

# Designing circular fixed-area plots in large-scale forest inventories: effect of horizontal distance measurement uncertainty and tree position pattern

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## Abstract

Plot design is one of the key elements that must be defined in forest inventories. This is particularly challenging in large-scale inventories, as both forest variability and measurement uncertainty generally increase with scale. Nonetheless, plot design is usually based exclusively on targeting (i) an average minimum number of trees to reduce the random measurement errors, and (ii) an average maximum number of trees to optimize the efficiency of fieldwork, while ignoring the uncertainty in tree position measurement. The present study focused on the effect of horizontal distance measurement errors on stand level estimates in large-scale forest inventories including circular fixed-area plots. The error was characterized in forests with non-regular (natural stands) and regular (plantations) patterns of tree positions. The effect on stand volume, stand basal area, and stand density estimates was simulated using Monte Carlo techniques. Different horizontal distance measurement uncertainty was observed in natural stands and plantations. However, similar effects were observed in the three stand variables estimates for both tree spacing patterns, with stabilization of errors for radii between 12 and 20 m. Doubling or halving the error uncertainty yielded similar results. The proposed method can help with selecting plot size in forest inventories based on circular fixed-area plots.

**Key words:** plot design, error distribution, tree inclusion criterion, inventory design, error propagation

## 1. Introduction

Forest inventory is an important means of determining the state of forests and of monitoring forest growth and development. Continuous forest inventories are dynamic systems that must be updated and adapted to societal needs and changes in the natural environment. As forest inventories are often resource intensive and time consuming, their main design elements should be optimized to produce the required information at the target uncertainty and with the available resources.

The FAO (2008) established a series of general principles for planning the different stages of forest inventories. These principles apply to the data collection design, which is one of the most important parts of a forest inventory and involves deciding which type of data should be collected at each sampling point, at the plot design stage. This will largely determine the resources needed to carry out the inventory and its efficiency.

Fixed-area plots are the most common observational designs used in forest inventories, and circular, square, and rectangular plots (RPs) are the most usual. Circular plots are used in forest inventories in many countries, especially those with boreal and temperate climates (McRoberts et al. 2010). Circu-

lar plots have a number of advantages over square and RPs: (i) they require only one control point (the centre), as opposed to the four points required in square and RPs; (ii) the smaller perimeter to area ratio facilitates decisions regarding the inclusion and exclusion of trees; and (iii) determining the coordinates of individual trees is easier in circular plots (McRoberts et al. 2015).

Circular plots also have advantages in terms of efficiency, as measurement times are shorter than in RPs (Paudel and Mandal 2019). In a comparison of circular, square, and RP shapes of area 1000 m<sup>2</sup>, Tello (1980) concluded that circular plots were the most efficient. Other authors have also reported that circular plots are the least time consuming and most cost efficient (González-Cueva 2002). On the other hand, values of stand density, basal area, and volume measured in circular plots are closest to population-level values (Paudel and Mandal 2019).

When planning the plot design, it is important to identify the sources of error in the estimation process. Cunia (1965) identified several sources of non-sampling error: (i) error due to the chance location of sample plots; (ii) regression error; and (iii) measurement error. While the first two factors mainly affect the sampling design, measurement error

generally affects the plot design. Thus, in operational forest inventories it is common practice to use a rule of thumb approach to plot design, such as selecting the plot area (fixed-area plots), the opening angle (angle-count sample points), or  $k$  number of trees ( $k$ -tree plots) to ensure a given average number of trees.

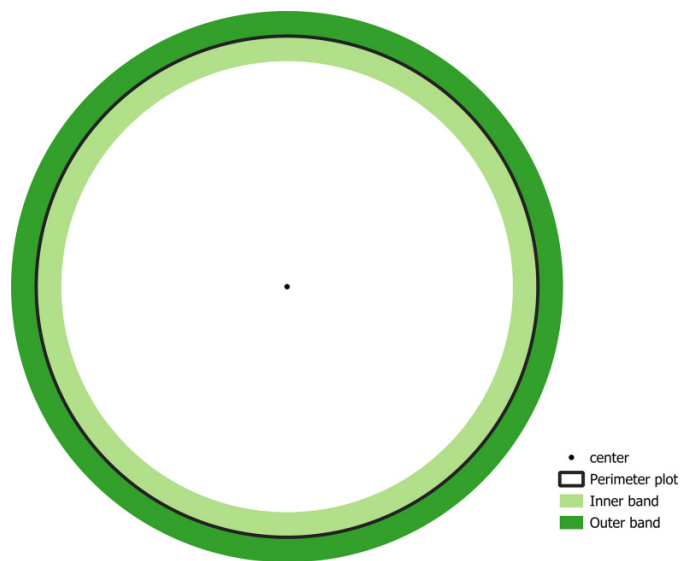
As the specific data processing and calculation methods depend on plot design (Prodan et al. 1997), most measurement errors in the plot design process are dealt with in a similar way. This basically consists of averaging the effect of random measurement errors in the elements by including as large a number of elements (trees) as possible. However, tree position errors may not follow this trend, particularly when circular plots are considered. Tree position errors are mainly affected by uncertainty in measurement of the horizontal distance from the plot centre to the tree in circular plots, although some other factors also influence, such as tree diameter measurement errors. Nevertheless, only the horizontal distance measurement error affecting trees at the edge of the plot (the number of which increases with plot radius) has a real effect when computing plot-level estimates in practice. Most studies assessing measurement errors focus on variables related to tree size, such as diameter and height (e.g., Gertner 1990; Kitahara et al. 2009; Berger et al. 2014), rather than on variables related to tree position (Pérez-Cruzado 2015; Pérez-Cruzado et al. 2017).

In circular plots, the horizontal distance measurement errors are greatest in the area around the plot perimeter, increasing the risk of wrong decisions being made when the inclusion criterion is applied to trees located in this position. Considering the simple case where the tree inclusion criterion only depends on the horizontal distance value, if the error distribution is known, for a fixed probability  $p$ , an outer band around the plot perimeter can be identified as the area where trees outside plot limits are incorrectly included with probability greater than  $p$  due to the horizontal distance error (Fig. 1, dark green band). Similarly, an inner band in which trees are wrongly excluded with at least the same probability,  $p$ , can also be identified (Fig. 1, light green band). If, in addition, the error distribution is symmetrical, the width of the outer and inner bands will be the same ( $w_b$ , m), but the area of the inner band will be smaller than the outer band (Fig. 1). Thus, in a population with random tree position pattern, there will be more candidate trees with a higher probability of being incorrectly included than of being wrongly excluded. This effect can be determined by computing the ratio between the areas of the outer and inner bands (OIBR) as

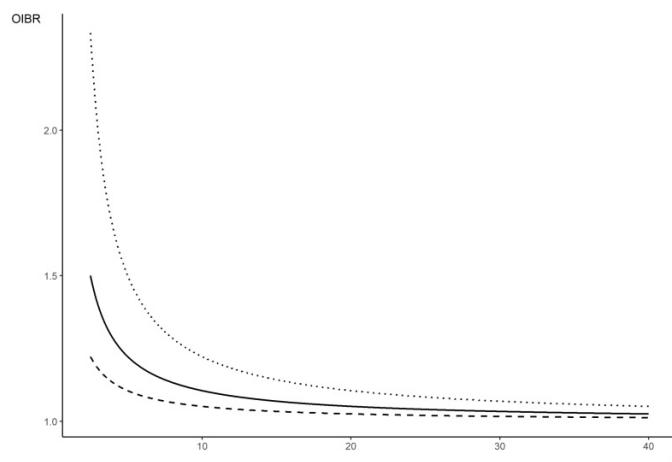
$$(1) \quad \text{OIBR}(r) = \frac{\pi(r + w_b)^2 - \pi r^2}{\pi r^2 - \pi(r - w_b)^2} = 1 + \frac{2w_b}{2r - w_b}$$

where  $r$  is the radius (m) of the circular plot. Although values differ according to the fixed  $w_b$ , OIBR tends to 1 as the plot radius increases (Fig. 2). Therefore, the proportion of candidate trees inside the plot that will be wrongly excluded and the proportion of candidates outside the plot that will be incorrectly included are almost equal for large enough radii.

**Fig. 1.** Outer band (dark green) and inner band (light green) of a circular plot for a known and symmetrical horizontal distance measurement error distribution and a fixed band width.



**Fig. 2.** Outer and inner bands ratio in terms of the radius of the circular plot ( $r$ ) for band width equals to 0.5 m (dashed line), 1 m (solid line), and 2 m (dotted line).

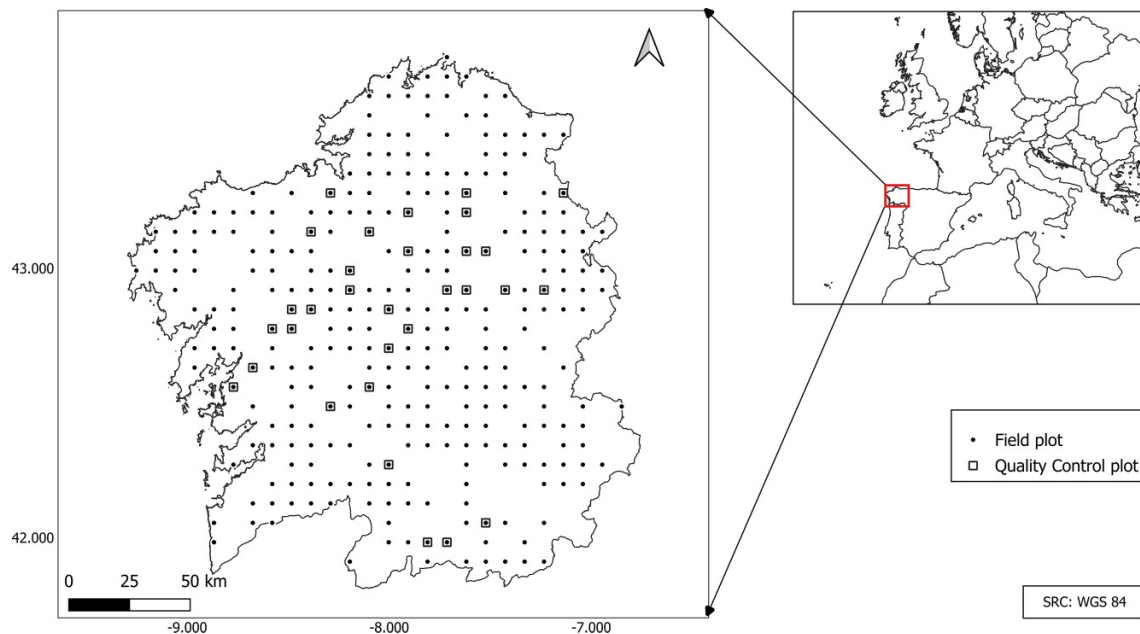


Stand variables, many of which are determined by aggregating values obtained for individual trees, are commonly expanded to area-based values, e.g., stand volume is usually expressed in cubic metres per hectare ( $\text{m}^3/\text{ha}$ ). This is usually done by applying an expansion factor relating the area of the plot to a hectare. Thus, the area of the plot is included in the denominator of this expansion factor, so that as the area increases, the specific contribution of each tree in the final value of the stand variable decreases. Consequently, the effect of the errors associated with the tree inclusion criterion, such as those derived from horizontal distance measurement errors, becomes less important as plot size increases.

Another factor that may add some uncertainty to the process under study is the tree spacing pattern in the population of interest. In artificially established stands, the trees are

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**Fig. 3.** Geographical location of the rectangular plots in the pilot inventory and plots subject to quality control. Figure was created using QGIS version 3.40. Base maps from BDLJE CC-BY 4.0 Instituto Geográfico Nacional (left panel) and CartoBase ANE 2006–2024 CC-BY 4.0 Instituto Geográfico Nacional (right panel), both of them courtesy of Instituto Geográfico Nacional.



almost always regularly spaced, whereas in natural stands the pattern is often non-regular due to purely random processes or natural clustering. Thus, different tree spacing patterns may lead to different levels of uncertainty, which justifies examining how these patterns influence the effect of measurement errors on the estimates of the stand variables of interest.

In this study, the horizontal distance measurement errors were characterized by empirical data obtained when establishing fixed-area circular plots in an operational forest monitoring exercise covering a large area. The effect of the horizontal distance measurement error on the stand volume ( $V$ ,  $\text{m}^3/\text{ha}$ ), stand basal area ( $G$ ,  $\text{m}^2/\text{ha}$ ), and stand density ( $N$ , trees/ha) variables was subsequently evaluated by means of a simulation process considering two different patterns of tree spacing: naturally regenerated stands (natural stands) and plantations. This enabled analysis of the relationship between the radius of the circular fixed-area plot and uncertainty of estimated stand level variables that could potentially be used in plot design for different conditions of tree location pattern and horizontal distance measurement errors.

## 2. Materials and methods

### 2.1. Study area

The study was conducted in Galicia (north-west Spain). Galicia occupies an area of  $29\,574\text{ km}^2$ , of which  $14\,573\text{ km}^2$  is forestland (Xunta de Galicia 2023), i.e., almost half of the land area of the region. Galician forestland is highly fragmented, with a median cadastral plot area of  $747\text{ m}^2$  (Martínez-Calvo et al. 2022). In addition, the rate of land use change is very

high in Galicia owing to forest fires and logging. For instance, in 2002 a total area of  $516\text{ km}^2$  of forestland was burnt (Instituto Galego de Estatística 2022) and the harvested area was  $456\text{ km}^2$  (Xunta de Galicia 2022).

### 2.2. Field data

To monitor and evaluate the state of forests in Galicia, the regional administration has been implementing a continuous forest inventory (IFCG, for the abbreviation of the name of project in the Galician language) since March 2020. A pilot inventory completed in 2022 served to characterize the population of interest and to collect the data required for optimizing all design elements of the IFCG.

In the pilot inventory conducted by the IFCG, 305 RPs of fixed area  $30 \times 90\text{ m}$  were established, with the long side aligned to north, at the intersections of an  $8 \times 8\text{ km}$  grid in Galicia (Fig. 3). Each RP was subdivided into subplots (SPs) according to strata detected within, and each stratum corresponded to different tree species or mixtures, stand structure, stand origin, or type of forest management. The SPs are therefore irregular shapes contained within the perimeter of the RP. The subdivision was carried out by a fieldwork team during the inventory, i.e., the field teams visually delimited the different strata in situ. The number of SPs within a RP is a random variable, ranging from 1 to 12 in the pilot inventory. The total number of SPs sampled in the IFCG pilot inventory was 1193, and the total number of trees of diameter at breast height equal or greater than  $7.5\text{ cm}$  measured in these was 38 968. More details on the pilot inventory field protocol and data gathered are reported in the IFCG technical documentation (Pérez-Cruzado et al. 2022).

During the pilot inventory, data were collected at both SP and individual tree levels. The SP level data included variables related to the origin and management of the stand, the species, and the location of the auxiliary reference stations from which the trees were positioned. The following variables (among others) were measured at tree level: horizontal distance (HD, m), measured to the nearest decimetre with a laser rangefinder (TruPulse360R); azimuth (AZ, °), measured to the nearest tenth of a sexagesimal degree with a laser rangefinder (TruPulse360R); diameter at breast height (dbh, cm), measured to the nearest millimetre with a calliper, and total height (*h*, m), measured to the nearest decimetre with a hypsometer (Vertex IV). The previous variables were registered only for trees so that dbh ≥ 7.5 cm.

The tree spacing pattern is usually determined by the stand origin and forest management method. Regarding the origin recorded in the pilot inventory, SPs were classified into two groups: natural stands and plantations. Natural stands originate from natural regeneration and the tree location does not follow any regular pattern, whereas plantations are established artificially by planting following a regular pattern of tree spacing. For the specific purposes of this study, the data corresponding to natural stands and plantations were considered separately.

A quality control process was carried out during the pilot inventory to characterize the measurement errors and monitor the work performed. The quality control consisted of re-measuring some of the RPs and was conducted by a quality control team. In this process, the quality control team performed the same operations as the fieldwork team, but without time restrictions for the measurements. They also prioritised minimizing all sources of uncertainty in the measurements. The remeasurement process took three times longer than the original measurements made by the fieldwork teams. From among the controlled RPs, a total of 25 SPs classified as plantations and 21 SPs classified as natural stands were used for characterization of HD measurement error as described below.

## 2.3. Distribution fitting for horizontal distance measurement error

### 2.3.1. Error computation

In the quality control, the HD values were measured from the same positions by the fieldwork team and the quality control team, as the exact locations were permanently marked with a metal pole driven into the ground and later located with the aid of a metal detector. The same measuring equipment was used for both measurements.

In this study, the effect of the HD measurement error was assessed in two different ways, i.e., by assuming that this error is either additive or multiplicative, because it was not possible to judge this with the available data. On the one hand, the additive error  $e_{ij}^a$  (m) for  $j$ th tree in  $i$ th SP, i.e., the difference between the HD measured by the quality control team ( $HD_{ij}^{QC}$ , m) and the HD measured by the fieldwork team

( $HD_{ij}^F$ , m), was computed as

$$(2) \quad e_{ij}^a = HD_{ij}^{QC} - HD_{ij}^F$$

On the other hand, the multiplicative error  $e_{ij}^m$  for  $j$ th tree in  $i$ th SP was calculated as

$$(3) \quad e_{ij}^m = \frac{HD_{ij}^{QC}}{HD_{ij}^F} - 1$$

In both cases it was assumed that the measurement by the quality control team was the true value, as the measurements were conducted more rigorously.

### 2.3.2. Error distribution fitting

Descriptive analysis of additive and multiplicative HD measurement errors was conducted for natural stands and plantations, including computation of basic descriptive statistics and graphical plotting of kernel density estimates. The two sample Kolmogorov–Smirnov test was performed to test the null hypothesis that errors in natural stands and plantations were drawn from the same continuous distribution with a significance level of  $\alpha = 0.05$ .

The Kolmogorov–Smirnov test was then used to test the hypothesis that observed HD measurement errors originate from a parametric distribution, specifically the normal distribution, the Cauchy distribution, or the logistic distribution. The same significance level as before was applied. The aim was to test whether any of the most usual parametric distribution families resembled the empirical distribution function more closely, to increase the applicability of the methodology proposed in this study. This process was carried out by separating natural stands and plantation errors.

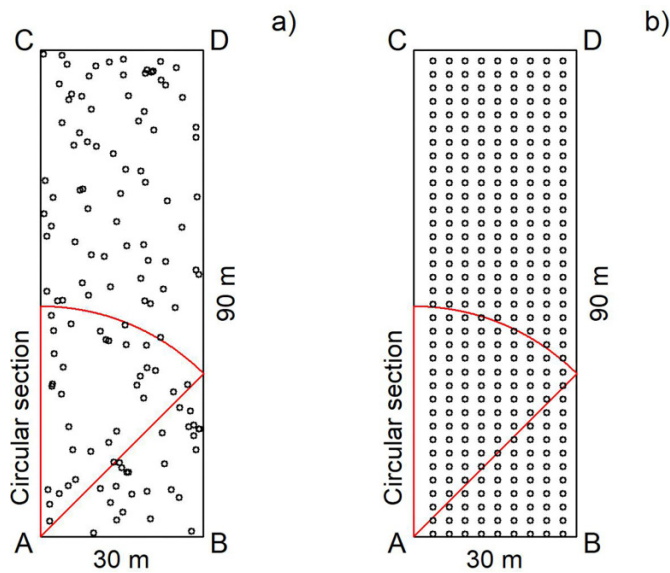
The R software (R Core Team 2024) was used for all statistical analysis. One and two sample Kolmogorov–Smirnov tests were implemented by means of the function *ks.test* in the *dgof* package (Arnold and Emerson 2011). The distribution parameters required for the one sample Kolmogorov–Smirnov were estimated by the maximum likelihood method using the function *fitdistr* in the *fitdistrplus* package (Delignette-Muller and Dutang 2015). Most of graphics in Section 3 were constructed using the *ggplot2* package (Wickham 2016).

## 2.4. Effect of horizontal distance measurement error on stand variable estimates

### 2.4.1. Construction of circular sections

In each RP in the pilot inventory, a circular section (CS) was delimited by bisecting the RP from each of its corners to a maximum distance  $r$ , so that  $0 < r \leq r_{\max}$ , where  $r_{\max} = 42.426$  m, as shown in Fig. 4. It was assumed that the CS area is one eighth of a circular fixed-area plot of radius  $r$ . The  $r_{\max}$  is the length of the maximum radius that is reached at an angle of 45° from the corner of the plot, bordering the perimeter. This process was repeated at all corners, and four CSs were thus delimited in each RP.

**Fig. 4.** Circular section extracted from corner A in a rectangular plot containing a unique subplot (i.e., a unique stratum), classified as (a) natural stand and (b) plantation.



The set of CS constructed as mentioned above was indexed by  $i$ , and the set of IDs of trees belonging to the RP containing the  $i_{th}$  CS was denoted by  $T_i^{RP}$ . If the HD between the RP corner where the  $i_{th}$  CS was located and a tree  $j \in T_i^{RP}$  ( $HD_{ij}$ , m) was less than or equal to the radius  $r$  of the  $i_{th}$  CS, then tree  $j$  was assigned to the CS. Hence, the set of tree IDs belonging to the  $i_{th}$  CS can be expressed as a function of the radius  $r$  as follows:

$$(4) \quad T_i(r) = \{j \in T_i^{RP} | HD_{ij} \leq r\}$$

and the number of trees assigned to the CS is the cardinality of  $T_i(r)$ , denoted by  $|T_i(r)|$ . Only CSs with trees coming from a unique stratum (i.e., a unique SP) were included in the analysis, and thus CS containing trees belonging to several strata were excluded from further analysis.

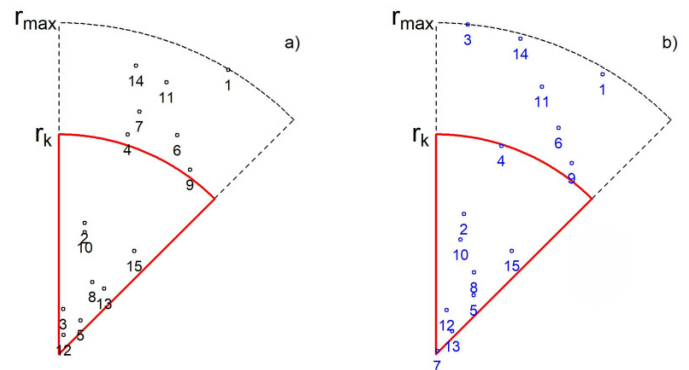
### 2.4.2. Stand variable estimation

Volume ( $v_j$ ,  $m^3$ ) and basal area ( $g_j$ ,  $m^2$ ) were estimated individually for each tree  $j$ . The taper models of Diéguez-Aranda et al. (2009) were used to estimate volume. For species not included in the previous work, the models of the Spanish National Forest Inventory were applied. Finally, the Denzin formula was used for the species that were not found in either the two preceding cases. The individual tree variables were aggregated and expanded to a per hectare basis, according to CS area. For the  $i_{th}$  CS of radius  $r$ , the stand volume  $V$ , stand basal area  $G$ , and stand density  $N$  were calculated on the basis of  $r$ , as follows:

$$(5) \quad V_i(r) = \frac{80\,000}{\pi r^2} \sum_{j \in T_i(r)} v_j$$

$$(6) \quad G_i(r) = \frac{80\,000}{\pi r^2} \sum_{j \in T_i(r)} g_j$$

**Fig. 5.** Generation of new horizontal distance values during the simulation process: (a) location of the trees included in a circular section (or around it) according to the initial field measurements, and (b) simulated location of the same trees after drawing new horizontal distance values during an iteration of the simulation process.



$$(7) \quad N_i(r) = \frac{80\,000}{\pi r^2} |T_i(r)|$$

where  $T_i(r)$  is as defined in eq. 4. It must be remarked that, due to the available field data, stand variables were then computed using only one CS, which may lead to large errors depending on the stand characteristics. Nevertheless, this issue was not considered in the study because of being out of the work scope.

### 2.4.3. Monte Carlo simulations

To characterize the effect that the error in HD has on the stand variables estimates depending on circular plot size, the Monte Carlo method was applied to a sequence of radius of the CS varying from 5 to 35 m ( $r_k \in \{5, 6, 7, \dots, 35\}$ ). The simulation process consisted of obtaining new HD values for every tree in each CS from the initial HD by adding a measurement error drawn from the fitted HD error distribution (Fig. 5). Both additive and multiplicative error case were simulated. The number of simulations for each error type, CS and radius was  $n_{sim} = 5000$ .

For each iteration  $l \in \{1, \dots, n_{sim}\}$  of the simulation procedure, a new HD for each tree  $j$  in the  $i_{th}$  CS of radius  $r_k$  was simulated using the following expression:

$$(8) \quad HD_{ijl}^s = HD_{ij} + e_{ijl}^a$$

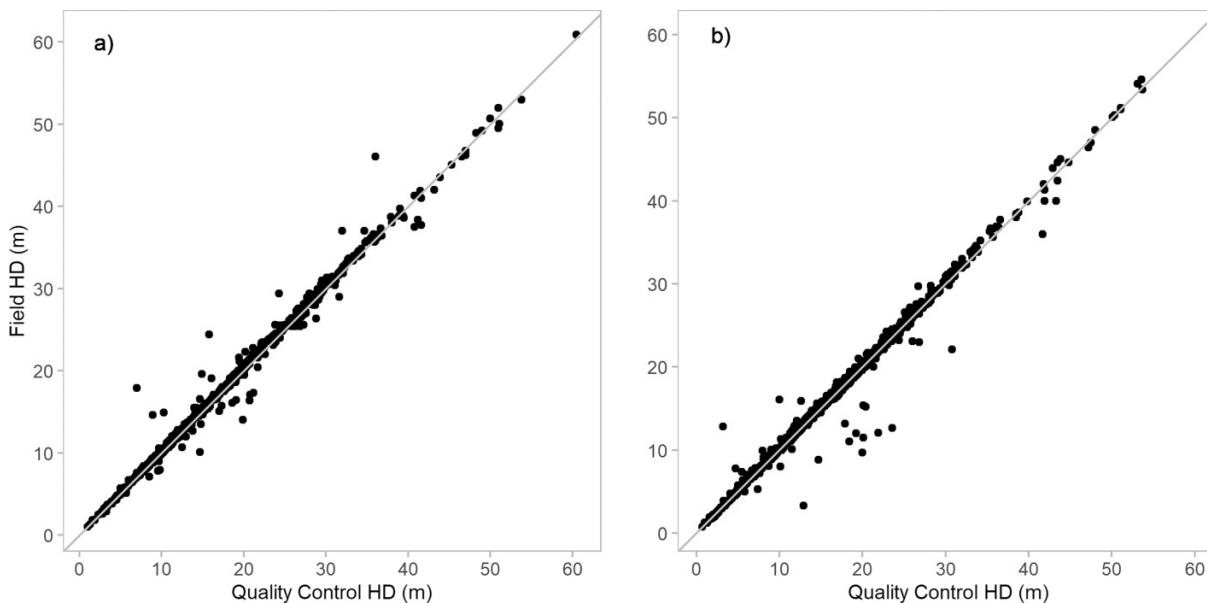
where  $e_{ijl}^a$  is drawn from the distribution fitted to the additive errors computed as eq. 2, or using the following:

$$(9) \quad HD_{ijl}^s = HD_{ij} * (1 + e_{ijl}^m)$$

where  $e_{ijl}^m$  was generated by the distribution fitted to the multiplicative errors calculated as eq. 3. The stand volume, stand basal area, and stand density were then obtained using the eqs. 5, 6, and 7 as

$$(10) \quad V_{ikl} \equiv V_i(r_k)$$

**Fig. 6.** Horizontal distance measured by the fieldwork team versus horizontal distance measured by the quality control team in (a) natural stands and (b) plantations. The grey line represents the identity line.



$$(11) \quad G_{ikl} \equiv G_i(r_k)$$

$$(12) \quad N_{ikl} \equiv N_i(r_k)$$

respectively, but replacing  $HD_{ij}$  by  $HD_{ij}^s$  within the definition of  $T_i(r)$  in eq. 4.

To evaluate the effect of larger or smaller values of HD measurement errors, the simulation process was repeated twice more, by doubling the dispersion measure of the fitted HD measurement error distribution and halving it. The standard deviation was used as the dispersion measure.

#### 2.4.4. Error effect on stand variables estimation

Uncertainty in stand variables due to HD measurement error was analysed by randomly simulating new tree positions by varying HD according to the fitted HD error distributions as described in Section 2.4.3. In each iteration of the simulation process, the effect of HD errors in stand estimates for circular plot sizes from 5 to 35 m was determined by computing the differences between the values of the stand variables for each random realization and the values obtained using the initial tree positions.

Specifically, differences in stand volume ( $\Delta V_{ikl}$ ,  $m^3/ha$ ), stand basal area ( $\Delta G_{ikl}$ ,  $m^2/ha$ ), and stand density ( $\Delta N_{ikl}$ , trees/ha) corresponding to the  $l_{th}$  simulation for the  $i_{th}$  CS with radius  $r_k$  were computed as follows:

$$(13) \quad \Delta V_{ikl} = V_{ikl} - V_{ik}$$

$$(14) \quad \Delta G_{ikl} = G_{ikl} - G_{ik}$$

$$(15) \quad \Delta N_{ikl} = N_{ikl} - N_{ik}$$

where  $V_{ik} \equiv V_i(r_k)$ ,  $G_{ik} \equiv G_i(r_k)$ , and  $N_{ik} \equiv N_i(r_k)$ . To simplify the presentation of the results obtained, graphical representations of the 5% and 95% percentiles of the differences for natural stands and plantations were generated by stand variable, error type, and dispersion measure values of error distribution. All calculations were conducted using R software (R Core Team 2024), and the graphics were generated using the ggplot2 package (Wickham 2016).

## 3. Results

### 3.1. Distribution fitting for horizontal distance measurement error

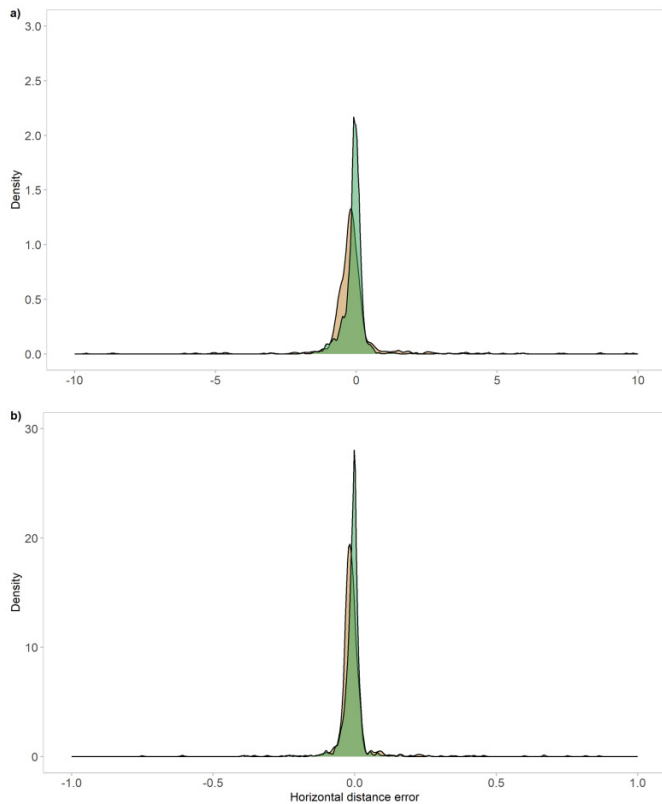
When plotting the  $HD_{ij}^F$  values, measured by the fieldwork team, versus the  $HD_{ij}^{QC}$ , measured by the quality control team, it was found that a few values deviated greatly from the identity line for both considered error types (Fig. 6). These extreme outliers were generally due to transcription errors, i.e., errors committed in writing down or digitalizing figures. In addition, the range of HD values used for fitting the error distribution covers the range of HD used to simulate the error effect on stand estimates.

An initial descriptive analysis of observed HD errors in natural stands and plantations, assuming either additive or multiplicative errors, was carried out (Table 1). The estimated error densities were plotted (Fig. 7) to assess whether the error distributions are similar. In the case of additive errors, the mean value for plantations was  $-0.42$  m, whereas the mean value for the natural stands was  $-0.24$  m. The mean is affected by extreme values, and the median is therefore a more robust estimator for analysing differences. The median value in the plantations was  $-0.09$  m, whereas it was  $-0.20$  m in natural stands, indicating no bias in the measurements. Regarding the standard deviation, both distributions yielded

**Table 1.** Descriptive analysis of the horizontal distance measurement errors in natural stands and plantations, when considering either additive or multiplicative errors.

		Min	Q1	Med	Mean	Q3	Max	SD	MAD
Additive error (m)	Natural stands	-10.9	-0.40	-0.20	-0.24	0.00	5.90	1.02	0.30
	Plantations	-9.60	-0.20	-0.09	-0.42	0.07	10.94	0.97	0.16
Multiplicative error	Natural stands	-0.61	-0.03	-0.01	-0.01	0.00	0.46	0.06	0.02
	Plantations	-0.75	-0.02	0.00	0.00	0.00	1.06	0.08	0.02

Note: Min: minimum; Q1: first quartile; Med: median; Q3: third quartile; Max: maximum; SD: standard deviation; and MAD: mean absolute deviation.

**Fig. 7.** Kernel density estimates of the horizontal distance measurement errors in natural stands (brown) and plantations (green), considering either (a) additive or (b) multiplicative errors.

similar values: 0.97 m in plantations and 1.02 m in natural stands. The mean value of multiplicative errors was 0.00 in the plantations and  $-0.01$  in natural stands. The same median values were obtained in both cases. The standard deviation in both cases was also almost equal: 0.08 for plantations and 0.06 for natural stands. The  $p$ -value resulting from the two-sample Kolmogorov–Smirnov test was less than  $\alpha = 0.05$ , and it was therefore assumed that the error distributions of natural stands and plantations are different.

To check wherever a parametric distribution could be assumed for HD errors in natural stands or plantations, the one-sample Kolmogorov–Smirnov test was performed for normal, Cauchy, and logistic distribution, again at the  $\alpha = 0.05$  significance level. All of the  $p$ -values obtained were lower than  $\alpha$ , and the null hypothesis was therefore rejected in the three

cases. Consequently, empirical distributions were chosen in this study to simulate the error in the simulation process.

### 3.2. Effect of horizontal distance measurement error on stand variable estimates

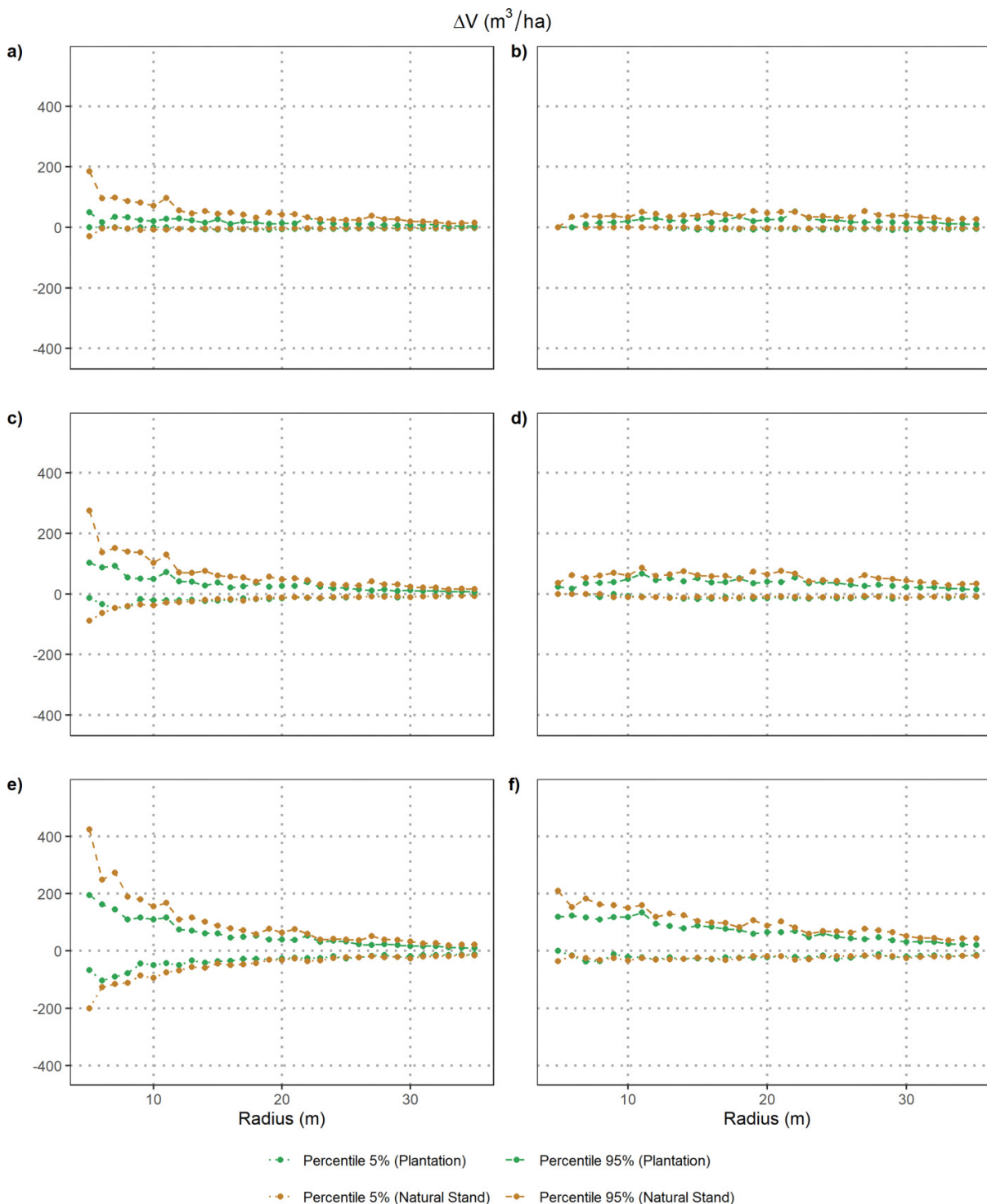
The estimated trends in variability were broadly similar in the three variables under study (Figs. 8–10), tending to zero as the radius increased. For stand volume and stand basal area, the trends in additive errors were different from those for multiplicative errors, except in case of doubling the error standard deviation. In general, the HD error had less impact on the final stand estimates for multiplicative errors than for additive errors.

In terms of stand volume (Fig. 8), for additive errors the differences between the natural stands and plantations percentiles decreased as the plot radius increased with all considered standard deviations. Doubling or halving the standard deviation of the empirical error distribution had increasing and decreasing effects on the final estimate variability, respectively, although the trend did not vary overall. The behaviour was very similar for natural stands and plantations, the latter showing the closest to zero differences in volume. When the standard deviation was halved, the absolute differences did not exceed  $100 \text{ m}^3/\text{ha}$  in any case, while when it was doubled, differences of  $424.14 \text{ m}^3/\text{ha}$  were obtained in natural stands and  $194.81 \text{ m}^3$  for the 95% percentile.

In the case of multiplicative error, when halved and observed standard deviations were used, the differences in stand volume trend moved away from zero for the first radii and then slowly tended to zero for the largest radii. Nevertheless, for doubled standard deviations, the trend was similar to that obtained for additive error simulations, with differences in volume always converging to zero in absolute terms as the radius increased. For multiplicative errors, the best results were obtained by using the halved standard deviation, with all values in absolute terms below  $55 \text{ m}^3/\text{ha}$  both in natural stands and plantations, whereas the worst ones corresponded to the doubled standard deviation case, with values in absolute terms below  $209.66 \text{ m}^3/\text{ha}$  in the natural stands and  $134.12 \text{ m}^3/\text{ha}$  in the plantations.

For stand basal area (Fig. 9), as with stand volume, the differences between natural stands and plantation percentiles decreased as the plot radius increased when additive error was considered. Overall, differences in stand basal areas estimates were smaller, in absolute values, for plantations than for natural stands. The best values were again obtained when the standard deviation was halved, and the absolute

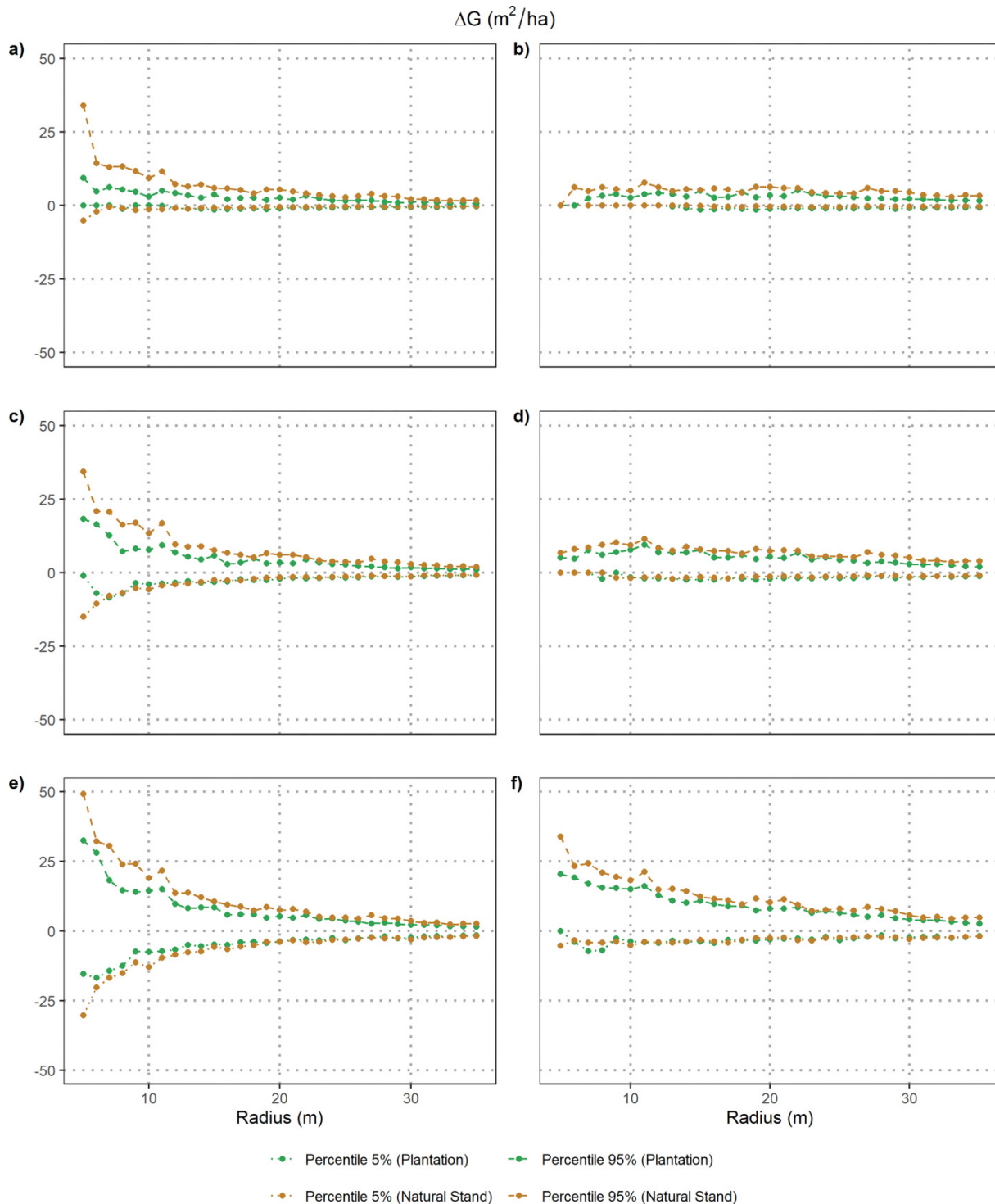
**Fig. 8.** Percentiles 5% and 95% of the differences in stand volume ( $\Delta V$ ,  $m^3/ha$ ) in natural stands (brown) and plantations (green), considering (a) additive error with halved standard deviation, (b) multiplicative error with halved standard deviation, (c) additive error with observed standard deviation, (d) multiplicative error with observed standard deviation, (e) additive error with doubled standard deviation, and (f) multiplicative error with doubled standard deviation.



values of the percentiles were  $33.95 m^2/ha$  for natural stands and  $9.33 m^2/ha$  for plantations. By contrast, the worst values were obtained when doubling the standard deviation, with  $49.20$  and  $32.52 m^2/ha$  being the furthest, in absolute terms, from zero values for natural stands and plantations, respectively.

Considering multiplicative errors, the trends with halved and observed standard deviation were similar to each other, but different from those for the doubled standard deviation. In the first two, the trend initially tended away from zero, and it then tended slowly to zero. In the latter case, when absolute values were used, the values always tended towards zero

**Fig. 9.** Percentiles 5% and 95% of the differences in stand volume ( $\Delta G$ ,  $m^2/ha$ ) in natural stands (brown) and plantations (green), considering (a) additive error with halved standard deviation, (b) multiplicative error with halved standard deviation, (c) additive error with observed standard deviation, (d) multiplicative error with observed standard deviation, (e) additive error with doubled standard deviation, and (f) multiplicative error with doubled standard deviation.

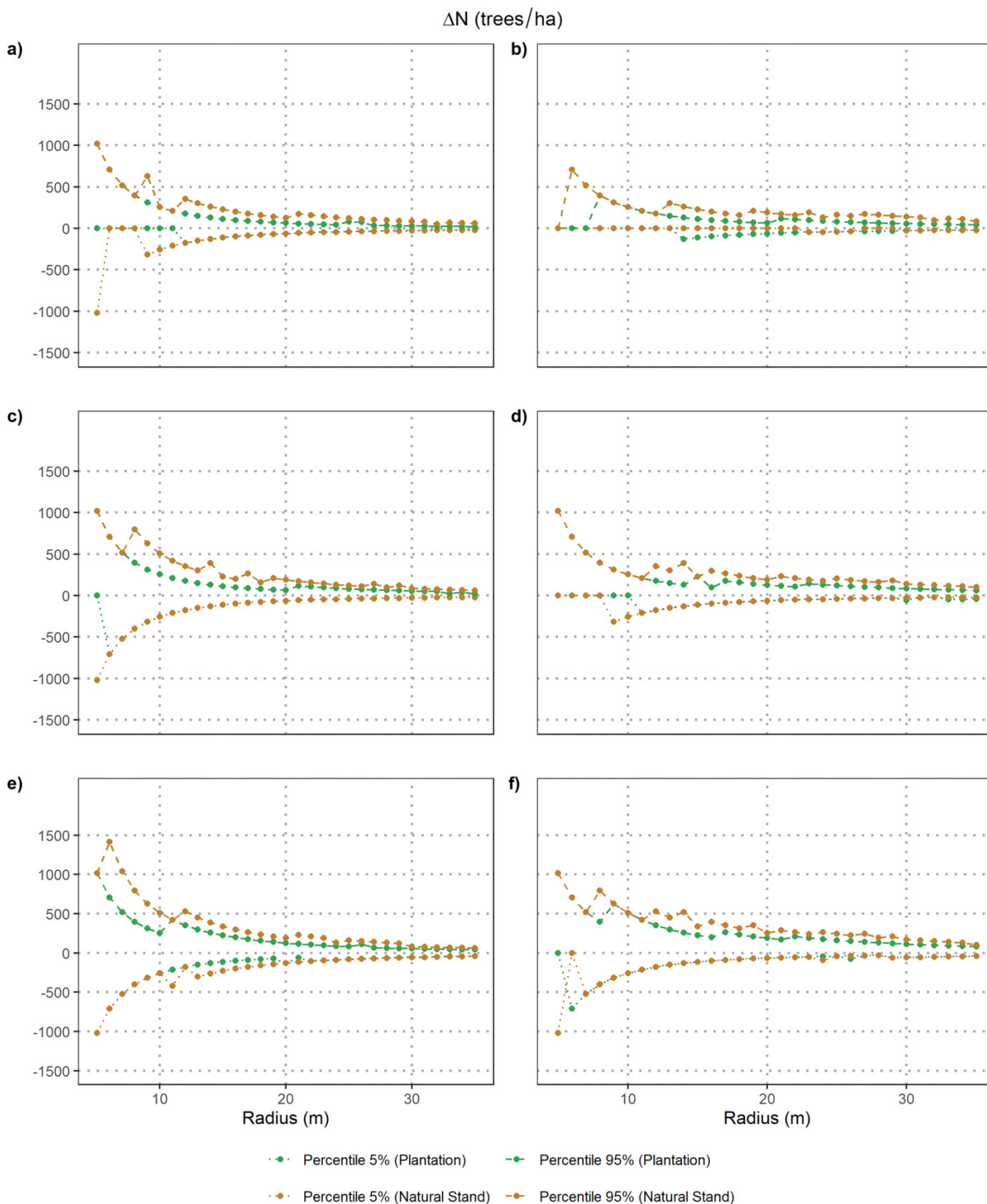


as the radius increased. As observed for additive errors, the smallest differences in stand basal area, in absolute terms, were obtained for the halved standard deviations, with maximum values of 7.71 and 5.17  $m^2/ha$  for natural stands and plantations, respectively. The highest values were obtained

when the standard deviation was doubled, with maximum values of 33.95  $m^2/ha$  for natural stands and 20.48  $m^2/ha$  for plantations.

Finally, the percentiles of differences in stand density (Fig. 10) appeared to follow a slightly different pattern from the

**Fig. 10.** The 5% and 95% percentiles of the differences in stand volume ( $\Delta N$ , trees/ha) in natural stands (brown) and plantations (green), considering (a) additive error with halved standard deviation, (b) multiplicative error with halved standard deviation, (c) additive error with observed standard deviation, (d) multiplicative error with observed standard deviation, (e) additive error with doubled standard deviation, and (f) multiplicative error with doubled standard deviation.

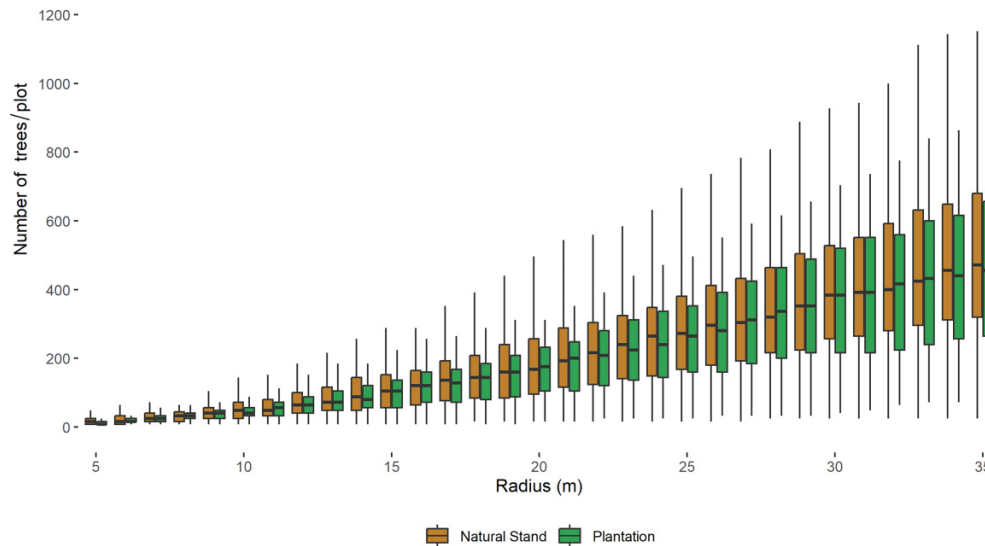


trends in stand volume and stand basal area, especially for multiplicative errors. When the error was considered additive, the trends for natural stands and plantations followed a similar pattern to that obtained for the stand volume and stand basal area. The best results were obtained with the

halved standard deviation, and the worst ones with the doubled standard deviation, i.e., 1415 and 1019 trees/ha for natural stands and plantations, respectively.

Regarding multiplicative errors, similar patterns were observed, with the best values being obtained for the halved

**Fig. 11.** Boxplots of the number of trees involved in the stand variables estimation when initial tree positions were considered, in natural stands (brown) and plantations (green).



standard deviation, when all of them in absolute value were lower than 707 trees/ha in natural stands and 398 trees/ha in plantations. The worst results were obtained for the doubled standard deviation, with maximum values in absolute terms being 1019 trees/ha for natural stands and plantations.

Despite the different patterns obtained for each of the cases considered, the estimated variability was reduced when the radius of circular plot was increased, in all cases. However, the minimum radius from which variability began to stabilise differed depending on the stand variable, the error type, and the error dispersion value, for both natural stands and plantations. Hence, choosing a single radius simultaneously minimizing variability in all circumstances would not be possible. In this context, a compromise solution based on the results obtained could be to select a value in the range 12–20 m, as the differences in the three stand variables generally tended to stabilize. For example, in a plot with a radius of 15 m, the results obtained showed that 90% of the differences, in absolute terms, were below 100 m<sup>3</sup>/ha for stand volume, 15 m<sup>2</sup>/ha for stand basal area, and 500 trees/ha for stand density could be used.

### 3.3. Number of trees per radius

As additional information derived from the Monte Carlo simulations for natural stands and plantations, Fig. 11 shows boxplots corresponding to the number of trees involved in the estimation of stand variables when the initial trees positions were considered, i.e., those trees included in  $V_{ik}$ ,  $G_{ik}$ , and  $N_{ik}$  calculation, for the different simulated radii. Although the median values were similar in natural stands and plantations, the number of trees was much more variable in natural stands than in plantations. This figure can be taken as a measure of measurement effort as plot radius increases, but also as a design element for averaging random errors.

## 4. Discussion

In this study, the size of circular fixed-area plots was assessed by considering uncertainty in the horizontal distance measurement and its effect on stand variable estimates. The proposed methodology was based on Monte Carlo simulations with horizontal distance measurement errors and two different tree spacing patterns within the stand, yielding an uncertainty estimate for the variables of interest. This approach allows decisions to be made about plot size according to specific requirements in terms of costs, resources, and target uncertainty.

Error characterization is one of the most important components of the proposed approach. The pattern of tree positions was confirmed to affect the horizontal distance measurement error distribution. Both additive and multiplicative empirical errors were generally smaller in plantations (stands with a regular tree location pattern) than in natural stands. Although the horizontal distance measurement error was characterized by only one remeasurement, no bias was observed, as previously found for the horizontal distance variable with multiple remeasurements (Pérez-Cruzado 2015). This observation may be due to the large effort invested in the remeasurement process by the quality control team, which was three times greater than for the first measurement carried out by fieldwork teams. Regular tree spacing patterns were observed in the forest plantations in the study area, with square and rectangular being the most common patterns, and with inter-row distances of at least 2.5 m. The probability of horizontal distance measurement errors greater than this value was therefore low (for instance, in the case of additive errors 0.017 and 0.027 for plantations and natural stands, respectively). The results obtained can probably be explained by this and by the fact that tree density was usually lower in plantations than in naturally regenerated stands.

Several authors have assumed that measurement errors are normally distributed and with zero mean when unbi-

ased and nonzero mean when biased (Kangas 1998; Kozak 1998; Williams and Schreuder 2000; Phillips et al. 2000; Haara 2003). However, other authors have demonstrated that this assumption is incorrect in some cases (Canavan and Hann 2004; Westfall and Patterson 2007; Pérez-Cruzado 2015). Specifically, the Cauchy distribution has been used for different purposes in various forestry contexts (e.g., Salugin et al. 2021), and also for characterizing the measurement errors in forest inventories (Pérez-Cruzado 2015). Thus, after testing various distributions, Pérez-Cruzado (2015) observed that the Cauchy distribution provided the best fit to the measurement errors for diameter at breast height and horizontal distance in tropical peat-swamp forests in Indonesia, while tree heights were normally distributed. Nevertheless, in the present study the empirical distribution of horizontal distance measurement error was considered in both the additive and multiplicative cases, since fitting any of the usual parametric distributions was ruled out after testing.

In general, similar findings were obtained for stand volume and stand basal area regarding the effect of uncertainty in stand level estimation as plot radius increases. However, a different trend was observed for stand density, particularly in the case of the multiplicative error. In line with the fact that the specific weight of each tree in the stand variable estimate decreases when plot radius increases, the estimation uncertainty decreased monotonously as radius increased when the horizontal distance error was considered additive, even though a larger number of trees could be affected by the errors associated with the inclusion criterion. In the case of multiplicative errors, the variability in estimates increased for stand volume and stand basal area in the first few radii because the more reduced error effect at these distances but then adopted a downwards trend as in the previous case. This was not observed for the stand density variable, in which a similar trend was observed when additive and multiplicative errors were used.

The effect of doubling and halving the dispersion measure of empirical error distribution for horizontal distance on stand level estimation uncertainty was simulated to evaluate the effect on stand level estimates that could be expected from values affected by other measurement errors. As expected, larger measurement errors led to greater uncertainty in stand level estimates for all variables under study, but no unduly large changes were observed in the radius above which the uncertainty values stabilized. Thus, although the stand level uncertainty can be reduced by improving horizontal distance measurement errors, e.g., by improving training and supervision of field crews (Prodan et al. 1997) or by implementing specific quality improvement programs (Kitahara et al. 2009), the plot radius at which the error stabilised seems to remain invariable for different conditions of measurement quality. In any case, the results highlight the importance of implementing quality control programs to quantify measurement uncertainty.

In all cases where differences between the estimates for natural stands and plantations occurred, the uncertainty in stand level estimates was generally larger for natural stands than for plantations. However, the differences decreased with increasing plot radius, which may be due to the abovementioned

reduction in the effect of the tree inclusion criterion error as the plot size increased, which therefore smoothed out the differences between the two tree spacing patterns.

The results show that uncertainty generally stabilized in the interval between 12 and 20 m in all cases, and the difference between natural stands and plantations was small for the specific case under study. This is consistent with the findings of other studies evaluating plot size. For example, Lombardi et al. (2015) reported that the area of the sampling plot should be at least 500 m<sup>2</sup> to produce a good inventory database in old-growth forests. Using plots of larger radius implies measurement of a greater number of trees, and the cost of the fieldwork would therefore increase, because the time taken to measure trees is one of the most important components in the total cost (Lynch 2017). Henttonen and Kangas (2015) reported that the optimal radius of circular plots, in terms of costs and estimations, was 6–7 m in North Finland, although further adjustments may be required in other locations. The procedures described here can be used to establish the design of circular fixed-area plots in other forest types.

The study findings enable us to conclude that plot size plays an important role in the error propagation in circular fixed-area plots. This was also observed in previous studies (Pérez-Cruzado 2015), in which the contribution of horizontal distance measurement error to total stand level biomass uncertainty was found to be larger than the diameter at breast height and tree height measurement error in circular nested plots in peat-swamp forest in Indonesia. However, small, nested plots may therefore be more prone to stand level uncertainty owing to horizontal distance measurement error than fixed-area plots. Further research is needed to evaluate the effect of different nested design elements in stand level estimation uncertainty.

In this study, the effects of horizontal distance measurement error on uncertainty in stand volume, stand basal area, and stand density estimates were determined for circular fixed-area plots. The use of a large-scale forest monitoring exercise as a case study enabled the observed horizontal distance measurement error to be modelled by simulating the effects of doubling and halving the dispersion of horizontal distance measurement errors and evaluating the effect of the tree location patterns. The following can be concluded on the basis of the study findings: (i) the horizontal distance measurement error cannot be correctly modelled with any of the usual parametric distributions; (ii) the horizontal distance measurement error directly affects the uncertainty in the final estimates of stand volume, stand basal area, and stand density, although it has less effect as plot radius increases (e.g., for the specific conditions of the present case study, estimates of the uncertainty broadly stabilised for radii between 12 and 20 m); (iii) naturally regenerated stands and forest plantations do not share the same horizontal distance measurement error distribution; (iv) doubling or halving the dispersion of the horizontal distance measurement error affects estimation of the uncertainty magnitude but does not generally alter the plot radius from which the error stabilises; and finally, (v) multiplicative errors have a smaller impact on the final stand variable estimates than additive errors.

The methodology described in this study can be used as a support tool for determining the plot size in forest inventories based on circular fixed-area plot designs. Further studies are required to evaluate the effect of the horizontal distance measurement error in other designs, such as non-circular plot or nested plot designs. However, although the horizontal distance measurement was the main factor involved in inclusion criteria error in this study, it would also be worthwhile investigating the effect of other issues related to individual trees variables (e.g., tree diameter), stand or plot characteristics (e.g., tree density, understory presence, plot slope), or operational conditions (e.g., weather conditions) that could also have influenced this error.

## Acknowledgements

The authors thank Mario López Fernández and Diego Lombardero Barrera for assistance with fieldwork. The authors would also like to thank Christine Francis for assistance with English language usage.

## Article information

### History dates

Received: 20 November 2024

Accepted: 31 March 2025

Accepted manuscript online: 9 April 2025

Version of record online: 13 May 2025

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### Data availability

This work does not report data.

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## Competing interests

The authors declare that they have no conflict of interests.

## Funding information

This work was supported by the Galician Regional Government within the framework of the project “Development of the continuous forest inventory of Galicia” (2020-CP3031). The authors received financial support from the following organisations: JRR was supported by the Campus Terra (Universidad de Santiago de Compostela) through a predoctoral program; AMC was supported by Galician Regional Government within the framework of the agreement “Development of the Galician continuous forest inventory” (2020-CP031); and CPC was supported by the Spanish Ministry of Science and Innovation (RYC2018-024939-I).

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