Thinking outside the square: Evidence that plot shape and layout in forest inventories can bias estimates of stand metrics

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Abstract

1. Plot-based data collection is an important component of quantitative ecological research and is widely used. Some of the most extensive plot-networks can be found in country-wide forest inventories, which provide critical information about the state of forest ecosystems. While sampling designs for forest inventories have been well studied, plot design and installation has received less attention.

2. The New Zealand National Forest Inventory of natural forest uses a nested plot design with a 0.126 ha circular plot superimposed concentrically on a 0.04 ha square plot. Stems ≥ 60 cm diameter at breast height (DBH) are measured in the circular plot while stems ≥ 2.5 DBH are measured in the square plot. Stem density of ≥60 cm DBH stems measured in the circular plots were compared with those from square plots.

3. Stem densities estimated from square plot measurements were 23.7% higher than those estimated from circular plot measurements in the 2002–2007 inventory, and 18.4% higher in the 2009–2014 inventory. The main cause of this discrepancy appears to be due to the placement of plot boundaries during establishment of square plots. This effect may have resulted from a subconscious tendency of field teams to include large trees inside plots when laying out these boundaries. It is concluded that estimates from the circular plots are unlikely to be biased while those from the square plots are positively biased.

4. This study highlights the critical importance of plot design and plot placement in forest inventories to ensure that estimates of stand attributes are unbiased. Especially on undulating or uneven terrain, methods of determining whether trees are inside or outside plot boundaries of circular plots are likely to be more accurate than those typically used for square or rectangular plots.

KEYWORDS
bias prevention, field methods, forest inventory, plot-design, sampling

1 | INTRODUCTION

A common aim of forest inventories and ecological studies using plot-based sampling is to obtain estimates of various stand metrics or variables describing forest condition and structure. Recently, the estimation of carbon stocks per hectare has become a central requirement of national forest inventories (NFIs; e.g. Tomppo, 2000) with carbon estimates obtained from plot-based measurements of stand structure variables. Stem numbers and basal area per hectare are core variables used in combination with tree heights to estimate total above-ground biomass and carbon. Therefore, there is a requirement for these to be estimated accurately and with known...
precision. Most NFIs use fixed-area plots to estimate stem density (number of stems per hectare) by counting the trees that fall within plots and dividing by the plot area (Tomppo, Gschwantner, Lawrence, & McRoberts, 2010). Usually all stems above a specified minimum diameter are counted. It is important that plots in large-scale forest inventories and ecological studies are established in a manner which provides unbiased estimates of forest parameters such as stem density and basal area. Curtis and Marshall (2005) note that imprecisely surveyed plots are a frequent cause of errors in the calculation of plot area and corresponding values of stand statistics.

Although there is no consensus concerning plot shape, in most cases circular plots are preferred over square or rectangular plots as they require only a single control point at the plot centre compared with the four corner points required for square or rectangular plots. In addition, circular plots have the shortest plot perimeter for a given plot area meaning that they require fewer decisions regarding inclusion or exclusion of trees close to the plot boundary (McRoberts, Tomppo, & Czaplewski, 2015). However, only a few studies have tested the effect of plot shape on stand descriptors. Comas, Mateu, and Delicado (2011) looked specifically at the effect of plot shape and the number of plots on the sample variance of stem numbers per unit area and found dependencies indicating that plot shape might be critical for accurate sampling.

Condit et al. (1996) tested plot size in regard to tree-diversity in three tropical rainforests and showed that species-area curves (species numbers as a function of plot size) had different forms for stems of different diameters, and showed that in tropical forests 20 × 20 m plots are inadequate to estimate large-tree species composition. Laurance, Ferreira, Merona, and Hutchings (1998) studied the effect of large square (100 × 100 m) and rectangular plots (40 × 250 m) on estimates of tree diversity and composition in a tropical rainforest. They did not find any significant differences in tree species diversity while the size of their plots met the requirement in regard to the minimum sampling area for phytosociological studies (Mueller-Dombois & Ellenberg, 1974), informing current efforts to establish NFIs in tropical and subtropical countries (Saket et al., 2010; Vidal, Alberdi, Hernández, & Redmond, 2016). The rectangular plots used in these countries are large in area with an average plot-size of 0.36 ha. Smaller square plots are used only in China which uses a plot-size of 0.06 ha. In the past, New Zealand has used even smaller square plots of 0.04 ha although its current NFI only uses these smaller square plots for stems < 60 cm diameter at breast height (DBH).

No study known to the authors has closely examined practical difficulties associated with the setting up of circular versus square or rectangular plots that could influence the estimation of area-based variables in large-scale forest inventories or ecological studies. However, Daubenmire (1959) highlighted the practical limitations of overly elongated plots. The limitations mentioned were the difficulty of laying out such plots, and the high proportion of plants close to plot boundaries requiring decisions as to whether the plant is inside or outside the plot.

While New Zealand, like most other countries, uses circular plots in its NFI for planted forests (Beets et al., 2011, 2012; Herries et al., 2017) surveys and ecological studies of New Zealand’s indigenous forests have since the 1970s made extensive use of a 20 × 20 m square plot design (Allen, 1979, 1993). This plot design was therefore chosen as the base unit for New Zealand’s inventory of natural forest, which consists of land classified as forest in 1990 excluding planted forest, and is comprised predominantly of tall indigenous forest (Payton, Newell, & Beets, 2004). The use of different plot shapes between strata (planted vs. natural) was accepted in order to maintain compatibility with previous datasets (Coomes, Allen, Scott, Goulding, & Beets, 2002; Payton et al., 2008), often an important consideration when updating current forest inventories designs (Tomppo et al., 2010). It was also considered useful to utilise the analytical and data storage systems that had been developed for analysing plant composition and change (Allen, 1979, 1993; Hurst & Allen, 2007). This was despite some concern about the desirability of deriving estimates (e.g. of carbon and stand volume) using plot designs developed under a theoretical background of vegetation ecology/phytosociology (Mueller-Dombois & Ellenberg, 1974) rather than forest mensuration (Husch et al., 2003).

Data collected in natural forests using the 20 × 20 m plot design have been used recently to classify the indigenous forests in New Zealand (Wiser, Hurst, Wright, & Allen, 2011). This intended use is reflected in the design and field manual that describes the plot establishment and the data collection methods. The focus of placing plots in “homogenous” areas of vegetation and site conditions (Hurst & Allen, 2007) is common in such qualitative phytosociological studies (Mueller-Dombois & Ellenberg, 1974), but can result in less than stringent operating procedures for laying out plot boundaries as described in Hurst and Allen (2007) or Payton et al. (2004).

Because there was concern that 20 × 20 m plots were too small to sample the large trees often found in New Zealand’s natural forest, it was decided to use a nested plot design in the natural forest NFI, consisting of a 20 m radius plot for stems ≥ 60 cm, superimposed on a 20 × 20 m square plot for stems ≥ 2.5 DBH (Figure 1).
The use of square plots as sampling units introduces the challenge of laying out plot boundaries in a manner that ensures plot size can be precisely determined and vegetation is sampled in an unbiased fashion. Goulding and Lawrence (1992) advocate establishing a square plot by initially setting up a diagonal line from the start corner to the furthest plot-corner, then establishing the other two corners, and stretching lines between corners to determine which trees are inside or outside the plot. However, such a procedure is difficult to apply in uneven terrain and in natural forest with large trees or dense vegetation, and the methods used to establish 20 × 20 m plots in New Zealand’s natural forest NFI differ from this approach in a number of ways. Briefly, each nested plot is laid out using the following procedure (Payton et al., 2004):

1. Use a GPS unit to navigate to within 30 m of the plot location. Then use the compass bearing and 30 m tape from the GPS location to establish point P (Figure 1).
2. The perimeter line P–A is laid out on a compass bearing at right angles to the slope following the predominant contour of the slope, or if the terrain is flat on a northerly bearing (magnetic 0°).
3. The perimeter line P–M is laid out at right angles to the P–A line.
4. The open ends of the plot are then connected using two 20 m tapes to form a 20 × 20 m square.
5. Once the outer boundary of the 20 × 20 m plot is laid out, the inner subplots are segregated by laying tapes across the plot at 5 m intervals along each boundary, resulting in a grid with 5 × 5 m subplots.
6. All stems ≥ 2.5 cm DBH in the 20 × 20 m plot are tagged and measured and their subplot location noted. Stems are determined to be inside the plot if the stem centre at ground level is inside the boundary line.
7. The centre point of the plot is located at the crossing point of the most inner tapes.
8. Distances to the centre of the stem at ground level of all potential stems ≥ 60 DBH are measured from the plot centre using a Vertex IV to determine whether they are inside the 20 m radius circular plot. Stems ≥ 60 DBH that are inside the plot are tagged and measured. The area of the circular plot outside the square plot is referred as the EXT (external) subplot.

Some concern about the plot design used in New Zealand’s natural forest NFI began after analysis of data from the first inventory carried out between 2002 and 2007 revealed the estimate of stem density of large diameter trees based on trees measured in the 20 m radius circular plots was lower than the estimate based on trees measured in the 20 × 20 m square plots. At first it was believed this discrepancy could have been caused by field teams overlooking some trees near the perimeters of circular plots. Great care was therefore taken during the second inventory carried out during 2009–2014 to ensure that all trees ≥ 60 cm DBH within the circular plots were identified and measured. However, analysis of data from the second inventory revealed that the stocking discrepancy remained. Suspicion then fell on the methodology used to lay out plot boundaries of 20 × 20 m square plots. Careful examination of the protocols used suggested there could be scope for field teams when establishing boundary lines to subconsciously adjust them so as to include stems close to the plot boundary.

The objective of this study was to test the hypothesis that stem density of large trees is overestimated in the 20 × 20 m square plots used in New Zealand’s natural NFI. A secondary objective was to test the hypothesis that large trees are over-represented close to plot boundaries in the 20 × 20 m plots.

2 | MATERIALS AND METHODS

2.1 | Data

The New Zealand natural forest inventory, which is now in its third cycle of measurement, was implemented as part of the larger NFI in 2002 by the Ministry for the Environment to meet international reporting requirements for natural forests under the United Nations Framework Convention on Climate Change and the Kyoto Protocol. The inventory of pre-1990 natural forest is based on an 8 km grid with a randomly located starting point. At every grid point that intersects natural forest, an inventory plot is installed. Plots were first measured during 2002–2007, and remeasured after 7 years in 2009–2014. The inventory is now continuous with the measurement cycle having recently been extended to 10 years.

Of 925 nested plots in New Zealand’s natural forest NFI measured in 2002–2007 and again in 2009–2014, 676 plots had at least one stem, either live or standing-dead, with DBH ≥ 60 cm in at least one of the measurements. Only data from these 676 plots were used in this study as the remaining 249 contributed no information on the relative performance of the 20 m radius and the 20 × 20 m...
square plots. The final dataset used in the analysis consists of measurements for each stem including plot location, subplot, measurement date, status (live or standing-dead), and DBH (cm).

2.2 | Calculations

Areas of all 20 m radius plots in the inventory are 0.1257 ha because the radii are measured horizontally and plot areas are therefore not affected by terrain unevenness or slope. However, in uneven terrain, the approach used to establish the 20 × 20 m plots results in nonsquare plot shapes of variable area. Tapes also often have to be laid around boundary trees introducing problems when calculating area-based estimates such as basal area or stand density. The true horizontal areas of the 20 × 20 m plots are generally less than their nominal 0.04 ha because the boundary is laid out with tapes that follow the terrain surface. To allow the horizontal area to be calculated, the horizontal lengths and bearings of the four sides of each plot are measured using the Vertex IV (Haglofs, 2016). To calculate the horizontal area of each 20 × 20 m plot, we used Bretschneider’s formula for the area of a convex quadrilateral:

\[
\text{Area} = \sqrt{(s-a)(s-b)(s-c)(s-d) - \frac{1}{2}abcd[1 + \cos(A+C)]},
\]

where \(a, b, c,\) and \(d\) are the lengths of the four sides, \(s = (a + b + c + d)/2,\) and \(A\) and \(C\) are the internal angles of the quadrilateral for either of the two opposite corners. In a few cases due to uneven terrain, a plot side was measured in multiple sections, each with a separate length and bearing. In such cases, the horizontal distance and bearing of the straight line between plot corners was calculated from the separate section measurements, and used as the boundary line for that side of the plot.

We compared estimates of stem density (stems per ha) of ≥60 cm DBH stems in the 20 m radius circular plots with those obtained from the 20 × 20 m square plots. As is standard practice in forest inventories, we used ratio estimators to calculate stem densities. If \(N_i\) is the number of stems with DBH ≥ 60 cm in plot \(i\) and \(A_i\) (ha) is its area, then the ratio estimator of stem density \(D\) (stems per ha) is:

\[
D = \frac{\Sigma N_i}{\Sigma A_i}.
\]

We calculated bootstrap 95% confidence intervals of the difference in stem density estimates between circular and square plots. These were calculated using the bias-corrected and accelerated method (Efron, 1987) and were performed using the SAS macro %BOOTCI. Under this procedure, bootstrap samples were obtained by sampling with replacement from the list of 676 grid points in the inventory, with each bootstrap sample of size 676. Ratio estimates of stem density were calculated from the stem counts and plot areas for both the circular and square plots for each sample, and the difference between the two estimates calculated for each sample. The empirical distributions of differences between the two estimates were then used to estimate 95% confidence intervals of the difference and perform two-tailed bootstrap tests of the null hypothesis of no difference between the two estimates using 20,000 bootstrap samples. Differences with \(p\)-value < 0.05 were taken to be statistically significant. This procedure was applied for live stems, standing-dead stems, and all stems, with separate analyses for the 2002–2007 and 2009–2014 measurement cycles of the inventory.

Because we envisaged that there could be issues with sampling trees near the boundaries of 20 × 20 m plots, we next compared stem density estimates based on stems in the twelve 5 × 5 m perimeter subplots in each 20 × 20 m plot (subplots A, B, C, D, E, L, M, N, O, P, I, H, Figure 1) with those from the four central subplots (subplots F, G, J, K), using data from the 2009–2014 measurement cycle of the inventory. To obtain ratio estimates for these groupings of subplots, we assumed that the area of each subplot was \(1/16\) of the horizontal area of the complete 20 × 20 m plot. Although this assumption is not true for individual subplots as their areas can vary depending on the terrain, when averaged across grid locations the assumption is valid. We obtained bootstrap 95% confidence intervals and tests of significance of differences in density of ≥60 cm DBH stems between perimeter and central subplots, and between these and circular plots. To test whether sampling issues might also apply to smaller stems, we calculated ratio estimates in perimeter and central subplots by DBH size class (10–20, 20–60, 40–60, ≥60 cm), and compared them using bootstrap tests. We also carried out a more detailed examination of the perimeter subplots by obtaining ratio estimates for the first subplot established in each 20 × 20 m (subplot P), the six subplots along the first two established plot boundary lines (subplots A, H, I, M, N, O), and the remaining boundary subplots (subplots B, C, D, E, L), and compared them with the central subplots using bootstrap tests. Finally, we repeated the above analyses comparing perimeter and central subplots, but using the percentage of stems within each DBH size class as the dependent variable. These were calculated as follows. If \(n_i\) is the number of stems in a size class and \(N_i\) is the total number of stems with DBH ≥ 10 cm within a particular grouping of subplots of plot \(i\), then the percentage of stems for the size class in that subplot grouping was calculated using 100 × \(\Sigma n_i/\Sigma N_i\).

3 | RESULTS

In the 2002–2007 measurement cycle, the number of live stems measured in the circular plots with DBH ≥ 60 cm was 2,989. This increased by 120–3,109 stems in the 2009–2014 measurement cycle. In contrast, the number of live stems in the square plots decreased slightly from 1,010 to 986 stems. For standing-dead stems, the number in the circular plots increased slightly from 715 to 726, and decreased slightly in the square plots from 222 to 214.

Mean stem density for live stems ≥ 60 cm estimated from data from the 2002–2007 measurement cycle was 35.4 stems per ha in the circular plots and 43.8 stems per ha in the square plots, a difference of 8.4 stem per ha which was statistically significant (\(p < 0.0001,\) Table 1). In the second measurement, the mean stem density estimates for live trees ≥ 60 cm DBH were 36.6 and 43.2 stems per ha, respectively, for circular and square plots, a difference of 6.6 stems per ha which was also
statistically significant ($p < 0.0001$). Thus, densities of large live stems in the 20 × 20 m plots were 23.7% higher than those in 20 m radius circular plots for the 2002–2007 measurement cycle, and 18.0% higher for the 2009–2014 measurement cycle. There were also significant differences in stem density of standing-dead stems between circular and square plots in both measurement cycles ($p < 0.012$ and $p < 0.044$ respectively; Table 1).

When stems were remeasured during the 2009–2014 measurement cycle, it was noticed that a number of stems, mainly in the EXT subplot (outside the square but inside the circular plot) had been missed during the first measurement cycle, and correction for this omission may be the reason for the increase in stem density estimates for circular plots between the two measurement cycles. Therefore, subsequent analyses focus only on data from the 2009–2014 measurement cycle.

Examination of the numbers of ≥60 cm DBH stems in the sixteen 5 × 5 m subplots summed across the entire inventory shows that larger numbers of stems were sampled in subplots along sides P-A and P-M, and to a lesser extent in subplots along sides A-D and D-M compared with the centre four subplots (Figure 2). This suggests that when laying out these boundary lines, there could have been a subconscious tendency for field teams to vary the position of the line slightly to include large stems close to the plot boundary. We therefore next examined stem density estimates based on perimeter subplots and centre subplots, and for various groupings of the perimeter subplots (Table 2). This analysis showed that perimeter subplots had significantly higher stem densities than circular plots, but that estimates from centre subplots did not differ significantly from circular plot estimates. A detailed analysis of various groupings of perimeter subplots indicated that the highest stem density was recorded for the first subplot established in each 20 × 20 m square plot (subplot P), followed closely by subplots along the first two established perimeter lines, followed by subplots along the remaining perimeter lines (Table 2).

When the analysis was extended to compare stem density estimates from perimeter subplots with centre subplots by DBH size class, only the ≥60 cm DBH size class showed a significant difference in stem density between perimeter and centre subplots (Table 3). Comparison of the percentage of stems by DBH size class between perimeter and centre subplots showed there was a higher percentage of ≥60 cm DBH stems in the perimeter subplots (Table 4).

### Table 1

| Data                          | Inventory period | 20 m radius plot | 20 × 20 m plot | Difference ± 95% CI | Significance of difference (p-value) |
|-------------------------------|------------------|------------------|----------------|---------------------|-------------------------------------|
| Live stems (stems per ha)     | 2002–2007        | 35.4             | 43.8           | 8.4 ± 2.3           | <0.0001                             |
|                               | 2009–2014        | 36.6             | 43.2           | 6.6 ± 2.2           | <0.0001                             |
| Standing dead stems (stems per ha) | 2002–2007 | 9.2              | 10.7           | 1.5 ± 1.2           | 0.012                               |
|                               | 2009–2014        | 9.1              | 10.2           | 1.1 ± 1.1           | 0.044                               |
| All stems (stems per ha)      | 2002–2007        | 44.7             | 54.6           | 9.9 ± 2.7           | <0.0001                             |
|                               | 2009–2014        | 45.7             | 53.4           | 7.7 ± 2.5           | <0.0001                             |

Notes. DBH: diameter at breast height; NFI: national forest inventory.

4 | DISCUSSION

Our dataset from the inventory of New Zealand’s natural forests is unique in providing a comparison of square and circular plots. The discrepancy between estimates of large-tree stem densities obtained from the two different plot types presents a cautionary example of how plot design, establishment and placement can introduce bias in estimates of stand metrics. The differences in estimates of stem density of 23.7% (2002–2007 cycle of inventory) and 18.0% (2009–2014 cycle of inventory) are surprisingly large considering that the two plot types were installed as nested plots with the smaller square plot entirely contained within the larger circular plot at each grid location in the inventory.

The discrepancy between estimates is most likely caused by the setup and design of the 20 × 20 m plot, rather than the 20 m radius circular plot. Although there is evidence that stem density estimates from the 20 m radius plot obtained in the 2002–2007 measurement cycle were too low due to trees being missed, this issue was corrected in the 2009–2014 cycle, and estimates from these plots in this cycle are unlikely to be biased as procedures for checking trees close to plot boundaries for circular plots are well defined and accurate (e.g. Herries et al. (2013)). The decision of whether a stem is inside or outside the plot boundary is made by determining whether the measured distance from the plot centre to the centre of the stem at ground level is greater or less than the plot radius, which can be achieved simply and accurately in most cases (Herries et al., 2017; Husch et al., 2003). Furthermore, the placement of plot centres which are located at the intersection of the 20 × 20 m plot diagonals is unlikely to be influenced by the local distribution of large stems.

In contrast, careful consideration of the protocols used to establish the 20 × 20 m plots reveals several steps where errors could occur. Firstly, the initial corner point (point P, Figure 1) is established 30 m along a bearing from a GPS location using a compass and tape. However, even if bearings are predefined and accurate mensuration compasses are used, the accuracy of actual bearings will be much poorer than the nominal accuracy of the compass due to operator error. Audits of plots reveals that actual bearings commonly vary from predetermined bearings by up to 5º (field staff pers. comm.). A ± 5º variation in bearing corresponds to a variation of ±2.6 m...
### TABLE 3
Estimates of stem density (stems per ha) of live stems for various diameter at breast height (DBH) classes for the centre four subplots and the 12 perimeter subplots for 20 × 20 m plots from the 2009–2014 cycle of New Zealand’s natural forest. Also shown is the difference between the two estimates with bootstrap 95% confidence interval, and p-values of bootstrap tests of the differences.

| DBH class | Central subplots | Perimeter subplots | Difference ± 95% CI | Significance of difference (p-value) |
|-----------|------------------|--------------------|---------------------|-------------------------------------|
| ≥60 cm    | 37.4             | 45.1               | 7.8 ± 5.8           | 0.010                               |
| 40–60 cm  | 70.4             | 71.0               | 0.6 ± 8.1           | 0.89                                |
| 20–40 cm  | 329.4            | 319.6              | −9.8 ± 19.4         | 0.33                                |
| 10–20 cm  | 759.4            | 765.0              | 5.6 ± 32.0          | 0.69                                |

### TABLE 4
Percentage of live stems in various DBH classes to all live stems ≥ 10 cm DBH, for the centre four subplots, and all 12 perimeter subplots, for 20 × 20 m plots from the second inventory of New Zealand’s natural forest NFI. Differences between the two estimates with bootstrap 95% confidence interval, and p-values are also shown.

| DBH class | Central subplots | Perimeter subplots | Difference ± 95% CI | Significance of difference (p-value) |
|-----------|------------------|--------------------|---------------------|-------------------------------------|
| ≥60 cm    | 3.10             | 3.73               | 0.63 ± 0.48         | 0.012                               |
| 40–60 cm  | 5.83             | 5.86               | 0.03 ± 0.67         | 0.94                                |
| 20–40 cm  | 27.28            | 26.37              | −0.91 ± 1.36        | 0.19                                |
| 10–20 cm  | 63.88            | 64.19              | 0.31 ± 1.49         | 0.69                                |

Notes. DBH: diameter at breast height; NFI: national forest inventory.
perpendicular to the bearing at the end of a 30 m line. Therefore, when determining the location of the P subplot, in practice a field crew can vary it by several metres, and a subconscious tendency to include rather than exclude large trees could account for the excess stem density in the P subplot compared with the centre subplots (Table 2). Our analysis also shows that there is a higher stem density along the P-A and P-M sides of the 20 × 20 m plots compared with the central four subplots. These boundaries are established using compass bearings and tapes, and if operational accuracy of bearings is ±5º the placement of endpoints of the 20 m lines could vary by ±1.7 m. It is possible that to avoid intersecting a large tree along a given compass bearing, field crews tended to adjust the line slightly, more often including than excluding the tree. A further issue with these plot boundary lines is that, except on flat terrain where a northerly bearing is used, the bearings used to lay out sides P-A and P-M are determined on site based on field observations of the slope.

Although we have identified a serious issue in the sampling of large diameter stems in the square plots, there fortunately appears to be less of an issue with smaller stems. Although it is possible that estimates of carbon in smaller size classes based on the 20 × 20 m plots, could be compromised, the lack of evidence of differences in stem densities of smaller size classes between edge and centre subplots suggests that these are less affected by plot bias issues than large stems. However, in the case of some unidentified sampling bias in smaller stems, it would be prudent to consider lowering the DBH size threshold in EXT plots in future inventory measurement cycles. This approach would align with NFIs used in a number of European countries such as Spain and Portugal that have lower DBH thresholds in large-tree plots of similar or greater size than the New Zealand 20 m radius plot (see Table S1).

Estimates of carbon from the New Zealand NFI based solely on the 20 × 20 m plots are likely to be biased due to the excess representation of large trees. This bias also potentially compromises previous use of such plots for estimating tree-based quantitative metrics from permanent sample plots measured with the “standard” New Zealand 20 × 20 m approach, still widely used by researchers, government agencies and departments and this could be the case for other studies worldwide using similar plot setups in forests with large widely distributed emergent trees. Our study unfortunately casts doubt on the applicability of the New Zealand 20 × 20 m plot design for quantitative studies that require accurate estimation of stem numbers, biomass or carbon of large trees. Even for semi-quantitative and plant-compositional studies, there could be issues in the use of these plots as large trees are likely to be overrepresented. However, plant composition studies using common semi-quantitative analysis methods based on species cover (e.g. Wiser et al. (2011)) should not be significantly impacted as it is unlikely that canopy cover and species number would be affected in a detectable way. For example large trees just inside or outside a plot would contribute equally to canopy cover (Kent & Coker, 1992).

We note that large 100 × 100 m square plots are often used in tropical forest inventories (FAO, 1998). These are preferred to circular plots because in such large plots, trees near the plot boundary cannot be seen from the plot centre making it difficult to establish the plot boundary of a circular plot. In large plots, missed trees can be a significant source of error, and to assist in reducing this error, the plots are usually subdivided into subplots. Each large plot is effectively a cluster of contiguous smaller square subplots, typically of 20 × 20 m. Edge effects between the subplots are of no consequence because the subplots are contiguous, and decisions regarding whether trees are inside or outside a plot boundary will only be an issue along the outer perimeter of the large plot. In such large plots, edge effects caused by the inclusion or exclusion of boundary trees will have a smaller influence on estimates of stand metrics than they do in small square plots such as those used in the New Zealand NFI.

However, based on our study, apart from such large-plot surveys, we would recommend the use of circular plots in preference to square or rectangular plots. The plot centres of such circular plots should be established using a predetermined compass bearing and distance from a GPS location. Inclusion or exclusion of stems near the plot boundary should be determined by measuring the distance from the stem centre to the plot centre. To aid in tracking stems through time in permanent forest plots, distances and bearings of all measured stems from the plot centre should be recorded. However, if square or rectangular plots are used, we would recommend the following procedures to minimise potential bias. Firstly, the plot centre (not a plot corner) should be established using a predetermined compass bearing and distance from a GPS location. Diagonal lines should then be laid using compass bearings and distances from the plot centre to locate the four corner points. Boundary lines should then be laid between corner points. Stems intersecting a boundary line should be included in the plot if the stem centre falls inside the boundary line. In some cases when boundary lines intersect large trees, it may be necessary to lay a tape offset a fixed distance from each corner, and to use the offset distance from the tape when determining the inclusion or exclusion of boundary trees.

In summary, the less stringent rules of plot establishment used in earlier localised inventories in New Zealand have compromised the new aim of producing precise and accurate estimates of carbon stocks and stock changes in the New Zealand NFI. Our study provides an example of a procedure that was adequate for one purpose being insufficient to meet new and more rigorous requirements. It highlights the importance of providing clear and accurate methods of establishing and measuring plots in forest inventories, and provides a demonstration of how inferior procedures in plot establishment can lead to biased estimates. Clearly defined field procedures should be given and documented and it is important that field crews are well trained and are fully aware of the importance of applying procedures rigorously to avoid estimation bias. Finally, except in very large-scale plots, circular plot designs are generally superior to square or rectangular plot designs for the collection of quantitative and area-related ecological data because plot boundaries can be established by directly measuring distances to plot centre, and directional layout decisions are not required.

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AUTHORS’ CONTRIBUTIONS
T.S.H.P., M.O.K. and P.N.B. developed the idea and jointly prepared the manuscript; M.O.K. designed analysis approach; T.S.H.P. collated the data; M.O.K., T.S.H.P. and P.N.B. analysed the data; All authors contributed critically to the drafts and gave final approval for publication.

DATA ACCESSIBILITY
The third party data used for this study is held in the New Zealand National Vegetation Survey (NVS) Database (https://nvs.landcareresearch.co.nz/) and can be obtained from the Database Administrator (nvs@landcareresearch.co.nz) by requesting the LAUCAS natural forest data. A request to archive this data in a publicly accessible repository was denied.

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SUPPORTING INFORMATION
Additional supporting information may be found online in the Supporting Information section at the end of the article.

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