Plant and Soil **37**, 159–169 (1971) Ms. 1671

PRINCIPLES AND PRACTICE OF FOLIAR ANALYSIS AS A BASIS FOR CROP-LOGGING IN PINE PLANTATIONS

II. DETERMINATION OF CRITICAL PHOSPHORUS LEVELS

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SUMMARY

Progress towards the introduction of crop-logging as a management tool is illustrated by the development of multiple regression equations relating basal area increment to various stand parameters including foliar phosphorus levels. Mixed mode regression analysis was used, removing foliar P variables first and adding other variables stepwise. The model which best described the relationships sought was of the form:

$$\log B = a_1P + a_2P^2 + a_3\frac{BA.SI}{Age} + a_4\frac{SI}{BA.Age}$$

where B = average annual basal area increment for the three-year period preceding or subsequent to foliar sampling; P = percentage phosphorus in foliage; BA = basal area standing at the time of sampling; SI = site index, defined as predominant height (predicted or actual) in feet at age 25 years; and Age = age of plantation in years at time of sampling.

Using this equation, the critical level of phosphorus in slash pine (*Pinus elliottii* Engelm.) is set at 0.075–0.080 per cent and in loblolly pine (*P. taeda* L.) at 0.095–0.105 per cent. Critical level is here defined as the foliar P concentration associated with 90 per cent of maximum basal area increment. Over the range of parameters examined, the critical levels so determined are, for all practical purposes, independent of age, site index and stand density.

Utilization of critical foliar nutrient levels in crop-logging requires a knowledge of fertilizer – soil – plant interactions which can be derived in part from the fertilizer trials used to establish critical levels in the first instance.

INTRODUCTION

Following a survey of the literature, a method has been proposed [10] to utilize foliar diagnosis as a basis for crop-logging in pine plantations. The present paper describes how this method was used to establish critical foliar phosphorus concentrations in *Pinus taeda* L. (loblolly pine) and *P. elliottii* Engelm. (slash pine) and gives tentative recommendations for the implementation of crop-logging in plantation management. Field trials installed and maintained by the Queensland Forest Service provided the data for this investigation. The existence of these experiments, designed to test incremental dressings of phosphate fertilizers, combined with the knowledge that phosphorus was the only limiting nutrient in the plantations concerned, meant that the source material was well suited to the determination of critical foliar phosphorus levels.

EXPERIMENTAL

The study was based on six slash pine and six loblolly pine fertilizer trials established using routine plantation techniques on Beerwah and Beerburrum State Forests in southeast Queensland. Sampling was carried out over a period of years, and one trial was sampled on three occasions,* giving a small measure of control over year-to-year variation in nutrient concentration and change in growth rate as the stands aged. A total of 70 data sets from 70 plots were used for slash pine, and 67 data sets from 45 plots for loblolly pine. All plot data for each species were pooled for separate multiple regression analyses on an IBM 1620 computer.

The data collected for each plot at every sampling date were: age, basal area per acre, site index, periodic mean annual increment in basal area (mean of 3 years' increment of 2 years' if data of three years were not available) for the period prior to sampling (BAI_a) and following sampling (BAI_b). In addition, each plot was allocated to a 'site type' based on Great Soil Group in relation to topography; five such site types were recognized. It quickly became apparent, however, that this factor accounted for little of the varation in the data that could not adequately be removed by site index. Consequently, site type was deleted as a variable during subsequent testing of the models. The distribution of the basic data according to the stand parameters examined is given in Table 1.

Sampling of foliage was carried out by a standard procedure; winter sampling (late May-early August) was the rule with the exception of one midsummer sampling in one slash pine trial. Foliage samples comprised 50 terminal (*i.e.* recently matured) fascicles taken from a branch on the northern (sunny) side of the two-year old spring whorl. All sample trees were codominants of close to average diameter for the plot concerned. Between 3 and 9 trees were

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* Actual dates (month/year) of sampling for the slash pine experiments were: Exp. 268, 280, 339 – 7/63; Exp. 211 – 12/63; Exp. 256 – 7/65; Exp. 364 – 5/66. For the loblolly pine trials, sampling dates were: Exp. 210 – 6/59, 6/62, 8/64; Exp. 145, 197, 198, 227 – 8/65; Exp. 131 – 6/66.

TABLE 1

Frequency distribution of sets of source data

Species	Age (years)				Total
	1–10	11–20	21–30	31–40	
Slash	42	16	12		70
Loblolly	25	21		21	67

	Site index (predom. ht at 25 years, ft)					
	41–50	51–60	61–70	71–80	81–90	
Slash	5	13	12	34	6	70
Loblolly	3	3	29	25	7	67

	Stand basal area (sq ft/ac)						
	26–50	51–75	76–100	101–125	126–150	151–175	
Slash	20	13	33	4			70
Loblolly	13	17	17	14	5	1	67

	Foliar phosphorus (%)						
	.041–.060	.061–.080	.081–.100	.101–.120	.121–.140	.141–.160	
Slash	5	27	33	5			70
Loblolly	1	20	29	13	3	1	67

sampled in each plot (average sampling intensity, 68 per acre) and the needles combined to produce a composite sample presumed representative of the population. The samples were dried at 70°C in a mechanical convection oven, ground to pass a 1 mm sieve, wet ashed in ternary acid, and phosphorus estimated by the arseno-molybdate blue method.

ANALYSIS OF THE RESPONSE CURVE

Since basal area increment was chosen as the dependent variable, it was necessary to take into account the effect of other stand variables on this parameter, viz. stand density, site index and age. This was done by utilizing modifications of a relationship previously established [1] for slash pine between basal area increment and other factors, *i.e.* $\text{BAI} = f\ (\text{BA. SI/Age, BA/Age, BA}^2\text{/Age})$. The basic model used for determining the nature of the relationship between basal area increment and foliar P levels was that described elsewhere [9] for relating height increment to N and P concentrations in *Araucaria cunninghamii*, *i.e.* $\triangle H = f\ (N, \log N, 1/N, P, P^2, N/P)$.

TABLE 2

Basic models tested during preliminary analysis

Model	Equation	Coeff. of Determination (R^2)			
		Slash		Loblolly	
		BAI_a	BAI_b	BAI_a	BAI_b
A	$\log BAI = a_1P + a_2P^2 + a_3BA.SI/Age + a_4BA/Age + a_5BA^2/Age + a_6ST + a_7P.SI + a_8 P/Age + a_9P.ST$	.818	.934	.891	.914
B	$\log BAI = a_1P + a_2P^2 + a_3\log BA.SI/Age + a_4/BA.Age + a_5BA/Age + a_6ST + a_7P.SI + a_8P/Age + a_9P.ST$	.844	.967	.889	.917
C	$BAI = a_1\log P + a_2/P + a_3P + a_4BA.SI/Age + a_5 BA/Age + a_6BA^2/Age + a_7ST + a_8P.SI + a_9P/Age + a_{10}P.ST$	.744	.955	.932	.928
D	$BAI = a_1\log P + a_2/P + a_3P + a_4\log BA.SI/Age + a_5/BA.Age + a_6BA/Age + a_7ST + a_8P.SI + a_9P/Age + a_{10}P.ST$	.735	.955	.925	.928

Legend: BAI = Basal area increment; P = foliar P percentage; BA = basal area per acre; SI = site index; ST = site type

Following graphical analysis [5] of the data from selected individual experiments a logarithmic parabola was found appropriate for describing the phosphorus response curve, and the basic model was therefore modified accordingly. The most satisfactory relationships for individual fertilizer trails of slash and loblolly pines were, respectively, as follows:

$$\log BAI_a = 11.981 + 292.13P - 1279.6P^2 \quad R^2 = .604^{***}$$

$$\log BAI_b = 2.8407 + 97.632P - 464.95P^2 \quad R^2 = .725^{***}$$

These sub-models were subsequently built into more complex models which took account of the other stand variables recorded (models A and B, Table 2).

In addition to a logarthmic parabola, a form of logistic curve was also tested (models C and D, Table 2). Both kinds of model permitted analysis of the data by multiple linear regression techniques after logarithmic transformation of the appropriate variables. A combination of straight forward and stepwise regression, known as mixed mode regression analysis [12], was employed. A similar approach has been used in the analysis of Douglas fir growth patterns.[4] Since our experimental data showed phosphorus to be limiting nutrient, foliar P variables were removed first, the remaining components (including interaction terms between foliar P and other variables) being removed stepwise. After each iteration, the significance of the multiple correlation coefficient was tested, and the process repeated until none of the remaining variables made a significant contribution to the variance as measured by an F-test. The four basic equations evaluated are shown in Table 2, together with the coefficients of determination (R^2) obtained during the initial runs. All the models accounted for a high degree of the variation in basal area increment. The results for BAI_a were not quite as satisfying as those for BAI_b, which is not surprising since it seems logical to expect a closer causal relationship between foliar P and growth just subsequent to sampling than growth immediately prior to sampling.

One of the major difficulties with multiple linear regression analysis is the problem of intercorrelations among the independent variables so that it becomes difficult to determine what fraction of the total variance is accounted for by each of the components. Since the total variance is determined not only by the variances of the individual determining variables but also by their covariances [7], some measure of interaction among the independent variables is desirable. The latter was achieved by treating the interactions between pairs of independent variables as if they were additional independent variables, the former (i.e. covariance) was not measured. Certain interactions were excluded as having little if any biological significance, and the only interaction tested which involved site type was that with phosphorus (P. ST). Because of intercorrelation, several components were found to be equally efficient at accounting for the same proportion of the total variance. Thus site type (ST), the phosphorus × site index interaction (P.SI) and the phosphorus × site type interaction (P.ST) contributed little to the overall variance once the effects of phosphorus and site index had been removed.

Models B and D were chosen for further analysis, and after simulating basal area increment for various values of the X variables in order to examine the shape of the derived response curves, model B was ultimately selected for concentrated modification. The final model was of the general form:

$$\log \mathrm{BAI} = a_1P + a_2P^2 + a_3\frac{\mathrm{BA.SI}}{\mathrm{Age}} + a_4\frac{\mathrm{SI}}{\mathrm{BA.Age}}$$

The stepwise build-up of this model for both BAI_a and BAI_b is illustrated in Table 3. The regression coefficients shown for P and P^2 differ from those given earlier for individual fertilizer trials because they were calculated from the pooled data sets. The final model accounted for more than 80 per cent of the total variation in the original data and while this is not as high as that explained by the initial models, the final equation is simpler and quite amenable to biological interpretation. The ultimate choice of X-variables, while guided largely by the degree to which they contributed to a reduction in the total variance, was done subjectively as being the most likely to describe adequately the relationships sought. This approach

TABLE 3

Regression coefficients derived during stepwise buildup of model: Log Y = f (P, P^2, BA.SI/Age, SI/BA.Age)

Y	Constant	P	P^2	BA.SI/Age	SI/BA.Age	n	R^2
Slash pine							
BAI_a	.63770	18.895^{γ}				70	.171
	−1.6482	77.484	−364.11			70	.183
	−.37420	28.911	−103.71	$.00197^{\delta}$		70	.769
	−1.1449	57.692^{α}	-288.62^{α}	$.00150^{\delta}$	$-.05598^{\delta}$	70	.888
BAI_b	.74190	16.186^{β}				70	.124
	−3.8020	132.47^{α}	-723.79^{α}			70	.174
	−2.5560	84.967^{α}	-469.11^{α}	$.00193^{\delta}$		70	.733
	-3.1893^{β}	108.61^{γ}	-621.04^{γ}	$.00154^{\delta}$	$-.04600^{\delta}$	70	.813
Loblolly pine							
BAI_a	.22390	17.658^{δ}				67	.378
	-2.7296^{δ}	74.500^{δ}	-257.030^{δ}			67	.571
	-1.5967^{β}	45.878^{δ}	-164.86^{γ}	$.00181^{\delta}$		67	.740
	−.72660	26.588^{β}	-101.81^{β}	$.00244^{\delta}$	1.8635^{δ}	67	.815
BAI_b	.23590	17.498^{δ}				67	.422
	-2.8413^{δ}	76.721^{δ}	-267.79^{δ}			67	.659
	-2.2899^{δ}	62.791^{δ}	-222.94^{δ}	$.00088^{\beta}$		67	.705
	-1.1942^{β}	38.499^{γ}	-143.54^{δ}	$.00143^{\delta}$	2.3467^{δ}	67	.840

α Significant at 5% level
β Significant at 1% level
γ Significant at 0.1% level
δ Significant at 0.01% level

is admittedly liable to operator bias, and such an analysis 'can only yield a quantitative expression of a preconceived qualitative assessment of the growth pattern, based on a sound knowledge of the silvicultural characteristics of the species'.[1]

Having decided upon a satisfactory growth model, the next step was to establish the critical foliar P level. First the P concentration corresponding to maximum basal area increment (Y_{max}) was obtained by differentiation of the equation to the model, using the coefficients from Table 3 and solving for $dy/dP = 0$. This 'optimum P level' was then used to calculate Y_{max} for a given stand density, site index and age. In turn, the foliar P concentration corresponding to 90 per cent of Y_{max} was calculated for the selected values of the other variables, and this figure accepted as the critical level. Table 4 shows critical P levels for both species and both increment periods together with the corresponding optimum P levels. For management purposes a critical level of .075–.080 per cent is proposed for slash pine and .095–.105 for loblolly pine. The lower values for slash compared to loblolly reflect the greater tolerance of the former species to lesser availability of soil phosphorus. This is also reflected in a comparison of the models, where during the stepwise build-up phase (Table 3), the simple logarithmic parabola involving only foliar P accounted for just 17–18 per cent of the variability in the slash pine data but 57–66 per cent of that in the loblolly data.

DISCUSSION

There is little published information on foliar phosphorus levels in slash and loblolly pines, and virtually none on critical percentages. Pritchett[8], using data from field trials in Florida, considered that the critical P level for slash was slightly above 0.09 per cent. The critical level as he defined it corresponds to the optimum P concentration in the sense used in this paper, hence the two findings are in good agreement. Pritchett also assembled data published on foliar P levels in both slash and loblolly pines before and after fertilizing, and in general these too fit the values derived in the present study.

The earliest published report on foliar nutrient levels in these Southern pines was that of Young[13], based on a fertilizer trial in Beerwah State Forest. We did not use Young's data in our analysis because his foliage sampling techniques were somewhat different (Young sampled 2 to 4 trees per plot, taking the terminal needles of a branch arising at a stem diameter of two inches). The trial was a 5 × 5 latin square planted mainly to loblolly pine but with a number of slash pines present also, which enabled the growth of both species to be related to their respective needle phosphorus concentrations. Young's results show both diameter and height increment of 11 year-old trees, over the seven year period prior to sampling, approaching a maximum with the addition of 818 lb/ac of superphosphate, and corresponding foliar P levels of .098 per cent for slash and .129 per cent for loblolly. These values agree very well with the optimum levels found in the current study for the pre-sampling increment period (Table 4).

To what extent do the critical levels established meet the requirements that they should apply throughout the life of the crop and over a wide range of environments? Our analysis is based on pooled data derived from samples collected over a seven year period, but not every trial was sampled each year. In fact, only one stand was sampled more than once, and that only at intervals of two or three years. Further sampling is desirable, at more frequent intervals, to ensure that the range of year-to-year variation in foliar P concentration is adequately covered. The model also needs to be tested over a wider range of soils and climates, and work along these lines is in progress. The present study was restricted to one climatic region in the subtropical coastal lowlands of Queensland, and to a small range of soils within one or two Great Soil Groups. There was considerable variation in soil type however, from shallow, poorly drained gleys to deep, well drained yellow and red podzolics.

Since no interaction terms between foliar P and other variables are included in the model, the optimum level of P is independent of age site index and stand density. Furthermore, the effect of other stand variables on the slope of the response curve at 90 per cent of maximum increment is very slight, so that for all practical purposes the critical level is also independent of these other factors. This is not to say that the critical level does not vary with age, for example, but only means that the variance due to any such change is accounted for by the interaction terms between age, site index and stand density. The extent to which the internal nutrient requirements of forest trees alter with age, if at all, is unknown. Tamm[11]

TABLE 4

Critical and optimum levels of phosphorus in foliage of slash and loblolly pines

Species	Critical level (%)		Optimum level (%)	
	(a)	(b)	(a)	(b)
Slash pine	.081	.075	.100	.087
Loblolly pine	.098	.107	.131	.137

(a) Pre-sampling increment period
(b) Post-sampling increment period

expressed doubt that this question could ever be resolved satisfactorily by field trials, because the environmental conditions with saplings and mature trees experience are never quite the same, irrespective of whether they are grown in even-aged or all-aged stands. If this is so, then a pragmatic approach to the problem is justified, and the finding that the same critical levels apply to stands ranging in age from under ten to over thirty years greatly simplifies the use of foliar analysis in plantation management. The fact that the source data came from stands which were, except for the experimentally applied fertilizer treatments, subject to standard management procedures is also of practical significance.

While the model will doubtless be refined after further testing over a longer period of years and a wider range of environments, it is unlikely that the critical levels already established will be altered appreciably. There may be situations, such as where high foliar aluminium levels increase the internal demand for phosphorus [3] [6], which will complicate the interpretation of foliar analysis, so that experience is essential if crop-logging is to be implemented successfully. We envisage the use of crop-logging as a tool in pine plantations as follows. Assuming that all nutrient deficiencies have been properly diagnosed, *and this is an essential prerequisite,* field trials involving the deficient element(s) should provide a sound basis for designing a fertilizing schedule which will permit satsifactory establishment and early development of the plantation. The need for subsequent fertilizing can then be assessed by crop-logging. Critical foliar nutrient levels, however, are no real guide to the magnitude of fertilizer response, and the amount of fertilizer necessary will be determined by the interactions between the fertilizer, the soil and the stand; this can only be gauged from the response obtained in convential fertilizer trials on similar sites. Such field experiments (which may include those installed at time of planting) are normally available and, as in the present instance, are often identical with those trials used for establishing the critical level. They should provide the data required to determine how much fertilizer needs to be added on a given soil type to raise the nutrient status of the stand to the optimum level, or above, as desired. This brief description is, of course, an oversimplification, and continuing research into fertilizer-soil-plant interactions is essential for the proper implementation of crop-logging procedures. The technique has been used successfully on a pilot scale in plantations from the study area.

How frequently the nutrient status of the crop need be determined has yet to be decided. For orchards, Cain [2] recommended sampling every second or third year for the life of the crop, and suggested that sampling of forest trees should be no less intensive. We propose at present to sample every five years, in association with routine remeasurement of sample plots used for yield prediction; selected plots could be sampled more frequently just as they are for mensurational purposes. The number of trees which must be sampled in order to obtain a precise estimate of the nutrient status of each stand is one point that requires early clarification. The sampling intensity used to establish critical levels in this study (about 68 trees per acre) might prove too costly in practice and no doubt could be reduced considerably without unduly sacrificing precision.

ACKNOWLEDGMENTS

We express our thanks to Prof. J. Burr, Mathematics Department, University of New England, for making available his multiple regression analysis programme BAR3, and to the Queensland Forestry Department and the New South Wales Forestry Commission for providing staff and facilities for data collection. Particular acknowledgment is due to Mr. J. Hopcraft (NSW FC) for extracting and collating the data from Qld. Forestry Dept. files and for preparing the initial computer runs; to Messrs. J. Simpson and J. Zolte (QFD) for their efforts in acquiring field data and foliage samples; and to Mr. M. Finch (QFD) for chemical analysis. Professors W. L. Pritchett (Soils) and F. G. Martin (Statistics), of the Institute of Food and Agricultural Sciences, University of Florida, kindly read and commented on the manuscript.

Received February 2, 1971

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