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Abstract: Bias due to the sampling procedure may occur in estimates from forest inventory when sampled trees are close to the forest edge. The 'mirage', 'walkthrough' and 'walk through and fro' methods are three practically useful measurement methods developed to avoid this problem. However, as an increasing proportion of the sample requires use of these methods, the precision of the population estimates made from the sample is likely to decline. Simulation studies were undertaken of forest inventory, using point sampling, to estimate mean stand basal area and stocking density in both an even-aged, monoculture radiata pine plantation forest and an uneven-aged, multi-species, complex primary rainforest. In both forest types, bias arising from use of any of the three methods appeared to be negligible. As well, precision of estimates from the inventory was reduced only slightly even when a high proportion of the samples required use of any one of the three methods. None of the methods appeared appreciably superior in this respect to any of the others. It was concluded that use of any of the three methods was unlikely to have any substantial effect on the overall precision of estimates made from forest inventory.

Introduction

Tree growth at the forest edge can differ from that in the interior of the forest; this occurs because trees near the edge have extra space into which they may grow and because micro-climatic factors vary between the edge and the interior. Thus, it is important in forest inventory that the sampling procedure used allows that trees near the forest edge be included properly in the sample or bias may occur in the estimates of the forest characteristics made from the sample. This note is concerned with techniques that have been developed for forest inventory to ensure that sampling near the forest edge is conducted appropriately.

Taking a sample of trees in forest inventory involves assigning implicitly an area about each tree within which the sample point must lie for that tree to be included in the sample; this area is known as the 'inclusion zone' of the tree. For point samples, the inclusion zone of any tree within the vicinity of the sample point is a circular area centered about the tree with a radius of $D/(2\sqrt{\beta})$ m, where D is the diameter at breast height of the tree (cm) and β is the basal area factor (m^2/ha) being used for the point sample; the methods of point sampling are described in forest measurement texts (e.g. Schreuder et al. 1993, pp. 117-122; Gregoire and Valentine 2008, Chap. 8). For fixed area plot samples, the inclusion zone of any tree equals the plot area; its geometrical position depends on the plot shape and the tree position within the plot (Gregoire and Valentine 2008, pp. 210-215).

Bias may occur in estimates from forest inventory when any sample includes at least one tree located sufficiently close to the forest edge that part of its inclusion zone falls outside the forest (Gregoire and Valentine 2008, Sect. 7.5). Known as the 'boundary overlap' or 'edge effect' problem, this bias tends to lead to under-estimates in the inventory results (Iles 2003, p. 624). It is a consequence of the sampling procedure itself, not of the fact that trees close to the forest edge may grow and develop somewhat differently from trees growing well inside the forest

Since the 1950s, a number of 'edge overlap' methods have been proposed to avoid this problem (Schreuder et al. 1993, pp. 297-301; Iles 2003, Chap. 14; Gregoire and Valentine 2008, pp. 223-231). Two of these, the 'mirage' method (Schmid-Haas 1969) and the 'walkthrough' method (Ducey et al. 2004), have been found to be practical and are in common use (Iles 2003, Chap. 14). Both are difficult to apply where the sample falls close to a corner of the forest edge or if the edge has a convoluted shape. A third, the 'toss back' method (Iles 2003, pp. 641-647), deals more satisfactorily with complex edge shapes but requires taking measurements outside the forest edge; this gives problems if the edge adjoins a lake or a cliff. The method has been little used in practice. The fourth, the 'walk through and fro' method (Flewelling and Strunk 2013) deals effectively with complex edge shapes, does not require going beyond the forest edge and appears to avoid other practical problems that exist with the other methods. However, there is some complexity in its use. Because it is newly developed, it has had little practical use to date. The mirage and walkthrough methods retain some bias under some circumstances. Although this bias is likely to be small, it means that those two methods do not resolve the edge effect completely. Both the toss back and walk through and fro methods are unbiased estimators (Iles 2003, p. 641; Gregoire and Valentine 2008, pp. 223-231; Flewelling and Strunk 2013) and so deal fully with the edge effect.

Whilst these methods have been developed to avoid the edge effect, the precision of estimates made using any of them is likely to be reduced as the proportion of samples that requires their use increases. For most forest inventories over large forest areas, the majority of samples will be taken well away from the forest edge where use of these methods is unnecessary. However, when they are needed, the more samples taken that require their use the greater will be their impact on the precision of the final estimates from the inventory.

Through simulation studies, this work explores the practical impact on precision of estimates made from forest inventory with the commonly used mirage and walkthrough methods and with the newly proposed walk through and fro method.

Methods

Inventory simulations were done using point sampling to estimate stand mean basal area and stand mean stocking density in two diverse forest types. The first was an 11-year-old radiata pine (*Pinus radiata* D. Don) plantation, located in temperate south-eastern South Australia (37° 44′S, 140° 43′E), that had been thinned at 9 years of age. Simulations were based on measurements available to the author from that forest. It was assumed the trees were planted in rows, with 3 m between trees in a row and 4.4 m between rows. The second forest type was a primary, closed canopy rainforest growing in a warm temperate climate on Yakushima Island in southern Japan (30° 25′N, 131° 25′E). The forest was dominated by the Isu tree (*Distylium racemosum* Siebold. & Zucc), with *Litsea acuminata* (Teschner) Kosterm. and *Neolitsea aciculata* (Blume) Koidz. also prominent, together with 27 other tree species. Simulations were based on information provided for this forest by Kohyama (1986). It was assumed that trees were positioned randomly in this forest.

The frequency distributions of tree diameters at breast height over bark of these two forest types are shown in Fig. 1. Their shapes are typical of an even-aged, species monoculture plantation forest and an uneven-aged, multi-species, complex primary rainforest. They were chosen to represent a wide range of circumstances that might be encountered in forest inventory. In the simulations, diameters were ascribed randomly to trees to be consistent with these diameter distributions.

For the simulations it was assumed that the forest population was scattered over the landscape in circular tracts; a circular shape was chosen as it simplified the geometry involved. This means that the edge of any tract was slightly curved; this may render some slight bias in the mirage method, but not the walkthrough method (Gregoire and Valentine 2008, p. 229) nor the walk through and fro method (Flewelling and Strunk 2013).

Sample points were chosen at random locations within any tract. A basal area factor of 3 m^2/ha was used in the radiata pine simulations and a factor of 4m^2/ha in the rainforest simulations; these gave an average of 9 trees included in the point samples. If part of the inclusion zone of any tree included in any point sample lay beyond the forest edge, each of the mirage, walkthrough and walk through and fro techniques was applied to that tree. That sample was then termed an ‘edge point’ sample because it included at least one tree for which the edge overlap methods had been applied.

A large number of simulations was carried out to give a large set of samples. Samples were identified as edge point samples or not. Small tract areas (0.45 ha for the radiata pine and 4.2 ha for the rainforest) were used in the simulations to ensure that results were obtained frequently for edge point samples.

Results and conclusions

Table 1 shows estimates of population mean stand basal area and mean stand stocking density when a sample of size 100 was drawn at random from the entire set of simulated samples to represent a random sample drawn from each of the two forest types. Results are shown for the cases that the sample included no edge points or that the sample was composed entirely of edge points. Also shown are confidence limits about the means, expressed as a proportion of the means; confidence limits were determined simply from the variance of the selected sample with p=0.05.

The results show no evidence of any appreciable bias in the estimates of mean stand basal area or stocking density; the confidence limits about the estimates always included the population true mean. Whilst both the mirage and walkthrough methods have inherent bias, it is evident from these results that this is negligible in a practical sense.

As expected, all of the mirage, walkthrough and walk through and fro methods gave proportional confidence limits somewhat higher than the cases where there were no edge points. However, the increases were modest, generally being no more than 2-5%. As Flewelling and Strunk (2013) suggested, the walk through and fro method was generally slightly more precise than the walkthrough method. As might be expected also, the precision of the estimates from the radiata pine plantation was higher than that from the rather more variable primary rainforest.

Similar results were obtained if the sample size was increased, except that the size of the confidence limits were reduced as is expected for larger samples. For example, increasing the sample size to 1,000 reduced the confidence limits for the estimates of stand stocking density in the primary rainforest from the rather unsatisfactory levels of 23-25% in Table 1 to 7-8%.

In practical forest inventory of a forest estate of a large area, it would be common for edge point samples to occur less frequently than non-edge point samples. However, a high proportion of edge point samples could be expected where the forest population was scattered widely over the landscape in many rather small areas, where the landscape was more broken with riparian areas forming long edges running through the forest or where there were many gaps within the forest making long edges.

The present results suggested there was only a slight difference in precision of the three edge overlap methods considered here and that the bias inherent in two of them was insufficient to be of practical importance. This suggests that any of them would generally be suitable for practical inventory. The choice of which to use would depend on the circumstances of the forest being considered and, in particular, the complexity of the shape of the forest edge at any point under consideration. Indeed, there appears to be no inherent reason why all three could not be employed in the one inventory;

whichever method is appropriate and easiest would be used for any edge plot that is being considered.

The results suggest also that inclusion of edge plots in the sample will reduce the precision of estimates from the inventory as a whole only slightly, even when edge plots occur relatively frequently.

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Table 1. Estimates of population mean stand basal area and stocking density, together with their confidence limits (expressed as a proportion of the mean and determined with p=0.05), from simulations using 100 sample points. Results are shown where the sample included no edge points or, for different edge overlap methods, where all the sample points were edge points. The population true mean values of stand basal area and stand stocking density for the radiata pine plantation were 27.6 m^2/ha and 758 stems/ha, respectively, and for the rainforest were 36.8 m^2/ha and 3,638 stems/ha.

Type of sample	Basal area (m^2/ha)		Stocking density (stems/ha)	
	Mean	Confidence limit (%)	Mean	Confidence limit (%)
Radiata pine plantation				
No edge points	27.4	3.1	727	3.0
Edge points only with mirage method	27.3	3.5	764	7.5
Edge points only with walkthrough method	26.7	5.5	748	8.6
Edge points only with walk through and fro method	27.2	4.5	762	8.0
Primary rainforest				
No edge points	36.2	6.1	4,061	23.5
Edge points only with mirage method	38.6	6.8	3,434	25.3
Edge points only with walkthrough method	38.1	7.4	3,369	25.1
Edge points only with walk through and fro method	38.7	7.0	3,381	25.1

Fig. 1. Frequency distributions of tree diameters at breast height over bark for a radiata pine plantation in South Australia (o—o) and a primary rainforest in southern Japan (●- - -●) as used for the basis of the simulations performed here.