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Seeing the forest from drones: Testing the potential of lightweight drones as a tool for long-term forest monitoring

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ABSTRACT

Long-term ecological monitoring has contributed substantially towards advancements in theoretical and applied ecology. However, the costs to maintain a long-term monitoring site are enormous. Lightweight unmanned aerial vehicles (UAVs or drones) have been rapidly emerging as a new tool for local-scale monitoring. To evaluate the value of drone applications in long-term ecological studies, we combined drone-derived canopy variables, detailed ground-based stem-mapping data and topographic and edaphic variables from a 20-ha forest dynamics plot in a species-rich subtropical forest. Specifically, we evaluated the relative importance of these variables in explaining local-scale variation in forest stand and species measures. We found that drone-derived canopy variables contributed substantially towards explaining local patterns of biodiversity and more specifically in supporting a gap dynamics hypothesis in structuring observed forest biodiversity. Stand basal area was positively related with canopy closure, indicating the importance of protecting old-growth forests as carbon sinks. The importance of topographic and edaphic variables was also demonstrated, supporting a niche differentiation hypothesis in structuring patterns in biodiversity. Species-level analyses illustrated that light-demanding species were more strongly correlated with canopy variables than shade-tolerant species. We provide convincing evidence that drones can add substantial value to long-term ecological monitoring by providing low cost, high resolution data. Drones should be included in the ecologist's toolbox to complement traditional field surveys.

1. Introduction

High-quality biodiversity data on species' distributions and its integration with environmental variables are critical for addressing basic research questions in ecology, tracking biodiversity changes, and developing effective conservation actions. Although we gain a wealth of knowledge by spending an enormous amount of time and energy in the field, traditional field surveys can be exhausting and costly (Lawton et al., 1998; Gardner et al., 2008). For example, a field team of 12 to 14 individuals took ~3 years to complete the first tree census for a 50 ha forest dynamics plot in Barro Colorado Island, Panama. Costs to establish similar plots are estimated at about US$100,000 to US$500,000 (Condit, 1998). Additional measurements and monitoring of tree height, canopy openness, forest disturbance and other forest parameters are limited by available human labor and financial resources. Due to these limitations, ground-based surveys are not as frequent as required for analysis and monitoring of short-term change. Therefore, a key challenge remains on how to collect forest attribute data in a timely and cost effective manner.

Remote sensing techniques are increasingly being used to assess changes in forest cover (Hansen et al., 2013; Nijland et al., 2015), tree density (Crowther et al., 2015), species distributions (Cord et al., 2013), canopy height (Simard et al., 2011; Nijland et al., 2015; Zhang et al., 2016), and carbon stocks (Saatchi et al., 2011; Zhang et al., 2014). However, satellite and airborne sensors can be expensive and inaccessible for most researchers, requiring trade-offs between resolution, scale, and frequency (Anderson and Gaston, 2013). For ecological studies at local and regional scales, satellite and airborne data are not often well-suited to the scale of the study (Wulder et al., 2004). Small unmanned aircraft systems, also known as lightweight unmanned aerial vehicles (UAVs) or drones, provide "a promising route to responsive, timely, and cost-effective monitoring of environmental phenomena" (Anderson and Gaston, 2013). Although drones in military applications have a relatively long history, civilian applications have only recently emerged (Koh and Wich, 2012; Anderson and Gaston, 2013). Pioneering ecologists and conservation biologists have recently been using drones to monitor wildlife and plant populations (Jones et al., 2006; Chabot and

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Bird, 2012; Vermeulen et al., 2013), wildlife poachers (Schiffman, 2014), vegetation structure (Getzin et al., 2012; Dandois and Ellis, 2013; Puliti et al., 2015), and mapping of land cover change (Rango et al., 2009). Compared with satellite and airborne remote sensing techniques, drones can fly at low altitudes and at slow speeds, allowing them to take ultra-high spatial resolution (1–20 cm) imagery and thereby collect near-earth data of plant and wildlife populations and biophysical variables (Rango et al., 2009; Koh and Wich, 2012; Whitehead and Hugenholtz, 2014). Using drones also avoids many limitations associated with satellite data, including the lack of sufficient spatial resolution to detect and measure certain critical biophysical properties (e.g., forest canopy gaps and single-tree identification), the lack of sufficient temporal resolution data to detect changes in phenology and stand structure by disturbance events, and long-duration cloud contamination over many types of tropical and subtropical forests (Paneque-Gálvez et al., 2014; Whitehead et al., 2014). Additionally, the cost of one camera-equipped drone is relatively low (Koh and Wich, 2012). Despite these advantages, current cost-effective drones have relatively limited spatial extent per flight, small payloads and low spectral resolution (Paneque-Gálvez et al., 2014; Whitehead et al., 2014), and therefore this technology has yet to receive much attention by field ecologists, especially for long-term ecological studies.

Long-term ecosystem monitoring is the keystone of ecological research and management (Callahan, 1984; Likens, 1989; Condit, 1995; Lindenmayer et al., 2012) because these data provide important insights to complex ecological systems. There are a number of well-known long-term ground-based monitoring programs, such as International Long Term Ecological Research Network (ILTER, http://www.ilternet.edu), North American Breeding Bird Survey (BBS, https://www.pwrc.usgs.gov/bbs), United States Forest Inventory and Analysis National Program (FIA, http://www.fia.fs.fed.us), Amazon Forest Inventory Network (RAINFOR, http://www.rainfor.org), and the Center for Tropical Forest Science and Forest Global Earth Observatory (CTFS-ForestGEO, http://www.forestgeo.si.edu). Using the CTFS-ForestGEO network as an example, this network comprises over 60 plots from 24 countries across the Americas, Africa, Asia, and Europe, on over 10,000 woody plant species, and more than 6 million living individuals (Anderson-Teixeira et al., 2015). Since the first 50-ha forest dynamics plot was established at Barro Colorado Island in Panama in 1980, over 200 researchers have published over 1000 scientific articles using CTFS-ForestGEO data. These publications have had a substantial impact across a large variety of science and policy issues (e.g., Hubbell et al., 1999; Harms et al., 2000; Hubbell, 2001; Condit et al., 2006; John et al., 2007; He and Hubbell, 2011; Stephenson et al., 2014). Likewise, remote-sensing-based long-term monitoring, such as the National Ecological Observatory Network (NEON, http://www.neoninc.org) and NASA's Moderate Resolution Imaging Spectroradiometer (MODIS) platform, have contributed substantially to our understanding of a variety of ecosystems at regional and global scales (Kerr and Ostrovsky, 2003).

Despite the tremendous value of these long-term data sets, many data gaps remain. First, ground-based monitoring sites only cover a small fraction of the Earth's surface and are not representative with several geographic biases. Martin et al. (2012) analysed the distributions of 2573 terrestrial ecological sites, and found that these sites overrepresented protected areas and wealthy countries, and were rarely distributed in the 75% of the terrestrial world where humans live. One main reason for the paucity of these ground-based sites is their high monitoring and maintenance costs. Second, challenges remain between linking broad-scale remote sensing data with local-scale ground data (Kerr and Ostrovsky, 2003; Wulder et al., 2004). The problem of mismatch of spatial scales results in limitations to monitoring and predictions of species distributions and dynamics (e.g., Saveraid et al., 2001). Likewise, mismatches in temporal scales also occur. Broad-scale remote sensing data are not generally as frequent as required to address a number of pressing ecological questions. For instance, human and natural disturbance events at local and/or regional scales, such as forest harvesting, windfall and drought, may not be captured by satellite remote sensors (Wulder et al., 2004). Therefore, drone-based ecosystem monitoring that can be applied at the temporal and spatial scales relevant to ground measures will greatly benefit long-term studies of ecological properties, potentially “revolutionizing spatial ecology” (Anderson and Gaston, 2013).

In this study, we explore the utility of using lightweight drones as a flexible, cost-effective, and accurate method for mapping forest stand characteristics in a 20-ha CTFS-ForestGEO subtropical forest plot in China. By combining aerial photographs collected by the drone with photogrammetry and using detailed ground survey data on species distribution, topography and edaphic variables, we mapped forest canopy structure, and analysed the relative contribution of drone-derived canopy attributes, topography and edaphic variables to observed patterns of biodiversity and tree regeneration. Specially, we assess: (1) the feasibility of using drone technology to collect high resolution aerial photographs for mapping three-dimensional (3D) forest canopy structure; (2) to what extent drone-derived canopy attributes contribute to our understanding of local-scale patterns in biodiversity and biomass storage; and (3) how species with different life history strategies (i.e., light-demanding vs. shade-tolerant species) respond to drone-derived canopy attributes and other environmental variables.

2. Materials and methods

2.1. Ground inventory data

This study was conducted in a 20-ha (500 m × 400 m) forest dynamic plot in the Dinghushan (DHS) National Nature Reserve (23°09′–23°11′N, 112°30′–112°33′E) in Southern China (Fig. 1). The DHS reserve, which was established in 1956 as China's first nature reserve, encompasses approximately 1155 ha of forests with elevations ranging from 14.1 m to 1000.3 m above sea level. This reserve joined the International Man and Biosphere Reserve Network (MAB) as a global conservation hotspot in 1979. The region is characterized by a south subtropical monsoon climate, with mean annual temperature of 20.8 °C, and monthly mean temperatures varying between 12.6 °C in January to 28 °C in July (Huang et al., 1998). Mean annual precipitation is 1929 mm, with most precipitation occurring between April and September. Mean annual evaporation is 1115 mm with relative humidity averaging 80% (Huang et al., 1998). The vegetation is mainly covered by well-protected monsoon evergreen broadleaved forest. In contrast to the surrounding disturbed forests, the reserve contains rare primary forests of at least 400 years of age that were conserved by monks at the Buddhist temple near the plot (Fig. 1c).

The 20 ha DHS plot was established in 2004–2005 (Fig. 1). Following the protocols from the CTFS-ForestGEO network (Condit, 1998), all stems with ≥1 cm diameter at breast height (DBH) were tagged, georeferenced, and identified to species. The first inventory of this plot was completed in 2005, and has been re-censused at five-year intervals ever since. Data for the 2010 census were used for the current analysis which includes 60,015 living individual stems with ≥1 cm DBH representing 177 woody plant species. Among these species, 47% (84 species) are considered rare as defined as being less than one individual per hectare (Ye et al., 2008). Based on importance values, Chinese chestnut (*Castanopsis chinensis*, Fagaceae), Chinese gugertree (*Schima superba*, Theaceae), and yellow basket-willow (*Engelhardtia roxburghiana*, Juglandaceae) are the three most dominant species.

2.2. Topographic and edaphic variables

Topography of the study plot was measured by four variables: elevation, slope, aspect, and convexity. Elevation was surveyed on a 20 m × 20 m grid within the 20-ha plot using an Electronic Total Station with elevation values averaged from the four corner of each 20 m × 20 m quadrat (Ye et al., 2008). Slope was defined as