method depends on how comparable the experimental plants were to the plants used to establish the critical values (Armson 1973). This relationship has been defined in several different ways:

1) The concentration that is just deficient for maximum growth (Ulrich 1952).

2) The concentration that is just adequate for maximum growth (Ulrich op. cit.).

3) The concentration within the transition zone at the breaking point of the curve, or mathematically when dx/dy = 0 (Ulrich 1976).

4) The concentration beyond which further application of nutrient does not return a profit (Bates 1971).

These definitions are similar, but the differences are based on the criteria being used to determine yield. In some crops maximum dry matter production does not necessarily correspond to either the better plant or to optimum economic yield. Instead some combination of quantity, quality, and plant performance is used to define the better plant. This is probably the case in forestry.

Critical nutrient concentration can be viewed in two ways. It can be seen as a minimum value below which production is inadequate or as a maximum value above which production is unsatisfactory. This may seem a belaboring of a relative minor point. However, the most difficult part of evaluating mineral nutrition is defining yield, or setting an optimum value that is to be attained. Probably the most useful definition of critical nutrient concentration is "the level of a nutrient below which crop yield, quality, or performance is unsatisfactory" (Tisdale et al. 1985).

The relationship between yield and nutrient concentration has been illustrated in several different ways (Figure 10.2). The most commonly used curve is drawn without the dilution or toxic areas defined (Ulrich and Hills 1967). Using this simpler curve makes sense from a practical application point of view. Neither the dilution or toxic phases commonly occur in an operational forest nursery.

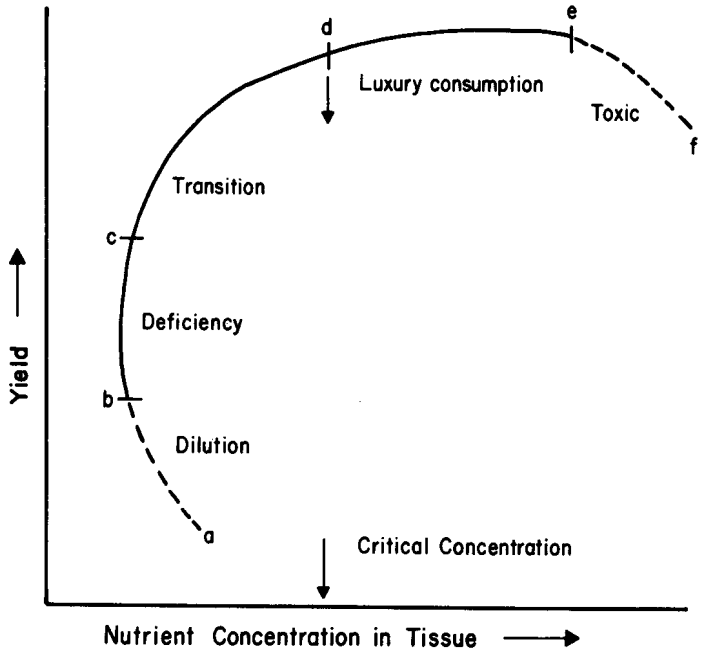

Figure 10.2—*Relationship between yield and nutrient concentration. With the exception of the dilution and toxic phases (dashed lines), the trend is for greater yield as nutrient concentration increases. The critical concentration is loosely defined as the middle part of the critical nutrient range. This range includes part of the transition and luxury consumption phases. Lowercase letters indicate the start and end points of the different phases.*

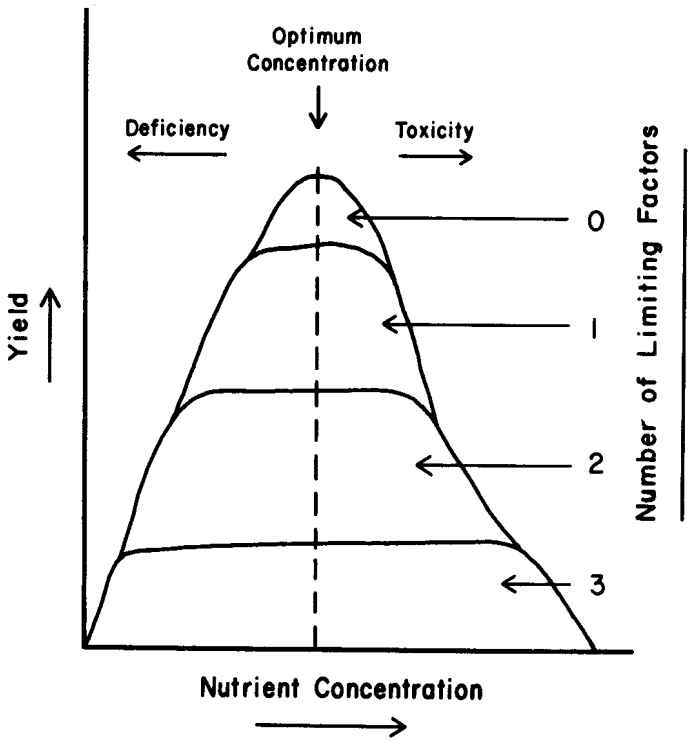

Figure 10.3—*Relationship between yield and the number of factors that limit yield. The optimum concentration is similar to the mean of a normal distribution and represents the concentration of nutrient in the plants with the greatest yield. (Adapted from Sumner and Farina 1986.)*

However, both are useful in building an understanding of the overall processes involved. The dilution phase was first described by Piper (1942) and was later described in more detail by Steenbjerg (1951). In this phase, biomass increases while nutrient concentration goes down. This is usually viewed as a constant amount of nutrient being diluted by greater growth. The exact cause of this phase has been the subject of debate. It is usually explained as either being caused by a variation in physiological age (Bates 1971) or by a change in element mobility in deficient plants (Loneragan 1978). Similarly, the toxic phase can be explained in two ways. First, a simple concentration effect where so much of the nutrient has been applied as to cause cell damage. Second, the element being supplied has an antagonistic effect on a second element which is in relatively short supply. An example would be precipitation of phosphorus by calcium. Both ways would cause a decrease in yield.

A flat luxury consumption phase is most commonly illustrated. If all other elements are present in optimal supply this portion of the curve will not be flat; rather, it will be curved (Bouma 1983). If an element other than the one being tested for is in low supply, then the luxury consumption phase will be flat and relatively long. Imagine an experiment done to evaluate the effects of nitrogen on the plant dry weight. In this experiment phosphorus, potassium, and calcium were inadvertently supplied at suboptimal levels. With all three of these elements limiting growth, the critical concentration curve would look like the bottom most curve in Figure 10.3. Assume that the phosphorus deficiency was corrected and the experiment was repeated. The curve would now resemble the second curve in Figure 10.3. The outermost, bell-shaped curve would be evident only if all elements were supplied at optimal levels. This curve illustrates three important points:

1) The optimum concentration for one element cannot be determined if other elements are deficient.

2) The yield curve is nearly statistically normal when all factors are optimum.

3) A flat-topped curve is probably an indication that a factor other than the one being tested is deficient.

This is in fact a graphic representation of Mitscherlich's Law of the Minimum (1921). His law states, "The increase in crop production by unit increment of *any* lacking fac-

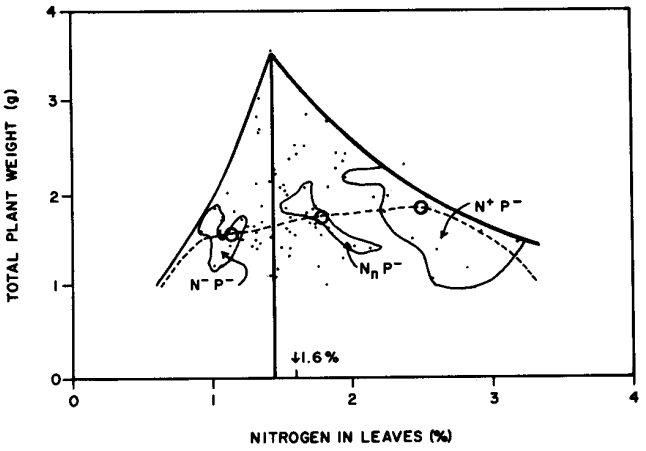

Figure 10.4—*Total plant weight and nitrogen concentration in leaves of plants from the comparison experiment that were harvested in December. The outer heavy lines enclose the data in a roughly bell-shaped curve. The vertical line shows the nitrogen concentration of the largest plants to be about 1.5%. The average nitrogen concentration for all plants in the experiment was 1.6% (arrow). The light lines inside the heavy lines surround all plants in each of three treatments (N- P-, Nn P-, N+ P-). The open circles are means from each of these groups. The dashed line connecting the means approximates a critical concentration curve.*

tor is proportional to its decrement from the optimum." In most nursery situations the deficiency picture is not black and white. Many factors are limiting growth, but none are totally lacking. For example, nitrogen and phosphorus might be deficient, but neither may be stopping growth. The complication arises if it is arbitrarily decided that nitrogen is the most lacking factor when in fact the most lacking factor is phosphorus. Mitscherlich's law says there will be a growth response to increased nitrogen, but not as much as there would have been if phosphorus had been added. The obvious answer to the problem is to examine several factors simultaneously. It is equally obvious that economics, and not biology, will dictate exactly how many factors will define the word several.

Figure 10.4 shows coordinate pairs for weight and nitrogen concentration for plants from all treatments, harvested in December in the comparison experiment. The dashed line goes through the means (open circles) for the phosphorus deficient treatments. This line approximates the lower curve in Figure 10.3. If this experiment had been done to establish the nitrogen critical concentration, and the low phosphorus concentration has been used, then the critical concentration curve would have been the dashed line. The dashed line drops quickly at about 1 percent nitrogen. That value would probably be chosen as the critical concentration. Compare this value to the average nitrogen content for all plants in all treatments (1.6 percent). However, because the luxury consumption phase was wide (1 percent to 2.6 percent nitrogen) and relatively flat (1.5 to 1.7 g), the deficiency of another nutrient was indicated. Success in determining critical values is dependent on all other factors being at optimum levels.

A quick study of the curve in Figure 10.2 shows that the placement of the critical concentration value is arbitrary. Dow and Roberts (1982) argue that establishing a single point on a curve to serve as the critical nutrient concentration is mostly an academic question. This is because the same critical value would not be obtained in successive experiments. Indeed if the experiment was repeated as exactly as possible it is unlikely that a mathematically equal value would be seen. The alternative is a critical nutrient range. Dow and Robert's definition is "that range of nutrient concentration at a specified growth stage above which we are reasonably confident the crop is amply supplied and below which we are reasonably confident the crop is deficient." They also note that Ulrich (1976) had earlier stated that critical nutrient concentration "as determined experimentally is not a point as the word concentration implies, but a narrow range of concentrations, above which the plant is amply supplied and below which the plant is deficient." From a practical point of view it is the transition zone of Figure 10.2. The sharper the break in the curve between deficiency and luxury consumption, the narrower the transition zone and the narrower the critical nutrient range.

The major advantage of using either critical nutrient range concentration or critical nutrient range is they are fairly simple to apply, *if the critical values are known.* There are at least two disadvantages. First, critical values have to be determined for each situation. Values for one species would be different from those for other species. Furthermore, there would be differences for plants of the same species and seed origin when grown under different conditions. Only when environment, genetics, sampling, analytical methods, etc., are similar will pre-determined critical values be accurate (Leaf 1973). Second, it is hard to tell if other nutrients are limiting the plant's response to a given nutrient. It will not always be possible in a single test to determine which nutrient is limiting growth. This is the fundamental difficulty with critical nutrient concentration. The technique is based on the principle that nutrients other than the limiting one will be present at optimum levels. In practice this is seldom the case. Consequently, multiple deficiencies will be particularly difficult to unravel and the determination of critical values will require large experiments.

Table 10.4—*Total dry weight (g), week 4 root growth capacity (cm), and concentrations (%) of nitrogen, phosphorus, and potassium in leaves for all treatments in the comparison experiment.*

Treatment	T.D.W.	R.G.C.	N%	P%	K%
N- P-	1.57	29	1.14	0.09	0.78
N- Pn	1.44	81	1.34	0.20	0.86
N- P+	1.46	95	1.27	0.38	0.94
Nn P-	1.74	47	1.77	0.07	0.83
Nn Pn	1.71	101	1.61	0.13	0.75
Nn P+	2.17	160	1.48	0.21	0.76
N+ P-	1.84	43	2.48	0.07	0.75
N+ Pn	2.46	128	1.68	0.10	0.80
N+ P+	2.29	165	1.59	0.21	0.93

Table 10.4 shows some of the results of the comparison experiment. By excluding plants in the P- and P+ treatments it is possible to determine an approximate critical value for nitrogen of 1.6 percent. Likewise by excluding plants in the N- and N+ treatments, the critical value for phosphorus can be seen to be 0.13 percent. Using these values as reference points it is seen that all of the trees from the low nitrogen treatments have low leaf nitrogen. Similarly all plants in the low phosphorus treatments have phosphorus levels below the critical concentration. However, there are some other relationships that are not as clear. For example, the Nn P+ treatment has a nitrogen value which is below the critical concentration (1.48 percent) with the plants being among the largest from the experiment.

The clearest example of the need for other nutrients to be optimum is in the low phosphorus treatments. A nitrogen range experiment using just these three treatments (N- P-, Nn P-, N+ P-) would have seemed successful. These three treatments have plants in the deficiency, transition, and luxury consumption ranges. Naturally when seen in the context of the whole experiment, it is plain these plants are phosphorus deficient. However, it would not have been obvious if treatments using different levels of phosphorus had not been used. To determine critical values, all nutrients must be present in adequate, but not toxic amounts. Suppose the critical values for nitrogen, phosphorus, potassium, calcium, magnesium, sulfur, and iron were to be determined. If just three levels of nutrient were to be added for each of these elements, and if a factorial experiment were done, then the experiment would have 2,187 treatments. When this is coupled with the number of species/seed zone combinations that most nurseries work with, the experiment becomes unmanageably large.

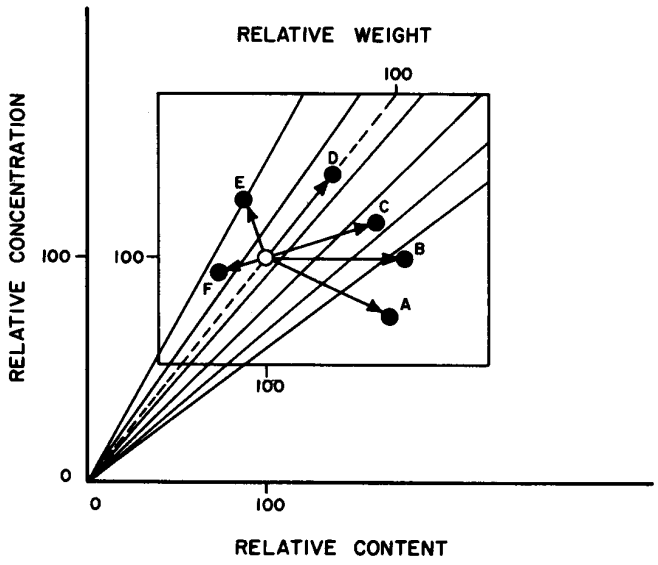

Figure 10.5—*Explanation of vectors in relative weight, nutrient content, and concentration between plants from different nutrient treatments. The open circle represents the control treatment after adjustment to 100. Vectors described by lettered points are interpreted in Table 10.5. (Adapted from Timmer and Armstrong 1989.)*

10.5.2 Vector analysis

One of the problems associated with using critical nutrient concentrations is determining the correct values for each nutrient-species-nursery combination. A re-examination of Figure 10.2 shows that this may not always be necessary. If at least two groups of plants with different levels of fertilizer can be compared, then the critical value does not need to be established. Instead it is possible to diagnose the change in nutrient status by examining the directional changes in yield and nutrient concentration. As an example, consider the following hypothetical experiment using nitrogen fertilizer. The results showed that when plants in the control or beginning treatment were compared to plants in the experimental or added fertilizer treatment there was no change in yield, but the nitrogen concentration in leaves increased. This is as if the control treatment was at point d on Figure 10.2 and the experimental treatment at point e on Figure 10.2 (increased nitrogen in leaves with no increase in yield). This could be interpreted as luxury consumption. Table 10.5 summarizes the directional changes in yield and concentration. This is the starting point for the vector analysis approach to analyzing plant nutrition.

Vector analysis or vector diagnosis has been developed by V.R. Timmer and his associates (Timmer and Stone 1978, Timmer and Morrow 1984, Timmer 1985, Timmer

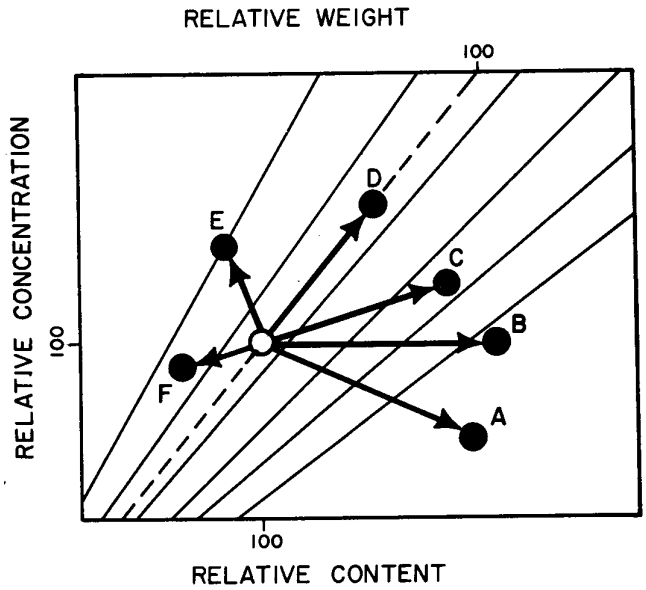

Figure 10.6—*Enlargement of Figure 10.5 showing the role of the origin in the placement of relative weight isolines. (Adapted from Timmer and Morrow 1984.*

Table 10.5—*Interpretation of relationships between yield and nutrient concentration as described in Figure 10.2.*

		Directional change in	
Area of curve	Location	Yield	Concentration
DILUTION	A to B	INCREASE	DECREASE
DEFICIENCY	B to C	INCREASE	NO CHANGE
TRANSITION	C to D	INCREASE	INCREASE
LUXURY CONSUMPTION	D to E	NO CHANGE	INCREASE
TOXICITY	E to F	DECREASE	INCREASE

and Armstrong 1987, Timmer and Ray 1988, Timmer and Armstrong 1989, Munson and Timmer 1989a, Munson and Timmer 1989b). Vector analysis is done by using a nomograph (Figure 10.5 and Table 10.6). This analysis is slightly different from what which was just explained in that nutrient content is added to the analysis. Nutrient content is simply the absolute amount of a mineral nutrient found in a needle. In practice, a given amount of needles are collected and the nutrient content analyzed and the result is expressed on a single needle basis. Thirty needles per seedling were used in the comparison experiment.

Nutrient content is added to the analysis to help clarify a problem with using concentrations. Concentration can remain equal in three situations: when weight and content go up equally, go down equally, or remain the same. It is usual for the addition of an element to cause the leaves to become larger. If content also increases, the, the concentration will remain the same. This is more of a problem when evaluating a nutrient other than the target nutrient. For example, fertilizing with one nutrient may cause the concentration of a second nutrient to go down. This is a dilution effect. Larger leaves with the same content of the second nutrient would have a lower concentration. In this case it is useful to know what has happened to the conent. If it has gone down, then the addition of first nutrient has caused antagonism. On the other hand, if content has remained the same or gone up, then it is a simple dilution of the second nutrient. This can also occur with luxury consumption (Timmer and Stone 1978). Adding content to the analysis helps prevent these misinterpretations.

Nutrient content and nutrient concentration form the axes of the graph and weight is added as diagonal lines starting at the origin. Figure 10.5 does not show the origin, rather it is a section of a graph with truncated axes (Figure 10.6). The window is drawn so it that includes just the part where the points have been plotted. Relative, not absoute, values are used for weight, concentration, and content. In addition to simplifying the graph, it also makes the analysis/graphing procedure fairly easy to do with a spreadsheet.

Table 10.6—*Interpretation of relationships between weight, nutrient concentration, and nutrient content as described in Figure 10.5 (after Timmer and Armstrong 1989).*

	Change in relative nutrient			
Direction of shift	Weight	Conc.	Content	Possible interpretation of vector
A	INCREASE	DECREASE	INCREASE	CAUSED DILUTION
B	INCREASE	NO CHANGE	INCREASE	WAS JUST SUFFICIENT
C	INCREASE	INCREASE	INCREASE	WAS DEFICIENT
D	NO CHANGE	INCREASE	INCREASE	CAUSED LUXURY CONSUMPTION
E	DECREASE	INCREASE	EITHER	CAUSED TOXICITY
F	DECREASE	DECREASE	DECREASE	CAUSED ANTAGONISM

It should be noted that this is not the only way to do a vector analysis. Valentine and Allen (1990) do a similar analysis using concentration and weight as the axes and content as isolines on the graph. The underlying principles are the same, but the picture is different.

Vector analysis is done by comparing the vector shift between the control and experimental treatments. The following points refer to Figure 10.5 and may make the figure easier to read:

1) Values below the 100 line indicate more weight. Those above the 100 line show less weight.

2) Horizontal vectors to the right of the 100,100 point indicate a higher nutrient content. Those to the left of this point mark a lower nutrient content.

3) Vertical vectors above the 100,100 point indicate a higher concentration. Those below this point signify a lower concentration. All possible shifts are summarized and interpreted in Table 10.6.

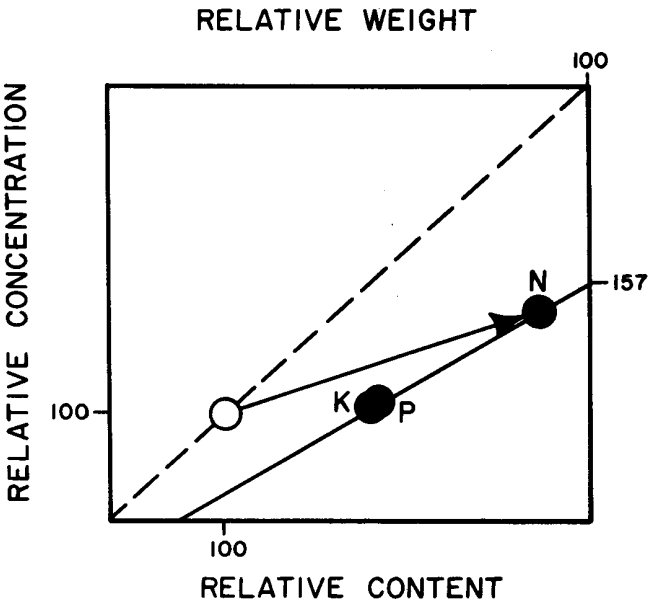

Figure 10.7—*Results of the comparison experiment. Plants in the December harvest in the N- P- treatment were compared with plants in the N+ Pn treatment. Relative N, P. and K for N- P- treatment are all represented by the open circle on the 100 weight line. Relative N, P. and K for the N+ Pn treatment are shown on the line representing the relative weight (157%). The longest vector is in C direction (Figure 10.5 and Table 10.5) which leads to the interpretation of a nitrogen being most deficient in the control treatment. Details of the calculations are presented in Appendix Table A1.*

Figure 10.7 shows some of the results of the comparison experiment as interpreted by vector analysis. The N- P- treatment was compared to the N+ Pn treatment. The convention for vector analysis is that the biomass of the treatment with the lower fertility is represented by the 100 line and all nutrients being evaluated are drawn at the 100,100 point (see Appendix Table Al for detailed calculations). In this case the N- P- treatment had the lower fertility. Because relative values were used in constructing the graph, this point (100,100) is the same for nitrogen, phosphorus, and potassium. Similar to the control plant being represented by a single relative point, the weight, nitrogen, potassium, and phosphorus values of the N+ Pn plants can be represented on a single weight line. In this case the biomass of N+ Pn plants was 157 percent of the N- P- plants and the weight line is labeled with a 157. All that remains is to locate the coordinates for each nutrient being evaluated along the weight line. Consequently, all four variables can be interpreted at the same time on a single graph. Vectors are then drawn to each nutrient point. The longest vector is considered to be the most limiting nutrient. In Figure 10.7 only one vector has been drawn in order to simplify the drawing. In this case, nitrogen was most limiting and the vector was interpreted as being most like vector C in Figure 10.5. The lower fertility treatment can be considered to have been deficient when weight, concentration and content all increase (Table 10.6). If a vector had been drawn to the potassium and phosphorus points it would have corresponded to vector B. The concentration has remained constant, while weight and content have increased. In this case greater growth and greater uptake of phosphorus and potassium have kept pace with each other and the concentration has remained unchanged.

Timmer's vector analysis has several advantages when compared to critical nutrient concentrations. Perhaps the greatest of these is the elimination of the determination of the critical concentration for each nutrient. It is also simple to do and fairly easy to interpret. Figures have been used in this paper to illustrate the results. However, in practice it would be less time consuming to compare the results to the description of vectors in Table 10.6. Both the graphic presentation and comparison to table values can be adapted to spreadsheets.

Vector analysis has two disadvantages. First, representing several treatments on the same graph can make the interpretation difficult. An obvious solution to this problem is to make several graphs and do each interpretation separately. However, there are times when the relationship between several treatments is as important as the relationship of each treatment to the control. Second, there is no simple way to account for the differences in magnitude between treatment responses. In the comparison experiment the phosphorus concentration ranged from 75 percent to 418 percent. This is a problem in statistics. Two

Table 10.7—*Results of the comparison experiment. Values given are relative to the N- P- treatment. Least significant differences (L.S.D.) were done after a two-way analysis of variance was done on the data*

Treatment	Nitrogen		Phosphorus		Potassium		Weight
	Conc.	Cont.	Conc.	Cont.	Conc.	Cont.	
N- P-	100	100	100	100	100	100	100
N- Pn	118	111	216	204	111	106	92
N- P+	111	99	418	366	122	107	93
Nn P-	155	189	80	96	106	128	111
Nn Pn	141	184	138	178	96	124	109
Nn P+	130	226	227	399	98	168	138
N+ P-	218	298	75	96	97	129	117
N+ Pn	147	311	111	223	103	217	157
N+ P+	139	256	225	406	120	216	146
L.S.D.	19	42	33	55	14	35	21

Table 10.8—*Results of the comparison experiment. The N- P- treatment was used as control. A zero in the table indicates the value was not statistically different from the control treatment. A plus means the value is statistically larger.*

Treatment	Nitrogen		Phosphorus		Potassium		Weight
	Conc.	Cont.	Conc.	Cont.	Conc.	Cont.	
N- P-	100	100	100	100	100	100	100
N- Pn	0	0	+	+	0	0	0
N- P+	0	0	+	+	+	0	0
Nn P-	+	+	0	0	0	0	0
Nn Pn	+	+	+	+	0	0	0
Nn P+	+	+	+	+	0	+	+
N+ P-	+	+	0	0	0	0	0
N+ Pn	+	+	0	+	0	+	+
N+ P+	+	+	+	+	+	+	+

values may be mathematically different, but statistically equal. This problem can be solved by subjecting the data to either a t-test or an analysis of variance before interpreting the vectors. Any means that were statistically equal would either not be used in the vector analysis or would mean no difference between treatments. Adding the statistical analysis adds complexity to the results. Tables 10.8 and 10.9 show the results of the comparison experiment after a statistical analysis. Some of the treatments have given clear, unambiguous results. Many have not. Unfortunately, doing the interpretation without statistically separating the means leads to even more questionable results. For example, in the N- Pn treatment, there

Table 10.9—*Results of the comparison experiment. The N- P- treatment was used as control. The vector letter refers to those listed in Figure 10.5 and Table 10.5. A zero indicates the treatment was not statistically different from control. A letter within parentheses indicates two of the variables were statistically different but the third was not*

Treatment	Nitrogen	Phosphorus	Potassium
N- P-	control	control	control
N- Pn	0	(C)	0
N- P+	0	(C)	0
Nn P-	(C)	0	0
Nn Pn	(C)	(C)	0
Nn P+	C	C	B
N+ P-	(C)	0	0
N+ Pn	C	(A)	(A)
N+ P+	C	C	C

was an increase in the concentration and content of N, P, K, and a decrease in weight (Table 10.7). This is interpreted as Vector E; adding phosphorus has caused toxicity. However, only the phosphorus values were statistically different from the N- P- means. This could be interpreted as nothing happened to the nitrogen content when phosphorus was added.

There is a practical solution to this problem; recognition of the fact that interpretation is never absolute. Simple statistics need to be used with this procedure and followed by a careful, reasoned interpretation of what happened to the plants. It is worth remembering the advantages of this method before dwelling on what may seem to be sizable problems. Critical concentrations do not have to be known and the results of the analysis are usually clear when used with statistics.

10.5.3 DRIS

The diagnosis and recommendation integrated system (DRIS) was conceived by Beaufils in the 1950's (Beaufils 1957). Originally called physiological diagnosis, it has primarily been used on agricultural crops like rubber and maize (Beaufils 1971, Beaufils 1973). Ideally DRIS uses all factors known to contribute to yield. However, DRIS can be effective with just a few factors being evaluated. The more factors that are evaluated the more effective the method becomes. To simplify the discussion, only mineral nutrients will be considered. Factors other than nutrients (e.g., water or light) could be have easily been used in DRIS. Several reviews of the DRIS method are available (Sumner 1978, Sumner 1982, Sumner and Farina 1986, Walworth and Sumner 1987, Walworth and Sumner 1988).

One of the fundamental principles behind DRIS is the evaluation of nutrient ratios. It is important that it be clear these ratios are not physiologically based. While there are physiologically important ratios (like calcium/potassium), DRIS ratios have no physiological base. This particular section is long and is divided into three subsections. First is a general introduction to the DRIS system and some of the underlying principles. Next is a subsection that deals with the calculation and application of DRIS indices and functions. This part may seem mathematically complex. However, these indices become less complex when a personal computer and a spreadsheet are used to do the arithmetic. Finally, a graphic method using DRIS charts is presented.

10.5.3.1 Introduction and principles of DRIS

One of the fundamental problems with nutrient analysis is a lack of a consistent correlation between nutrient content and yield. A re- examination of Figure 10.4 shows that the observations with the largest and smallest yields had the same nitrogen concentration. Surely this has a simple explanation. Most likely the small plant was deficient in another element, or had a disease, or damaged roots, or any one of number of possible problems. While all this may be true, they still had the same nitrogen concentration. Figure 10.8 is an illustration of what any nutrient analysis needs to accomplish. In this diagram the lowest yield is at the outside rim of the circle (arrow) and the greatest yield is in the middle at the intersection of the three circles. Yield can go from large to small when the level of any single nutrient is optimum. Two things happen when two nutrients are at optimum levels. First, yield is somewhat higher (intersection of two circles, like P + K). Second, the range of nutrient concentrations is smaller. Ultimately, when all three nutrients are optimum, the yield is maximized and falls within the N + K + P area of the figure. This is a restatement of the principle shown in Figure 10.3; the more nutrients that are optimum the greater the yield. DRIS is based on simultaneous analysis of several nutrients. At least three nutrients must be used for DRIS to work.

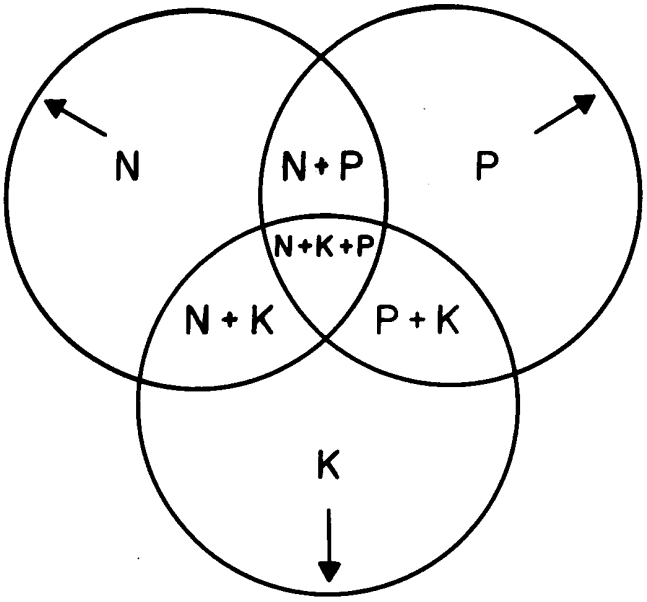

Figure 10.8—*Venn diagram illustrating the relationship between optimum yield and nutrient concentration. Arrows point to minimum yield for nitrogen, phosphorus, and potassium. Maximum yield is in the middle of the N + K+ P area on the diagram. As more nutrients are present in optimum quantity, the yield is increased.*

10.5.3.2 Calculation and application of DRIS indices

The DRIS system is based on a comparison between a high yielding population called the norm (control) and an experimental group. Figure 10.9 shows a cutoff between culls and usable plants which would in practice be determined by experience. This is nothing new to nursery managers. A cutoff like this is used every year when a forester asks for a minimum caliper or height. If a full range of heights were evaluated, a full range of nitrogen values would be found. Three facts can be seen in this illustration:

1) The tallest trees have to have close to the optimum amount of nitrogen. These trees do not have high or low levels of nitrogen (trees in the shaded areas).

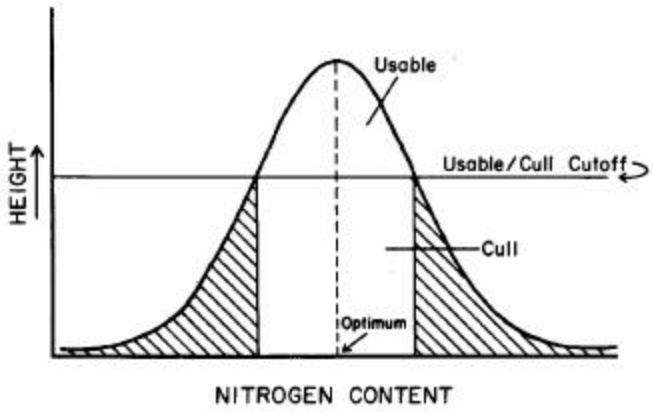

Figure 10.9—*Representation of how DRIS norms are derived. The usable/cull cutoff is determined by experience or prescription. Based solely on nitrogen content, plants in the unshaded area cannot be determined to be usable or cull. Plants in the tail areas of the curve represent those that are definitely culls by virtue of nitrogen content being too high (toxicity) or too low (deficiency).*

2) Short trees can also have the optimum amount of nitrogen because some other unknown factor has influenced growth. These trees can have high and low levels of nitrogen.

3) The plants in the tails of the curve (shaded area) can be eliminated solely on the basis of nitrogen being too low or too high. For each seedling represented by this illustration there were two values: nitrogen content and height. A normal curve-results from a plot of these values if the sample size was large enough. It would be possible to treat the data as coming from two populations by culling the curve in half at the usable/cull cutoff. Only the mean and variance for the usable group will be used in the calculation of the DRIS norm.

If the analysis were expanded to include phosphorus and potassium, there would be four values for each seedling (height, nitrogen, potassium, and phosphorus). As a first step in the application of the DRIS system the seedlings in the comparison or experimental group will be compared to the norm or control group. Rather than use N percent or P percent, DRIS uses the ratio of each pair of nutrients. Ratios such as N/P, P/K, etc., are calculated and their variances determined. Any one pair of nutrients such as nitrogen and phosphorus could be expressed in three different ways (N/P, P/N, or P times N). Which of the three expressions used is based on the ratio of the variances of between plants from the norm or high yielding sample to the experimental plants. The variance ratio calculation is done for each different expression of the ratio (Appendix Table A3). The expression with the highest variance is used in further calculations. This procedure gives greater separation between norm and treatment groups. In the case of the comparison experiment N/P had a ratio of 6.23, P/N was 3.24, and N*P was 0.20. Therefore, the ratio of N/P was chosen to be used in the analysis. Similarly K/N and K/P were picked for further use.

(NOTE: Throughout this section each step will be highlighted and numbered so that the process can be repeated without reviewing the text explanation. Detailed calculations are provided in Appendix Tables A2, A3, A4, and A5 at the end of the chapter.)

STEP 1: Establish the norm (control). Ideally this will be the best plant. It is recognized that best is a subjective term. In this experiment the Nn Pn treatments were chosen as the norm.
There are two ways to approach the DRIS norm. The ideal is to establish a norm for the species that is applicable in most situations. This approach requires a considerable amount of time and effort. However, once established this type of norm is very useful. A more short-term approach can be used. In this case one group of plants is simply assumed to be the norm. Remember the DRIS process is relative and the goal is to compare two or more treatments to each other. Once this concept is accepted, the relatively uncomfortable idea of it not being important which group is the norm (or control) becomes more palatable.

STEP 2: Calculate the variance ratio for each possible expression for each nutrient pair (N/P, P/N, P*N) (Appendix Tables A2 and A3).

STEP 3: Divide the variance of the comparison group (in this case N- P-) by the variance of the norm group. Determine which expression has the highest variance ratio (Appendix Table A3).
The determination of the expression form, variance ratios, and development of norms is the starting point for the calculation of DRIS indices. The expression with the highest variance ratio is used in the calculation of DRIS indices.

STEP 4: Determine DRIS functions using the function formula.
The first step in calculating the indices is the determination of the DRIS function for each pair of elements in the experiment. The mean of the ratio is used, not the variance. In the following equations the cv is the coefficient of variation for the norm (usable) population, n/p is the ratio of nitrogen to phosphorus for the norm population, and N/P is the ratio of nitrogen to phosphorus for the comparison population.

$$f(N/P) = \frac{N/P}{n/p} - 1 \quad \frac{1000}{cv} \qquad \text{when } N/P > n/p$$

$$f(n/p) = 1 - \frac{n/p}{N/P} \quad \frac{1000}{cv} \qquad \text{when } N/P < n/p$$

STEP 5: Determine the DRIS indices using the formulas.
The functions are combined in equations to used to calculate the indices. Indices for nitrogen, phosphorus, and potassium were needed for the comparison experiment.

$$\text{N index} = \frac{f(N/P) - f(K/N)}{2}$$

$$\text{P index} = \frac{f(N/P) - f(K/P)}{2}$$

$$\text{K index} = \frac{f(K/N) + f(K/P)}{2}$$

In general, the indices can be determined for as many elements as were evaluated in the experiment. The DRIS functions are added and divided by the number of comparisons. The sign is minus if the element being evaluated appears in the denominator of the function and positive if

it is in the numerator. So N/P is positive in the N index, but is negative in the P index. The only unusual circumstance arises when the product (N*P) is used instead of some form of division (N/P). In this case the 1/P is redefined as a new element arbitrarily designated as Q. Then N*P = N/Q and the calculations are done as described above. When the Q index is determined the sign is changed and it becomes the P index. DRIS indices are unitless and represent relative abundance of nutrients in the plant.

STEP 6: Evaluate the indices.
An interesting extension of the method allows a comparison between mineral nutrients and the amount of C, H, and O that have been accumulated (Walworth and Sumner 1988). The authors caution this idea needs further support from experimental data. The concept is the relationship between dry matter and mineral nutrients is what defines deficiency. If there is too little nitrogen relative to the amount of tissue produced, then nitrogen would be considered deficient. The three expressions to be evaluated are nutrient divided by dry matter (N/DM = N%), dry matter divided by nutrient (DM/N = 1/N%), and nutrient times dry matter (N*DM). DRIS indices are then calculated and placed in ascending order. Any nutrient index that has a more negative value than the dry matter index is considered deficient.

Results of the comparison experiment are shown is Table 10.10 and summarized in Tables 10.11 and 10.12. All nutrients with a DRIS index lower than dry matter were considered deficient. In the N- P- treatment, both nitrogen and phosphorus were deficient. Adding phosphorus in the N- Pn and N- P+ treatments left only nitrogen deficient. In the N+ P- and N+ Pn treatments only phosphorus was deficient. Similar evaluations can be made for the other treatments. A close examination of Table 10.10 shows that as a deficiency is removed the index values become more positive. Thus the DRIS index is an indicator of the magnitude of the deficiency. For example, the phosphorus values for the N- P-, N- Pn, N- P+ treatments were -13, 27, and 92. When these values were used in a simple linear regression with the amount of phosphorus supplied in each treatment (P- = 1 .1, Pn = 3.25, P+ = 9.75, Table 10.3), the r^2 value was 0.98. Similar values for the coefficient of determination can be obtained by using data from the literature. Table 10.3 in van den Driessche's (1989) paper on nutrient deficiency lists values for plant N percent, P percent, K percent, dry weight, and level of nutrient supplied (among other things). Because variance was not listed, an arbitrary coefficient of variation of 20 percent was used in the calculation of DRIS indices. When the resulting indices were correlated to the amount of nutrient supplied, the r^2 values were 0.98 for nitrogen, 0.87 for phosphorus, and 1.00 for potassium.

Like many procedures, the advantages and disadvantages of the DRIS method are reflections of one another. The advantages are the results are easy to interpret, variation within the sample is considered, and the results are quantitative. The disadvantages are the amount of calculation required, larger sample sizes are needed, and the calibration of the norm or control group.

DRIS indices are easy to interpret. This is particularly true when the dry matter index is included. More deficient nutrients have a larger, more negative index. Including the variance in the calculation of a DRIS index helps solve the problem of what is statistically valid.

Unlike other methods the results are quantitative and related to the relative abundance of the nutrient in the tissue. This holds true until the nutrient reaches the luxury consumption range. In the comparison experiment the nitrogen levels (N-, Nn and N+) and DRIS indices were compared within each phosphorus treatment. Within the P- treatment the r^2 value for nitrogen level and DRIS index was 0.91. As nitrogen level increased, the DRIS index became more positive. For nitrogen levels within the Pn treatment the r^2 value was 0.67 and was 0.52 for the P+ treatment. The indices showed less change once the plants reached luxury consumption levels of nitrogen. This was most noticeable between the Nn and N+ treatments. A threefold addition of nitrogen did not show a similar change in the DRIS index.

The amount of calculation required may seem the greatest disadvantage. However, the calculations are quick and relatively easy to do using a personal computer and a spreadsheet. Once the spreadsheet is completed, it can be used for other analyses. It is better to do two spreadsheets. One is used for the calculation of the variance for each nutrient expression and one for the calculation of the DRIS indices.

An examination of the DRIS function equations shows that the coefficient of variation is used as a divisor. Because DRIS uses variance in this calculation, larger sample sizes may be required. It is difficult to argue this as a disadvantage. Larger sample sizes virtually always mean more accurate, precise estimates of populations values. From an economic point of view it may be a disadvantage, but from a scientific point of view it is not.

The most frequent criticism of DRIS concerns establishing DRIS norms. From a practical view this is not a problem. DRIS norms can be used as species standards or as a comparison in an experiment. DRIS norms can be established and used as benchmarks against which all other crops of the same species are evaluated. DRIS norms have been established for many crops, including: maize, soybeans, sorghum, potatoes, wheat, rubber, sugarcane, sunflower, alfalfa (Letzsch and Sumner 1983), Populus deltoides

Table 10.10--*Nutrient concentrations, DRIS indices, and yields for the comparison experiment. Nn Pn was arbitrarily chosen as the norm or control treatment. DRIS indices were calculated using the expressions with the highest variance ratios shown in Appendix Table A3.*

					Indices			
Treatment	Tot.DW.	N%	P%	K%	N	P	K	DM
N- P-	1.57	1.14	0.09	0.78	-19	-13	16	16
N- Pn	1.44	1.34	0.20	0.86	-27	27	6	-6
N- P+	1.45	1.27	0.38	0.94	-65	92	-1	-25
Nn P-	1.74	1.77	0.07	0.84	21	-44	18	6
Nn Pn	1.71	1.61	0.13	0.75	0	0	0	0
Nn P+	2.16	1.48	0.21	0.76	-18	30	-6	-6
N+ P-	1.84	2.48	0.07	0.75	57	-56	2	-3
N+ Pn	2.46	1.68	0.10	0.80	7	-16	7	1
N+ P+	2.28	1.59	0.21	0.93	-16	24	7	-14

Table 10.11—*Factors evaluated in the comparison experiment listed in ascending order for each treatment. DRIS indices in Table 10.10 were used to determine rankings. Nn Pn was arbitrarily chosen as the norm or control treatment.*

Treatment	Ranking
N- P-	N <P <DM = K
N- Pn	N < DM < K < P
N- P+	N < DM < K < P
Nn P-	P < DM < K < N
Nn Pn	CONTROL OR NORM
Nn P+	N < DM = K < P
N+ P-	P < DM < K < N
N+ Pn	P < DM < K = N
N+ P+	N < DM < K < P

Table 10.12—*DRIS indices and nutrient ranking for the comparison experiment. In this comparison, the group with the highest total dry weight (N+ Pn) was designated as the norm or control group.*

	DRIS Indices				
Treatment	N	P	K	DM	Ranking
N- P-	-28	8	9	12	N <P < K < DM
N- Pn	-47	68	-7	-14	N <DM < K < P
N- P+	-110	182	-26	-46	N <DM < K < P
Nn P-	9	-19	8	2	P<DM<K<N
Nn Pn	-9	21	-10	-3	K<N<DM<P
Nn P+	-36	73	-22	-15	N<K<DM<P
N+ P-	45	-35	-8	-2	P < K < DM < N
N+ Pn	0	0	0	0	CONTROL OR NORM
N+ P+	-33	61	-6	-21	N < DM < K < P

(Leech and Kim 1981, Kim and Leech 1986), and *Pinus radiata* (Svenson and Kimberly 1988). Some of these norms have been established using worldwide databanks and are remarkably uniform throughout the world. While the developing this sort of norm is an admirable goal, it is not required for the use of DRIS on a individual nursery basis. However, if the experience gained with other crops is an indication of what could be expected with trees, then the norms could be established fairly quickly.

At the beginning of the comparison experiment it was decided to use the Nn Pn plants as the control or norm. These plants did not produce the greatest dry matter. An examination of the dry weight data in Table 10.10 shows that while Nn Pn treatment averaged 1.71 grams, the N+ Pn treatment averaged 2.46 grams. Table 10.12 was done after the DRIS norm was changed from Nn Pn to N+ Pn. A comparison of the relative rankings of the data in Tables 10.11 and 10.12 shows that very few were altered by this change. None of the changes are substantial enough to have caused a change in the prescription to correct deficiencies. The major change that redesignating the norm group brings about is a comparison of the previous norm group becomes possible (see Nn Pn data in Tables 10.11 and 10.12).

10.5.3.3 Construction and application of DRIS charts

The mathematical approach in the preceding section is more complicated than many people would like. The DRIS chart is a simpler, less accurate, alternative method that is somewhat easier to develop. This alternative is successful if no more than three or four factors are being evaluated. Beyond that the charts become difficult to read. More than four factors will require the use of DRIS indices.

DRIS charts consist of an axis for each nutrient ratio and two concentric circles (Figure 10.10). The diameter of the inner circle is set at the mean plus and minus 4/3 times the standard deviation of the norm or control group. Likewise the outer circle diameter is mean plus and minus 8/3 standard deviation (Table 10.13). Plants in a treatment are considered to have balanced nutrition if the ratio falls within the inner circle. If the ratio falls between the two circles there is a moderate imbalance and beyond the outer circle is considered to indicate marked imbalance (Walworth and Sumner 1987). When conflicting answers are obtained in two subsections it is considered to indicate a slight to moderate imbalance. By convention only insufficiencies are recorded during the analysis. The rationale for this convention is that in terms of balance, a deficiency in one element corresponds to an excess of the other element in the ratio. A comparison of the N- P- treatment (Table 10.14) to the graph in Figure 10.10 would be done as follows:

1) The ratio of N/P was 12.67 which is within the inner circle (N → P →).

2) K/N was 0.68 which is between the two circles (N ↘ K ↗).

3) For K/P the ratio was 8.67 which is also between the two circles (P ↘ K ↗). At this point there should be an arrow by each element. If this is not the case, then a horizontal arrow is placed next to the element without an arrow. At the end of this analysis, the individual steps are added together. If a horizontal and a diagonal or vertical arrow are shown for a given element, then the horizontal arrow is discarded. If there are two vertical or diagonal arrows, they are retained to indicate greater magnitude. For the above analysis, N has ↗ arrows, P has →↘ arrows and K has ↑↑ arrows. The summary statement would be N ↘ P ↘ K ↗.

4) The interpretation for this treatment is N = P < K. Nitrogen and phosphorus are more limiting than potassium.

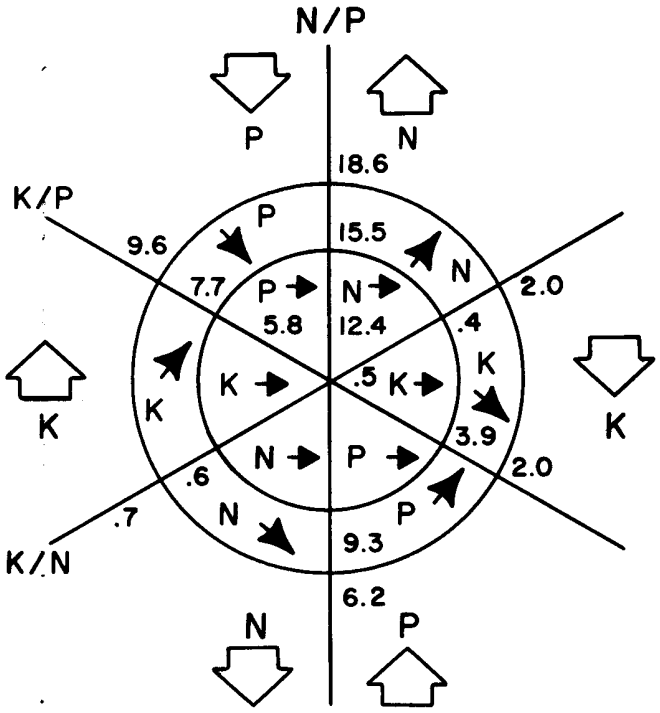

Figure 10.10—*DRIS chart for qualitative determination of nitrogen, phosphorus and potassium requirements of plants in the comparison experiment (see Table 10.13). Seedlings in the Nn Pn treatment were used as norms. Values for the N/P line as displayed from top to bottom were 18.6, 15.5, 12.4, 9.3, and 6.2. The mean value for the Nn Pn treatment was 12.4. Values greater than 9.3 and less than 15.5 (inner circle) were considered normal. Values less than 9.3 and greater than 6.2, or greater than 15.5 and less than 18.6 (area between the two circles) represented a moderate imbalance in the N/P ratio. Values greater than 18.6 or less than 6.2 represented a marked imbalance in the N/P ratio. Similar interpretations can be done with K/P and K/N. (Adapted from Sumner 1982.)*

This does not mean that nitrogen and phosphorus are certain to be deficient. Rather this gives a relative ranking for the nutrients in the study, the answer being that nitrogen and phosphorus are more limiting than is potassium. More extensive discussions on the preparation of DRIS charts can be found in Sumner (1982) and Walworth and Sumner (1987).

DRIS charts have the advantage of being easily prepared and quickly interpreted. There are three disadvantages. If the sample size is small, the standard deviation will tend to be large and most of the values will fall within the inner circle. Although there may be some indication of relative abundance, the information will be less useful than that from the DRIS indices. Second, the method is not quantitative. The rankings are strictly relative and do not indicate more than general magnitude of deficiency.

Table 10.13—*Means, standard deviations, and circle diameter sizes used to draw DRIS chart using Nn Pn as the control or norm (see Figure 10.10). Circle diameters were set at the mean plus and minus 4/3 standard deviation for the inner circle and mean plus and minus 8/3 standard deviation for the outer circle.*

			Inner circle		Outer circle	
Ratio	Mean	s	+	-	+	-
N/P	12.38	2.33	15.5	9.3	18.6	6.2
K/N	0.47	0.09	0.6	0.4	0.7	0.2
K/P	5.77	1.43	7.7	3.9	9.6	2.0

Table 10.14—*Values for nutrient ratios for each of the treatments in the comparison experiment.*

Treatment	N/P	K/N	K/P
N- P-	12.67	0.68	8.67
N- Pn	6.70	0.64	4.30
N- P+	3.34	0.74	2.47
Nn P-	25.29	0.48	12.00
Nn Pn	12.38	0.47	5.77
Nn P+	7.05	0.51	3.62
N+ P-	35.43	0.30	10.71
N+ Pn	16.80	0.48	8.00
N+ P+	7.57	0.59	4.43

In contrast, the absolute size of a DRIS index is a good indication of how abundant or lacking a nutrient is within a given system. Finally, the means and standard deviations still have to be calculated. The hard work has been done. If a spreadsheet is being used to analyze the experiment, then the calculation of the indices is faster than the construction of the DRIS chart.

10.6 Conclusions

Both vector analysis and DRIS are improvements over the use of critical nutrient concentrations. Both simplify the process of gathering and interpreting the information. Either method gives a clear, unambiguous answer to the question, "What is wrong with my trees?" The authors of this paper prefer DRIS because of the more quantitative nature of the information. It is very likely that others will dislike DRIS for exactly the same reason.

The real problem with nutrient analysis has not been brought up and will not (cannot) be answered in this paper. Vector analysis and DRIS both require a control against which other trees can be evaluated. Analysis is a simple problem. The real challenge is in defining the perfect tree which is to serve as the control. Table 10.15 illustrates the problem. This is the result of a DRIS analysis that used the treatment with maximum root growth capacity as the norm. A comparison of Table 10.15 to Tables 10.11 and 10.12 highlights the problem. In Tables 10.11 and 10.12, nitrogen is shown as the most deficient nutrient five out of eight times. In contrast, phosphorus is shown as most deficient five out of eight times in Table 10.15. Note the effect of phosphorus on root growth capacity. Within each nitrogen grouping as phosphorus increases, so does root growth capacity. This would seem to indicate that if the goal is greater root growth, then more phosphorus needs to be added. In contrast, if maximum biomass is the goal, then more nitrogen will be required.

Defining the perfect tree is a rubber cookie question. The perfect tree is conditional. Preparing a tree for some field conditions might require a high root growth capacity, or height, or caliper, or frost tolerance, or—? Most of these goals are conflicting. The nutrient prescription for one goal will not meet another goal. Furthermore, the prescription will differ by nursery and species. It seems likely that the perfect tree will be defined as a combination of goals. The norm against which other trees are compared will reflect this combination. A procedure like DRIS or vector analysis would work as well with an arbitrary tree score. This score might be defined as 40 percent height, 30 percent caliper, 20 percent root growth capacity, and 10 percent frost tolerance. A tree score would be adaptable to different nurseries and field conditions. Using the principles of nutrient analysis can help reach the goals implicit in the definition of the perfect tree.

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Table 10.15—*DRIS indices and nutrient ranking for the comparison experiment. The group with the highest root growth capacity (N+ P+) was chosen as the norm or control group. RGC 4 is the root growth capacity (cm) measured after four weeks growing time.*

	DRIS Indices					
Treatment	N	P	K	DM	Ranking	RGC 4
N- P-	-8	-39	17	29	P < N < K < DM	29
N- Pn	-10	2	1	7	N <K < P < DM	81
N- P+	-31	42	-7	-4	N <K < DM < P	95
Nn P-	36	-77	21	21	P<DM=K<N	47
Nn Pn	16	-21	-8	13	P<K<DM<N	101
Nn P+	1	6	-14	7	K<N<P<DM	160
N+ P-	88	-96	-6	15	P<K<DM<N	43
N+ Pn	24	-46	5	16	P<K<DM<N	128
N+ P+	0	0	0	0	CONTROL OR NORM	165

Appendix Table A1—*Results of the comparison experiment used in the construction of Figure 10.7. Content was determined by evaluating the nitrogen content of the leaves on the plant. Concentration is the percent nutrient contained in all needles. The lower fertility treatment was considered the control and had a relative value of 100 % concentration and 100% content. The relative values for the N+ Pn treatment were calculated by dividing the N+ Pn value by the N-P- value and multiplying b y 100. For example, relative N content was 14.93 / 4.80 * 100 = 311, which means the nitrogen content of the N+ Pn plants was 311 % of N- P- plants. The total dry weight of the N- P-plants was 1.57 g and that of the N+ Pn plants was 2.46. This gives a relative plant weight value of 157 for the N+ Pn treatment (see Figure 10.7)*

	N-P-		N+Pn	
	Concentration	Content	Concentration	Content
Nitrogen	1014	4.80	1.68	14.93
Phosphorus	0.09	0.39	0.10	0.87
Potassium	0.78	3.33	0.80	7.24
Relative N	100	100	147	311
Relative P	100	100	111	223
Relative K	100	100	103	217

Appendix Table A2—Raw *data, treatment means and standard deviations (s.d.) for N%, P% and K% from the December harvest of the comparison experiment. Only the N- P- and Nn Pn treatments are listed.*

	N- P-			Nn Pn		
	N%	P%	K%	N%	P%	K%
	1.11	0.10	0.67	1.55	0.10	0.75
	1.17	0.14	0.83	1.35	0.12	0.87
	1.00	0.10	0.92	1.77	0.13	0.60
	1.00	0.11	0.64	1.35	0.09	0.75
	0.99	0.10	1.02	1.55	0.14	0.87
	0.91	0.08	0.81	1.59	0.17	0.74
	1.24	0.08	0.63	2.01	0.17	0.85
	1.75	0.07	0.86	1.64	0.11	0.68
	1.06	0.05	0.67	1.73	0.13	0.67
	1.20	0.08	0.71	1.53	0.09	0.69
mean	1.14	0.78	0.78	1.61	0.13	0.75
s.d.	0.238	0.025	0.133	0.197	0.029	0.092

Appendix Table A3—*Determination of variance ratios for the different ways of expressing DRIS ratios. Data is for the December harvest of the comparison experiment and only the N- P- and Nn Pn treatments have been used. The variance ratio is calculated by squaring the standard deviation (s.d.) for each treatment and then dividing. Expressions with the highest variance ratios are marked with an asterisk. All expressions are in concentration (percent), which are derived by dividing nutrient content by dry weight.*

Form of	N- P-		Nn Pn		Variance Ratio
expression	mean	s.d.	mean	s.d.	(N-P-)/(Nn Pn)
N	1.14	0.238	1.61	0.197	1.46
1/N	0.88	0.148	0.62	0.076	3.79*
N*DW	1.97	0.351	2.59	0.330	1.31
P	0.09	0.025	0.13	0.029	0.74
1/P	11.11	4.116	7.69	1.910	4.64*
P*DW	0.12	0.033	0.16	0.039	0.716
K	0.78	0.133	0.75	0.092	2.09
1/K	1.28	0.215	1.33	0.173	1.54
K*DW	1.02	0.181	0.95	0.142	1.63
N/P	12.67	5.815	12.38	2.329	6.23*
P/N	0.08	0.027	0.08	0.015	3.24
NP	0.10	0.030	0.21	0.067	0.20
P/K	0.12	0.035	0.17	0.040	0.77
K/P	8.67	2.826	5.77	1.438	3.86*
PK	0.07	0.026	0.10	0.028	0.86
N/K	1.46	0.361	2.15	0.420	0.74
K/N	0.68	0.184	0.47	0.093	3.91*
NK	0.89	0.25	01.21	0.207	1.46

Appendix Table A4—*Calculation of DRIS functions for the comparison experiment. In the following equations, N/P is the nitrogen/phosphorus ratio in the N- P- treatment; n/p is the nitrogen/phosphorus ratio in the Nn Pn treatment, and cv is the coefficient of variation for the Nn Pn treatment. By convention, the treatment being used as the DRIS norm (control) is denoted by lowercase letters. The cv was calculated by dividing the standard deviation by the mean and multiplying by 100. Means and standard deviations are from Appendix Table A2.*

DRIS functions are calculated by the formula:

$$f(N/P) = \frac{N/P}{n/p} - 1 \; \frac{1000}{cv}$$ when N/P is greater than n/p and by:

$$f(N/P) = 1 - \frac{n/p}{N/P} \; \frac{1000}{cv}$$ when n/p is greater than N/P.

Other nutrient ratios are done in the same manner.

N/P (cv) = 2.329/12.38 * 100 = 18.81
K/P (cv) = 1.438/5.77 * 100 = 24.92
K/N (cv) = 0.093/0.47 * 100 = 19.79
1/N (cv) = 0.076/0.62 * 100 = 12.26
1/P (cv) = 1.910/7.69 * 100 = 24.84
K (cv) = 0.092/0.75 * 100 = 12.27

f (N/P) = ((12.67/12.38) -1) * 1000/18.81 = 1.2
f (K/P) = ((8.67 / 5.77) - 1) * 1000 / 24.92 = 20.2
f (K/N) = ((0.68 / 0.47) - 1) * 1000 / 19.79 = 22.6
f (1/N) = ((0.88 / 0.62) - 1) * 1000 / 12.26 = 34.2
f (l/P) = ((11.11 / 7.69)- 1) * 1000 / 24.84 = 17.9
f (K) = ((0.78 / 0.75) - 1) * 1000 / 12.27 = 3.3

Appendix Table A5—*Calculation of DRIS indices for the comparison experiment. A DRIS index is calculated by adding all of the functions that contain the element being evaluated and dividing by the number of functions used. The N index was calculated by adding f (N/P), f (K/N) and f (1/N%) and dividing by 3. By convention, a minus sign is given to the function if the element being evaluated appears in the bottom of the ratio fraction. Values of DRIS functions are from Appendix Table A3.*

$$\text{N index} = \frac{f(N/P) - f(K/N) - f(1/N\%)}{3} = \frac{1.2 - 22.6 - 34.2}{3} = -19$$

$$\text{P index} = \frac{-f(N/P) - f(K/P) - f(1/P\%)}{3} = \frac{-1.2 - 20.2 - 17.9}{3} = -13$$

$$\text{K index} = \frac{f(K/P) + f(K/N) + f(K\%)}{3} = \frac{20.2 + 22.6 + 3.3}{3} = 16$$

$$\text{DM index} = \frac{f(1/N\%) + f(1/P\%) - f(K\%)}{3} = \frac{34.2 + 17.9 - 3.3}{3} = 16$$

Any element with an index more negative than the Dry Matter (DM) index would be considered to be deficient. In the above comparison (N- P- to Nn Pn), nitrogen was most limiting. Phosphorus was nearly as deficient, while potassium was not limiting.

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