https://doi.org/10.17221/92/2018-JFS

Assessing horizontal accuracy of inventory plots in forests with different mix of tree species composition and development stage

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Abstract

Murgaš V., Sačkov I., Sedliak M., Tunák D., Chudý F. (2018): Assessing horizontal accuracy of inventory plots in forests with different mix of tree species composition and development stage. J. For. Sci., 64: 478–485.

Global navigation satellite systems (GNSS) have a wide range of applications in forest industry, including forest inventory. In this study, the horizontal accuracy of 45 inventory plots in different forest environments and 5 inventory plots under open sky conditions were examined. The inventory plots were located using a mapping-grade GNSS receiver during leaf-on season in 2017. True coordinates of the plot centres were acquired using a survey-grade GNSS receiver during leaf-off season in 2018. A study was conducted across a range of forest conditions in the forest unit Vígľaš, which is located in Slovakia (Central Europe). Root mean square error of horizontal accuracies was 8.45 m in the plots under forest canopy and 6.61 m under open sky conditions. We note decreased positional errors in coniferous forests as well as in younger forests. However, results showed that there is no statistically significant effect of tree species composition and stand age on horizontal accuracy.

Keywords: GNSS; positional error; satellite navigation; spatial coordinates

Global navigation satellite system (GNSS) is the generic term for satellite navigation systems that provide autonomous geo-spatial positioning with global coverage. Current fully-operational GNSS include the United States Global Positioning System (GPS) and the Russian Globalnaja Navigatsionnaja Sputnikovaja Sistema (GLONASS). The European Union and China are developing their own satellite-based systems Galileo and BeiDou-2/Compass, respectively (Xu, Xu 2016).

In recent decades, there has been growing interest for GNSS applications in forestry because obtaining spatial data can be performed rapidly, efficiently and accurately. Typical GNSS-based application includes plot establishment for forest inventory or environmental monitoring (Johnson, Barton 2004; Awange 2012). Of the many variables resulting from forest inventory, plot position is yet essential. The reason is that accurate information regarding plot position (*i*) enables quick revisitation of the plot for subsequent remeasurement, (*ii*) provides relevant spatial information for mapping, and (*iii*) is crucial for many analyses using remote sensing and GIS techniques. However, only handheld recreational- or mapping-grade receivers are commonly used in establishing

Supported by the Slovak Research and Development Agency, Project No. APVV-15-0393.

and relocating inventory plots (Hoppus, Lister 2007). The declared horizontal accuracy of these receivers is within 6–10 m, but there has been no detailed or wider study revealing the explicit horizontal accuracy of inventory plots in different forest conditions.

It is common knowledge that tree canopies adversely affect the accuracy of GNSS positioning because they obstruct and reflect radio signals and deteriorate the receiver ability to fix location (D'Eon 1995; Deckert, Bolstad 1996; Hasegawa, Yoshimura 2003). According to Sigrist et al. (1999), the presence of an overhead canopy may degrade the positional precision by one order of magnitude. Additional errors to GNSS observations are introduced due to ionospheric effects, atmospheric effects, relativistic effects, clock errors, and other (Xu, Xu 2016). Weaver et al. (2015) found that there is significant influence of holding position of a GNSS receiver on static horizontal accuracy. Their results indicated that higher positional accuracies can be obtained if the GNSS receiver is held vertically. It has been demonstrated that raising the antenna height significantly enhances the positioning accuracy of GNSS measurements especially during the leaf-off season (Brach, Zasada 2014). Nonetheless, placing an antenna in close proximity of tree crown and foliage results in decreased measurement accuracy. As noted by Karsky (2004), there are several ways to correct GNSS acquired data. For example, it is possible to apply real-time corrections by using differential GPS (DGPS) and the wide-area augmentation system (WAAS). However, the most accurate positioning information is derived using static method with longer observation times and requires post-processing.

Numerous studies have examined the performance of different GNSS receivers and positioning methods under a variety of environmental conditions (e.g. Yoshimura, Hasegawa 2003; Bolstad et al. 2005; Piedallu, Gégout 2005; Rodríguez-Pérez et al. 2007; Wing et al. 2008; Bettinger, Fei 2010; Valbuena et al. 2010; Wing 2011; Tomaštík et al. 2016). As described in Wing et al. (2005), users equipped with recreational-grade GPS receivers could expect positional accuracies within 5 m of true position in open sky conditions, 7 m in young forest conditions, and 10 m in closed canopies. Application of mapping-grade GPS receivers with real-time differential corrections would provide average measurement error smaller than 1 m in open area conditions as well as in young forests, and 2.2 m under forest canopy (Wing et al. 2008). Tuček and Ligoš (2002) investigated positioning errors of three GPS receivers under the forest canopy during leaf-on season. They used multi-factor analysis of variance to assess the influence of receiver type, stand age, tree species composition and terrain configuration. Their analysis showed significant influence of stand age and receiver type on positioning error. The effects of tree species composition and terrain configuration on positioning errors were ambiguous. On the contrary, Bettinger and Fei (2010) found that positional error significantly differs in broadleaved, older pine, and young pine stands, regardless of season. The annual mean horizontal accuracy value was best in the older pine stand (6.6 m), second best in the broadleaved stand (7.9 m) and worst in the young pine plantation (11.9 m). Bettinger and Merry (2012) assessed the GPS accuracy with regard to spatial arrangement of nearby trees in a young loblolly pine (*Pinus taeda* Linnaeus) plantation. They concluded that the presence of live deciduous trees within the plantation may affect the static horizontal accuracy. Naesset et al. (2000) demonstrated that employing combined differential GPS and GLONASS measurements resulted in increased positional accuracy in a mixed forest of spruce, pine and birch in Norway. Hasegawa and Yoshimura (2003) suggested the use of dual-frequency GPS receivers to acquire the most accurate positional data under tree canopies. Nonetheless, Valbuena et al. (2010) found no significant difference between single- and dual-frequency receivers. However, there has been little discussion on whether positional errors of established inventory plots were inside admissible boundaries needed for further data processing (Mauro et al. 2009; Kitahara et al. 2010; Zald et al. 2014). For example, Kitahara et al. (2010) examined the horizontal accuracy of national forest inventory plots in Japan. The total mean positional error and precision were 8.6 and 12.6 m, respectively. When it comes to the tree species composition, lower values of positional errors were found in broadleaved forests (5.6 m) and higher positional errors in coniferous forest (9.6 m). Zald et al. (2014) showed that improved GPS plot locations had little impact on the accuracy of derived imputation maps.

The aim of the paper is to evaluate the horizontal accuracy of established inventory plots in different forest structures and outline the applicability of a handheld mapping-grade GNSS receiver in forest surveys. We hypothesize that higher positional errors are more pronounced in (*i*) broadleaved forests, (*ii*) older forests, and (*iii*) forests with dense canopy cover.

MATERIAL AND METHODS

Study area. The study was conducted in the territory of the forest unit Vígľaš (Fig. 1) located in central Slovakia (approximately 48°32'N, 19°21'E). The total area is 12,472 ha and forests occupy 3,215 ha of this area. The elevation of the study area reaches 374–978 m a.s.l. Dominant species in the area include European beech (*Fagus sylvatica* Linnaeus), Sessile oak (*Quercus petraea* (von Mattuschka) Lieblein), and European hornbeam (*Carpinus betulus* Linnaeus) with 65% coverage. The area of the remaining part is covered by conifers, such as European silver fir (*Abies alba* Miller) and Norway spruce (*Picea abies* Linnaeus).

Dataset from forest inventory. Forest inventory was carried out during the leaf-on season in 2017. A total number of 295 inventory plots were established into a systematic 250 m grid (Fig. 1). We used a Topcon FC-25A field controller (Topcon Corporation, Japan) embedded with a mapping-grade GNSS receiver (Topcon 2018a). Duration of the observing sessions was within 10 min. Technical specifications for the mapping-grade receiver are summarized in Table 1. Finally, centre of each plot was invisibly fixed by a steel tube.

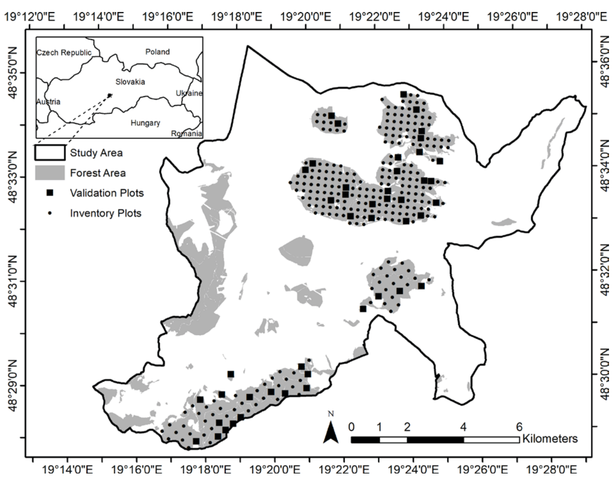

Fig. 1. Location of the validation plots in study area

Dataset from validation survey. For the present study, 45 of 295 inventory plots were selected by post-stratification, which was focused on the creation of nine strata (five plots per stratum). The main criteria for stratification were tree species composition and mean DBH as a surrogate for stand age. At first, coniferous stratum (C, conifers ≥ 70%), broadleaved stratum (B, broadleaves ≥ 70%), and a mixed stratum (M, conifers or broadleaves < 60%) was created. At second, each stratum was divided into three development stages of forest stand. Here, the limits of mean diameter < 20 cm (C1, B1, M1), 20–30 cm (C2, B2, M2), and > 30 cm (C3, B3, M3) were used. In addition, 5 of 295 inventory plots in open sky conditions were selected for comparison of horizontal accuracy.

The validation survey was performed for selected inventory plots during leaf-off season in 2018 (Fig. 1). We used a survey-grade GNSS receiver Topcon Hiper GGD (Topcon Positioning Systems, Inc., USA) (Topcon 2018b) to obtain true coordinates of the plot centre that had been already found by metal detector. Technical specifications for the survey-grade receiver are summarized in Table 2. The validation measurements were conducted using static GNSS survey technique. The elevation mask and antenna height were set at 5° and 2 m, respectively. Duration of the observing sessions was about 25 min. Acquired data were post-processed in Topcon Tools processing software (Version 8.23, 2012). Subsequently, resulting positions were transformed into the Slovak national coordinate system S-JTSK (System of Trigonometric and Cadastral Network) using the official transformation service (https://zbgis.skgeodesy.sk/rts/sk/Transform).

Accuracy assessment. The differences (Δx_i and Δy_i) between coordinates derived from a survey-grade GNSS receiver (x_{iR}, y_{iR}) and target coordinates (x_{iT}, y_{iT}) of a systematic 250 m grid were computed using Eqs. 1 and 2:

Table 1. Technical specifications for mapping-grade receiver Topcon FC-25A (Topcon Corporation, Japan)

GNSS type	SiRFstar III chipset, GPS L I (C/A), 20 channels
Horizontal accuracy*	DGPS using SBAS: 1–3 m, point positioning: 5 m
Processor frequency	533 MHz
Memory	256 MB SDRAM, 2GB flash memory
System	Microsoft Windows Mobile 6.5
Antenna	internal

*Accuracy depends on the number of satellites used, SBAS data quality, multipath objects, device position/posture and other environmental conditions

Table 2. Technical specifications for survey-grade receiver Topcon Hiper GGD (Topcon Positioning Systems, Inc., USA)

GNSS type	GPS L1 + L2 + GLONASS (GGD), 40 channels
Horizontal accuracy	static method: 3 mm ± 0.5 ppm; RTK: 10 mm ± 1.0 ppm
Recording frequency	up to 20 Hz
Memory	96 MB
System	Topcon's PC-CDU software (Version 7.12, 2007)
Antenna	microstrip

RTK – real-time kinematic

$$\Delta x_i = x_{iR} - x_{iT} \quad (1)$$

$$\Delta y_i = y_{iR} - y_{iT} \quad (2)$$

For each inventory plot position, the individual positional error (D_i) was calculated according to Eq. 3:

$$D_i = \sqrt{\Delta x_i^2 + \Delta y_i^2} \quad (3)$$

For each stratum, the mean positional error ($\bar{D}$), the standard error of the mean (SE), and the standard deviation of positional error (SD) were calculated using Eqs. 4–6:

$$\bar{D} = \frac{\sum_{i=1}^{n} D_i}{n} \quad (4)$$

$$\text{SE} = \frac{\text{SD}}{\sqrt{n}} \quad (5)$$

$$\text{SD} = \sqrt{\frac{\sum_{i=1}^{n}\left(D_i - \bar{D}\right)^2}{n-1}} \quad (6)$$

Then we determined mean coordinate errors (RMSE) across all strata (n) according to Eqs. 7 and 8:

$$\text{RMSE}_x = \sqrt{\frac{\sum_{i=1}^{n} \Delta x_i^2}{n}} \quad (7)$$

$$\text{RMSE}_y = \sqrt{\frac{\sum_{i=1}^{n} \Delta y_i^2}{n}} \quad (8)$$

The root mean square coordinate error (RMSE_{xy}) of inventory plots as a measure of the horizontal accuracy depicts the deviation from the truth and was calculated by Eq. 9:

$$\text{RMSE}_{xy} = \sqrt{\text{RMSE}_x^2 + \text{RMSE}_y^2} \quad (9)$$

Shapiro-Wilk normality test was carried out at 95% confidence level in order to determine if the positional errors (Δx_i and Δy_i) follow a normal distribution. If the positional errors were normally distributed, the parametric Student's *t*-test was performed in order to validate the null hypothesis (Eqs. 10–13):

$$H_0\text{: } \Delta\bar{x} = 0 \quad (10)$$

$$H_0\text{: } \Delta\bar{y} = 0 \quad (11)$$

$$H_1\text{: } \Delta\bar{x} \neq 0 \quad (12)$$

$$H_1\text{: } \Delta\bar{y} \neq 0 \quad (13)$$

The null hypothesis states that the mean positional error is equal to zero, against the alternative hypothesis that it is not equal to zero. In the case of non-normal distribution of the positional error, the non-parametric Wilcoxon signed rank test was used.

To clarify the effect of tree species composition and stand age on horizontal accuracy, one-way ANOVA or Kruskal-Wallis H test was applied according to normal or non-normal distribution of positional errors, respectively. In the cases where ANOVA or Kruskal-Wallis H test proved significance of differences at the significance level 0.05, mean values of positional errors were compared by Duncan's multiple range test or Wilcoxon signed rank test, respectively. The statistical analysis was conducted in R software (Version 3.5.1, 2017).

RESULTS

The individual positional errors D_i of validation inventory plots are shown in Fig. 2.

Analysing D_i for the 45 inventory plots under forest canopy, it was observed that 16% of the errors were smaller than 5 m, 60% of the errors were within 5–10 m, and 24% of the errors exceeded 10 m. In addition, 55% of the errors angled south-westwards, 20% of the errors angled southwards, 16% of the errors angled westwards, 7% of the errors angled north-westwards and only 2% of the errors angled northwards.

Results obtained from the 5 inventory plots under open sky conditions showed that 40% of D_i were under 5 and 10 m. But 20% of the errors were greater than 10 m. Again, when compared to the di-

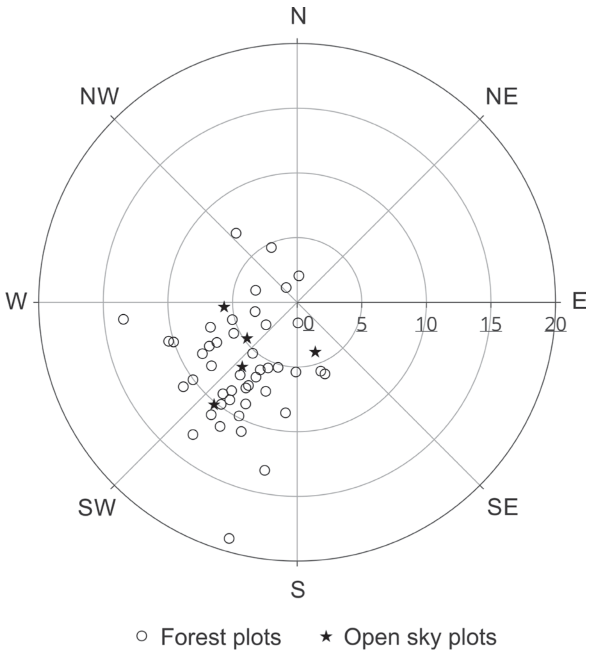

Fig. 2. Direction and magnitude of individual positional error – D_i (m) of inventory plots under forest canopy and open sky conditions

rection, 60% of the errors were angled south-westwards and 20% of the errors were angled southwards and westwards.

Descriptive statistics for individual positional errors (D_i) and horizontal accuracies ($RMSE_{xy}$) across all strata are illustrated in Table 3.

The minimum and maximum value of D_i for inventory plots under forest canopy was 1.42 and 19.00 m, respectively. The mean value of D_i was 7.72 ± 0.51 m. The variability of D_i ranged from 1.44 to 6.25 m. In total, 75.6% of the 45 inventory plots had a value of D_i less than 10 m. The $RMSE_{xy}$ for various combinations of tree species composition and stand age varied from 6.11 to 10.31 m. According to tree species composition, the $RMSE_{xy}$ varied slightly between broadleaved (9.01 m) and mixed (9.1 m) stratum. However, lower value of 7.06 m was obtained for coniferous stratum. Thus, coniferous stratum was characterized by higher horizontal accuracy than the broadleaved and mixed stratum. Regarding stand age, lower values of $RMSE_{xy}$ are characteristic for younger development stages of forests, except for stratum C2. The highest horizontal accuracy was found for stratum C1. On the contrary, the lowest horizontal accuracy was found for stratum B3. The highest and lowest variability of D_i was found for stratum M2 and M3, respectively.

The minimum and maximum values of D_i for inventory plots under open sky conditions were 4.09 and 10.2 m, respectively. There, the mean value of D_i was 6.25 ± 1.07 m.

Results of the Shapiro-Wilk normality test are reported in Table 4. In most cases, the *P*-value is not less than the significance level of 0.05. Therefore, the tested errors along the *x* axes and the *y* axes are confirmed to follow a normal distribution. The exceptions are stratum B1 and M3 for errors along the *x* axes as well as stratum C2 for errors along the *y* axes.

The results of statistical tests (Table 5) confirmed that the errors along the *x* and *y* axes are biased in case of all forest plots and strata with different tree species composition ($P < 0.05$). This also shows Fig. 2 where a clear direction of D_i to the south-west is visible in both types of inventory plots under for-

Table 3. Horizontal accuracy (m) of inventory plots under forest canopy and open sky conditions

Stratum	*n*	$\bar{D}$	SE	Minimum	Maximum	SD	$RMSE_{xy}$
C	15	6.49	0.74	1.42	10.39	2.88	7.06
B	15	8.37	0.89	1.60	13.51	3.45	9.01
M	15	8.31	0.99	3.33	19.00	3.84	9.10
C1	5	5.59	1.24	1.42	9.11	2.78	6.11
C2	5	7.75	0.77	5.62	9.84	1.72	7.90
C3	5	6.13	1.75	2.05	10.39	3.91	7.06
B1	5	7.05	1.09	4.68	10.96	2.44	7.38
B2	5	8.71	1.34	5.23	13.02	2.99	9.11
B3	5	9.36	2.16	1.60	13.51	4.83	10.31
M1	5	7.22	1.19	3.34	10.88	2.67	7.61
M2	5	9.56	0.65	8.25	11.30	1.44	9.65
M3	5	8.15	2.79	3.33	19.00	6.25	9.88
Forest plots	45	7.72	0.51	1.42	19.00	3.45	8.45
Open sky plots	5	6.25	1.07	4.09	10.20	2.39	6.61

C – coniferous, B – broadleaved, M – mixed, *n* – sample number, $\bar{D}$ – mean positional error, SE – standard error of the mean, SD – standard deviation of positional error, $RMSE_{xy}$ – root mean square coordinate error (horizontal accuracy)

Table 4. Results of the Shapiro-Wilk normality test

Stratum	Δx_i		Δy_i	
	W	*P*-value	*W*	*P*-value
C	0.939	0.375	0.974	0.914
B	0.974	0.915	0.977	0.941
M	0.930	0.272	0.941	0.394
C1	0.784	0.059	0.919	0.524
C2	0.861	0.233	0.758	**0.036**
C3	0.832	0.145	0.914	0.490
B1	0.668	**0.004**	0.968	0.865
B2	0.826	0.131	0.829	0.137
B3	0.881	0.313	0.825	0.128
M1	0.890	0.358	0.922	0.541
M2	0.972	0.887	0.893	0.373
M3	0.773	**0.048**	0.938	0.650
Forest plots	0.971	0.324	0.987	0.898
Open sky plots	0.993	0.989	0.844	0.177

C – coniferous, B – broadleaved, M – mixed, Δx_i, Δy_i – differences between coordinates; significant *P*-values (< 0.05) are shown in bold

Table 5. Results of Student's *t*-test or Wilcoxon signed rank test

Stratum	Δx_i		Δy_i	
	df	*P*-value	*df*	*P*-value
C	14	**0.007**	14	**< 0.000**
B	14	**< 0.000**	14	**0.001**
M	14	**< 0.000**	14	**< 0.000**
C1	4	**0.038**	4	**0.034**
C2	4	0.229	–	0.125*
C3	4	0.202	4	0.053
B1	–	0.125*	4	0.154
B2	4	**0.013**	4	**0.002**
B3	4	**0.043**	4	0.154
M1	4	**0.035**	4	**0.001**
M2	4	**0.001**	4	**< 0.000**
M3	–	0.063*	4	**0.024**
Forest plots	44	**< 0.000**	44	**< 0.000**
Open sky plots	4	**0.033**	4	0.052

C – coniferous, B – broadleaved, M – mixed, Δx_i, Δy_i – differences between coordinates, *df* – degree of freedom; significant *P*-values (< 0.05) are shown in bold; *results of Wilcoxon signed rank test

est canopy and open sky conditions. Between strata depicting both tree species composition and stand age, however, the results are ambiguous. According to obtained results, only errors along the *x* axes are biased in open sky plots.

On the other hand, the one-way ANOVA showed no significant effect of tree species composition and stand age on positional error of inventory plots.

DISCUSSION

Our results demonstrated that the D_i and RMSE$_{xy}$ varied greatly between inventory plots. Moreover, the difference between RMSE$_{xy}$ for inventory plots under forest canopy (8.45 m) and RMSE$_{xy}$ for plots under open sky conditions (6.61 m) was expected to be somewhat larger.

The largest and smallest positional error for a single position within plots under forest canopy was 19.00 and 1.42 m, respectively. In addition, the largest value of RMSE$_{xy}$ was obtained in stratum B3 whereas the smallest value of RMSE$_{xy}$ was obtained in stratum C1.

Unexpectedly, the minimum value of D_i within plots under open sky conditions was 4.09 m. We can assume that the satellite constellation was probably not optimal and the nearby forest edge caused degradation of satellite signal. Our argument is indirectly confirmed by Yoshimura and Hasegawa (2003) who found RMSE$_{xy}$ at landing within the range of 2.42–6.67 m. Tuček and Ligoš (2002) tested three survey-grade GNSS receivers. They reported mean positional errors within the range of 1.96–7.50 m for open sky areas. Wing (2011) reported positional error of 1.5 m for the best performing consumer-grade GNSS receiver in the open sky course.

To examine the presence of bias in tested errors along the *x* and *y* axes Student's *t*-test or Wilcoxon signed rank test were applied. Statistical analysis revealed that the systematic error was introduced into errors in case of all inventory plots under forest canopy and strata with different tree species composition. This is a surprising result because we expected random direction of errors. The cause of biased errors can partly be attributed to the GNSS receiver and satellite errors. Our argument is based on the fact that approximately 8 inventory plots per day were established. On the other hand, we found no evidence of systematic error for few strata which represent combination of tree species composition and stand age. Biased error for open sky plots was only confirmed along the *x* axes.

Previous studies indicated that there is a significant difference between forest types, i.e. species composition or development stage (Bettinger, Fei 2010; Weaver et al. 2015). With respect to our study, we can conclude that there is no significant difference between mean positional errors across different forest strata. Although ANOVA did not prove significant effect of selected factors on positional errors, we observed that the positional errors more decreased in coniferous forests resulting in increased horizontal accuracy. Also, several studies

(Tuček, Ligoš 2002; Valbuena et al. 2010) did not confirm the influence of tree species composition on positioning errors. More pronounced degradation of satellite signals in broadleaved forests has been previously noted (Wing 2011). Our results of positional errors in broadleaved and mixed strata were ambiguous. Nevertheless, positional errors tended to decrease in mixed strata compared to broadleaved strata. Controversially, horizontal accuracies were higher in broadleaved strata than in mixed strata. The results thus support the findings of Weaver et al. (2015). Bettinger and Merry (2012) noted that if the proportion of broadleaved trees at a radius of 4–5 m of a test point increased, the mean positional error increased. On the contrary, Deckert and Bolstad (1996) reported increased positional errors in coniferous forests when compared to broadleaved forests. As noted by Weaver et al. (2015), this result could be attributed to differences in forest density and canopy cover. Horizontal accuracy was found to increase with decreasing mean diameter in broadleaved and mixed forests. This finding is in line with previous studies. For example, Wing et al. (2005) showed that users could expect horizontal accuracies within 7 m in young forest conditions and 10 m under closed canopies of older forest stands.

Overall, the horizontal accuracy of established inventory plots can be seen as satisfactory related to the used receiver, but this strongly depends on user's preferences. Moreover, the DGPS may be considered a promising aspect of improved positional accuracy. Therefore, forest managers deciding between GNSS receivers should choose one which supports DGPS corrections and allows connecting an external antenna. For example, Wing et al. (2008) have reported smaller positional errors due to the use of external antennas when using GPS receivers in closed canopy sites.

CONCLUSIONS

This study examined the horizontal accuracy of 45 inventory plots established in different forest environments and 5 plots established in forests under open sky conditions.

The level of horizontal accuracy of mapping-grade receiver tested in this study, especially within plots under open sky conditions, was worse than expected. However, application of a mapping-grade GNSS receiver is still suitable for common establishing inventory plots; if there is no emphasis on high positional accuracy (< 1 m).

We observed that $RMSE_{xy}$ decreased in coniferous forests and younger forest stands. In this respect, we may conclude that admixture of broadleaved trees and higher stand age adversely affect horizontal accuracy. However, our results indicated that effect of tree species composition and development stage on horizontal accuracy is not statistically significant.

The ongoing modernization and expansion of GNSS will offer much improved horizontal accuracy, integrity and efficiency performances for different specific areas over the world. In this context, GNSS-based forestry applications are expected to be on the uptrend. Consequently, continuous accuracy assessment of GNSS receivers seems to be valid and necessary (Bettinger, Fei 2010). This is an issue for future research to explore.

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Received for publication August 31, 2018
Accepted after corrections November 19, 2018