Applications

ForestScanner: A mobile application for measuring and mapping trees with LiDAR-equipped iPhone and iPad

Shinichi Tatsumi[1,*], Keiji Yamaguchi[2], and Naoyuki Furuya[1]

[1] Hokkaido Research Center, Forestry and Forest Products Research Institute, Hokkaido, Japan

[2] Mapry Inc., Hyogo, Japan

*Corresponding author: Shinichi Tatsumi

Address: Hokkaido Research Center, Forestry and Forest Products Research Institute, Hitsujigaoka 7, Toyohira-ku, Sapporo, Hokkaido 062-8516, Japan

Email: community.ecologist@gmail.com

ORCID: 0000-0002-1789-1685

Running headline: Terrestrial laser scanning with iPhone/iPad

ABSTRACT

1. Terrestrial laser scanning (TLS) is becoming increasingly popular as an alternative means to conventional forest inventory methods. By gauging the distances to multiple points on the surrounding object surfaces, TLS acquires 3D point clouds from which tree sizes and spatial distributions can be rapidly estimated. However, the high cost and specialized skills required for TLS have put it out of reach for many potential users.
2. We here introduce ForestScanner, a free, mobile application that allows TLS-based forest inventories by means of iPhone or iPad with a built-in LiDAR sensor. ForestScanner does not require any manual analysis of 3D point clouds. As the user scans trees with an iPhone/iPad, ForestScanner estimates the stem diameters and spatial coordinates based on real-time object detection and circle fitting. The users can visualize, check, and share the results of scanning *in situ*.
3. By using ForestScanner, we measured the stem diameters and spatial coordinates of 672 trees within a 1 ha plot in 1 h 39 min with an iPhone and in 1 h 38 min with an iPad (diameter ≥5 cm; detection rate = 100%). ForestScanner reduced the person-hours required for measuring diameters to 25.7%, mapping trees to 9.3%, and doing both to 6.8% of the person-hours taken using a dimeter tape and a conventional surveying method. The diameters measured by ForestScanner and diameter tape were in good agreement; R^2=0.963 for iPhone and R^2=0.961 for iPad. ForestScanner and the conventional surveying system showed almost identical results for tree mapping (assessed by the spatial distances among trees within 0.04 ha subplots); Mantel R^2=0.999 for both iPhone and iPad.
4. Our results indicate that ForestScanner enables cost-, labor-, and time-efficient forest inventories. The application can increase the accessibility to TLS for people beyond

specialists and enhance resource assessments and biodiversity monitoring in forests worldwide.

Keywords: Augmented reality, Diameter at breast height, Forest inventory, Light detection and ranging, Mobile phone, Remote sensing, Smartphone, Terrestrial laser scanning

1 | INTRODUCTION

Forest inventory has been an essential component of forest management for over 200 years and constitutes the basis for forest ecology and environmental policymaking today (Corona, Chirici, McRoberts, Winter, & Barbati, 2011; Newnham et al., 2015). With increasing recognition of forest multifunctionality, the use of forest inventory data has expanded from quantifying timber productivity to assessing forest biodiversity and carbon sequestration (Corona et al., 2011). Spatial data of trees in forest inventory plots allow detailed analyses of forest dynamics (Tatsumi, Cadotte, & Mori, 2019; Tatsumi, Iritani, & Cadotte, 2021) and species coexistence (Kunstler et al., 2015; Tatsumi, Owari, & Mori, 2016). As such, forest inventories offer a fundamental step toward studying forest ecology and understanding the benefits forests provide to humanity.

Terrestrial laser scanning (TLS) is becoming increasingly popular as an alternative means to conventional forest inventory methods (Newnham et al., 2015; Liang et al., 2016). By gauging the distances to multiple points on the surrounding object surfaces, TLS acquires 3D point clouds from which trees' sizes and spatial distributions can be rapidly estimated. However, the high cost of TLS devices, typically priced at over US $40,000, has put them out of reach for many potential users (Eitel, Vierling, & Magney, 2013). The heaviness of TLS devices has also been a challenge, making their transportations to/within some areas difficult as well as adding shipping costs (Eitel et al., 2013). The need for specialized computer programs has further limited the TLS user base (Dassot, Constant, & Fournier, 2011; Bunting, Armston, Lucas, & Clewley, 2013). Broader acceptance of TLS as a valid alternative to conventional methods thus requires affordable and efficient hardware and software (Newnham et al., 2015).

Since 2020, Apple Inc. (Cupertino, CA, USA) have introduced a light detection and ranging (LiDAR) sensor in some iPhone and iPad models, namely iPhone 12 Pro, iPhone 12 Pro Max, iPhone 13 Pro, iPhone 13 Pro Max, iPad Pro 2020, and iPad Pro 2021 (as of December 2021).

Compared to other TLS devices in the market, the LiDAR-equipped iPhones/iPads are available at cheaper prices (US ≥$749) and are lighter in weight (187–684 g). These iPhones/iPads have been found suitable for acquiring 3D point clouds in forests (Gollob, Ritter, Kraßnitzer, Tockner, & Nothdurft, 2021; Mokroš et al., 2021). However, to derive tree information (e.g., stem diameter) from the acquired point clouds, one must conduct post-analyses on a separate device using multiple software with command-line interfaces, due to the current lack of dedicated iPhone/iPad application programs.

Here, we introduce ForestScanner, a free application that allows LiDAR-based forest inventories by means of iPhones/iPads. As the user scans trees with the device by walking in the field, ForestScanner estimates the stem diameters and spatial coordinates in real-time (Figure 1; see also Video S1 at FigShare, https://doi.org/10.6084/m9.figshare.17161823.v1). The users can visualize, check, and share the results of scanning *in situ*. These features of ForestScanner allow rapid forest inventories and increase the accessibility to TLS for people beyond specialists.

2 | FORESTSCANNER APP

2.1 | Description

The ForestScanner application is available for free on the App Store (https://www.apple.com/app-store). The application operates on the above-mentioned iPhone/iPad models that have a time-of-flight LiDAR sensor. As the user moves the device, ForestScanner scans objects within a distance of 5 m (i.e., the maximum scanning range of the sensor), acquiring a 3D point cloud of the surrounding object surfaces. When using ForestScanner, the point cloud and 3D triangle meshes appear on the screen in real-time, allowing users to visually recognize the scanned surfaces (Figure 1a; Video S1). The point cloud is colorized with RGB information collected by the camera on the device. During the scan, ForestScanner keeps track of the device’s relative

coordinates from the starting point based on the inertial measurement unit (IMU) (i.e., dead reckoning). The absolute location (i.e., geographic coordinates) of the starting point is determined by the GNSS built into the iPhone/iPad.

Similar to other existing methods for TLS-based forest measurements (e.g., Dassot et al., 2011; Pueschel et al., 2013; Calders et al., 2015), ForestScanner performs stem detections and circle fitting as separate tasks. First, real-time object detection of individual stems is conducted. Circles are then fitted to the cross-sections of the segmented trees in the point cloud space by means of the Levenberg-Marquardt non-linear least-squares method (Björck, 1996). The recommended lower threshold of target tree diameter is 5–10 cm (Gollob et al., 2021; Mokroš et al., 2021), as the current iPhone/iPad LiDAR sensor has limited capability of detecting objects that are a few centimeters in size (Vogt, Rips, & Emmelmann, 2021). Diameters at breast height (DBH) (or any other height of one's choice) and coordinates of the trees are estimated as the diameters and centers of the fitted circles.

2.2 | Usage

- Tap the "Record" button on the screen to start scanning. A crosshair symbol, a slider bar, and the "Tree", "Pause", "Back", "Note", "Stop", "Tree species", and "Album" buttons will appear on the screen (Figure 1a, Video S1).
- While walking in the field, scan target trees individually from a distance of 0.3 m to 5 m. Use the slider bar to fix the maximum scanning distance.
- For each tree, overlay the crosshair symbol at the height where the diameter should be measured (e.g., 1.3 m). Then tap the "Tree" button to identify the stem. The stem diameter will appear on the screen in an augmented-reality manner (Figure 1a).
- If multiple trees are to be scanned in one survey, move to the next tree while scanning.

Alternatively, tap the “Pause” button, move to the next tree, and tap the “Record” button to resume. During the pause, the LiDAR sensor stops scanning while the IMU continues to keep track of the device’s location. Using the pause function helps to reduce the file size of the point cloud.

- Tap the “Tree species” button to enter the tree species (optional). The tree species can be entered by using either the screen keyboard or voice input (i.e., iPhone/iPad’s microphone).
- Tap the “Back” button to delete the tree previously scanned.
- Tap the “Note” button to add a note about the tree previously scanned.
- Tap the “Stop” button to end the survey. The acquired point cloud will be displayed on the screen (Figure 1b).
- After the survey, tap the “Tree List” button to show the list of tree ID, diameters, geographic

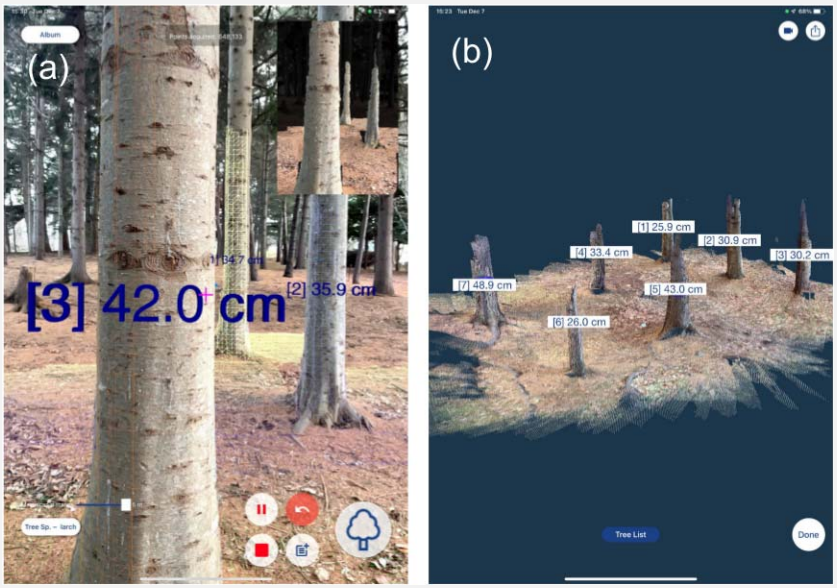

Figure 1. ForestScanner screenshots. (a) As the trees are scanned, stem diameters appear instantly on the screen in an augmented-reality manner. (b) An example of point cloud and tree diameters obtained by ForestScanner. See also Video S1 (https://doi.org/10.6084/m9.figshare.17161823.v1) for a demonstration of the app’s usage.

coordinates, tree species, and notes. The list can be sent to other devices by email or AirDrop.

- Tap the “Album” button to show the results of previous surveys.

3 | FIELD APPLICATIONS

3.1 | Data collection and analyses

We applied ForestScanner to a 1 ha (100 m × 100 m) plot composed of twenty-five 0.04 ha (20 m × 20 m) subplots in the Hokkaido Research Center, Forestry and Forest Products Research Institute, Japan (42°59'57" N, 141°23'29" E) (Figure 2a). The plot encompasses mosaics of

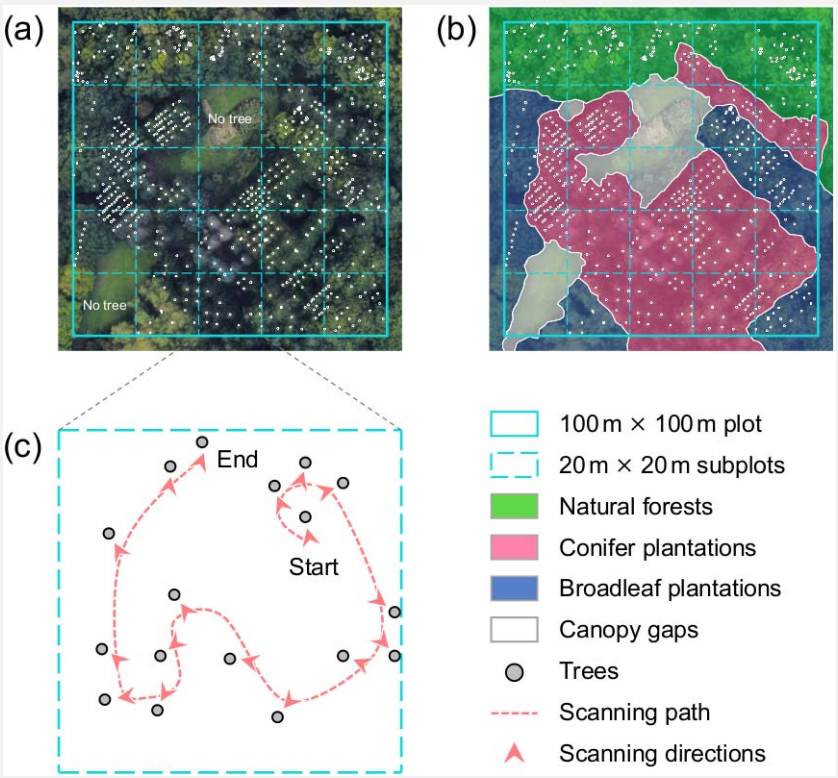

Figure 2. Overview of the study plot. (a, b) The 100 m × 100 m plot consisting of 20 m × 20 m subplots and multiple forest types. (c) An example of the path walked during scanning and the directions from which trees were scanned by ForestScanner. Background image: Google Earth.

multiple forest types including conifer and broadleaf plantations of different stand ages and natural secondary forests (Figure 2b).

All the trees with DBH ≥5 cm were measured and mapped using an iPhone 13 Pro and an iPad Pro 2021. We defined the 0.04 ha subplots as the unit of scanning, with consideration given to the plot sizes often adopted in national forest inventory programs (Paul, Kimberley, & Beets, 2019) and previous iPhone/iPad assessments which used 0.016 ha (Gollob et al., 2021) and 0.063 ha plots (Mokroš et al., 2021). Using each device, the surveyor (author ST) scanned the trees consecutively in each subplot (Figure 2c). Scanning was conducted in 23 subplots since there were no trees in two subplots (Figure 2a).

To compare the results of ForestScanner with conventional methods, we measured the DBH using a diameter tape. The measurement was conducted by one measurer and one note-taker (authors ST and NF). We also measured the spatial coordinates of the trees using a combination of laser range-finder, electronic inclinometer, and electronic compass (Impulse 200 and MapStar Compass Module; Laser Technology Inc., Centennial, CO, USA) attached to a personal digital assistant (PA692; Unitech Electronics Co., Ltd., New Taipei City, Taiwan). Using this surveying system, two people conducted the survey; one person operating the system and the other holding a reflection board by the trees (authors ST and NF). We conducted closed traverses, starting from a control point with known geographic coordinates (i.e., a corner of the plot, a midpoint of the plot edges, or the plot center) and either returning to the same point or closing on another control point. Trees were mapped by measuring the distances and angles from the traverse stations.

We assessed the congruence between the DBH measured by ForestScanner and a diameter tape based on the coefficient of determination (R^2) and the root mean squared error (RMSE). The results of tree mapping by ForestScanner and the conventional surveying system were compared

using Mantel R^2; i.e., we assessed the association between two matrices representing the spatial distances among trees within each subplot. We assessed the trees' relative distances but not their absolute locations because the latter depends not only on the accuracy of the IMU but also the GNSS built into the iPhone/iPad (see *2.1 Description*) and on various field settings (e.g., availability of known points for dead reckoning) which were beyond the scope of this study.

3.2 | Accuracy of scanning

The DBH of all the 672 trees (≥5 cm) in the plot were successfully measured by ForestScanner. Tree detection rate was 100% as the trees were scanned independently on-site. The DBH measured by ForestScanner and a diameter tape were in good agreement; the R^2 values were 0.963 using iPhone and 0.961 using iPad (Figure 3a, 3b). The RMSE were 2.27 cm using iPhone and 2.32 cm using iPad. Our results were comparable with the results from previous studies based on manual post-analyses of iPhone/iPad-acquired point clouds; detection rate = ~80%, R^2 = 0.973, and RMSE = 3.13–4.51 cm (Gollob et al., 2021; Mokroš et al., 2021). Spatial distances among trees measured by ForestScanner and the conventional surveying system were almost identical; the mean Mantel R^2 (averaged across 23 subplots) were 0.999 using both iPhone and iPad (Figure 3c, 3d).

3.3 | Time spent for scanning

Using an iPhone, it took 1 h 39 min (= 1.66 h) for one person to measure the DBH and coordinates of all the 672 trees in the plot (Table 1). It took 1 h 38 min (= 1.64 h) with an iPad to do the same things. Using a diameter tape, it took 3 h 13 min (= 3.21 h) for two people to measure the DBH (Table 1). To map the trees using the conventional surveying system, it took 8 h 53 min (= 8.88 h) for two people (Table 1). As such, compared to the conventional tools,

ForestScanner reduced the person-hours (i.e., the number of workers × hours) required for measuring DBH to 25.7% (= 1.65/6.42), for mapping trees to 9.3% (= 1.65/17.76), and for doing both to 6.8% (= 1.65/24.18).

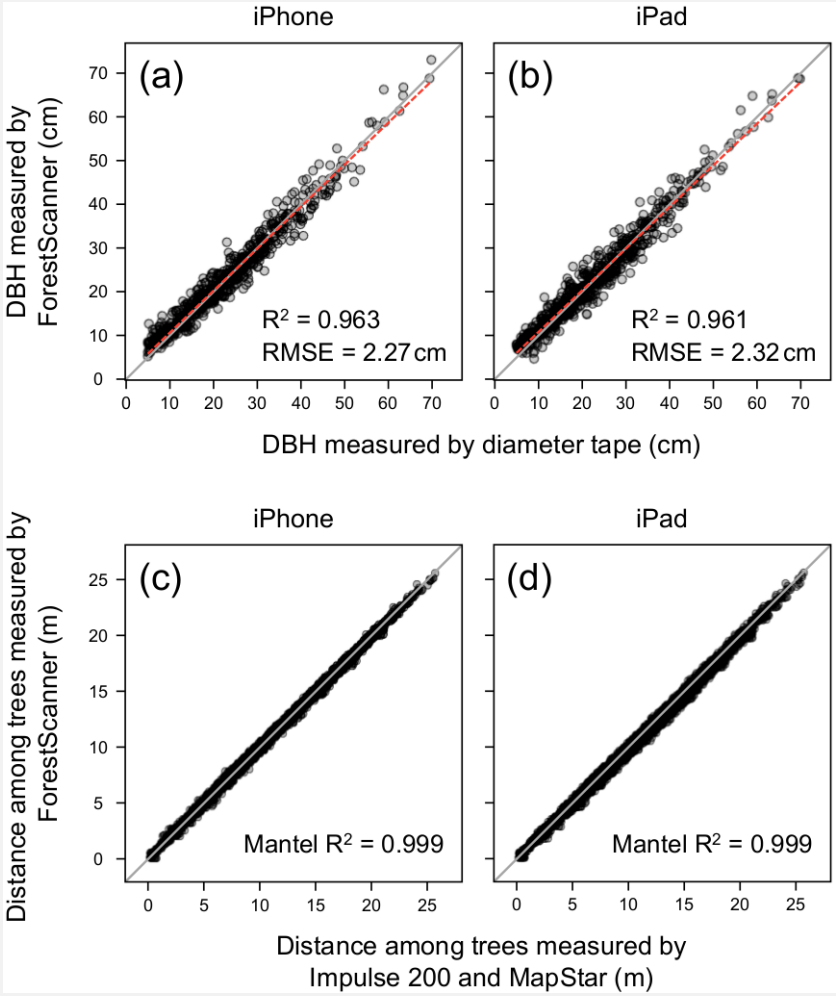

Figure 3. Measurement accuracy of ForestScanner. (a, b) Congruence between DBH measured by a diameter tape and ForestScanner using iPhone and iPad. The red dashed lines indicate regression lines. (c, d) Congruence between the distances among trees measured by a conventional surveying system (a combination of Impulse 200 and MapStar Compass Module) and ForestScanner using iPhone and iPad.

4 | CONCLUSIONS

ForestScanner is a free iPhone/iPad application that allows on-site, real-time measurements of tree diameters and spatial coordinates. We demonstrated that the application requires less labor and time in the field compared to conventional forest inventory tools (Table 1). Tree diameters and coordinates measured by ForestScanner and conventional tools showed good agreement (Figure 3). Future works require further evaluations of the application's performance under various environmental conditions and comparisons with other TLS devices. ForestScanner is intuitively operable and does not require any manual post-analyses of 3D point clouds, providing access to LiDAR technology for non-specialists (e.g., students). We believe that ForestScanner will facilitate TLS-based resource assessments and biodiversity monitoring in forests worldwide.

AUTHORS' CONTRIBUTIONS

ST conceived the study. KY developed the application with inputs from ST and NF. ST and NF

Table 1. The number of workers and time spent to measure the DBH and spatial coordinates of 672 trees in a 1 ha plot using ForestScanner (iPhone and iPad), a diameter tape, and a conventional surveying system (a combination of Impulse 200 and MapStar Compass Module).

	iPhone	iPad	Diameter tape	Impulse 200 and MapStar
Items measured	DBH and coordinates	DBH and coordinates	DBH	Coordinates
Number of workers	1	1	2*	2†
Time spent (hours)	1.66	1.64	3.21	8.88
Workers × hours	1.66	1.64	6.42	17.76

* A measurer and a note-taker.

† An operator and a reflection-board holder.

conducted the fieldwork. ST analyzed the data and wrote the manuscript. All authors contributed to manuscript revisions.

DATA ACCESSIBILITY

Tree diameter and coordinate data obtained by iPhone, iPad, and conventional methods will be made available at FigShare upon acceptance. A demonstration of ForestScanner usage (Video S1) is available at https://doi.org/10.6084/m9.figshare.17161823.v1.

ACKNOWLEDGEMENTS

This work was supported by the Japan Society for the Promotion of Science (Grant-in-Aid for Early-Career Scientists 21K14880) and the Council for the Development of Smart Forestry EZO Model.

REFERENCES

Björck, Å. (1996). Numerical methods for least squares problems. Society for Industrial and Applied Mathematics.

Bunting, P., Armston, J., Lucas, R. M., & Clewley, D. (2013). Sorted pulse data (SPD) library. Part I: A generic file format for LiDAR data from pulsed laser systems in terrestrial environments. *Computers and Geosciences*, *56*, 197–206.

Calders, K., Newnham, G., Burt, A., Murphy, S., Raumonen, P., Herold, M., … Kaasalainen, M. (2015). Nondestructive estimates of above-ground biomass using terrestrial laser scanning. *Methods in Ecology and Evolution*, *6*, 198–208.

Corona, P., Chirici, G., McRoberts, R. E., Winter, S., & Barbati, A. (2011). Contribution of large-scale forest inventories to biodiversity assessment and monitoring. *Forest Ecology and*

Management, *262*, 2061–2069.

Dassot, M., Constant, T., & Fournier, M. (2011). The use of terrestrial LiDAR technology in forest science: Application fields, benefits and challenges. *Annals of Forest Science*, *68*, 959–974.

Eitel, J. U. H., Vierling, L. A., & Magney, T. S. (2013). A lightweight, low cost autonomously operating terrestrial laser scanner for quantifying and monitoring ecosystem structural dynamics. *Agricultural and Forest Meteorology*, *180*, 86–96.

Gollob, C., Ritter, T., Kraßnitzer, R., Tockner, A., & Nothdurft, A. (2021). Measurement of forest inventory parameters with Apple iPad Pro and integrated LiDAR technology. *Remote Sensing*, *13*, 3129.

Kunstler, G., Falster, D., Coomes, D. A., Hui, F., Kooyman, Robert, M., Laughlin, D. C., … Ruiz-Benito, P. (2015). Plant functional traits have globally consistent effects on competition. *Nature*, *529*, 1–15.

Liang, X., Kankare, V., Hyyppä, J., Wang, Y., Kukko, A., Haggrén, H., … Vastaranta, M. (2016). Terrestrial laser scanning in forest inventories. *ISPRS Journal of Photogrammetry and Remote Sensing*, *115*, 63–77.

Mokroš, M., Mikita, T., Singh, A., Tomaštík, J., Chudá, J., Wężyk, P., … Liang, X. (2021). Novel low-cost mobile mapping systems for forest inventories as terrestrial laser scanning alternatives. *International Journal of Applied Earth Observation and Geoinformation*, *104*, 102512.

Newnham, G. J., Armston, J. D., Calders, K., Disney, M. I., Lovell, J. L., Schaaf, C. B., … Mark Danson, F. (2015). Terrestrial laser scanning for plot-scale forest measurement. *Current Forestry Reports*, 1, 239–251.

Paul, T. S. H., Kimberley, M. O., & Beets, P. N. (2019). Thinking outside the square: Evidence

that plot shape and layout in forest inventories can bias estimates of stand metrics. *Methods in Ecology and Evolution*, 10, 381–388.

Pueschel, P., Newnham, G., Rock, G., Udelhoven, T., Werner, W., & Hill, J. (2013). The influence of scan mode and circle fitting on tree stem detection, stem diameter and volume extraction from terrestrial laser scans. *ISPRS Journal of Photogrammetry and Remote Sensing*, *77*, 44–56.

Tatsumi, S., Cadotte, M. W., & Mori, A. S. (2019). Individual-based models of community assembly: Neighbourhood competition drives phylogenetic community structure. *Journal of Ecology*, *107*, 735–746.

Tatsumi, S., Iritani, R., & Cadotte, M. W. (2021). Temporal changes in spatial variation: Partitioning the extinction and colonisation components of beta diversity. *Ecology Letters*, *24*, 1063–1072.

Tatsumi, S., Owari, T., & Mori, A. S. (2016). Estimating competition coefficients in tree communities: A hierarchical Bayesian approach to neighborhood analysis. *Ecosphere*, *7*, e01273.

Vogt, M., Rips, A., & Emmelmann, C. (2021). Comparison of iPad Pro®'s LiDAR and TrueDepth capabilities with an industrial 3D scanning solution. *Technologies*, *9*, 25.