

Diagnosis and Interpretation of Forest Stand Nutrient Status

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ABSTRACT. Methods of evaluating forest stand nutrient status are discussed in the first part of the chapter. The various nutritional assessment techniques such as identification of visual symptoms, foliar analysis, pot culture tests, soil analysis, and fertilizer trials are compared with particular reference to the literature. Foliar analysis, in combination with information on site quality and stand growth performance, is suggested as the most suitable technique for assessing forest stand nutrient status. The importance of regional experience and knowledge of site and stand-specific variation in stand nutrition and interpretive criteria is stressed.

Assessment of forest stand nutrient status can have both practical and scientific value. Approaches in common use include: (1) identification of visual symptoms, (2) foliar analysis, (3) soil analysis, (4) pot culture techniques, (5) inference through site and stand characteristics, and (6) fertilizer trials. Considerations involved in choosing the appropriate diagnostic approach, by weighing the strengths and weaknesses of the various methods, have been discussed in several review papers, manuals, and textbooks (Morrison 1974; Mengel and Kirby 1982; Ballard and Carter 1986; Bowen and Nambiar 1984; Marschner 1986; van den Dreissche 1991). This chapter provides a brief review for land managers of the major subject areas within the broad theme of assessing forest stand nutrient status.

Diagnostic and Predictive Methods

Diagnosis of deficiencies generally involves identification of factors influencing growth. Predictive methods provide information that can be used to forecast growth response(s) to changes in growing condition (i.e., fertilization, site preparation techniques, etc.) (Morrison 1974). The following sections will introduce six general diagnostic approaches and provide a brief review of the literature.

Visual Symptoms

Diagnosis through visual symptoms uses field observations of anatomical and morphological abnormalities to identify nutrient deficiencies. The method is appealing because it is simple and laboratory facilities are not required. However, although needles appear to be particularly sensitive indicators of deficiency, not all deficiencies exhibit distinctive symptoms (e.g., chlorosis might occur as a result of nitrogen deficiency, sulfur deficiency, or poor health due to pathogen activity). An absence of visual symptoms does not necessarily mean that deficiencies are not present: nutrient deficiencies severe enough to impair growth are not always severe enough to produce visible symptoms (Ballard and Carter 1986). And visual symptoms may be misleading: foliar abnormalities can also be produced by physiological stress, pathogens, insects, and herbicides—although these causes are often readily identifiable. Visual symptoms caused by nutrient limitations are generally somewhat evenly dispersed throughout the stand, while symptoms of a nonnutritional nature are often found on individual trees or in clumps of trees (e.g., chlorosis of individual trees due to *Armillaria mellea* infection; poor foliage retention in individuals or clumps of trees due to *Phellinus weirii* infection). Visual symptoms should be considered a useful first indicator of nutritional disorders.

Color pictures illustrating common visual symptoms of nutrient deficiencies in forest crops can be found in Benzian (1965), Bengtson (1968), Baule and Fricker (1970), Morrison (1974), Kolari (1979), Will (1985), Ballard

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and Carter (1986), van den Driessche (1989, 1991), and Walker and Gessel (1991).

Foliar Analysis

Foliar analysis provides an index of the amount of nutrients actually taken up by the tree. At present, foliar analysis is most useful for identifying severely deficient nutrients, though it can be used to identify certain incipient deficiencies and nutrient interrelationships.

The methods recommended for routine foliar analysis are outlined in detail in Morrison (1974), Ballard (1985), and Ballard and Carter (1986). For routine operational use, the methods recommended in Ballard and Carter (1986) should give an adequate measure of forest stand nutrient status. Several studies have examined seasonal and spatial variability of nutrient elements in foliage; they have generally concluded that between 10 and 30 trees per stand should be sampled depending on the nutrient(s) of interest. Samples of the current year's foliage should be collected from open grown foliage located in the upper half or third of the live crown. Ballard and Carter (1986) recommend not sampling the upper two to three branch whorls. The following references provide further information on sampling considerations:

Crown position	Lavender and Carmichael (1966), Morrison (1974), White and Jokela (1980), MacLean and Robertson (1981)
Foliage age	Wells and Metz (1963), Lavender (1970), Lowry (1970), Morrison (1974), White and Jokela (1980)
Collection technique	Robinson and Freeman (1967), Turner et al. (1978), White and Jokela (1980)
Sample size and between-tree variation	Wells (1968, 1969), Lowry and Avard (1969), Lavender (1970), Everard (1973), Bickelhaupt et al. (1979), van den Driessche (1981), Ballard (1981), Richter (1983)

Of the several approaches widely employed in evaluating foliar chemical data, the most common is the use of critical levels. This method compares the concentration of each element in the foliage to interpretive criteria normally developed from fertilizer and/or pot trials. "Critical level" is generally defined in the agricultural literature as the nutrient concentration that is just deficient for maximum growth, although "the lowest

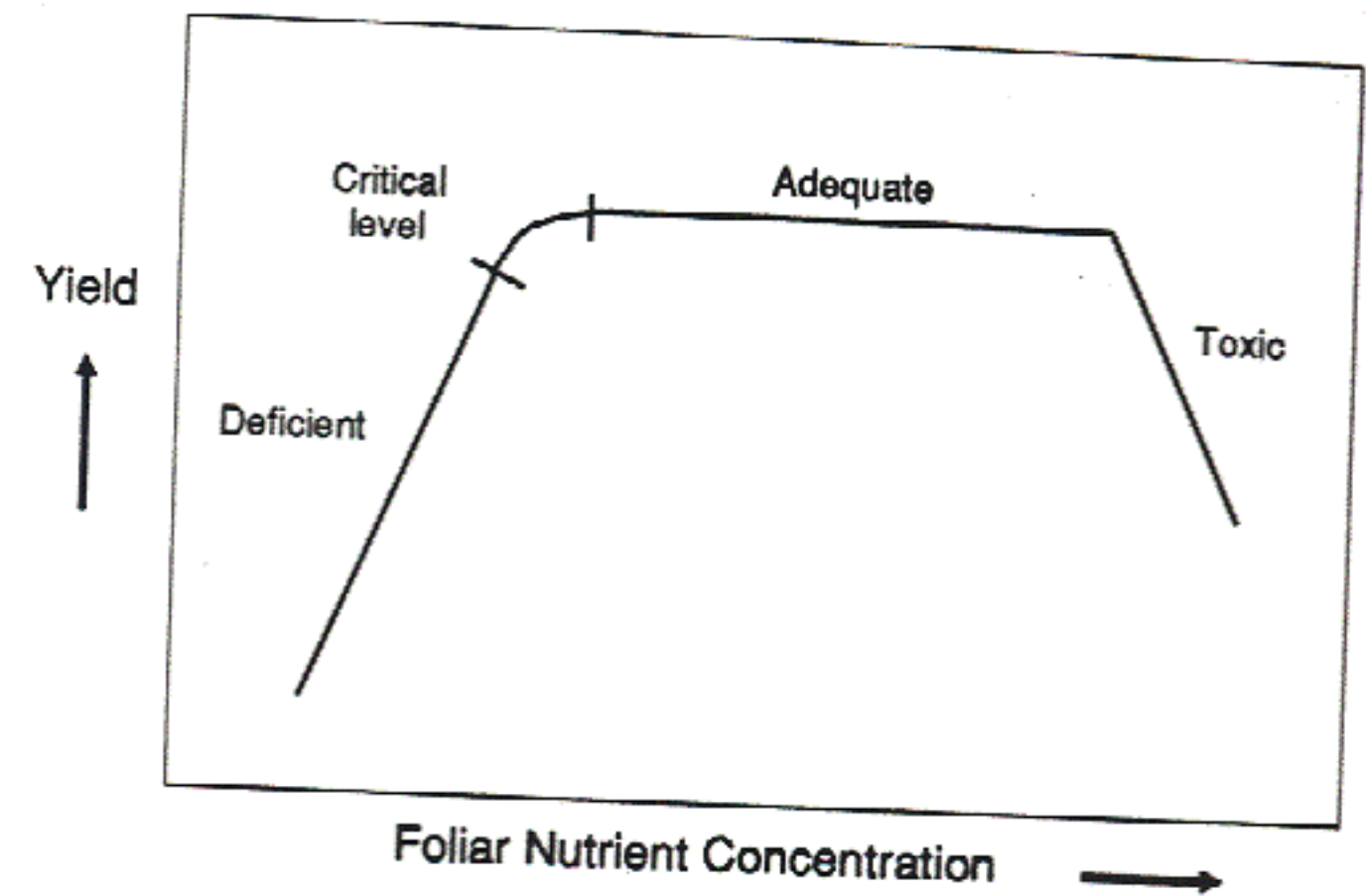


Figure 1. Relationship between foliar nutrient concentration and productivity, showing the proposed critical level range.

concentration of a nutrient accompanying the highest yield" and "the nutrient concentration where growth is 10% less than maximum" are also quite common definitions (Tisdale et al. 1985; Figure 1).

Foliar analysis is very popular but somewhat simplistic for the following reasons: (1) interpretative data are associated with considerable imprecision; (2) foliage samples collected at the end of the growing season may not accurately reflect nutrient status during the growing season, particularly for nutrient elements such as boron that are subject to periodic, acute deficiencies; and (3) interpretations cannot stand alone, but must be related to stand growth performance and site ecological characteristics, since tree nutrient requirements and allocation strategies change with site ecological conditions (e.g., the availability of solar radiation, moisture, and other nutrient elements).

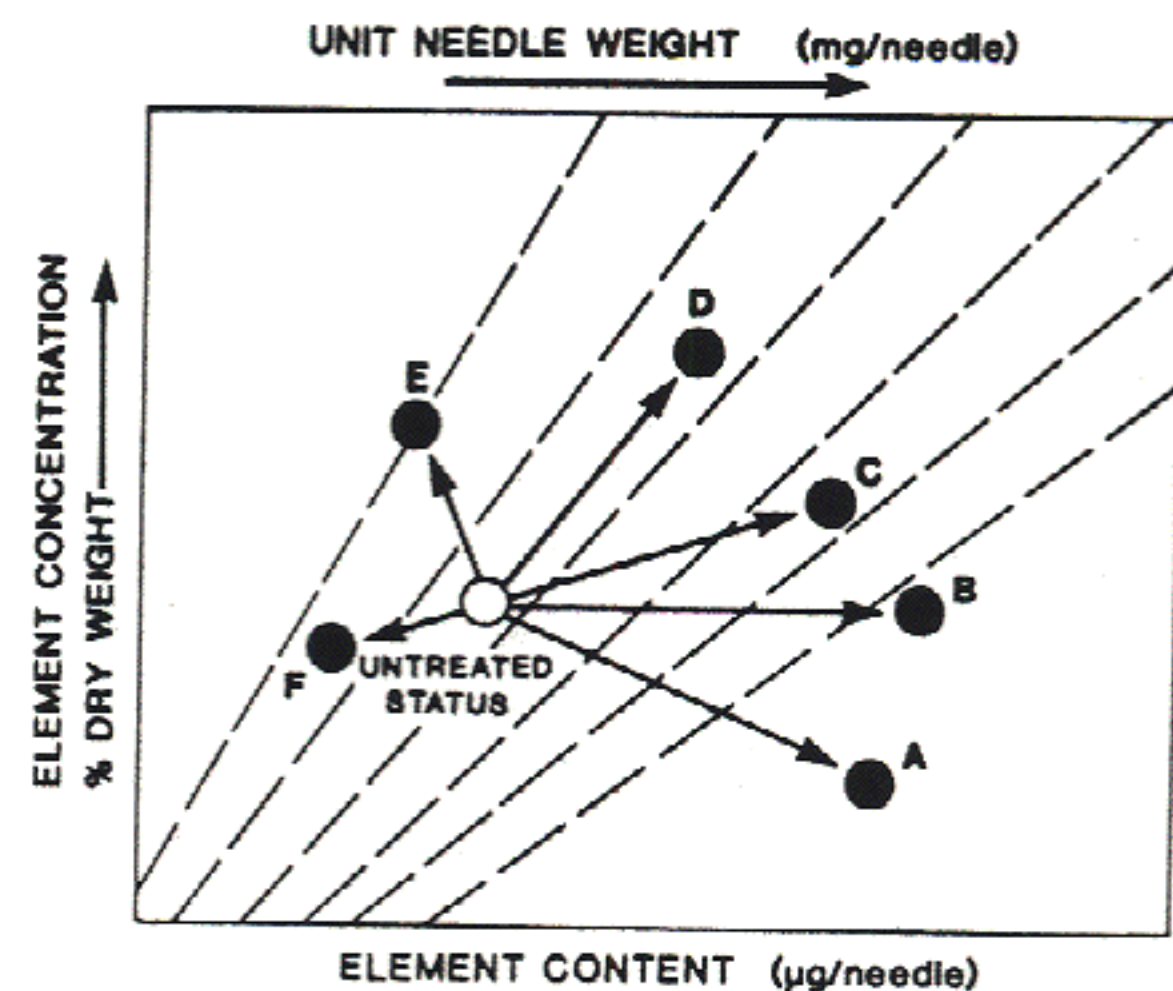
Approximate critical levels, modified from Ballard and Carter (1986), for each nutrient element are provided for five commercial coniferous species of the Pacific Northwest in Tables 1 and 2. Several alternative approaches currently gaining popularity examine critical nutrient ratios and interrelationships. The most common of these methods are the approach of Ingstad (1971) and the Diagnosis and Recommendation Integrated System (DRIS) of Beaufils (1973) (cf. Schutz and de Villiers 1988; Carter and Klinka 1988; Hockman and Allen 1990). The central theme in these techniques is that it is not the absolute concentration or content of each nutrient that is important but the proportion of each nutrient in relation to the other nutrients. Since both Ingstad's method and DRIS are still being examined experimentally and reliable standards have not been developed for conifer species of the Pacific Northwest, they are not recommended for routine operational use.

Table 1—Interpretation of macronutrient concentrations in current year's foliage of five commercial conifer species of the Pacific Northwest. Modified from Ballard and Carter (1986).

Element	Interpretation	Foliar Concentration (% dry mass basis)				
		Douglas-fir	Lodgepole pine	Western hemlock	White spruce	Western redcedar
Nitrogen	Very severely deficient	< 1.00	< 1.00	< 1.00	< 1.05	< 1.10
	Moderate to severe deficiency	1.00-1.20	1.00-1.15	1.00-1.20	1.05-1.25	1.10-1.30
	Slight to moderate deficiency	1.20-1.35	1.15-1.35	1.20-1.35	1.25-1.45	1.30-1.45
	Adequate	> 1.35	> 1.35	> 1.35	> 1.45	> 1.45
Phosphorus	Severely deficient	< 0.08	< 0.09	< 0.11	< 0.10	< 0.10
	Moderately deficient	0.08-0.10	0.09-0.12	0.11-0.15	0.10-0.14	0.10-0.13
	Slightly deficient	0.10-0.15	0.12-0.15	0.15-0.25	0.14-0.16	0.13-0.16
	Adequate	> 0.15	> 0.15	> 0.25	> 0.16	> 0.16
Potassium	Very severely deficient	< 0.35	< 0.35	< 0.40	< 0.25	< 0.35
	Moderate to severe deficiency	0.35-0.45	0.35-0.40	0.40-0.45	0.25-0.30	0.35-0.40
	Slight to moderate deficiency	0.45-0.65	0.40-0.55	0.45-0.65	0.30-0.50	0.40-0.80
	Adequate	> 0.65	> 0.55	> 0.65	> 0.50	> 0.80
Calcium	Severely deficient	< 0.15	< 0.06	< 0.06	< 0.10	< 0.10
	Moderate to severe deficiency	0.15-0.20	0.06-0.08	0.06-0.08	0.10-0.15	0.10-0.20
	Slight to moderate deficiency	0.20-0.25	0.08-0.10	0.08-0.10	0.15-0.20	0.20-0.25
	Adequate	> 0.25	> 0.10	> 0.10	> 0.20	> 0.25
Magnesium	Severely deficient	< 0.06	< 0.06	< 0.06	< 0.05	< 0.05
	Moderate to severe deficiency	0.06-0.09	0.06-0.08	0.06-0.08	0.05-0.08	0.05-0.09
	Slight to moderate deficiency	0.09-0.12	0.08-0.10	0.08-0.10	0.08-0.12	0.09-0.14
	Adequate	> 0.12	> 0.10	> 0.10	> 0.12	> 0.14

Graphical analysis, which examines relationships between foliar nutrient contents and concentrations, is also becoming a common diagnostic tool, although primarily as a method for assessing the effects of different silvicultural treatments on foliar nutrient levels (Timmer and Stone 1978; Timmer and Morrow 1984; Weetman and Fournier 1986a, 1986b; Timmer and Ray 1988). Graphical analysis facilitates interpretation of foliar nutrient status by identifying examples of dilution, sufficiency, deficiency, luxury consumption, and possible antagonism as a result of treatment (particularly fertilization) (Timmer and Ray 1988). Diagnostic interpretations assume a close correlation between needle weight and stemwood production in trees. Relative responses in element concentration (y-variable) and absolute content (x-variable) of foliage are plotted against gain or loss in needle mass (Timmer and Ray 1988). If nutrients are set on a common base (i.e., control set equal to 1), the response of different nutrients or stands can be compared simultaneously. Interpretations are based on the origin and magnitude of each response vector (Figure 2). The degree of responsiveness of added nutrients corresponds to the relative size of its vector.

Analyses suggested for routine evaluation of foliage samples generally include total nitrogen (N), phospho-



DIRECTION OF SHIFT	RESPONSE IN			CHANGE IN	
	NEEDLE WEIGHT	NUTRIENT CONC.	NUTRIENT CONTENT	NUTRIENT STATUS	POSSIBLE DIAGNOSIS
A	+	-	+	DILUTION	NON-LIMITING
B	+	0	+	UNCHANGED	NON-LIMITING
C	+	+	+	DEFICIENCY	LIMITING
D	0	+	+	LUXURY CONSUMPTION	NON-TOXIC
E	-	++	±	EXCESS	TOXIC
F	-	-	-	EXCESS	ANTAGONISTIC

Figure 2. Schematic relationships between nutrient concentration, nutrient content, and dry weight of needles following fertilization. From Timmer and Ray (1988).

Table 2—Interpretation of micronutrient concentrations in current year's foliage.¹ Modified from Ballard and Carter (1986).

Element	Foliar Concentration (ppm, dry mass basis) and Interpretation	
Manganese	< 4	Severe deficiency
	4-15	Probable deficiency
	15-25	Possible deficiency or near-deficiency
	> 25	No deficiency
Iron	< 25	Deficiency likely
	25-50	Possible deficiency
	> 50	Low probability of deficiency
Zinc	< 10	Probable deficiency
	10-15	Possible deficiency
	> 15	No deficiency
Copper	< 1	Probable deficiency
	1-2	Possible moderate deficiency
	2-3	Possible deficiency
	> 3	No deficiency
Boron	< 5	Deficiency likely
	5-12	Possible deficiency ²
	12-20	Boron likely not deficient ²
	> 20	No deficiency
Molybdenum	< 0.1	Possible deficiency
	> 0.1	No deficiency

¹These interpretations are not yet species specific.

²A boron deficiency may be inducible by nitrogen fertilizer application.

rus (P), potassium (K), calcium (Ca), magnesium (Mg), sulfur (S), sulfate-S ($\text{SO}_4\text{-S}$), copper (Cu), zinc (Zn), iron (Fe), manganese (Mn), and boron (B). Considerations involved in selecting a reputable laboratory and analytical methods are given in Ballard and Carter (1986).

Pot Trials

The techniques that fall into this category are known variously as pot cultures, soil cultures, greenhouse trials, biological assays, and bioassays. In general, these methods attempt to assess the productive potential of soils using test organisms—usually seedlings. Pot trials can be used to determine whether a particular species receives an adequate supply of nutrients from a soil. They can also be used to determine the nutritional requirements of a tree species by controlling the concentration of single elements from otherwise complete solutions.

The primary shortcoming of pot trial techniques is in relating results found for seedlings in the laboratory, or greenhouse, to natural environments and mature

trees. Nutrient requirements change with soil and air temperature, humidity, soil moisture availability, and the period of tree and stand development. The usefulness of pot trials depends on the degree of correlation between pot diagnoses and field trials (Morrison 1974). Consequently pot trials should be regarded as a research tool.

Examples of pot trial approaches in conifers can be found in Walker et al. (1955), Youngberg and Dyrness (1965), Swan (1966), Will and Knight (1968), Mead and Pritchett (1971), and Ingestad (1982).

Soil Analysis

Soil analysis is widely used in both forestry and agriculture. There are many analytical techniques used in nutritional evaluations, most of which are both time and cost intensive. Common methods used for forest stand nutrient status evaluation are reviewed in Binkley (1986) and Ballard and Carter (1986).

Soil analyses will probably be restricted to research rather than routine diagnostic applications for at least the near future. Five principal reasons are: (1) the costs of soil sampling and analysis are often prohibitive; (2) the extreme variability of forest soils may require an excessive number of samples to provide a representative sample; (3) decisions as to which part of the soil to sample (i.e., specified depths versus named horizons) are difficult and can rarely be standardized; (4) relationships between soil properties and growth and/or growth response tend to have poor portability outside the range in which they were developed; and (5) few empirical relationships have been developed between soil physical and chemical properties and the nutritional status and/or response to fertilization of forest stands in the Pacific Northwest.

Some of the most promising empirical relationships developed to date have involved the study of nitrogen mineralization using both anaerobic and aerobic incubation of soils either *in situ* or in the laboratory. Several studies have shown relationships between mineralizable N incubated in an anaerobic environment and response to nitrogen fertilization (Shumway and Atkinson 1978; Powers 1980; Miller et al. 1989). Peterson et al. (1984) found correlations between response to additions of urea and the C:N ratio of the forest floor and mineral soil in unthinned stands of Douglas-fir and the nitrogen content of the forest floor in thinned stands. Miller et al. (1989) and Carter et al. (1992) examined the results of Shumway and Atkinson (1978), Powers (1980), and Peterson et al. (1984) using data from an independent set of stands and found considerably

weaker relationships between fertilizer response and either C:N ratio or mineralizable N—again suggesting poor portability of these empirical relationships. Radwan and Shumway (1983) found extractable P was able to give a good response prediction for nitrogen fertilization of western hemlock (*Tsuga heterophylla*). Blake (1985) and Blake et al. (1988) found soil sulfate-sulfur to be a useful indicator of growth responses of nitrogen-fertilized Douglas-fir to additions of sulfur. These results were found to be considerably weaker for fertilized immature Douglas-fir stands in coastal British Columbia (Carter et al. 1992). Empirical relationships between soil tests for other elements and treatment response for tree species found outside the Pacific Northwest are reviewed by Binkley (1986).

Inference Through Site and Stand Characteristics

Integrated ecological approaches to developing and testing possible relationships between soil and site characteristics, site productivity, and response to fertilization are presented in Carter and Klinka (1988), Miller et al. (1989), Klinka and Carter (1990), Carter et al. (1992), and Carter and Klinka (1992). These studies suggest that knowledge of site quality assessed either directly through measures of productivity or indirectly through ecological site classification, possibly in combination with foliar analysis, affords the best opportunity of assessing future growth response to fertilization. (See the equations below and Figure 3.)

Coastal Douglas-fir individual-tree relative three-year basal area response to N fertilization (225 kg N/ha):

$$\%BA_{\text{response}} = 239.5 - 3.69 * (\text{Site index}) \quad (1)$$

$$R^2 = 0.55 \quad \text{S.E.E.} = 16.8$$

$$\%BA_{\text{response}} = 274.0 - 2.67 * (\text{Site index}) - 52.0 * (\text{Foliar N concentration}) \quad (2)$$

$$R^2 = 0.63 \quad \text{S.E.E.} = 16.2$$

The Pacific Northwest may be unique in that one nutrient element—nitrogen—appears to be the dominant element limiting growth. As a result, several studies have shown strong relationships between site index and response to nitrogen fertilization in the Pacific Northwest, particularly for coastal Douglas-fir (Miller et al. 1986; Godfrey 1986; Miller et al. 1989; Carter et al. 1992). Ecological strata at the level of "site association" in the biogeoclimatic ecosystem classification practiced in British Columbia (similar to habitat type in the Pacific Northwest) have also been shown to have high predictive utility (Carter et al. 1992). These inferred relationships appear to have good portability, require little expertise or expense, and are easily incorporated into

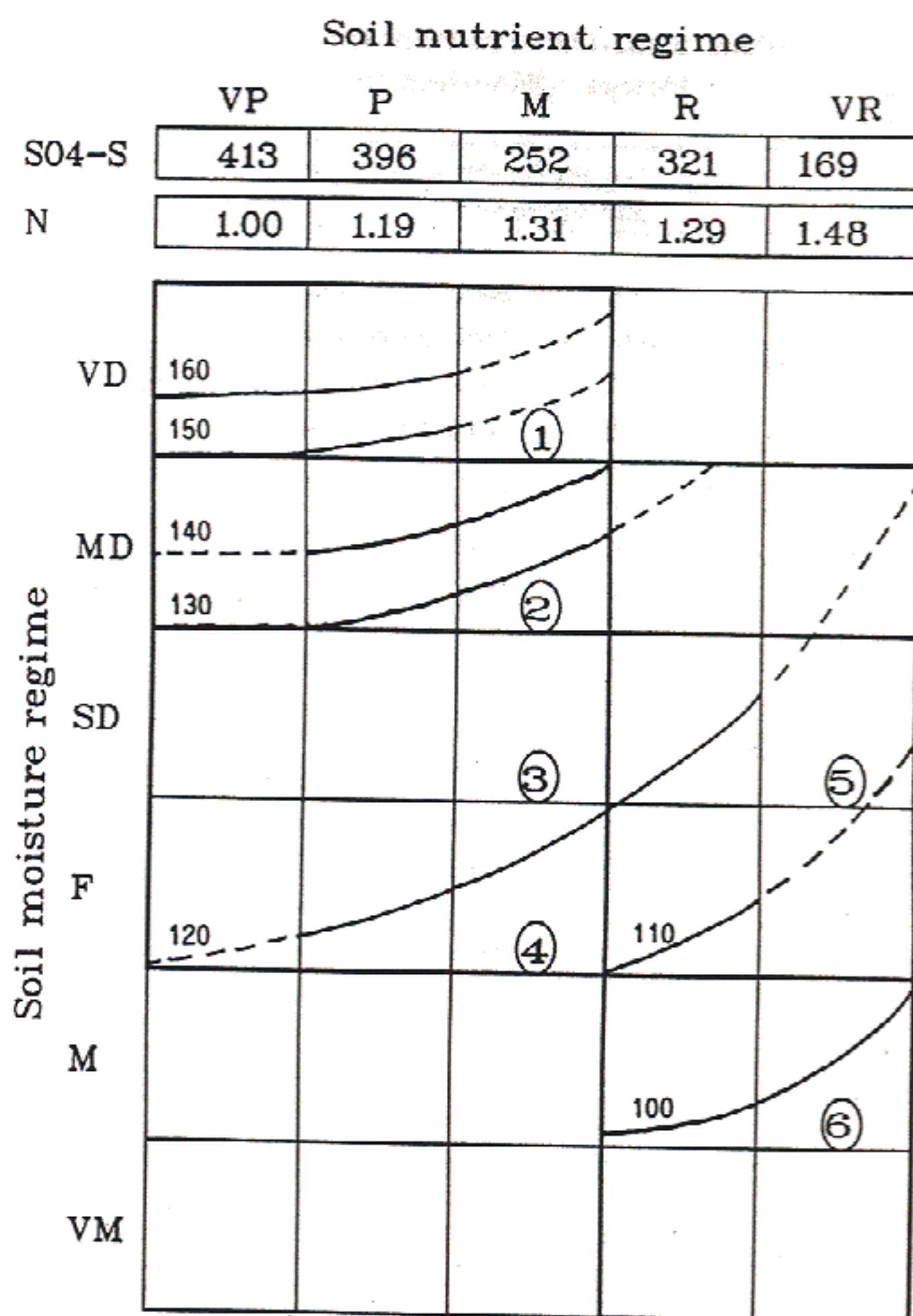


Figure 3. An edatopic grid showing site associations (1 through 6), pretreatment foliar N (%), and foliar sulfate-sulfur (ppm) concentrations, and isolines indicating the third-year basal area response of coastal Douglas-fir to fertilization with nitrogen (control = 100). Dashed isolines are beyond the range of the 13 soil moisture and soil nutrient regime combinations of the fertilization study. Soil nutrient regime symbols are: VP, very poor; P, poor; M, medium; R, rich; VR, very rich. Soil moisture regime symbols are: VD, very dry; MD, moderately dry; SD, slightly dry; F, fresh; M, moist; VM, very moist.

planning models. Carter et al. (1992) found site index and site association to have approximately the same utility for predicting three-year basal area response to nitrogen additions in coastal Douglas-fir. Addition of pretreatment foliar nitrogen concentration to the model further improved the relationship (Eq. 2).

Fertilizer Trials

Field fertilizer trials provide the ultimate proof of the benefits to be obtained through the application of fertilizer amendments. Fertilizer trials can be designed in many different ways to meet a multitude of short- and long-term objectives.

Two approaches are commonly employed in the establishment of fertilizer trials: an individual-tree—or screening—trial, and large fixed-area trials. The individual-tree approach has advantages in cost and ease of establishment, allowing trials to be employed over many locations with several replications of each treatment. The intention of these trials is usually to rapidly assess short-term treatment response—on the basis of first-year changes in tree diameter, height, or volume or the needle weight and foliar nutrient concentrations using graphical analysis (see Timmer and Morrow 1984; Timmer and Ray 1988). However, individual-tree trials have several limitations: (1) they are not appropriate for assessing long-term response; (2) assessment of fertilizer response on the basis of changes in foliar nutrient concentrations and needle (fascicle) weight may not be strongly related to long-term volume response; (3) they provide no information on the effects of treatment on mortality and ingrowth of associated trees; and (4) they do not provide reliable estimates of stand response.

Fixed-area designs generally have 15 to 50 or more treatment trees per plot, with treated buffer strips between plots. The trials are usually arranged with treatments in complete or confounded factorial designs. Inclusion of several treatments and replications in fixed-area designs can quickly make the number of plots and the area required for trial establishment unmanageable. Fixed-area designs are suited for assessing long-term treatment response. They normally allow measurement of mortality and ingrowth effects and calculation of both stand and crop-tree response.

Due to their low cost and ease of establishment, individual-tree plots probably offer the best opportunity for identifying nutrient limitations over a range of stand and site conditions. Fixed-area designs can then be established in "representative" stands or sites to identify stand response characteristics. In situations where several treatments and/or levels of a treatment are of interest, composite rotatable designs should be considered where only the major effects are examined (Clutter 1968).

Several review articles have described the basic elements of fertilizer trial design. The features and merits of complete factorial experiments, factorial experiments with confounding, and response surface designs are described by Clutter (1968) and Farnum (1981). Design and analysis of individual-tree plots are described by Viro (1967, 1970), Timmer and Stone (1978), Weetman and Fournier (1982, 1986), Timmer and Morrow (1984), and Binkley (1986). Information on the width of buffer strips, plot size and number of trees per plot, elements

to be applied, application rates, time and method, parameters to be measured, and methods of measurement is presented in Gessel et al. (1960), Carbonnier et al. (1969), and Morrison (1974).

All methods used for interpreting and predicting fertilizer response can be subject to serious shortcomings when used alone or outside of the environmental range used in calibrating interpretive criteria. Interpretations should always consider the current growth performance of the stand, environmental characteristics of the site, and, ideally, possible interactions of soil moisture and nutrients and their effect(s) on nutrient relations.

Selection of the most suitable approach, or approaches, for the evaluation of forest stand nutrient status should first consider the availability and reliability of interpretive data for the method and its applicability to the proposed study. Consideration must then be given to costs associated with the approach. In some situations it may be desirable to forfeit some interpretive accuracy if reduced costs will allow a greater number of stands to be sampled.

Summary

There are many different diagnostic approaches for the evaluation of forest stand nutrient status. Inference through site and stand characteristics, visual symptoms, and foliar analysis are suggested to have the greatest utility in routine evaluations, while soil analysis and pot trial techniques should primarily be regarded as research tools. Foliar analysis should always be considered in the context of site ecological characteristics, particularly growing season soil moisture availability, and stand structure and growth performance information.

Screening trials represent a quick and efficient approach to evaluating the responsiveness of stands to fertilizer amendments, and should be considered for routine use in stands where information on response to fertilization is lacking. However, large fixed-area trials established and maintained over long periods are absolutely necessary for identifying area-based stand response to fertilization.

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