Review of measures of site occupancy by regeneration

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Summary

This project investigated the potential to develop an indicator for national reporting of regeneration success. Systems of measuring site occupancy, including performance measures and sustainability evaluation, are reviewed to identify those worth further testing.

Current site occupancy measures are based on spatial statistics, frequency and/or intensity, and incorporate an evaluation of whether site resources are being fully utilised by the regeneration. The scientific basis of current measures can be improved by establishing the relationship between initial spatial distribution of regeneration and long-term wood production, including wood quality outcomes. Those measures based on both frequency and intensity are likely to be more sensitive, but more costly.

Recommendations are made for further actions to progress development of the national indicator of regeneration success. The key recommendations are to model the spatial pattern of regeneration and simulate the application of alternative measures of site occupancy to the modelled distributions.

Keywords: forests; regeneration; regeneration surveys; stand density; descriptors; distribution; occurrence; layout; standards; methodology; review

Introduction

Regeneration or renewal of the forest has been recognised as a fundamental part of sustainable forest management since intensive harvesting of Victoria's native forests began in the 1960s (Lutze *et al.* 1999). Since then there has been a growing need for greater accountability, and the development of formalised methods and standards to monitor regeneration success. The Department of Sustainability and Environment has developed a system of monitoring regeneration that is implemented state-wide (DNRE 1996; Dignan and Fagg 1997). Other State forestry agencies in Australia have also developed regeneration monitoring systems (CALM 1990, 1997; NSWFC 1994; Forestry Tasmania 1996, 1998, 2003). As part of the Wood and Paper Industry Strategy, projects have been undertaken to investigate Montreal process criteria and indicators (Commonwealth of Australia 1998). This paper reports on part of the project to investigate the potential for a standardised measure for national reporting of regeneration success.

Regeneration is measured to determine whether it meets the objectives of sustainable forest management, in particular whether the productive capacity and biological diversity of the forest are maintained. In the context of wood production, a measure of regeneration can indicate whether the forest maintains the ability to produce a range of forest products over a suitable time frame or rotation. The term 'site occupancy' is sometimes used to express the degree to which the timber production objective is met, and in that context it is defined as the degree to which trees use the soil and water resources of the site over an appropriate time frame.

The many measures of site occupancy aim to integrate the effects of seedling density and spatial distribution. Seedling density or number of seedlings in a given area (usually number per hectare) is difficult to interpret as a measure in stands regenerated from seed, because the seedling distribution is often aggregated. The trend to aggregation has been well established in various forest types of North America and Europe (Ghent 1963; Diggle 1983; Brand *et al.* 1991), and has also been demonstrated in at least one type of wet eucalypt forest in Tasmania (Mount 1961). The resulting spatial variation in density is likely to have an influence on stand yield and self-thinning rate (Opie *et al.* 1984; Lockett and Goodwin 1998). While stands may have sufficient seedlings per hectare, there may be areas where seedling density is below that required to maintain site productivity and good tree form.

Thus, understanding the spatial pattern of tree regeneration could be critical to the development of effective indicators of regeneration success. The analysis of the spatial distribution of seedlings is generally approached by considering seedlings as point locations. Data in the form of a set of points in a region of space, such as the position of seedlings in a forest stand, are often referred to as a spatial point pattern, and a number of methods have been developed to analyse and interpret such data. The broader ecological literature describes numerous spatial statistics and their application to spatial pattern analysis (Greig-Smith 1957; Kershaw 1964; Pielou 1974; Ripley 1981; Diggle 1983; Ludwig and Reynolds 1988; Dale 1999). The same spatial statistics are used in the systems of measuring site occupancy in forestry. A critical review of methods for measuring site occupancy, including their spatial statistics and evaluation systems, is required to identify those measures that are able to deal with a range of spatial patterns and which may be suitable for national reporting of regeneration success in native forests.

The objective of this review is to determine the most appropriate measures of site occupancy, including their spatial statistics and evaluation systems, for further testing as potential national indicators of regeneration success.

Evaluation of sustainability indicators

Measuring site occupancy will be considered within the context of the general framework of sustainability indicators. A useful indicator should meet the following criteria (DPIE 1996). The indicator will:

(i) be firmly linked to the criteria and relevant to the region and goals of forest management,

(ii) have a sound scientific or other relevant basis,

(iii) be understandable and clearly interpretable,

(iv) be sensitive and be able to measure critical change with confidence,

(v) have costs appropriate for the benefits,

(vi) be feasible and realistic to measure over relevant time frames and spatial scales,

(vii) have targets for thresholds built in, or be capable of having these applied, and

(viii) contribute directly to continuous improvement in management and performance.

A set of indicators taken together (including the indicator of regeneration success) must be able to adequately assess whether forest management is ecologically sustainable.

Intensity and frequency

The two spatial statistics most commonly used in measuring site occupancy are ‘intensity’ and ‘frequency’. The first-order property of a spatial point process is the way the mean number of points (seedlings) per unit area, that is intensity, varies through space (Kaluzny *et al.* 1998). It provides an alternative approach to nearest-neighbour distances (Pielou 1959) in determining spatial distribution. A region is subdivided into sub-regions or quadrats of equal area and the counts of points in the quadrats are used to indicate the variation in intensity. The mean of the point counts within a sample of quadrats is often used to calculate density, as the number of seedlings per hectare. A related statistic is the fraction of quadrats containing at least one seedling, or frequency. In the forestry literature frequency is often referred to as ‘stocking’ or ‘stocking per cent’ (Boyer 1977; MacLeod and Chaudhry 1979; Doucet 1991; Newton 1998), whereas in the broader ecological literature it has been referred to as ‘occupancy’ or ‘site occupancy’ (Pezeshki *et al.* 1996; Crawley and Brown 1995). In this review paper, site occupancy has a broader definition.

Site occupancy

Site occupancy is a measure of spatial distribution that reflects the ability of trees to grow and utilise the site resources. The most objective approach to quantifying site occupancy has been in established even-aged stands through the relationship between tree size and density. With the onset of self-thinning in a developing stand, increasing average tree size is associated with a decreasing number of trees, and a universal relationship of the form $Y = K\rho^A$ applies, where Y is mean size, ρ is trees/unit area, and A and K are constants (Long and Smith 1984). The relationship represents both a self-thinning trajectory and a maximum boundary for size or density. Comparison of the size–density combination of a developing stand with the maximum boundary provides an objective measure of site occupancy (Jack and Long 1996; Bi 2001). However, the usefulness of the relationship for naturally regenerated stands in an early stage of development — where there may be wide variation in density across the stand — is yet to be established.

The absence of a clearly defined relationship between initial density and spatial arrangement, and site occupancy, has seen the development of a large range of performance measures and sustainability evaluation systems. The performance measures are based on intensity and nearest-neighbour statistics, and include density (i.e. intensity) by quadrat counts, by distance to a closest individual (i.e. nearest-neighbour distances) or by triangular tessellation and stocking per cent (i.e. frequency) based on quadrats or on triangular tessellation density. The measures used in Australia cover the range of possible approaches, although there are so many variations in the way the measures can be applied that those tested represent only a subset of the available methods.

The systems reviewed here incorporate an evaluation of a spatial statistic against a threshold or standard which reflects the management objective, a specific aim in terms of long-term wood production. The evaluation sub-system usually includes a method for summarising the statistic to the required scale, a standard(s) or desirable level(s) to which the statistic is compared, and decision rules to determine appropriate action on the basis of the comparison.

Below are details of measures of site occupancy used in Australia, and some overseas examples, together with evaluation methods. All measures are applied at the coupe scale (10–100 ha) and use a similar field sampling procedure, a systematic grid with a random starting point. Typically, transects are spaced at 40–100 m and are aligned with the long axis of the regeneration area, and sample points are located at 20 m intervals along the transects.

Seedling density by quadrat count (4 m^2, 16 m^2 and 50 m^2 circular plots)

The quadrat count measure of density has been widely applied in ecological surveys (Kershaw 1964). The smallest plot sizes are 4 and 16 m^2, which correspond to the 1 and 4 milacre plots which have been routinely applied in forest regeneration studies in Victoria and Tasmania and in other countries (Lowdermilk 1927; Mount 1961; Loetsch *et al.* 1973; Dignan and Fagg 1997). Stand seedling density can be calculated as the mean of the quadrat counts (or back-transformed mean of the log-transformed counts) converted to a per-hectare value (Dignan and Fagg 1997).

Mount (1961) recommended that the seedling density be reported along with the heterogeneity factor to indicate how the density is distributed. The heterogeneity factor (h) relates the count to the frequency of quadrats,

$$h = (d_o - d_m) / (d_r - d_m) ,$$

where d_o is observed density, d_m is the minimum density for the measured frequency (f%) of stocked plots, and d_r is the random density for the measured frequency (f%); that is,

$$d_m = f/100 \text{ and } d_r = \log_e(100/100–f),$$

from the Poisson distribution. Heterogeneity factor $h = 1$ for random distributions, < 1 for uniform, and > 1 for aggregated distributions.

The advantage of the h factor is that it integrates the frequency with density data, whilst providing a measure of aggregation. Greig-Smith (1957) and Mount (1964) provide details of other measures of heterogeneity that are based on both observed density and frequency. According to Mount (1964), his measure is better because it removes the influence of frequency on the observed and random densities (the latter derived from frequency). Mount (1964) found that h was largely independent of quadrat size for a number of data sets, and concluded that it provided a good measure of the factors that produce aggregation.

However, seedling density by quadrat count is not routinely used for regeneration evaluation in Australia. Nevertheless, the current standards for regeneration success in Victoria are based on a seedling density exceeding about 2500 seedlings ha^{-1} in aggregated stands, the optimal level for combined sawlog and pulpwood production in ash stands (Edgar and Opie 1976). The density is about equivalent to a stocking of 65% by 16 m^2 quadrats (Squire *et al.* 1991).

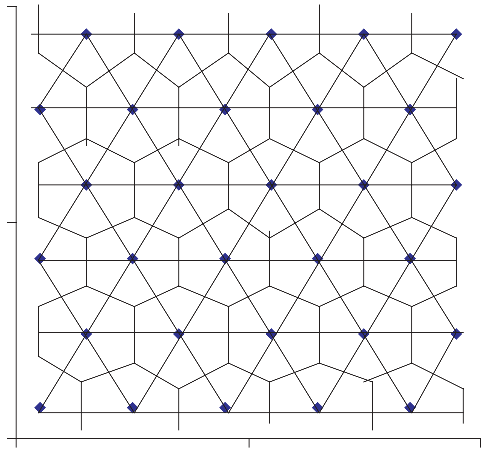
Use of much smaller plots has been reported in the broader ecological literature (Kershaw 1964). This usually reflects the difference in size of individual plants and the trade-off between precision and cost (Zhang *et al.* 1994). Fewer but larger plots (e.g. five plots of radius 3.99 m ha^{-1}) have been used in recent times in North American coniferous forests (Ministry of Forests 1999). In the latter forests, the approach has increased in complexity over the last two decades and can include the measurement and evaluation of seedling density, height and species composition. The survey is carried out about 5 y later than in Australian native forests, which permits the inclusion of growth and quality parameters. However, there are differences in early stand dynamics which prevent direct transfer of the methods used in mixed coniferous/deciduous forests to Australian eucalypt forests. In the case of eucalypt forests, the eucalypts normally dominate any competitive species, and it is not necessary to monitor whether non-productive species dominate at the later stage of development.

Although more accurate than distance-based methods, density-by-quadrat measures may produce biased estimates of seedling density, the size of the quadrat having an influence on the edge effect and wrongful inclusion or exclusion of seedlings (Ghent 1963).

Seedling density by triangular tessellation

The triangular tessellation measure is based on the concept that each seedling has its own domain bounded by a polygon which is nearer to that seedling than any other, a measure first introduced in plant ecology (Brown 1965; Mead 1966) a century after the geometrical construct had been presented. The arrangement of a

(a)



(b)

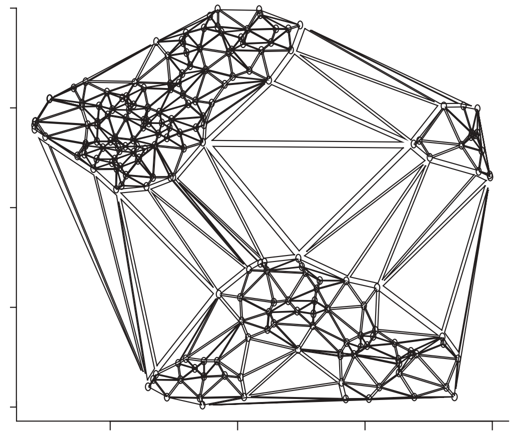


Figure 1. (a) Voronoi polygons and Delauney triangles for points located on a triangular grid (after Okabe *et al.* 1992); (b) Delauney triangles for an aggregated pattern

number of such polygons in a plane is usually referred to as a Dirichlet tessellation (Dirichlet 1850) or Voronoi diagram (Voronoi 1908). From the Dirichlet tessellation, a Delauney tessellation or triangular tessellation is formed (Delone 1961) consisting of triangles joining the points or seedlings for which the associated polygons have an edge in common (see Fig. 1). It follows that the triangles thus formed represent half the areas occupied by the seedlings (Okabe *et al.* 1992), and the inverse of the area of the triangles surrounding a sample point is directly proportional to seedling density at that point.

Although there was prior discussion of the potential utility of the concept in forest inventory (Loetsch *et al.* 1973), Ward (1991) was first to develop the method for use in regeneration surveys in Australian native forests. He recommended the following method of calculating point density:

$$D \text{ (seedlings ha}^{-1}) = 10\,000 \text{ (m}^2\text{ ha}^{-1}) / 2A \text{ (m}^2)$$

$$= 5000 / A ,$$

where A is the area of the tessellation containing the plot point, as determined by the Heron formula. Ward also developed a table for approximate calculation of point density from the length of the three triangle sides, which could be applied in the field (CALM 1990, 1997). The arithmetic mean of the point density estimates can provide an unbiased estimate of seedling density (Ward 1991). Seedling density by triangular tessellation is used to determine the requirement for infill planting when regeneration does not meet the stocking by triangular tessellation standard in Western Australia (CALM 1990, 1997).

Okabe *et al.* (1992) point out that clustered patterns produce Voronoi polygons of greatly varying sizes, whereas regular patterns produce little variation. The triangular tessellation is also likely to show a great range in triangle areas for clustered patterns, and the variance of the stand density estimate is likely to be high.

Seedling density by point-to-plant (distance to the closest seedling)

This measure is based on the principle that seedling density is inversely proportional to the square of distance from a sample point to the nearest seedling. It has been reported that this measure tends to be biased for all but random seedling distributions (Cox 1976; Fairweather and Amrhein 1989). A number of variations of the distance method have been tested, requiring more than one distance at each point (Buntine and Opie 1976), or measurement of the distance of the *n*th closest seedling, where $n > 1$ (Loetsch *et al.* 1973). None of the variations, however, has been shown to be unbiased for a large range of spatial distributions. Thus the basic method as applied in NSW State Forests (NSWFC 1994) is the only one presented here. The distance (in metres) to the closest individual (up to 5 m) is determined and stand seedling density is calculated by the following formula:

$$D \text{ (seedlings ha}^{-1}) = 10\,000 / (2 \times \text{mean distance (m)})^2,$$

a correction factor being applied for nil plots (NSWFC 1994). The evaluation system involves comparison of the coupe or strata density estimate to a standard of 500 stems ha^{-1} in NSW (Dr Geoff Smith, SFNSW Northern Research, Coffs Harbour, NSW, *pers. comm*. 2000).

The varying degree of bias in the estimate of seedling density with varying degree of seedling aggregation reduces the usefulness of measuring density by distance to the closest individual, in native forest. The system, however, may provide a sensitive indicator of site occupancy, regardless of whether it provides an accurate estimate of density. The sensitivity of the closest distances to aggregation is reflected in the use of related statistics to characterise spatial distribution; for example, the empirical distribution functions of the distances from origin (i.e. intersections on an overlaid grid) to nearest neighbouring point (seedling) (Kaluzny *et al.* 1998), and Pielou's index based on distance from a set of *nx* by *ny* grid points to the nearest seedling (Pielou 1959).

Stocking by quadrat (fraction (%) of 4 m^2 and 16 m^2 plots stocked)

Frequency, the percentage of quadrats with at least one seedling, is a commonly used measure in both plant ecology (Friedl and Shaw 1987; Bullock *et al.* 1994; Morrison *et al.* 1995) and in forest regeneration assessment where it is usually referred to as stocking (Forestry Tasmania 1996, 2003; Dignan and Fagg 1997). Often preference is given to frequency over intensity or density in both plant ecology and production forestry because it is quicker and simpler to apply. However, there has been a trend to combined measures of stocking and seedling density, because the results are easier to interpret. Nevertheless, stocking by quadrat is still the main measure of success in Tasmania and Victoria (Forestry Tasmania 1996, 2003; Dignan and Fagg 1997).

As Dignan and Fagg (1997) point out, the measure uses the concept of Lowdermilk (1927) that the occupancy by seedlings of a sample of quadrats, each equal to the area occupied by a single tree at some stage of stand development, provides a useful indicator of regeneration success. Thus the quadrat sizes of 1 milacre (4 m^2) and 4 milacres (16 m^2) are based on the requirement of 1000 and 250 evenly-spaced stems acre^{-1}, respectively, for full site occupancy (Lowdermilk 1927; Haig 1931). The target stocking at a given age is generally set high enough to ensure total volume production is not compromised, but low enough to promote rapid sawlog growth. Considering that natural regeneration is seldom evenly spaced, a very large plot size would be required to obtain at least one seedling in 100% of plots. For example, Mount (1961) deduced that 600 randomly-distributed trees ha^{-1} would give a 90% stocking by 40 m^2 quadrats. In order to reduce the time spent searching plots, it is usual to have smaller but more numerous plots, thus maintaining a sampling intensity of about 1% by area, but with the expectation that a smaller proportion of the plots will contain a seedling. This approach has the added advantage of being more sensitive to stocking variation both above and below the desired level.

Until recently, a mapping rule was applied to the stocking data in Tasmania. The system took the 4 m^2 or 16 m^2 stocking status for each quadrat on the sampling grid, and partitioned the coupe into stocked and unstocked areas. An unstocked area consisted of the area surrounding three or more consecutive unstocked plots, or groups of three or more consecutive unstocked plots separated by one or two stocked plots. The fraction of the area of the coupe that was mapped as stocked was then compared to the standard requiring 80% of the coupe to be mapped as stocked (Forestry Tasmania 1996). Where the measure fell below the standard, corrective action could be applied to bring the coupe up to standard.

In Victoria an evaluation occurs as part of the field monitoring system, where decisions are made about the health and competitive position of individual seedlings. Only seedlings meeting acceptable criteria of species, health and growth potential are recognised for site occupancy. The fraction of 16 m^2 plots stocked is compared with a coupe level standard of 65% (Dignan and Fagg 1997), which is the same standard recently adopted in Tasmania (Forestry Tasmania 2003). If the coupe fails to meet the standard, the understocked part of the coupe may be excised for further treatment and the stocking in the remaining area compared to the stocking standard. Another feature is a reduction in the stocking standard to 55% if sampling intensity is doubled. This is a result of the error allowance being included in the stocking standard. If sampling intensity is increased the error of the estimate is reduced, and this is accounted for by comparing the estimate to a lower standard.

There is a concern that the stocked quadrat approach is not effective in determining the extent of absences (Mount 1961) or voids (Fairweather 1981); that is, the areas that would be considered for retreatment to bring a regeneration area up to reasonable productive capacity. Fairweather (1981) suggests that the remedy of mentally keeping track of regeneration conditions between plots on the transects is ineffective because of the low intensity of surveys. He tested a number of mapping rules with milacre plots but found that further study was necessary to derive a satisfactory system.

A simple conversion of stocking standards to density, assuming an even distribution of seedlings gives the following density standards: Victoria and Tasmania: 625 stems ha^{-1} x 65% = 400 stems ha^{-1} (Dignan and Fagg 1997; Forestry Tasmania 2003); Tasmanian mapping rule: 625 stems ha^{-1} x 80% x 33% = 170 stems ha^{-1} (Forestry Tasmania 1996). These are apparently lower standards than applied in NSW (500 stems ha^{-1}), but the spatial pattern may not be even, and the equivalent density of the Victorian and Tasmanian standard may be of the order of 2500 stems ha^{-1} (Squire *et al.* 1991), which is based on studies of Lockett (1979) and Wehner (1989).

As part of the project to develop a national indicator of regeneration success, additional information on the relationship between stocking and seedling density in eucalypt forests is sought (Lutze *et al.* 2004). The difference between the former Tasmanian and current Victorian standards might be related to the criteria on which they are based; that is, fully stocked regrowth stands in Tasmania (Mount 1961), and the wood production objectives over the rotation in Victoria (Edgar and Opie 1976). Modelling of stand development past the stage for which reliable stand data is available indicates that the current standards should produce acceptable timber production outcomes (Lockett and Goodwin 1998; Hamilton 1989), but those analyses do not take into account the effect of initial spatial pattern on tree form.

The timing of surveys differs within the wet forests of Tasmania and Victoria (Dignan and Fagg 1997; Forestry Tasmania 2003). The Tasmanian system requires information after one year to make decisions about corrective action. Data from Victoria indicate that estimates of stocking (based on 16 m^2 quadrats) increased from year 1 to years 2 and 3, but was not significantly different 4 and 10 y after site preparation (Wehner 1984). Thus the final assessment of regeneration success was delayed until year 3 on marginal sites to enable potential improvement in the results. Compared with North American mixed coniferous/deciduous forests (Ministry of Forests 1999), the ecological response of eucalypt forests means that regeneration success may be determined at a relatively early stage. For the purpose of making stand management decisions and assessment of long-term productivity, surveys later than currently applied may be desirable, but differences in timing could require the adjustment of standards.

Stocking by triangular tessellation (fraction (%) of plots where triangular tessellation density exceeds plot minimum density)

The measure of seedling density by triangular tessellation has been extended to measure the spatial distribution of seedling density. The proportion of plots that exceed a specified point seedling density standard is the measure of success. This approach is unique to Western Australia, where point standards have been refined to take account of forest type and the growth stage of the trees (CALM 1990, 1997). The following discussion will focus on the system used in karri (*Eucalyptus diversicolor*). The plot level standard is applied about one year after harvesting and site preparation, and is based on the following three levels:

- *optimal stocking*, at which crop trees will develop the maximum clean bole length (seedling density greater than 3000 stems ha^{-1} at age 1 y)
- *adequate stocking*, at which crop trees will develop less than the maximum possible clean bole length but still provide a full stocking of acceptable crop trees at first thinning. (seedling density of 1666–3000 stems ha^{-1})
- *understocked*, at which the bole length of crop trees at first thinning will be unacceptable (seedling density less than 1666 stems ha^{-1} at age 1 y).

The assessment area is divided into cells based on features related to obvious changes in regeneration success. For each cell, the fraction of plots that have adequate and acceptable seedling density is compared to the minimum standard of 85%. The location and stocking status of all plots are mapped and the area requiring infill planting is determined. The mean seedling densities of the under-stocked areas are calculated to determine the density of infill planting required.

A simple conversion of stocking standards to density, assuming an even distribution of seedlings, as applied to the Victorian and Tasmanian standards, gives the following density standards for Western Australian forests: *E. diversicolor* 1666 stems ha^{-1} x 85% = 1400 stems ha^{-1}; *E. marginata* 5000 stems ha^{-1} x 65% = 3250 stems ha^{-1}. These standards are apparently higher than those for the other States. Bradshaw and Gorddard (1991) based the standard for *E. diversicolor* on the effect of stand density on tree form and branch-free bole length in stands less than 20 y of age, and information on the maximum number of potential crop trees at time of first thinning. They did not attempt, however, to balance those effects with the effects of density on individual tree size and thus total sawlog volume growth. The literature suggests that the different standard for *E. marginata* is related to differences in regeneration ecology (Abbott and Loneragan 1984), but there is no published material that establishes the link between the regeneration response and long-term wood production in that forest type.

Discussion: comparison of site occupancy measures

This discussion seeks to determine the most appropriate measures of site occupancy for further testing as potential national indicators of regeneration success.

Scientific basis of measures

The prime concern with the current measures of site occupancy is their capacity to satisfy criterion 2 (see 'Evaluation of sustainability indicators', above); that is, to have a sound scientific or other relevant basis. An analysis of the current regeneration standards of a number of government agencies with similar objectives indicates differences in this respect. The degree to which current standards reflect long-term productivity is a prime consideration in determining measures of regeneration success. The current literature on standards is deficient in that the relationship between initial density and long-term wood production, including the relationship with wood quality, has not been rigorously established.

Consequently it is difficult to justify the current standards, particularly as they relate to different forest types.

Spatial distribution is the prime output of stocking measures, and it is appropriate that there be consistent rules for excising understocked areas from stocked areas, and for the calculation of stocked versus unstocked areas. However, the standards applied to the point estimates differ between Western Australia and the two other States, which means that the area estimates are not directly comparable. Thus the differences in standards between measures may be considerable, and further evaluation and comparison is necessary. Considering the difficulty in directly comparing different measures, it may be appropriate to simulate the application of the different measures and their standards to a common set of stand structures.

Setting aside criterion 2, the alternative measures of site occupancy considered in this review generally have the properties of a useful indicator. The relative merits of the measures, however, are best assessed in terms of criteria 4 and 5 (i.e. their sensitivity, their ability to measure critical change with confidence, and their costs in relation to their benefits). In particular, the sensitivity and ability of the indicators to detect critical change with confidence is dependent on their accuracy, which in turn is determined by the precision and bias of the measures. The information content of the measure will also influence the sensitivity, as more relevant information will increase the ability to detect critical change. Costs associated with the introduction and on-going application may vary between systems. The question of whether the cost of collecting additional information is compatible with its benefit needs to be answered.

Sensitivity and ability to detect critical change

One concern with all the current measures is that they may not adequately detect voids, the areas that are of greatest concern to productive capacity. One suggestion is that a variable plot size or distance method is needed to effectively identify voids. This needs to be considered in the context that the main source of bias in estimates of site occupancy is probably the aggregation of regeneration. Current methods relying on distance from a point to the nearest seedling are likely to be biased for aggregated distributions, because sampling points tend to fall more often in gaps than in dense areas (Cox 1976). Both the closest individual and point-centred quarter methods used in New South Wales (NSWFC 1994; SFNSW 1999) are in this category, and are likely to underestimate seedling density.

The triangular tessellation method used in Western Australia provides an unbiased estimate of seedling density, regardless of spatial distribution (Loetsch *et al*. 1973; Ward 1991). The precision of this method, however, may be low in aggregated stands, because the effective plot size varies with the point density, a large area being measured when density is low and a small area when density is high. Increasing the sampling intensity of triangular tessellation to enhance precision could increase its cost relative to other methods. In view of these factors it is apparent there is a need to compare the precision and bias of current and alternative site occupancy measures in the range of stand structures.

Amongst the site occupancy measures used in even-aged stands, the most information is provided by the stocking-by-triangular-tessellation measure. The measure provides estimates of seedling density at locations distributed across the surveyed area. This is additional to the information provided by the stocking-by-quadrat measure, which establishes whether there is a minimum seedling density at locations distributed across the surveyed area. Seedling-density-by-quadrat also provides an estimate of seedling density at each point, although the estimate may not be accurate at high seedling density. The seedling-density-by-point-to-plant measure is a stand-level measure.

The timing of assessment also varies with different measures of site occupancy, and this may affect the sensitivity. The accuracy of larger, less frequent plots measured at a later age needs to be determined, if that option is to be considered. In fact, a number of other statistics relating to spatial distribution could be used to determine regeneration success on a routine basis, such as nearest-neighbour statistics based on mapped plots, and statistics compatible with quadrat or nearest-neighbour statistics. The system would necessitate the development of standards for these complementary measures. A review carried out by the senior author as part of this investigation found that, in general, there is only limited information about spatial distribution, other than those statistics reported as part of site occupancy evaluation. Testing of a range of measures of site occupancy needs to be over the range of stand types encountered in real stands. A useful approach is to simulate the range of stand structures, which enables testing over a large number of stands at minimal cost. There is, however, a need to characterise the real stand structures with a range of spatial statistics.

Costs vs benefits

The actual costs of applying the different measures of regeneration success in Australian eucalypt forests have not been reported, although Dignan and Fagg (1997) provide a summary of the relative costs. The discussion in this review about accuracy and information content suggests that there may be some real differences in sensitivity between measures, subject to further testing. However, the gains in sensitivity through triangular tessellation or quadrat-count methods come at an extra cost which may be warranted only if the information is used for some specific purpose such as planning intensive stand management. When further analysis of the scientific basis and sensitivity is completed, a cost–benefit analysis can be carried out.

Conclusion

Current site occupancy measures are based on a number of different spatial statistics, and include an evaluation of whether the site resources are being fully utilised by the regeneration. The relative value of these measures as indicators of sustainability was assessed using three key criteria: do they have a sound scientific basis; are they sensitive with an ability to detect critical change; and do their benefits match their costs?

Current measures may be improved with further study of their scientific basis, particularly the relationship between long-term wood production and the standard for the measure. Sensitivity and ability to detect change are most likely to be affected by accuracy and the information content of the measure. Stocking by triangular tessellation contains more information than the other measures, but there is some concern about its accuracy. The sensitivity of distance measures is likely to be low because of their bias in measuring aggregated distributions. Quadrat methods contain minimal information when measuring stocking alone, but almost as much information as triangular tessellation if seedlings within quadrats are counted. There is not as much concern about the accuracy of density as determined by quadrat counts as there is by triangular tessellation.

There is a trade-off between cost and sensitivity, as more information and greater accuracy come at a cost. The greater sensitivity of the triangular tessellation or quadrat-count measures might be warranted only if the information is used for some particular purpose other than the reporting of regeneration success.

In order to further the development of the national indicator of regeneration success the following actions are recommended:

- characterise spatial pattern of regeneration in a range of stand types with a range of spatial statistics
- develop models of spatial distribution of regenerating stands
- simulate a range of stand types using the models of spatial distribution
- simulate the application of various measures of site occupancy to the range of stand types
- compare the accuracy and the standards of regeneration success
- compare the benefits or costs of different measures of regeneration success.

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