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Enhancing a permanent sample plot system in natural forests

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Abstract. Permanent sample plots (PSPs) provide the basis for growth models and thus determine the quality of inferences made from decision support systems for forest management. Existing plots may have been adequate in the past, but changing needs and possibilities may have made data suboptimal for present demands. Funds for the establishment of additional plots are generally limited, so supplementary sampling should be based on an optimal sampling strategy employing prior information. This case study in south-east Queensland used topoclimatic strata and existing inventory data to identify where additional PSPs should be established, so as to increase the geographical and silvicultural range of the growth data collected. Some existing PSPs in areas considered over-sampled may be abandoned.

Introduction

Decision making by natural resource managers has been and continues to be impaired by deficiencies in the quality and extent of relevant information. This paucity of information on natural resources restricts the ability of management agencies to assess the impacts of alternative management strategies. One important objective for forest managers is sustainable timber production which requires reliable yield estimates and the ability to predict the future nature of the forest resource under alternative management strategies. Essential components for such estimates include the area information, resource inventory, a growth model and volume equations (Vanclay, 1989, Vanclay and Preston, 1989). The integrity of the growth model is dependent largely upon the quality of the data from permanent sample plots (PSPs). These plots have a special significance. All other data can be supplemented at short notice with the injection of additional resources. However, additional *growth* data can only be provided with the passage of time, and for many forests, 5 years or more may be necessary to provide a reliable indication of long term growth trends (Vanclay, 1991).

The accuracy and applicability of all decision support systems is limited by the collective organizational resources dedicated to system development and improvement, including activities as diverse as field data collection and computer programming. The permanent sample plot databases we inherit reflect the needs and capabilities of the past generation, and should be periodically reviewed and updated as necessary to satisfy current needs and to provide for future opportunities. Whilst financial constraints remain, technological advances have created new opportunities and needs which should be addressed. It is timely to review the Queensland Forest Service's PSP system because of several changes:

Objectives: The original PSPs were selected as part of a continuous forest inventory system in which a representative sample of typical commercial stands was used to indicate growth trends for managed forest. Now, the role of PSPs is to provide data for the construction of growth models comprising part of the decision support systems for forest management.

Forest Estate: Considerable changes to the forest estate have occurred since the PSP system was established. Some State Forests have been revoked for National Park, other areas have been converted to plantations or other uses, and extensive new areas of State Forest have been gazetted.

Technology: Technological changes have eliminated many previous obstacles to data collection, including travel to remote areas, and limitations in storing and processing volumes of data.

Finance and Manpower: Resources have become more limiting and demand an efficient PSP system. We can ill afford redundant plots, but need to sample the full range of site and stand conditions with minimal replication.

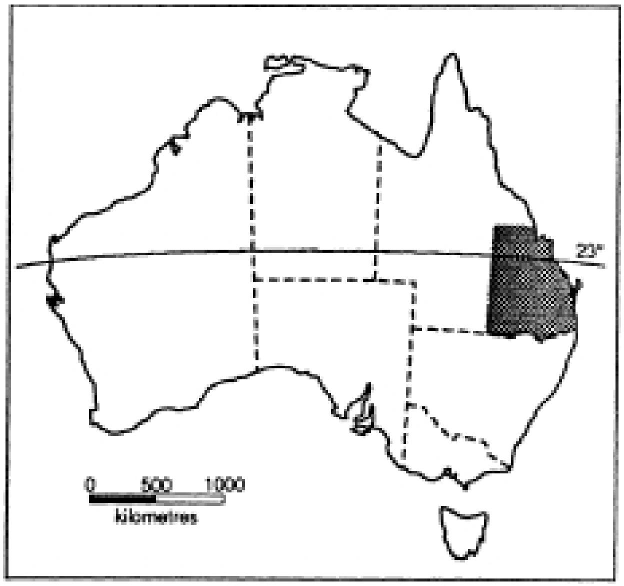

Fig. 1. Location of the study area (area emboldened).

This situation is not unique to Queensland, but is common to all Forest Services and natural resource agencies (e.g. Curtis, 1988). Thus, this study may be relevant to many other natural resource database managers. This paper considers the quality of data required for the development of reliable and accurate growth models, and outlines a review strategy being adopted to supplement the existing PSP system over an area covering approximately 40 million hectares of south-east Queensland, Australia (Fig. 1). About 10% of this area is State Forest which is managed by the Queensland Forest Service (QFS) for timber production and other compatible uses. Much of this forest is uneven-aged mixed species hardwood forest with more than 200 tree species, including more than 50 species of commercial importance. Such a diverse forest places additional demands on the PSP and decision support systems.

Criteria for a good database

One important criterion of a good database is the ability to make reliable inferences from it. All predictions are extrapolations in one sense (in time), but reliable inference requires an interpolation on the starting conditions. Thus if we develop a growth model from data for which some index ranges from I to 5 and attempt to make a prediction for a stand in which that index is 8, we are making an extrapolation rather than an interpolation, and our prediction is less likely to be reliable. In decision support systems for forest management, we are concerned with timber production and the growth of individual trees in the forest stand, and thus the important variables include site, stand and tree conditions. Site can be characterized by ecotype and some estimate of site quality. Stand and tree conditions can be characterized by tree size and competition.

Most of these variables of interest can be quantified in some sense, except ecotype which remains a qualitative variable. Whilst ecotype cannot readily be quantified, it remains possible to ensure that each ecotype is adequately sampled. One way is to ensure that the full range of latitude, longitude, altitude and rainfall is sampled. Another is to employ prior information such as vegetation and soil type maps to define homogeneous strata, and ensure that each stratum is adequately sampled.

It is easier to examine the sampling adequacy for the quantitative variables. These variables fall into two groups, the stand level and tree level variables. Competition may be expressed at the stand level as stand basal area (e.g. proxy for two-sided competition for water and nutrients) and at the tree level as basal area in larger trees (e.g. one-sided competition for light); both these variables have proved to be useful variables in growth models (Wykoff, 1990). Thus for growth models of native forests in which tree age is not known, the crucial stand level variables are site quality (SQ) and stand basal area (SBA), and the key tree level variables are tree size (DBH) and basal area in larger trees (BAL). We wish to sample the largest possible *range* of these four variables.

Most Forest Services conduct detailed resource surveys to determine the extent and nature of the forest resource, and these data may be contrasted with the PSP data to determine the adequacy of the PSP database. Ideally, an envelope drawn around the limits of the PSP data (Fig. 2[1]) should entirely enclose the resource survey data. In practice this is rarely possible, but the PSP envelope should still provide good coverage of the resource survey data (Fig. 3). This criterion should hold for both stand level data (SBA vs SQ) and tree level data for each species (BAL vs DBH).

These variables differ in their ability to be manipulated. For practical purposes, site quality is unchanging and cannot be manipulated, so our sampling strategy should sample the largest possible range of site quality. In contrast, stand basal area can be manipulated by thinning to lower basal areas. Generally we cannot expect to attain higher basal areas through growth (it may be possible depending on logging history, but may be unacceptably slow), so should ensure that our sampling provides data at the upper limits for stand basal area. Similarly, we should try to sample the full range of tree size for each species, and need to sample for high BAL, but can manage (by thinning) for low BAL.

Decision support systems for forest management should provide reliable predictions for the whole forest estate, and for a range of possible harvesting strategies and silvicultural treatments, and this places additional demands on our database. To find out what happens to a system when you interfere with it, you have to interfere with it, not just passively observe it (Box, 1966). Vanclay (1991) stressed the need to base growth models on experimental data as well as passive monitoring plots, and discussed the erroneous inferences that may be drawn from passive monitoring data in undisturbed natural forests where the correlation between site quality and stand basal area is high. Thus, it is necessary that we sample the widest possible range of site and stand condition, with particular emphasis on sampling a wide range of site quality and tree size, and on sampling high basal areas and BALs. One option to reduce confounding between SQ and SBA is to establish clusters of plots where SBA and BAL are high, to maintain one as a control, and to reduce the SBA of others by light and heavy thinning, both from above and below, so as to provide a good range of SBA and BAL for a single site.

Critical appraisal of the QFS database

The criteria outlined above provide a discriminating test of the PSP database. However, it presupposes meaningful ecotypes and adequate resource inventory to indicate the nature of the forest estate. Fortunately, the QFS has an extensive database of resource inventory collected during the past 30 years. Although some of these data are now rather old, growth in these forests is rather slow relative to the standing volume, and selection logging would normally leave the main characteristics of the forest unaltered; only stand basal area is expected to alter significantly. Thus even rather dated inventory may be useful in defining the relevant requirements for the PSP database.

Vegetation and soil type maps were not available at a suitable scale for the whole of the study area, so strata were defined using topography and climatic information. Twenty-one climatic indices were calculated for a network of weather recording stations across Queensland, and spatial interpolation (Hutchinson, 1987) was used to estimate corresponding values for each cell on a 0025 degree grid. Data were then aggregated to a more manageable 0.05 degree resolution and combined with eight terrain attributes for the topoclimatic classification using a non-hierarchical clustering procedure within the BIOCLIM package (Mackey et al., 1988, 1989). A subjectively determined threshold restricted the classification to 68 topoclimatic groups within the study area, 44 of which contained State Forest or Timber Reserve. Land of other tenures is also managed for timber production by the QFS, but, due to the high cost of establishment and maintenance, PSPs are only established on lands with the most secure tenure.

The area of State Forest or Timber Reserve within each topoclimatic group was determined using a geographic information system (ESRI Arc/Info) where suitable digital data were available. Elsewhere, transparencies of the State Forests and Timber Reserves were produced to the scale common to the topoclimatic graphic output. Areas were determined by the proportion of topoclimatic group cells to the total number of cells occurring in a State Forest or Timber Reserve, multiplied by the gazetted State Forest or Timber Reserve area. Topoclimatic groups were then amalgamated using the similarity dendrogram produced in clustering, resulting in 30 topoclimatic groups ranging in size from about 100

[1] Site form has ban used as a measure of site quality and is defined by Vanclay and Henry (1988) as 'the expected height of a 25 cm d.b.h.o.b [diameter at breast height over bark] tree predicted from the stand height-diameter relationship'.

hectares to over one million hectares. An example of topoclimatic groups 1 to 8 is shown in Table 1.

Further stratification of each topoclimatic group was based on a non-hierarchical cluster analysis (Genstat 5 Committee, 1988) of species composition within the individual temporary inventory plots (TIPs). This analysis was complicated by the different measurement standards used for these plots, and care was taken to ensure that the same standard applied (viz. lower limit for dbh measurement) to all plots within a topoclimatic group. In general, where a species exceeded 3-5% of the total basal area of the topoclimatic group, its percentage of the SBA of each TIP was included as a variable in the analysis. All remaining species that did not meet this criterion were bulked to create an extra variable.

In the three cases where the clustering within a topoclimatic group was considered unsatisfactory (such as when a cluster was dominated by two species which rarely associated together in the forest) further analyses were undertaken by varying the user specified number of clusters. The final clusters have been designated as forest types within topoclimatic groups. The area of each forest type within a topoclimatic group was then determined according to the proportion of inventory plots occurring in the forest type.

All existing PSPs were assigned to a topoclimatic group. Although stems as small as 2 cm DBH have been measured on some PSPs, the DBH limit used throughout these analyses was dictated by the TI Ps (see Table 1) and the need to ensure compatibility within topoclimatic groups. The forest type of each existing PSP was defined to be that of the cluster with the nearest centroid in n-dimensional Euclidean space. The typing of PSPs was considered to be successful as no PSP was near the mid-way point between two cluster centroids.

Table 1. Stratum summary for topoclimatic groups 1 l0 8

Topoclimatic Group no	Lower diameter limit (cm)	Forest type number	Forest type dominant species	Forest type (ha)	Mean basal area (m^2/ha)	Number of existing PSPs	Stand* data range index *(%)*	Stand* data capture index *(%)*	Tree† data range index *(%)*	Tree† data capture index *(%)*	Proposed number of PSPs
1	14	1	*Callitris glaucophylla*	10000	6.4	6	17	36	36	77	9
		2	Other spp.	59400	4.3	28	50	42	67	99	9
2	14	*1*	*Callitris glaucophylla*	9000	3.5	0	0	0	0	0	9
3	20	1	Callitris *glaucophylla*	207100	3.5	25	79(40)	62(76)	67	95	9
		2	*Eucalyptus crebra*	97100	5.7	6	42	73	42	87	9
		3	Other spp.	80000	5.8	5	61	89	20	68	9
4	20	*1*	*Eucalyptus crebra*	9200	8.2	0	0	0	0	0	9
		2	*Callitris* glaucophylla	7700	5.5	0	0	0	0	0	9
5	15	1	*Lophostemon confertus*	19700	28.5	0	0	0	0	0	13
		2	*Eucalyptus propinqua*	26800	19.5	0	0	0	0	0	13
		3	*Eucalyptus pilularis*	5600	23.1	0	0	0	0	0	13
		4	Other spp.	13100	13.4	0	0	0	0	0	13
6	15	*1*	*Lophostemon confertus*	24200	27.8	0	0	0	0	0	13
		2	*Eucalyptus propinqua*	38500	19.1	0	0	0	0	0	13
		3	*Eucalyptus pilularis*	7000	22.7	0	0	0	0	0	13
		4	Other spp.	22600	13.4	0	0	0	0	0	13
7	29	1	Other spp.	348800	6.2	32	61	97	23	85	13
		2	*Eucalyptus maculata*	744500	4.8	34	54	78	36	98	13
		3	*Callitris glaucophylla*	362700	1.3	20	26	94	31	97	13
8	29	1	*Eucalyprus maculata*	10600	3·7	0	0	0	0	0	13
		2	*Callitris glaucophylla*	215700	1.3	0	0	0	0	0	9
		3	*Eucalyptus maculata*	124500	4.3	3	11	23	I5	66	9
		4	Other spp.	52400	7.3	12	88	50	86	68	13
		5	*Eucalyptus crebra*	53600	5.1	5	23	24	22	64	9
Total:	24			2149800		176					264
Grand total‡:	90			3728700		315					970

* One-dimensional, based on SBA only.
† DRI and DCI are based on all species and are not species specific.
‡ Total for all 30 topoclimatic groups.
()Two-dimensional indices based on SBA and site form.

Site quality estimation poses a more difficult problem, and cannot be readily quantified for most forest types in the study area. For *Callitris* forest, site quality can be estimated using site form (Vanclay and Henry, 1988) and has been used in Figs 2 and 3. Meaningful estimates of site quality are not available for the other forest types, so the stand-level parameters must be contrasted in one dimension only, by comparing basal area ranges.

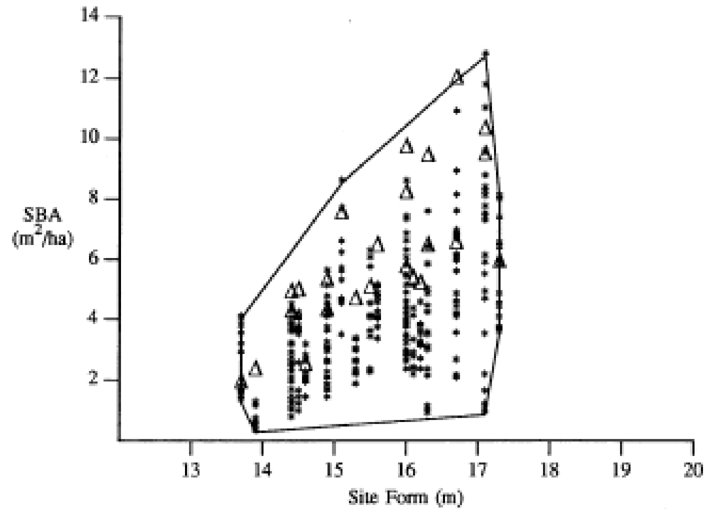

Fig. 2. Standing basal area versus site form of the permanent sample plot, for topoclimatic group three, forest type one, showing the data space sampled (Δ signifies the last measure of each PSP).

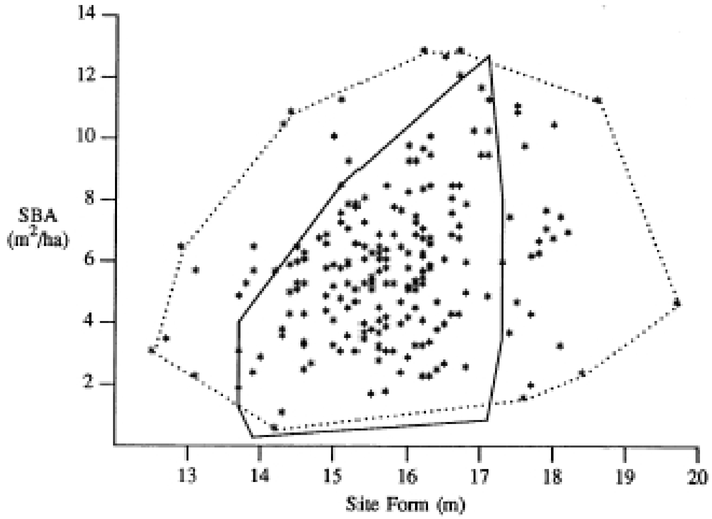

Fig. 3. Standing basal area versus site form of the temporary inventory plots for topoclimatic group three, forest type one, with the PSP data space shown as a solid line.

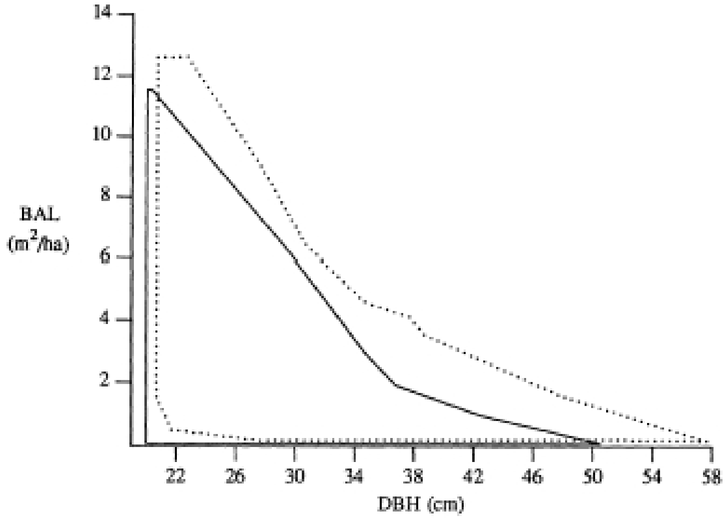

Fig. 4. Basal area of all larger trees versus diameter at breast height of *Callitris* in the PSPs (solid) and the TIPs (dotted) for topoclimatic group three, forest type one.

Figures 3 and 4 provide a graphic illustration of the adequacy of the PSP data for a single forest type (topoclimatic group 3, forest type 1), and clearly indicate the need to sample higher SBA, better sites and bigger trees. The database for some strata was even more limited and Fig. 5 illustrates the inadequacy of the existing five PSPs in topoclimatic group 8, forest type 5 at sampling *Eucalyptus crebra*. For the purposes of comparison and rapid appraisal it is convenient to have simple indices indicating the extent to which the PSPs sample the total data space defined by the TIPs within the stratum. Thus, we have defined the data range index, DRI, to be the range of the PSP data expressed as a percentage of the combined ranges of the PSP and TIP data. The PSP and TIP data are combined just in case a current PSP falls outside the range of the TIPs. Thus at the stand level where only basal area data are available, the data range index is given by:

$$DRI = \frac{\text{Max}(SBA_{PSP}) - \text{Min}(SBA_{PSP})}{\text{Max}(SBA_{PSP}, SBA_{TIP}) - \text{Min}(SBA_{PSP}, SBA_{TIP})} \times 100\%$$

The two-dimensional DRI is used where estimates of site quality are available (e.g. Fig. 3):

$$DRI = \frac{\text{area of PSP envelope}}{\text{area of envelope spanning the combined PSP and TIP data sets}} \times 100\%$$

These envelopes are illustrated in Fig. 3, and are defined as the convex hull of the SBASQ data pairs. The data capture index, DCI, is defined to be the percentage of TIP data points which fall within the PSP envelope. The DRI and DCI at tree level were computed in two dimensions, using a minimum-area polygon defined by the BAL-DBH data pairs and subject to certain monotonicity constraints. The minimum-area polygon, rather than the convex hull, was used for the tree level data because of the concave distributions commonly exhibited by these data (e.g. Figs 4 and 5). For brevity, the tree level DRI and DCI were computed across all species, ignoring species identities.

The DRI may be interpreted as the proportion of the potential data space for which PSP-based growth models will interpolate, rather than extrapolate. The DCI is a measure of the actual proportion of forest area for which the PSP-based models will interpolate. Thus 100-DRI tends to indicate the magnitude of extrapolations, whilst 100-DCI indicates the frequency. It is therefore desirable that both indices be as high as possible.

For example, topoclimatic group 7, forest type 1 has a reasonable stand level DRI but very good DO (Table 1), and these indices indicate that for most of the forest area, the PSPbased growth models will interpolate and gross extrapolation may be required for only a few small pockets of forest. This is further supported by the PSP and TIP histograms in Table 2. In contrast, topoclimatic group 8, forest type 4 has a high stand level DRI and mediocre DO which indicate that a large proportion of the forest area will require small extrapolations by PSP growth models.

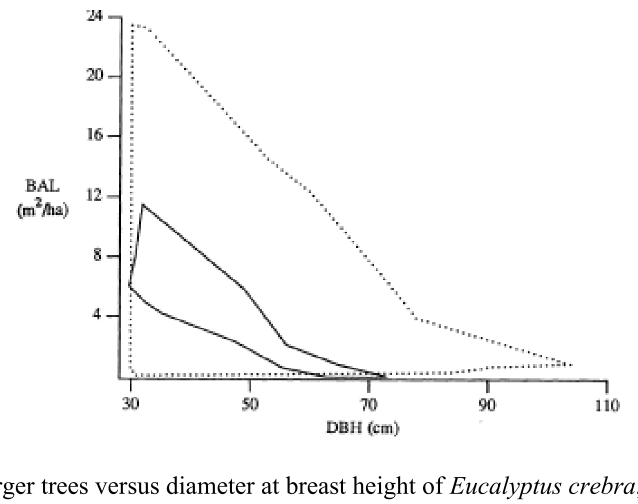

Fig. 5 Basal area of all larger trees versus diameter at breast height of *Eucalyptus crebra*, to the PSPs (solid) and the TIPS (dotted) for topoclimatic group eight, forest type five

Table 2. The basal area distribution of the temporary inventory plots (TIPs) and permanent sample plots (PSPs) illustrating the coefficient of variation (%) for PSP basal area increment between the last two measures

Topoclimatic group no.	Forest type no.	Mean basal area inc. (m'/ha/y,)	Basal area inc. coefficient of variation (%)	Data type	Basal area class midpoint (m^2/ha)						
					2	6	10	14	18	22	26
1	1			TIP	57	126	60	10			
		0.08	120	PSP		6					
3	1			TIP	508	243	46	5			
		0.20	50	PSP	3	16	6				
3	2			TIP	l06	l97	62	11			
		0·13	60	PSP	1	4	1				
7	1			TIP	1364	1228	731	278	70	13	1
		0·15	55	PSP	14	8	7	3			
7	3			TIP	3645	163	19	3	2		
		0.13	60	PSP	16	4					
25	3*			TIP	2	28	88	79	23	10	
		0.22	75	PSP			2	2		1	
25	5†			TIP	14	88	132	88	26	4	
		0.27	70	PSP		3	2	3			

Dominant species are *Eucalyptus acmeniodes** and *Eucalyptus maculata*†.

Supplementing the existing database

Number of permanent sample plots required

Most forest managers have difficulty in specifying the precision required in a resource estimate or yield forecast. Usually, they clutch at some accepted standard like within 10% at the 90% confidence level, even if they do not understand the implications and costs. The QFS aims for estimates of the allowable cut with an overall standard error (inclusive of error in area, inventory, growth prediction and volume estimation) not exceeding 20%. Clearly, the implications of this recommendation on the collection of growth data depend on the precision of other data sources, and the relative cost of improving the precision of each category of data. However, growth data have a special limitation-they cannot simply be obtained by the injection of additional resources as some time must elapse before new PSPs provide useful data. Financial limitations provide a ceiling on the number of PSPs to be maintained, whereas statistical considerations usually indicate ‘more than can be afforded’.

Reliable growth data can only be obtained from well managed and regularly measured plots, in which procedures and standards have been maintained. There is little point in trying to establish more plots than can be maintained, or similarly, not establishing sufficient numbers of plots. Unless plots are remeasured every 5 years or so, plots, number tags and records may become lost and the measure record useless. More frequent measurement is of limited utility in many forest types, as measurement errors approach the magnitude of the increment over shorter intervals. Thus, financial criteria provide a more tractable limit on the number of PSPs to establish, and we look to statistics to indicate the optimal placement of these plots.

There are two criteria we need to consider. We need to establish PSPs in strategic locations to expand the PSP envelope so that it equates to the resource inventory envelope. Then, if we still have funds available, we should establish additional PSPs to sample areas in the data-space where the variance associated with predictions is high.

It is difficult to determine the variance associated with predictions, especially since suitable growth models do not yet exist for some forest types. However, stand basal area increment *(SBAI)* is often relatively constant over a wide range of stand conditions, and the coefficient of variation (CV) of *SBAI* may provide an indication of site variability and thus of the variance of predictions. Thus CV may provide an indicator of the relative number of plots required:

$$n = CV^2/SE^2$$

where CV = coefficient of variation expressed as a % and SE = desired standard error expressed as a % of the mean.

The coefficient of variation in basal area increment was calculated for those strata with sufficient PSPs covering the basal area distribution of inventory plots. Table 2 shows that the coefficient of variation, in general, ranges from 55% to 75% (topoclimatic group 1 was ignored as the forest type only occupied 10000 ha of low grade forest). The remaining groups were amalgamated into two classes, the inland class (including topoclimatic groups 3 and 7) with a CV of about 60% and the coastal class (including topoclimatic group 25) with a CV of about 70%. With a target SE of 20%, this suggests that 9 and 13 PSPs per stratum, respectively, may be required. Other factors such as the ability to maintain the established PSPs and the relative importance of the stratum also require consideration when determining the number of PSPs for a stratum. Whilst the number of PSPs recommended (Table 1) is conservative, prevailing budgetary constraints limit the introduction of a less conservative sampling procedure.

Permanent sample plot selection procedure

Table 1 indicates that there are three cases to be considered in supplementary sampling: strata not previously sampled (e.g. topoclimatic group 2), strata sampled at about the intended intensity (e.g. topoclimatic group 8, forest type 4), and strata which contain more plots than proposed (e.g. topoclimatic group 3, forest type 1). This implies that we have both to examine the TIPs to identify plots that would improve the quality of the PSP database if re-established as PSPs, and also to examine the existing PSPs to identify those which contribute little and which could be abandoned or modified as required. These requirements are not exclusive; Fig. 4 illustrates that the present 25 plots in that stratum do not sample the full data space, despite the generous size of the sample, and that additional plots are required. Some plots may contribute data in an adequately sampled part of the data space, but could be moved to an unsampled part by thinning the plots. The thinning regime required will not be determined in the present paper, but will be addressed in a subsequent study. This disregards the fact that thinning an existing plot to a new extreme may be more cost effective than establishing a new plot, but ensures a comprehensive sample of natural and managed stand conditions. A good database requires both passive monitoring and experimental plots, and the latter can be added at the next stage of the study. Thus there are two steps involved: firstly to identify if additional plots are required to sample the data space adequately, and secondly to identify any PSPs which may be sacrificed for thinning studies, or abandoned in the interests of economy.

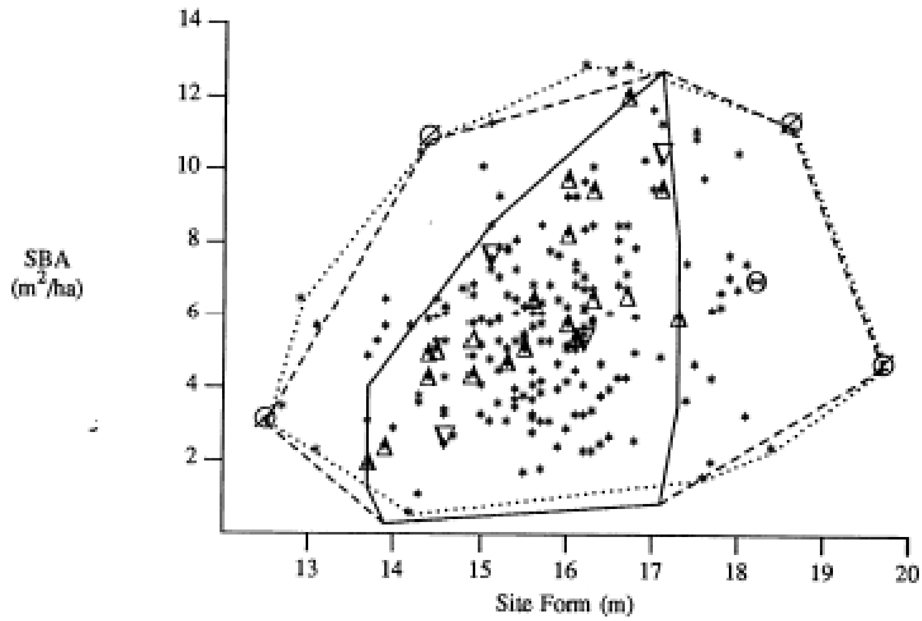

Fig. 6 Illustration of the PSP selection procedure showing the vertex plots (Ø), existing PSPs to be maintained as PSPs (▽), additional TIP to become a PSP(Θ), the remaining TIPs (*) and PSPs (Δ)and the new PSP envelope (dashed).

It is efficient to employ different strategies for sampling inter-tree competition and tree size. The three key components of tree level growth models, viz. diameter increment, tree survival and recruitment, all decrease monotonically with increasing competition (Wykoff, 1990). Similarly, diameter increment increases monotonically with increasing site quality. Thus it is particularly important to sample the extremes of *SBA, BAL* and SQ. In contrast, diameter increment and tree survival may exhibit a more complex relationship with tree size (i.e. the response surface has a maximum within the range of interest; Wykoff, 1990). Thus we should ensure a good spread of sample points across the entire range of DBH, not just at the extremes. This implies that we should concentrate on sampling the extremes of stand level data (i.e. SQ vs SBA graph, Fig. 3), but also sample the whole range of tree level data (i.e. DBH vs BAL graph, Figs 4 and 5). Thus supplementary sampling will first target extreme site and stand conditions (viz. extreme TIPs in Fig. 3), and secondly attempt to supplement the distribution of tree level data for each species. One obstacle is the lack of site quality estimates for many forest types, so we shall first examine the strategy for the *Callitris* forest for which site form estimates are available.

It is unlikely that perfect indices (stand and tree level DRI and DCI all 100%) could be achieved with the financial resources available, so assume that an adequate sample is provided when both the stand level DRI and DCI exceed 95%. This standard has not yet been attained in any stratum (Table 1), even where the number of existing plots exceeds the proposed number, so supplementary sampling of extremes is required in all cases. We iteratively examine, until this desired 95% level is attained, the simultaneous selection of 1, 2,..., *n*/2 extreme TIPs in the SQ vs SBA graph (i.e. Fig. 3) which, when added to the existing PSP data, would maximize the stand level DRI. The limit *n/2,* where *n* is the number of PSPs proposed (Table 1), is imposed to reserve half the plots for supplementary sampling at the tree level. Generally the 95% target should be attained without exceeding this limit. Figure 6 illustrates the TIPs which would be selected to supplement the existing PSPs in topoclimatic group 3, forest type 1 (cf. Fig. 3). It is clear that an additional four plots are required to complement the existing *25* PSPs. These plots which define the convex hull designating the PSP data space are called vertex plots, and are exempted from consideration for possible abandonment or modification in the second sampling state.

The second stage involves sampling to satisfy extremes in the tree level data (i.e. DBH vs BAL, Figs 4 and 5), and to fill voids in both the stand and tree level data. Because of the correlation between SBA and BAL, it is assumed that a strategy to fill voids in the tree level data would also fill the voids in the stand level data. Thus this stage focusses on the tree level TIP data. The ability of these data to fill voids in the tree level PSP data can easily be detected by examining the distance to the nearest neighbour, and the only complexity is that we may need to examine several species simultaneously. A suitable criterion may be to consider the largest void filled (i.e. square of distance to nearest neighbour), summed across all species on the plot; this recognizes the importance of sampling all the species in a stratum. High values of this statistic for TIPs indicate candidates for supplementary PSPs. Conversely, low values for existing non-vertex PSPs indicate candidates for experimentation or abandoning. Unfortunately, however, the statistic does not resolve when to substitute existing PSPs for new ones based on TIPs, and some subjective criterion is necessary. It is desirable to maintain some existing PSPs; remeasurement is cheaper than re-establishment, and long re-measurement histories are useful for model validation (Vanclay, 1991). We will arbitrarily choose to retain at least *n*/2 (where *n* is the proposed number of plots per stratum) of the existing PSPs, and will substitute TIPs for additional existing PSPs provided that the nearest neighbour criterion of the TIPs exceeds twice that for the PSPs. Figure 6 illustrates the establishment of one additional new PSP, and identifies 21 existing PSPs which could be modified or abandoned. It is important to note that if these or any other PSPs are abandoned, their existing measure record will not be discarded, but will be retained in the database and will continue to be available for model development and other research.

One possible deficiency with this procedure is that it will tend to favour the sampling of mixed species rather than monospecific stands. Some species such as *Eucalyptus maculata* may occur in both pure and mixed stands, and it is important to sample both cases. Thus the number of dominant species (those comprising more than 5% of the SBA) in a stand may be an important additional dimension to sample. *Callitris* forest is an exception, as it commonly occurs as pure or nearly-pure stands, and is already well sampled in most strata. The remaining forest types have no reliable estimates of site quality, and number of species can be used as the second dimension for the stand level data (i.e. instead of site form in Fig. 6), and the same procedure for supplementary sampling can then be adopted.

Implementation and establishment of new PSPs

The PSP selection procedure provides a theoretical basis for selecting new PSPs, but it may not be practical. Some of the selected TIPs will not provide the anticipated data because of imprecise locational details, measurement errors and changes in stand conditions. Thus effective implementation requires criteria for rejecting a plot, provision of suitable alternatives, and procedures to flag such rejected plots in the TIP database so that the same problem does not re-occur. This difficulty occurs only for TIPs selected to become PSPs, and does not extend to the PSPs to be retained or abandoned.

Although critical for effective implementation, these provisions are not difficult to satisfy. Search algorithms can be enhanced to provide next-best alternatives for each case. They can also print out the selection criteria, which in most cases are easily determined and need not be stringent. Clearly, all plots must conform to the forest type definition. Vertex plots (i.e. plots indicated as 0 in Fig. 6) are selected to provide specific extreme combinations of site form (SF) and stand basal area which thus provide the basis for plot rejection. Thus, for the vertex TIP at SF =19-7, SBA =4-6 in Fig. 6, we would require a new PSP to have SF_> 19, SBA _< 8. If these stand conditions could not be found in the vicinity of the given TIP grid reference, the vertex would be rejected and the alternative (in this case, the TIP at SF = 1&4, SBA =2-3) would be used. The identity of each TIP is known, so that rejected plots can be annotated in the TIP database and excluded from future attempts at PSP selection.

Other TIPs (such as the Θ in Fig. 6) may be selected to fill voids in the tree level data (i.e. the DBH vs BAL graph), and criteria for the rejection of such plots may be based primarily on the size of individuals of selected target species. BAL is impractical to use as a rejection criterion, as it generally cannot be determined without establishing and measuring a plot (but note that BAL =SBA for the smallest tree, and BALLS for the largest tree). However, since growth exhibits a more complex response with DBH than with BAL, the sampling of DBH is of greater importance. In some cases it is practical to specify extremes of both DBH and BAL (e.g. in Fig. 5, an *E. crebra* with DBH < 50 which was one of the biggest in the stand would also ensure BAL near zero). Generally, sufficient rejection criteria would be to specify the size and species of trees required within the plot, and a specified SBA range. Such criteria are feasible and practical.

Limitations of the present review

Whilst the present review of the PSP database employed the best available information and techniques, our conclusions are subject to deficiencies in these resources, and the present review should be seen as part of an on-going iterative process rather than the final authority. The following limitations may impinge on the results, and new developments in these areas may indicate a re-appraisal:

- The present study omits geology, lithology and soils data, which have obvious implications for the definitions of ecotypes.
- The digital elevation model was based on rather sparse data, especially in the western part of our study area, where topographic inference may be sub-optimal.
- The classification relies on the subjective choice of procedure and threshold values, and the implications of these choices on the classification results are not fully understood.
- Several different procedures have been used in resource inventory and these may influence the data and the definition of the feasible data space (Fig. 3).
- Changes due to forest management and natural processes throughout the time since the conduct of inventory have not been considered.
- This approach limits PSP placement to the forest estate previously surveyed, and does not venture into unsurveyed areas.

- Some inventory plots, when selected for PSP establishment, will not provide the anticipated data, due to imprecise locational co-ordinates, measurement errors and natural changes in stand condition. The severity of this problem will be gauged during the next few months when new PSP establishment is commenced.

- The present study assumes that SF, SBA, DBH and BAL are the major determinants or predictors of forest growth. For even-aged stands (e.g. plantations) it may be useful to include age as an additional stand-level variable.

- The present study has focussed on the selection of TIPs for use as PSPs in their existing condition. Some of these plots (both new PSPs chosen from TIPs, and existing PSPs) could be thinned to different prescriptions to provide new extremes of data. The feasibility of this remains to be investigated.

- This study has concentrated on sampling the range of natural and managed site and stand conditions. Experimental silvicultural studies also influence the quality of the database, and should be considered in a subsequent study. However, Fig. 2 illustrates that most existing plots sample a reasonable range of SBA, and that many existing PSPs constitute more than passive monitoring.

- Whilst the data range and data capture indices provide a useful summary of the PSP database, they inevitably contain an optimistic bias. Additional resource surveys may increase, but never decrease, the TIP data space, so the DRI and DO estimates may be inflated. The magnitude of this bias depends on the nature and extent of the resource surveys, and may be serious for samples with few TIPs.

The reliability of growth models depends directly upon the quality of the PSP database. Conditions and aspirations may change, so it is necessary to review the PSP database from time to time. PSP databases should encompass many dimensions of site and stand condition, and it is difficult to appraise their adequacy subjectively, so a formal procedure is preferred. The procedures and indices developed in this study contribute towards such a formal review procedure.

A review of the Queensland Forest Service database indicates that the present PSP sample is rather uneven, providing good coverage of some forest types, and neglecting other types. Objective selection of some TIPS for conversion to PSPs should provide a cost-effective way to remedy these deficiencies. We estimate that a minimum of 747 new PSPs selected in this way would provide a suitable database for future modelling attempts. Also, at least 92 of the existing PSPs in oversampled parts of the data space could be abandoned.

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