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PRACTICAL TOOLS

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Measuring understorey vegetation structure using a novel mixed-reality device

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Abstract

1. Most ecological studies of vegetation structure have relied on manual field measurements that are labour-intensive and time-consuming. Many current alternatives to classical measurements are expensive or difficult to transport to field settings.
2. Here we evaluated a new method for measuring understorey vegetation with a novel mixed-reality, remote sensing device, the Microsoft HoloLens. We developed a vegetation sensing application called VegSense that allows the HoloLens user to control the device's environmental scanners to measure understorey vegetation. Using VegSense, we tested the ability of the Microsoft HoloLens relative to classical field measurements to (a) detect trees and saplings, (b) measure diameter at breast height (DBH), (c) detect individual understorey vegetation structures and (d) estimate understorey vegetation complexity replicating the rod-transect method.
3. We found that VegSense performed well in detecting and measuring trees with a DBH of 17 cm or more and estimating vegetation complexity and performed moderately at detecting understorey vegetation.
4. Our results indicate that the HoloLens is a suitable alternative for multiple classical field measurements of understorey vegetation. This method costs much less than typical terrestrial LiDAR systems, and can facilitate efficient, high-quality environmental data collection. Further software development has the potential to reveal additional ways in which this device can be harnessed for applications to ecology and evolution.

KEYWORDS
forest ecology, Microsoft HoloLens, plants, remote sensing, trees, vegetation complexity

1 | INTRODUCTION

Understorey vegetation is a fundamental component of forest ecosystems and the ecological processes that occur within them, and it can affect populations, communities, species interactions, and ecosystem services (Chang-Yang et al., 2021; Zhao et al., 2015). Despite the scientific importance of understorey vegetation, many studies still rely on classical physical vegetation measurements, such as manual diameter at breast height (DBH) measurements, counts of the number of stems, and various transect and subplot sampling techniques. However, classical field techniques are often time-consuming and labour-intensive (Buckley et al., 1999; Zhou et al., 2018). As the complexity of the understorey increases, so too does the difficulty in obtaining representative data on vegetation structure. Complex spatially explicit data are particularly difficult to obtain through classical measurement because of the multidimensional arrangement of understorey vegetation (Yang et al., 2017).

Multiple technologies have simplified the measurement of complex understorey vegetation over the past few decades. Light detection and ranging (LiDAR) methods have been increasingly used to assess comprehensive three-dimensional vegetation structure (Tweedy et al., 2019; Zhang & Shao, 2020), but terrestrial LiDAR devices are often expensive (typically >$20,000; Mokroš et al., 2021; Stovall & Atkins, 2021; Tao et al., 2021) and difficult to transport. Cheaper, alternative technologies have been proposed and tested to generate 3D understorey data, such as LiDAR sensors on the iPad pro (Mokroš et al., 2021), and can be effective. The increased availability of high-quality spatial sensors on small personal devices raises the possibility of new applications for ecology and environmental science.

One new personal device with great potential for measuring understorey vegetation structure is the lightweight and relatively inexpensive Microsoft HoloLens. The Microsoft HoloLens, which was first released in 2016, is a head-mounted mixed-reality device, meaning that the user can interact with holograms projected on the surrounding environment in real time. The HoloLens is equipped with a variety of scanners that can detect, map and identify positions in the surrounding landscape; the scanners include four visible light cameras, two infrared cameras, a depth sensor and an inertial measurement unit (Evans et al., 2017). The device is completely self-contained with onboard processors, is rechargeable, and has 2–3 hr of battery life. One of the most promising aspects of this device for quantifying vegetation is its mixed-reality interface, in which virtual projections are overlaid on real-world surroundings. The ability to virtually interact with the surrounding environment through projections provides opportunities for software development for data extraction and visualization. Moreover, the HoloLens 2, which is the current model, is available for purchase for $3,500. At 0.56 kg in weight, it is easily transportable to remote field locations. HoloLens applications have been developed for a variety of fields including medicine (Hanna et al., 2018), education (Wyss et al., 2021) and engineering (Zhang et al., 2019). However, to our knowledge, the HoloLens has not yet been used to measure vegetation structure, and so the ability of this device to produce accurate measurements of understorey vegetation structure remains unknown.

Here we test the ability of the Microsoft HoloLens to reproduce results of classical field-based forest understorey vegetation measurements. Specifically, we present a new application for the HoloLens, VegSense, which allows users to control the environmental scanning capabilities of the device and use it to standardize data collection from understorey vegetation. We evaluate the ability of VegSense to (1) detect trees and saplings, (2) measure the DBH of trees and saplings, (3) detect understorey vegetation and (4) calculate plot-level understorey vegetation complexity. To assess these, we hypothesize that (1) the HoloLens will detect all trees and saplings in the sampling area, (2) DBH measurements from the HoloLens will be the same as manual DBH measurements, (3) the HoloLens will detect understorey vegetation as well as the rod-transect method, and (4) the HoloLens will produce measurements of plot-level vegetation complexity as well as the rod-transect method.

2 | METHODS

2.1 | VegSense application

We developed a HoloLens-specific vegetation sensing application 'VegSense' to detect and save the 3D spatial configuration of scanned understorey vegetation, including trees, shrubs and saplings (available at Gorczynski & Beaudrot, 2022). We developed the application in Unity (Juliani et al., 2018), a development platform for 3D games and interactive experiences, using the Microsoft Mixed Reality Tool kit (Microsoft Corporation, 2020) and deployed it using Microsoft Visual Studio (Visual Studio, 2019). The VegSense user interface is a four-button panel that controls various aspects of the environmental scanning process.

2.2 | HoloLens sampling

We developed the following protocol for collecting data on understorey vegetation structure using VegSense on the Microsoft HoloLens. We activated spatial scanning at the centre of each sampling area. We walked 5-m transects out and back in each of the four cardinal directions (north, south, east, and west) and the four intercardinal directions (northwest, northeast, southwest, and southeast). This was followed by a circular transect around the circumference of the sampling area at a radius of 5 m. While performing the transects, we pivoted the device to face up and down periodically (from ~30° to −30° from horizontal) to scan vegetation at multiple heights in the understorey, from ground level to over 2 m in height. We then returned the device to the centre of the sampling area, deactivated the spatial scanner and saved the environmental mesh onto the HoloLens as an Object file (.obj). This entire process on average took <5 min for each sampling area.

We extracted measurements of the understorey vegetation from the saved environmental mesh in Blender (Community, 2018), which is an open-source 3D computer graphics software toolset (Appendix S1), and compared them to measurements collected using classical field methods. Descriptions of the classical field methods used in this study are found in the supporting materials (Appendix S2). To measure diameter at breast height of each tree in the scanned environments (Figure 1a), we oriented the object files so that the origin in coordinate space (i.e. point 0, 0, 0) was within the tree. We used

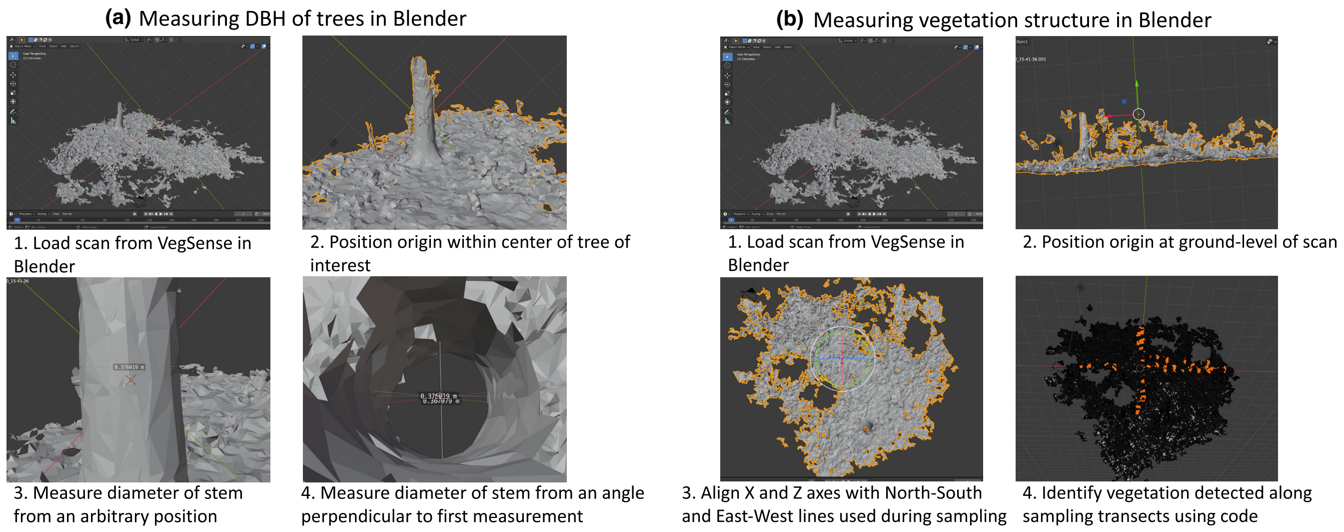

FIGURE 1 Visual description of vegetation measurement extraction process from VegSense scans in Blender. (Panel a) shows how to measure diameter at breast height from these scans as two perpendicular measurements of diameter that are then averaged. (Panel b) shows how to extract vegetation detection along 5-m transects in the four cardinal directions using code available in Appendix S1.

the measure tool to calculate the diameter at two arbitrary locations perpendicular to one another on the tree at a height of approximately 1.37 m above the ground. We used the mean of these two measurements as the diameter of the tree.

To measure vegetation structure (Figure 1b), the object files of each sampling area were oriented so that the centre of the area on the ground was aligned with the origin (i.e. point 0, 0, 0) in coordinate space. The environmental mesh was then rotated so that the *X*-axis aligned with measured North–South (positive and negative, respectively), and the *Z*-axis aligned with measured East–West (positive and negative, respectively). To replicate rod-transect measurements, we developed an automated system to determine whether vegetation had been detected in each of the four cardinal directions at intervals of 0.5 m from the origin and binned their heights from 0–0.5 m, 0.5–1 m, 1–1.5 m, 1.5–2 m and 2 or more meters.

To compare the measurements obtained using VegSense with classical field methods, we used generalized linear regression with response variable distributions selected based on the type of data being compared. A full description of the statistical methods is shown in the supporting materials (Appendix S2).

3 | RESULTS

Overall, we found that measurements collected using the HoloLens and VegSense replicated the classical vegetation measurements with varying degrees of success. The HoloLens was only able to detect 39.3% of trees and saplings over 1 m in height observed in plots overall, but detection increased with DBH (logistic regression, $E_{st} = 0.40$, $SE = 0.08$, $p < 0.001$, $R^2 = 0.82$, $df = 134$), indicating that larger trees and saplings were more likely to be detected using the HoloLens than smaller trees (Figure 2a). Based on predictions from the fitted model, trees with a DBH of 10 cm had a 49.6% chance of being detected, likely because of the near lack of detection of smaller stems, while detection probability was 95% for trees with a DBH of 17.32 cm. For trees detected by VegSense, there was a strong, significant positive relationship between the classical and VegSense DBH measurements (linear regression with log normal response, $E_{st} = 0.91$, $SE = 0.028$, $p < 0.001$, $R^2 = 0.96$, $df = 52$), which indicates that DBH estimates from the HoloLens were very similar to those measured by hand (Figure 2b).We also found a significant positive relationship between vegetation detection using rod transects and VegSense on the HoloLens (binomial regression including height as a fixed effect, $E_{st} = 1.17$, $SE = 0.15$, $p < 0.001$, $R^2 = 0.29$, $df = 2199$). However, VegSense detection probability progressively declined with increasing vegetation height (Figure 2c). Finally, there was a significant positive relationship between vegetation complexity measured using rod transects and VegSense on the HoloLens (linear regression with a Gaussian response, $E_{st} = 0.38$, $SE = 0.11$, $p = 0.008$, $R^2 = 0.56$, $df = 9$; Figure 2d).

4 | DISCUSSION

This study tested the utility of the VegSense application on the Microsoft HoloLens as a novel tool for measuring understorey vegetation. Overall, the HoloLens and VegSense show strong potential for measuring comprehensive, plot-level aspects of understorey vegetation and mature tree inventory, but limited ability to detect fine-scale vegetation structures such as saplings and thin branches.

VegSense detected all but two of the 48 trees with a DBH >10 cm (Figure 2a). This result indicates the usefulness of VegSense and the HoloLens for conducting mature tree inventories, which often set a cut-off at 10 cm DBH (Putz & Chan, 1986). Both non-detected trees were surrounded by a large amount of understorey vegetation including shrubs and saplings. Therefore, when using the

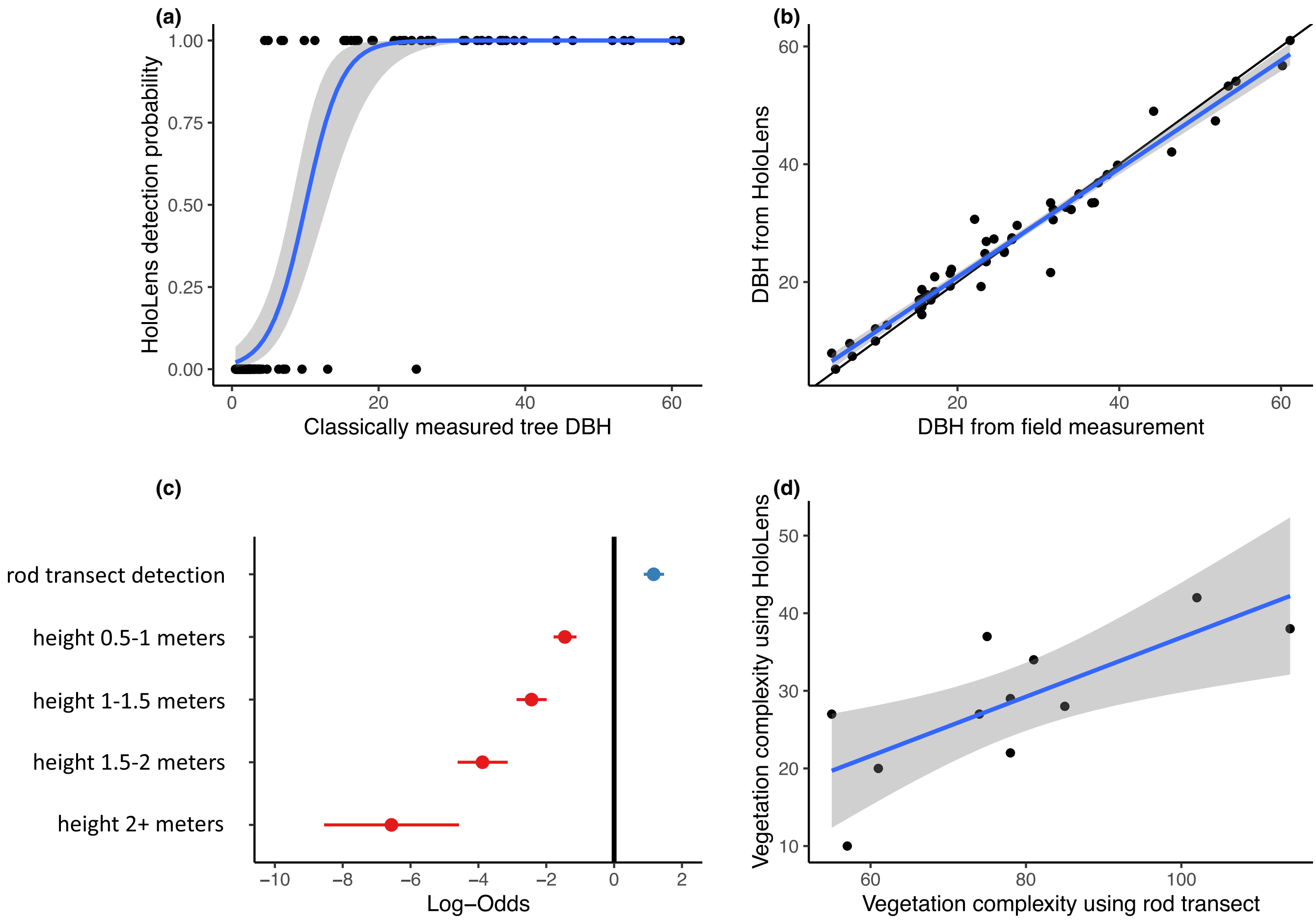

FIGURE 2 Comparison between classical field techniques and measurements derived from HoloLens. (a) Probability of tree detection using the Microsoft HoloLens increased logistically in response to tree DBH. (b) For stems detected by the HoloLens, DBH measurements extracted from VegSense scans showed a positive linear relationship with classical DBH measurements. The black line represents the one-to-one ratio of DBH. (c) VegSense vegetation detection probability progressively declined with increased vegetation height. The solid points indicate the log-odds ratio mean effect sizes, with the 95% confidence intervals shown by the horizontal bars. The black line represents a log-odds ratio of zero, with variables on the left indicating negative effects, and variables on the right indicating positive effects. (d) Plot-level vegetation complexity estimates derived from VegSense showed a positive linear relationship with estimates from the rod-transect method.

HoloLens to inventory mature trees, special care should be taken to document stems located in dense understorey vegetation to ensure they are not excluded from the scan. Because very few stems <5 cm DBH were detected, we conclude that VegSense is not appropriate for inventorying saplings.

In addition, our analyses demonstrate that DBH measurements derived from the HoloLens were very similar to those measured by hand (Figure 2b), indicating that the Microsoft HoloLens with VegSense provides a quick alternative to measuring DBH of mature trees by hand in forests. The method of extracting DBHs from environmental scans used in this study required manual measurement in Blender, which resulted in longer processing time and had the potential to introduce bias or error. This limitation could be improved by automation of the measurement extraction process.

Regarding understorey vegetation, although there was a significant association between detection using rod transects and VegSense, vegetation height also significantly affected detection (Figure 2c). Notably, VegSense vegetation detection increased closer to the ground, potentially due to the HoloLens sampling technique. Surveyors may be more likely to look at the ground to find their footing, and so incidentally introduce sampling bias, which warrants further investigation. Furthermore, transect-based metrics like the rod transect can detect a wide variety of vegetation cover from grasses to twigs to full trees (Godínez-Alvarez et al., 2009), while the HoloLens has difficulty in detecting thin structures. Nevertheless, with vegetation complexity calculated as the sum of all vegetation detected at a plot, VegSense performed well, showing a stronger association with vegetation complexity as measured by the rod transects. This result indicates that the HoloLens may perform well at the plot level with more comprehensive measurements of vegetation complexity, while it is less suited to parsing out fine-scale spatial position of thin vegetation structures. However, the classical rod-transect method is not without its own limitations and comparing VegSense detection to more comprehensive data collection methods, such as LiDAR, would provide important insight into the accuracy of the HoloLens and VegSense.

Finally, there are a variety of ways in which other sensors and features of the HoloLens can be developed to inventory vegetation in the future. The HoloLens' RGB camera could be integrated with VegSense to locate and identify individual plant species via machine learning. This camera could also be used to identify canopy gap measurements based on observed differences in light. Finally, the mixed-reality interface of the HoloLens can allow the user to interact with virtual scans and the surrounding environment simultaneously, potentially allowing for better visualization of changes in vegetation structure. We emphasize the multitude of potential future uses of this device, and we are enthusiastic about the HoloLens' potential to further ecological knowledge.

AUTHORS' CONTRIBUTIONS

D.G. conceived the ideas, designed the methodology and developed VegSense; L.B. advised data collection and analysis; D.G. collected and analysed the data; D.G. wrote the manuscript with feedback and editing from L.B. All authors contributed critically to the drafts and gave final approval for publication.

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CONFLICT OF INTEREST

The authors have no conflict of interest to declare.

PEER REVIEW

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DATA AVAILABILITY STATEMENT

Data used in the study, code used to process and analyse data, supplementary information, underlying VegSense application code, and the VegSense application are available for download on Zenodo (Gorczynski & Beaudrot, 2022) at https://doi.org/10.5281/ZENODO.6624972.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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