Chapter 25

Prescribing Fertilizers in New South Wales Plantation Forestry

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ABSTRACT. The problem of applying fertilizer research results to routine forest management is addressed, specifically in regard to radiata pine plantations in Australia. A soil-based decision-making system, using microcomputer data base software, can be employed to extrapolate results of fertilizer trials to general management forestry. A case study shows the different financial returns from a fixed investment, where a uniform application of fertilizer over all sites is compared with selecting for optimum biological response or for net present value.

The management of spatially complex referenced data can be greatly assisted by computer technology. Advances in personal computer hardware and relational data base software allow the forest manager to evaluate site- and stand-specific fertilizer prescriptions from a large number of research trials reflecting a wide range of nutritional characteristics. This capacity has been demonstrated using the results of several fertilizer trials in radiata pine (*Pinus radiata*) plantations in New South Wales, Australia.

Implementing the results of forest field research findings is seldom a simple exercise of routine plantation management. Prescriptions capable of eliciting maximum biological response are identified by evaluating results from individual trials, and cost-benefit analyses are undertaken to determine their commercial viability. Where these prescriptions are to be pursued through investment, the forest manager must be confident that the predicted gains will be realized in every unit treated.

If the forest is uniform and identical to the field trial plots in terms of site, age, and structure, the problem of extrapolating research findings is minimal. Where the forest is not uniform and the optimum treatments vary on different sites, the extrapolation problem becomes complex. The plantation must then be stratified according to attributes critical to biological response. Soil physical and nutritional characteristics are the principal factors used in assessing potential response to application of fertilizers.

The Decision-Making Process

The Forestry Commission of New South Wales manages more than 3.6 million hectares of native forests, mainly *Eucalyptus*, and has also developed an exotic conifer plantation estate (180,000 ha), mostly of radiata pine, to supply softwood requirements. These stands were established to provide sawlogs and they represent a substantial utilization of land and a large investment in money. The broad management objectives are to reach wood supply, productivity, and plantation establishment targets while maximizing the rate of return on silvicultural investment and maintaining high levels of environmental accountability. Site- and stand-specific fertilizer strategies are formulated on the basis of cost-benefit analysis.

Fertilizer applications can result in substantial growth responses at various stages in the rotation. The magnitude and duration of the response will depend on stand condition and on the form, rate, and method of fertilizer application. There are generally four reasons for fertilizing Australian plantations (Knott and Turner 1990):

1. To assist in successful plantation establishment. Usually this is achieved by individual-tree applications of phosphatic fertilizers, or nitrogen and phosphorus (NP), or NP plus trace elements at planting time or several months later.

2. To correct recognized nutrient deficiencies which result in economically significant levels of tree mortal-

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ity, deformity, or losses in growth potential. In these cases, treatments are generally applied where deficiency symptoms are obvious or verified by foliar chemical analysis.

3. To increase the rate of wood production in actively growing stands where no nutrient deficient symptoms are obvious. These stands are usually of precommercial age and selected for treatment on the basis of foliage analysis or an understanding of the nutritional status of stands on specific sites.

4. To maximize the economic benefit associated with the release of a stand by thinning, by increasing nutrient availability.

Assessment of forest research trials will generate inappropriate, inaccurate, or uncertain response predictions when these trials do not match managed stand conditions. In the past, the approaches to applying research results were both stand based and statistical; that is, a series of plots were established within the "management area." Based on the information obtained, the stand was typified and a decision was made on suitable treatments. Information gathered this way tends to be location specific and is rarely used off-site. Probable response to fertilization is determined by growth measurements, foliar chemical analysis, or soil data and chemical analysis, and the approach requires intensive sampling and close calibration with experimental results and other data. A well-defined relationship between foliar nutrients and potential response is necessary to provide results with confidence.

An alternative method is a soil-based decision-making system, as detailed below. The following processes need to be completed in order to extrapolate results of fertilizer trials to general management forestry by using a soil-based system: (1) Stratifying the total forest resource at the compartment (management unit) level, using microcomputer relational data base software; (2) linking multiple data bases in a common management unit (compartment) format to develop a forest information system; (3) implementing a soil technical classification system for radiata pine plantations as part of the broader forest information data base system; (4) stratifying the research experiment data base according to key attributes within the forest information system; and (5) packaging the information system to enable easy interrogation of the data base and hypothesis testing.

Soil Technical Classification (STC)

Critical to the present system was the availability of a specific soil classification system—that is, a crop-specific soil classification system. The soil technical classification (STC) system incorporates recognizable soil characteristics directly relevant to radiata pine growth and management and is intended to be used below the broad-scale level of climate (Turner et al. 1990; Turvey et al. 1990). In the development of the STC system, the key soil parameters for plantation productivity were identified. These parameters are of particular significance to Australian exotic conifer plantations.

Table 1—The main soil attributes included in the radiata pine soil technical classification (STC) system.

Group A	Parent material Soil texture, profile, and form Depth to, and type of, impeding layer
Group B	Texture of surface Surface condition Characteristics of surficial horizons or layers Condition of subsoil Color of subsoil

The STC system is hierarchical and in two main attribute groups (Turner et al. 1990): Group A attributes provide generalized soil information for planning purposes, and Group B attributes provide more detailed data for interpretation at the plantation management scale (Table 1).

The attributes are coded numerically for incorporation into computer data bases, and all are recognizable in the field. The level to which information is gathered depends on the intensity and type of management. The primary attribute, soil parent material, is recognized as critical, since many soils are formed *in situ* (not transported) and parent rocks strongly influence nutritional status and other soil characteristics. The parent rocks have been grouped and coded, not on the basis of traditional classification, but on how they form soil (Table 2). The details of the system are provided in

Table 2—Soil parent materials and parent rock codes (PRC) used for the radiata pine soil technical classification (STC) system.

Soil Parent Material	Parent Rock Code
Unknown	00
Carbonaceous	01
Quartzose	02
Sesquioxide	03
Calcareous	04
Argillaceous	05
Micaceous-chloritic	06
Feldspathic-quartzose-A	07
Feldspathic-quartzose-B	08
Feldspathic-micaceous	09
Feldspathic	10
Ferromagnesian	11
Magnesian silicate	12

Table 3—Soil chemical characteristics of soils derived from selected parent materials, reported by Turner and Holmes (1985).

Parent Material	Parent Rock Code	Organic Matter (%)	Soil Total P (ppm)	Ca (me%)	Mg (me%)
Sandstone	02	4.55	185	2.90	0.85
Shale	05	4.38	230	1.84	0.87
Conglomerate	07	0.64	185	0.33	0.20
Rhyolite	08	2.80	235	1.76	0.93
Mixed volcanics	10	5.84	290	8.09	2.12

Turner et al. (1990) and a handbook used for fieldwork and training purposes by Turvey (1987).

A third-digit number is appended to differentiate consolidated (001) from unconsolidated material (002); for example, silicious sandstone would be 011, while transported material from silicious sandstone would be 012. Analyses of this system on 181 sites of 11-year-old radiata pine from all parts of Australia allowed development of various models. The broadest model of the STC accounted for 75% of volume variance, whereas other general soil classification systems accounted for much less (Turvey et al. 1990). In the present exercise, only the parent material level has been incorporated in the data base to demonstrate extrapolation of research findings. Even at this level, broad differences in nutritional characteristics are apparent (Table 3).

Outline of Soils Data Base

The New South Wales plantation soils were classified at the parent rock code level (PRC) by mapping geological information, calculating areas of individual geological classes at the compartment level, and incorporating this stratified information into a relational data base. Rules were then applied to convert geological information into PRCs. The soils data base was then linked with plantation inventory, productivity, foliar nutrition, and research data bases at the compartment (management unit) level to create a forest information system. Compartments are the basic unit of subdivision for management and range from 10 to 50 ha in size. The resulting relational data base system was the basic tool for determining optimal fertilizer practices at the plantation management level.

Example Using Postthinning Fertilization

A specific example is offered to indicate how the system may be used. The problem can be defined as "Given a specific annual postthinning fertilizer budget for the organization, where should the fertilizer be applied and what are the optimum nutrients to maximize financial return (i.e., net present value)?" Three thinning-fertilization options were considered (first, second, and third thinning) for which the wood produced is of different value (after T1 = \$25/m^3, T2 = \$35/m^3, and T3 = \$45/m^3). The effects of different rates and forms of fertilizer were then evaluated in conjunction with soil types using PRCs. The predicted response was assessed over six years with interest rates fixed at 8% and the budget at \$500,000 per year.

Experimental Base

Eleven experiments were established at a range of plantation sites in New South Wales with various geologies (PRCs) and thinning operations (T1, T2, T3). The experimental designs varied, but it was possible to select similar treatments for comparison. Results from three additional sites reported in the literature (Crane 1981) were included for comparison purposes.

The experiments were located on sedimentary rocks, conglomerates, and granodiorites. Nutritionally, the sites ranged from deficient to adequate for nitrogen and phosphorus. There did not appear to be any limitation in calcium, magnesium, or potassium. Boron was deficient on one site and marginal on two others. The periodic annual increment six years after thinning ranged from 15 to 28 m^3/ha for the eleven New South Wales sites to as low as 12.8 m^3/ha when Crane's study (1981) was included. The mean annual productivity was 20.1 m^3/ha, with a coefficient of variation of 22% (Table 4). This unfertilized productivity appeared to be related to the foliar nitrogen-phosphorus ratio (Table 5).

All sites responded positively to application of nitrogen (ammonium nitrate) and phosphorus (superphosphate) together (nitrogen at either 200 or 400 kg N/ha and phosphorus at 75 or 225 kg P/ha) (Turner and Lambert 1987; Turner et al. 1990*a*). Annual response to nitrogen alone averaged an additional 2.3 m^3/ha but ranged from -3.4 to 6.3 m^3/ha; that is, some treatments depressed growth. N_1P_1 averaged an additional 4.6 m^3/ha, ranging from -0.63 to 8.2 m^3/ha; N_2P_1 averaged 7.2 m^3/ha, ranging from 2.1 to 10.5 m^3/ha; and N_1P_2 averaged 6.3 m^3/ha, ranging from 1.0 to 7.9 m^3/ha (Table 4). The negative result in growth from nitrogen application may be the result of various nutritional factors (Lambert 1986; Snowdon and Waring 1990; Turner et al. 1977, 1979, 1988). The evidence from the experiments is that all sites will respond to fertilizer applications after thinning but the absolute level of response in biological and economic terms needs evaluation.

Table 4—Annual volume growth (m^3/ha) and responses after six years to fertilizer applications after thinning in New South Wales radiata pine trials. Figures in parentheses are percentage increases.

				Additional Volume			
Location	Age at Start (yr)	Thinning[1]	Control[2] Volume	N_1	N_1P_1	N_2P_1	N_1P_2
Bondi	14	T_1	22.3	4.4 (19.7)	4.4 (19.7)	10.5 (47.1)	
Carabost	17	T_1	22.6	-3.4 (-15.0)	-0.63 (-2.7)		3.5 (15.6)
Carabost	24	T_3	19.8	-0.9 (-4.5)	8.2 (41.4)		5.7 (28.8)
Green Hills	14	T_1	18.4	4.8 (26.1)	6.4 (34.8)		7.9 (42.9)
Gurnang	14	T_1	18.5	6.3 (34.1)	7.8 (42.2)		7.9 (42.7)
Lidsdale	17	T_1	15.2		2.4 (15.8)		
Nundle	14	T_1	19.7	-3.4 (-17.3)	4.0 (20.3)	2.5 (12.8)	
Penrose	17	T_1	17.3	4.2 (24.3)	5.3 (30.6)	2.1 (12.3)	
Sunny Corner	16	T_1	24.7	-1.9 (-7.0)		7.7 (28.6)	
Sunny Corner	30	T_3	27.0	2.0 (7.4)	5.0 (18.5)	10.0 (37.0)	
Vulcan	24	T_2	28.0	1.0 (3.6)	3.0 (10.7)	6.0 (21.4)	
Belanglo (Crane)	16	T_1	20.1				1.0 (5.4)
Kowen (Crane)	25	T_1	12.8				5.1 (39.4)
Uriarra (Crane)	23	T_1	18.9			6.8 (35.5)	
Mean NSW			21.0 (4.34)*	2.3 (3.3)*	4.6 (2.8)*	7.2 (3.9)*	6.3 (2.1)*
Overall mean			20.1 (4.4)*				5.4 (2.5)*

N_1 = 200 kg N/ha
N_2 = 400 kg N/ha
P_1 = 75 kg P/ha
P_2 = 225 kg P/ha
*Standard deviation

[1] Thinning = T_1 (first), T_2 (second), T_3 (third).

[2] Control volume = Volume produced after thinning but without fertilizer.

Response to fertilization showed a pattern of increased growth (volume increment) for up to about four years, then decline, and then no difference in periodic annual volume increment compared with the control by the sixth or seventh year (Figure 1). The peak response and the duration of response have a significant bearing on the total extra amount of wood produced and the economic value of the treatment, as shown when cumulative response is plotted (Figure 2). This difference in responsiveness has been demonstrated for two identical trials (Turner et al. 1992) which before fertilization had essentially the same productivity .

The relational data base system detailing stand age, management history, thinning status, productivity, and soil type (parent rock) for each compartment was used to test the biological and economic ramifications of treatment of stands after first, second, and third thinning in accordance with the results from the fertilizer trials. The case study utilized all plantations to be thinned in 1991, and this area was stratified according to parent rock code and type of thinning (first, second, or third). The possible treatments, from the poorest to optimum, were considered and the discounted costs and returns were evaluated. Four alternative treatment strategies

Table 5—Foliar nutrient analyses of the experimental sites prior to treatment, indicating the variation between sites.

Location	Age (yr)	N (%)	P (%)	N/P (%)	Ca (%)	Mg (%)	K (%)	B (ppm)	Soil Parent Material	Parent Rock Code	Rainfall (mm)
Bondi	14	1.53	0.13	11.8	0.210	0.097	0.740	7	Shale	05	1,050
Carabost	24	1.39	0.13	10.9	0.193	0.339	0.705	20	Shale	05	960
Carabost	17	1.01	0.09	11.2	0.248	0.280	0.290	22	Shale	05	960
Green Hills	14	1.38	0.16	8.6	0.365	0.197	0.890	—	Granodiorite	09	975
Gurnang	14	1.35	0.14	9.6	0.312	0.177	1.360	24	Shale	05	835
Lidsdale	17	0.90	0.11	8.2	0.270	0.130	0.59	25	Feld/Quart[1]	07	865
Nundle	14	1.61	0.15	10.7	0.400	0.138	0.87	14	Shale	05	860
Penrose	17	1.35	0.08	16.9	0.155	0.169	0.691	27	Quart/Sand[2]	02	995
Sunny Corner	30	1.49	0.10	14.9	0.232	0.125	0.603	28	Shale	05	1,005
Sunny Corner	16	1.41	0.11	10.8	0.282	0.151	0.733	14	Shale	05	1,005
Vulcan	24	1.55	0.19	8.2	0.237	0.202	0.604	19	Granodiorite	09	910
Belanglo[3]	18	1.29	0.07	19.8			0.590		Sandstone	02	860
Belanglo[4]	16	1.31	0.10	13.1			0.484		Sandstone	02	860
Kowen[4]	25	0.84	0.13	6.5			0.797		Slate	05	660
Uriarra[4]	23	0.94	0.08	11.8			0.756		Granite	09	820

[1] Feldspathic quartzose.

[2] Quartzose-sandstone.

[3] Snowdon and Waring (1990).

[4] Crane (1981).

were evaluated, the criterion for relative success being the net present value associated with the expenditure of $500,000. The alternatives were:

1. Apply nitrogen fertilizer at a fixed rate over all available thinned forest, covering the range of available parent rock codes on a proportional basis.
2. Same as above, but using N_1P_1.
3. Treat the thinned forest giving priority to the treatments and areas that produce the optimum biological response according to parent rock code and thinning regime. That is, if PRC5 after the third thinning gives the best percentage increase in volume increment to N_1P_1, then all available land of third-thinned PRC5 is treated; the next most responsive combinations are then treated until all available funds are exhausted.

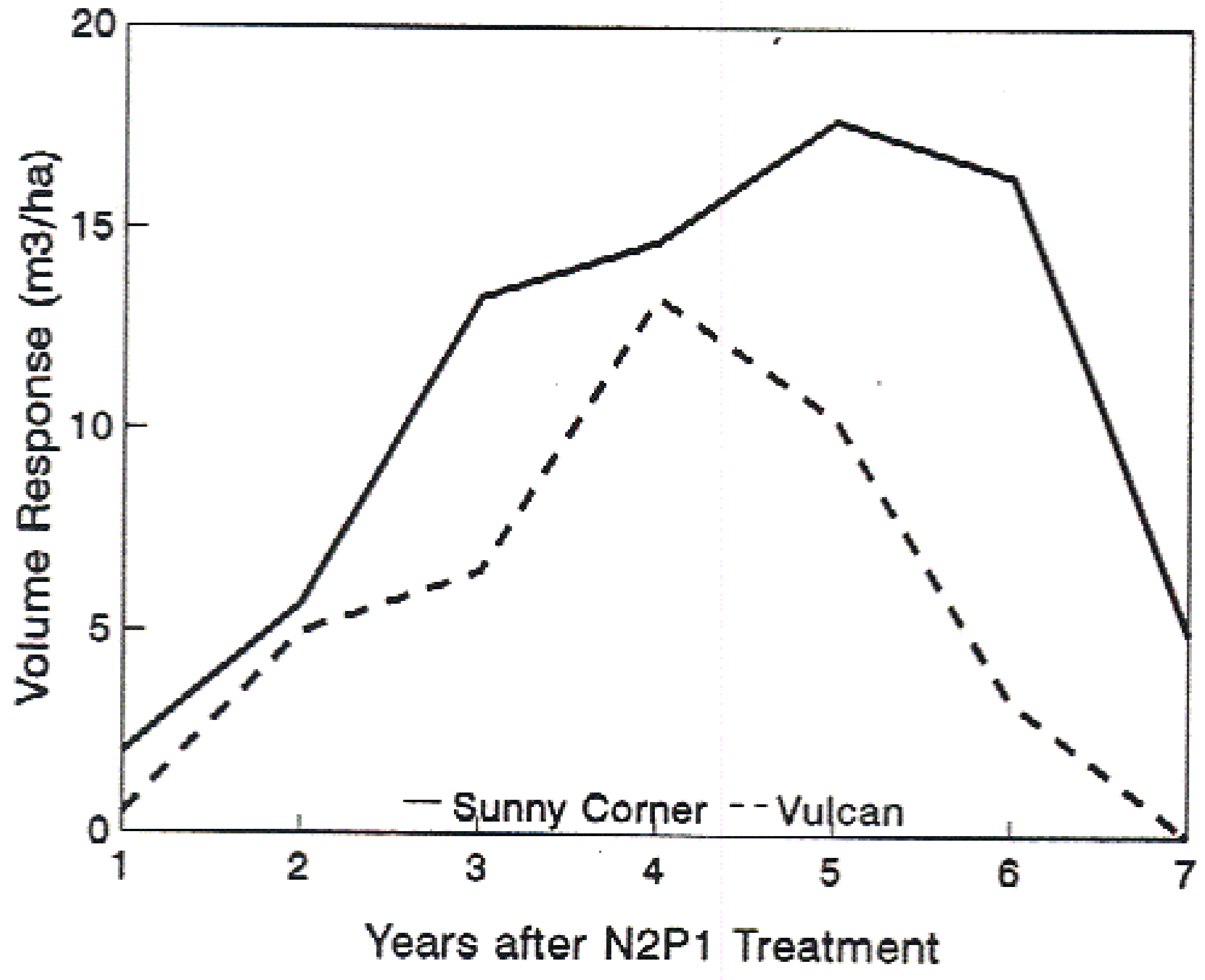

Figure 1. Annual growth response (m³/ha) to application of N_2P_1 (400 kg N/ha and 75 kg P/ha) fertilizer to radiata pine at two sites in New South Wales.

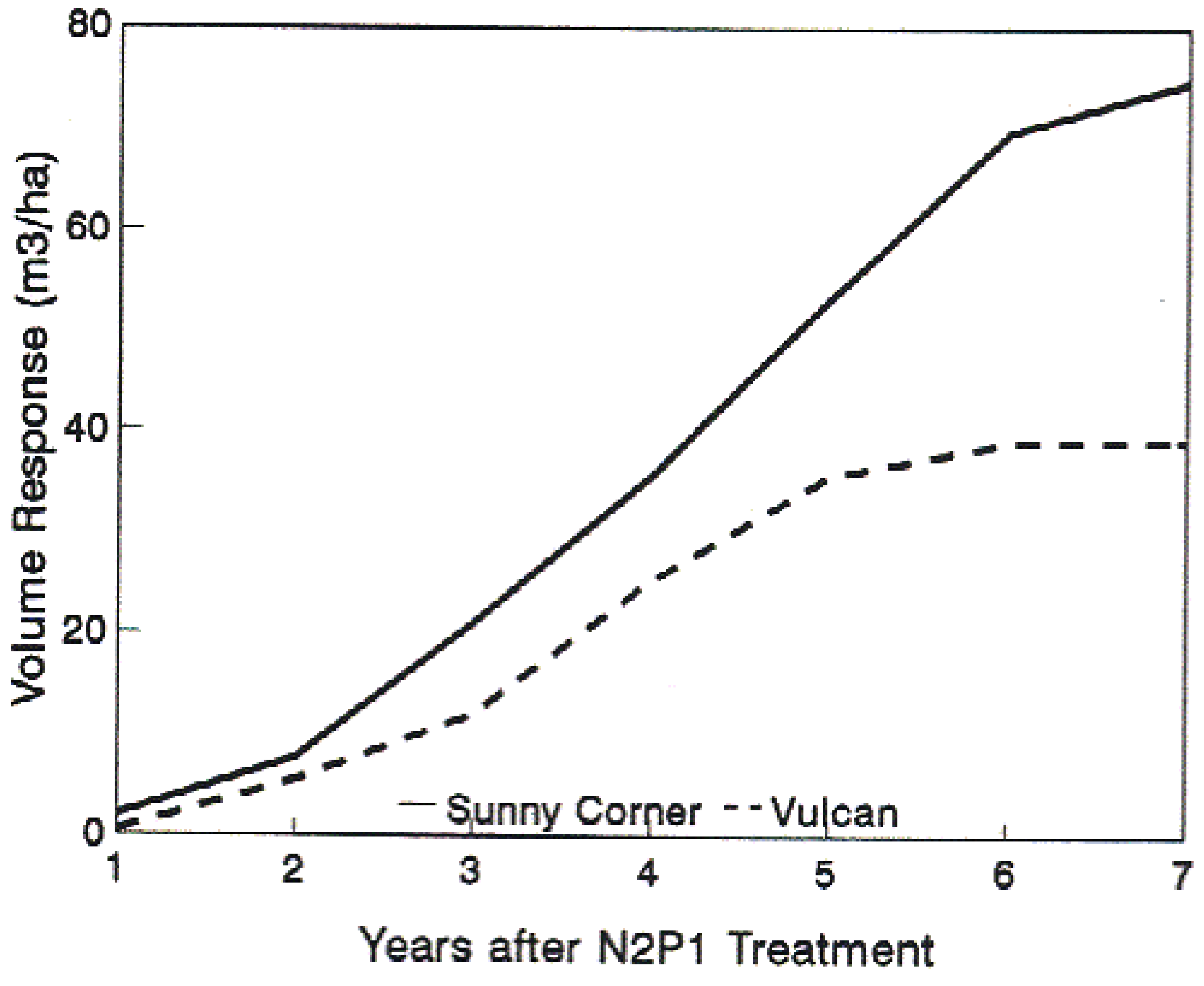

Figure 2. Cumulative growth response (m³/ha) over 7 years to application of N_2P_1 (400 kg N/ha and 75 kg P/ha) fertilizer to radiata pine at two sites in New South Wales.

Table 6—Summary of areas available, areas treated, and net present value for four alternative strategies of fertilization. The total cost was fixed at $500,000 and the interest rate at 8%.

Strategy	Available Area (ha)	Treated Area (ha)	Net Present Value (A$)
1. General treatment with N	4,656	1,961	-255,218
2. General treatment with N_1P_1	5,014	1,064	-178,578
3. Optimum biological response	1,156	985	397,814
4. Optimum selection for net present value	1,714	1,394	553,114

4. Same as for the third alternative except that the order of priority is based on net present value. This means that a suboptimal biological treatment may be selected but the lower costs may outweigh the reduction in value of the volume response.

The results indicate that broad-scale application of fertilizer, where there is a potential for low or negative response, can lead to financial losses even when there apparently is a positive growth response generally. Where the system is prioritized to select sites giving the highest biological response, there is a high positive return, but the highest net present value is gained by selecting sites and treatments giving the best financial return (A$/ha) (Table 6). The area available (Table 6) is the potential area available under the selected criteria, hence under treatment 4 there were 1,714 ha available but only enough finances to treat 1,394 ha.

Discussion

The successful extrapolation of fertilizer research results to the field depends on the nature of the resource being managed and the magnitude and variability of the responses obtained from experiments. The approach taken here is to characterize the total plantation resource in identifiable units (compartments) within a computerized data base. Each of these compartments is characterized in terms of soil and site parameters and silvicultural history. Areas with specified characteristics can be readily extracted from the data base and identified on maps and directly in the field.

The similar attributes are described for the factorially treated fertilizer trials, which provide information on a range of responses to different fertilizers. Cost-benefit analysis can be undertaken, and various hypotheses relating to areas treated and the alternative outcomes can be assessed. This study has assessed four alternative strategies for treatment, indicating a wide range in resulting net present value. These alternatives are only indicative, and when applied more routinely the scenarios will change, partly because the land base and the characteristics of available thinned areas change annually. Strategies can be varied by altering the thinning intensity, if the cost structure for fertilizer application changes (e.g., a more efficient method of application becomes available).

The critical aspect is that the data base and methodology are available to forestry managers—first to consider the alternatives, and then to reach an understanding of the implications of a selected treatment. The case study was carried out on a relatively small productive forest estate; the main differences for other estates would be in developing a data base specific to the area and in accumulating comparable data from experiments over a range of sites. The characteristics on which the management area is stratified have to be those which directly affect growth, and responsiveness to fertilizers. In the case of radiata pine in New South Wales, this is primarily taken into account through a specific soil classification system, but in other areas the factors may be other soil characteristics, elevation, or rainfall.

Finally, this work emphasizes the requirement for a soundly developed and maintained experimental data base from which the critical data are readily accessible.

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