Assessing the ForeStereo sensor and the FORTLS R package for estimating stand variables in mature forests

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1. Introduction

Information about forest resources is essential for sustainable forest management and development of forest policies. Forest inventories, which are used as a means of estimating these resources, are continuously influenced by the technological development of remote sensing for data acquisition. Proximal sensing (PS) techniques, in which sensors capture information from short distances, have a strong potential to complement and enhance forest inventories (White et al., 2016). Moreover, the measurement approach of some of these techniques in fixed-point sampling makes them suitable for implementation in conventional forest inventories.

Although several PS devices are available, most are based on optical and LiDAR technologies. As an example of the former, ForeStereo is a passive optical sensor composed of two fish-eye cameras optimized for forestry use (Montes et al., 2019). The main advantages of optical sensors are their low weight and energy consumption, high efficiency in fieldwork and the option of using the image information to retrieve the species or health status of the trees. Terrestrial Laser Scanning (TLS) (LiDAR-based) devices have generated great interest in forest inventories in recent years (Liang et al., 2016). These devices have a well known capacity to generate high density 3-dimensional point clouds with millimetre spatial resolution, making them particularly valuable for enhancing forest inventories (White et al., 2016). In addition, free applications for processing and analysing TLS data have increasing become available in recent years. For example, the recently developed R package FORTLS (Molina-Valero et al., 2021) is useful for extracting forest attributes at stand level based on a single-scan approach. Here, we assessed the performance of the ForeStereo sensor and the FORTLS package for estimating the following conventional forest inventory variables: density (N, trees ha^{-1}), basal area (G, m^2 ha^{-1}), mean diameter at breast height ($\bar{d}$, cm) and the diameter distribution.

2. Data and Methods

The data analysed correspond to 130 subjectively selected sample plots located in mature forest stands dominated (at least 90% of the G represented by the main tree species) by beech (*Fagus sylvatica* L.), maritime pine (*Pinus pinaster* ssp. *atlantica* Villar), Scots pine (*Pinus sylvestris* L.) and silver fir (*Abies alba* Mill.). These stands represent different European forest types: Nemoral and Mediterranean Scots pine forest (38 plots); Southwestern European mountainous beech forest, for both beech (38 plots) and beech-fir (11 plots) dominated communities; Atlantic Maritime pine forest (32 plots) and Mountainous Silver fir (11 plots) forest. These forest types cover a large area of the forest land in Spain. All plots were located in fully stocked stands with no evidence of recent disturbance or logging. Sampling was conducted between 2017 and 2019 and was implemented using a circular nested plot design, with 2 levels of nested plots. All live trees of diameter at breast height (*dbh*, measured at 1.3 m from the ground) greater than 7.5 cm in the first level (radius 5 m) and greater than 12.5 cm in the second level (radius 25 m) were measured with conventional inventory techniques. The plots were then also scanned from the plot centre with ForeStereo and TLS devices. Data were analysed with ForeStereo software and the

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R package FORTLS (Molina-Valero et al., 2021) developed for ForeStereo and TLS devices, respectively. Analysis of stereo pairs of hemispherical images acquired by ForeStereo is based on image segmentation and region-based matching of stems, followed by fitting taper equations for dbh estimation. TLS point cloud analysis uses density-based cluster detection on the horizontal projection of points extracted from one or several slices at approximately 1.3 m height and *dbh*, and tree position is estimated by minimizing radius variance.

We assessed the performance of TLS and ForeStereo devices for estimating *N*, G, $\bar{d}$ and diameter distribution. With this aim, we compared estimates based on field data with those obtained with ForeStereo and FORTLS for circular fixed area plots of 10 and 15 m radius. We also considered the occlusion correction methodology based on correcting the shadowing effect (Seidel and Ammer 2014), which is implemented in both ForeStereo and FORTLS. According to this correction, the effective reference sampling area is reduced by excluding the unsampled areas shadowed by trees. The performance of variable estimates was assessed by means of different statistics: relative RMSE (%), relative bias (%) and the Pearson correlation coefficient. Diameter distributions were assessed using the quadratic form distance: $d(H_{GroundTruth}, H_F) = \sqrt{(H_{GroundTruth} - H_F)^T A (H_{GroundTruth} - H_F)}$, where $H_{GroundTruth}$ is the matrix of histogram bin values as derived from calliper measurements and H_F is the matrix of histogram bin values derived from ForeStereo and TLS data. A is a similarity matrix, with $[a_{ij}]$ denoting the similarity between histogram bins i and j, calculated as $a_{ij} = 1 - |i-j|/\max(|i-j|)$. Lower values of the quadratic-form distance indicate greater similarity between histogram distributions.

3. Results and Discussion

In general, TLS data processed with FORTLS yielded lower RMSE and bias values and higher correlations than ForeStereo (Table 1). However, ForeStereo provided better estimates of *N* in *P. pinaster* stands of 10 m radius. This may be due to difficulties in distinguishing trees from shrub vegetation, which is especially dense in these stands. In these cases, FORTLS may have performed poorly because trees were detected at 1-1.6 m above ground level, in contrast to ForeStereo, which detected trees by matching the visible part of the stem. For almost all species and variables, FORTLS exhibited higher precision, accuracy and correlations for 15 m radius plots. Nevertheless, we did not observe any trends in the accuracy in estimates due to plot size with ForeStereo, even within the same species.

The estimates of *N* were most accurate with FORTLS for plots of 15 m radius (≈4% on relative bias) for all species except *P. pinaster*, for which ForeStereo yielded the lowest absolute value of relative bias with -5%. Although FORTLS tended to overestimate *N* for the 10 m radius plots, probably due to interception by branches or foliage, ForeStereo tended to underestimate *N* for 15 m radius plots as in a study case in mixed stands of *P. sylvestris* and *F. sylvatica* located in the Spanish Pyrenees (Montes et al., 2019), due to the increase in occlusions. The highest correlations corresponded to FORTLS estimates, with values of 0.89 for *P. sylvestris* and and 0.85 for *F. sylvatica*. Estimates of *G* yielded the lowest relative bias with FORTLS for 10 m radius plots of *P. pinaster* and *P. sylvestris* (3 and -1%),and 15 m radius plots of *F. sylvatica* and *A. alba* (0 and 6 %), lower than the 8% reported by Seidel and Ammer (2014) for dense poplar SRF stands. In those cases, the occlusion correction methodology based on correcting the shadowing effect was also applied. Again, the highest correlations corresponded to FORTLS, with a particularly high value of 0.85 obtained for *P. sylvestris*, and the poorest correlations were attained with both PS techniques for mixed *A. alba-F. sylvatica* stands. The *G* estimates produced by ForeStereo for the mature stands analysed in this study showed greater bias and lower correlations than those reported by Montes et al. (2019) for young *P. sylvestris-F. sylvatica* stands, for which the best results were attained with 8 m radius plots. Regarding $\bar{d}$, lower values of relative bias were yielded by ForeStereo, i.e. -2% for *F. sylvativa* and -11% *P. pinaster* stands, and by FORTLS, i.e. 0% for *A. alba* and -8% for *P. sylvestris* stands. The values were always lower than the -16% reported by Seidel and Ammer (2014) for TLS data obtained in densely stocked poplar short rotation stands. As in previous studies (Seidel and Ammer 2014), $\bar{d}$ was generally underestimated, probably due to systematic underestimation of *dbh* in small trees. The highest correlations were again yielded by FORTLS for *A. alba* (0.88) and *P. sylvestris* (0.89).

Quadratic-form distances (QFD) between diameter distributions retrieved from field data and PS techniques were lower considering plots of 15 m radius, especially when derived from ForeStereo, and they were always lower for TLS than for ForeStereo. The poorer performance of ForeStereo for 10 m radius plots may be due to the small sample of trees used for taper equation fitting. The best results were obtained for *P. sylvestris* with both PS techniques.

Table 2. Statistics calculated to assess accuracy in variable estimates.

		N			*G*			$\bar{d}$			
		Bias	REMC	r	Bias	REMC	r	Bias	REMC	r	QFD
					Silver fir / beech-fir						
Fore-	10 m	-23	53	0.31	16	91	0.18	10	30	0.36	427
Stereo	15 m	-49	62	0.20	-9	69	0.32	20	36	0.53	245
FOR	10 m	16	37	0.64	27	54	0.22	**0**	13	0.75	202
TLS	15 m	**5**	**23**	**0.77**	**6**	**32**	**0.40**	-2	**9**	**0.88**	**170**
					Beech						
Fore-	10 m	23	49	0.61	8	46	0.27	-11	27	0.31	297
Stereo	15 m	-15	37	0.49	-13	35	0.48	**-2**	22	0.22	180
FOR	10 m	11	26	0.83	6	29	0.59	-4	20	0.55	124
TLS	15 m	**3**	**19**	**0.85**	**0**	**25**	**0.60**	-4	**13**	**0.61**	**122**
					Maritime pine						
Fore-	10 m	**-5**	**42**	0.37	-14	39	0.45	-13	20	0.51	379
Stereo	15 m	-32	50	0.11	-35	44	0.47	**-11**	19	0.48	207
FOR	10 m	33	77	0.38	**3**	32	0.67	-14	20	0.62	185
TLS	15 m	17	51	**0.51**	-5	**25**	**0.73**	-12	**16**	**0.71**	**131**
					Scots pine						
Fore-	10 m	12	59	0.46	-10	42	0.58	-16	26	0.55	351
Stereo	15 m	-20	51	0.49	-33	47	0.57	-14	23	0.62	162
FOR	10 m	14	31	**0.89**	**-1**	23	0.80	**-8**	14	**0.89**	113
TLS	15 m	**4**	**25**	**0.89**	-8	**20**	**0.85**	**-8**	**13**	0.86	**106**

4. Conclusions

FORTLS produced better results than ForeStereo for estimating *G* in mixed *A. alba*- *F. sylvatica* stands and in pure *F. sylvatica*, *P. pinaster* and *P. sylvestris* stands and for estimating *N* and $\bar{d}$ in mature mixed *F. sylvatica* and *P. sylvestris* stands, always yielding the highest correlations and lowest quadratic-form distances for 15 m radius plots. Nevertheless, ForeStereo performed better for estimating *N* and $\bar{d}$ in *P. pinaster* stands, where dense understory intercepts LiDAR at 1.30 m height. The best results were achieved for 15 m radius plots in *P. sylvestris* stands. Nonetheless, differences between forest types or sites in plot radii that yielded improved estimates depended on forest structure and other factors influencing stand visibility. Future research should focus on exploiting the upper slices of the point cloud with TLS to prevent the understorey effect, increasing the range of detection with ForeStereo and combining both techniques to improve the precision provided by LiDAR and produce additional information for species classification or foliage health status monitoring from images.

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