Opening a new era of investigating unreachable cliff flora using smart UAVs

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Abstract

Cliff ecosystems are considered the ‘Last Unknown’ because cliffs may host ancient and unique species that are located in extremely hostile environments and are difficult to reach. However, comprehensive and systematic information and databases of cliff flora are unavailable; and obtaining information on these undisturbed ecosystems and cliff flora is fundamental and is of high priority for botanists. We present the first systematically sampled expert-verified checklist of cliff flora from the ground to the top of cliffs in these harsh environments based on high-resolution visible imagery captured with close-range photogrammetry by a smart remote-controlled unmanned aerial system (UAS). Using approximately 9200 records retrieved from high-resolution images of 197 cliffs in the Wulingyuan global cultural heritage area, a mid-subtropical region in China, we identified 267 vascular plant species, 140 genera and 58 families, excluding herbaceous plants. The maximum diversity was attributable to a few dominant families and genera, and most of the genera and families were represented by only a few species. Our findings highlight the unique floristic patterns as well as morphology on these cliffs that warrant further study and the potential for the use of a smart UAS to investigate cliff flora at large and global scales.

Introduction

Cliff flora refers to vegetation living on the vertical surfaces of cliffs, and this type of vegetation may include unique and ancient species (Boggess et al., 2017; Larson et al., 1999, 2000a). However, cliff flora is one of the least understood vegetation types, or the ‘Last Unknown’ (Cámara-Leret et al., 2020), because cliffs are hostile environments that are difficult to reach (McMillan & Larson, 2002). Furthermore, the relatively small and fragile habitats available to vegetation on cliffs are more likely to cause species extinction (Staude et al., 2020) as cliff habitats are very different from those on level ground or slopes (Larson et al., 2000a). Obtaining information on these undisturbed ecosystems and cliff flora is of high priority for botanists, ecologists, conservationists and environmentalists. Considering that cliffs are vertical or nearly vertical rock exposures and are characterized by limited resources in terms of soil, water and nutrients (Davis, 1951; Medina & Fernandes, 2007), cliff flora shows relatively high tolerance to such extremely harsh conditions and may be useful in restoring degraded rocky and karst ecosystems.
Although cliff flora has been studied since 1951 (Davis, 1951) and progress has been achieved (e.g., Boggess et al., 2017; Catling, 2009; Larson et al., 2000a, 2000b; Naqinezhad & Esmailpoor, 2017), cliff flora has gained less attention than other major biomes, mainly due to its unreachability and inaccessibility. Vegetation investigations of cliffs based on transects or sampling quadrats are limited to areas that can be reached by people. In recent decades, cliff flora has been investigated relatively extensively through rock climbing, such as by Boggess et al. (2017), Camp and Knight (1998), McMillan and Larson (2002) and Vogler and Christoph (2011). Nonetheless, rock climbing requires specific skills and carries high risks, limiting both the climbing height and investigation region, for example, the climbed cliff height is generally less than 50 m (Kuntz & Larson, 2006; Larson et al., 2000b); thus, such an investigation method cannot be used at a large scale to support a systematic study of cliff flora distributed vertically from the ground to the top of a cliff. Therefore, comprehensive and systematic information and databases of cliff flora are unavailable, which constrains our knowledge of species on Earth (Mora et al., 2011).

With the rapid development of the drone industry in recent years, unmanned aerial vehicles (UAVs), which have great flexibility in terms of flight, provide a new and innovational data collection method that is beyond the traditional methods used in environmental studies (Anderson & Gaston, 2013; Coops et al., 2019; Pajares, 2015). Ultrahigh spatial resolution (<5 cm) imagery obtained by UAVs has been widely used in vegetation surveys (e.g., Hao et al., 2021; Maes & Steppe, 2019; Mohan et al., 2017; Zarco-Tejada et al., 2014). Coops et al. (2019) suggested that the use of UAVs could be extended in environmental research by improving flight control and regulation and related measurement technologies. Recent innovations in smart UAVs are regarded as the next major revolution in the drone industry (Shakhatreh et al., 2019). As such, a smart UAV enables the use of close-range photogrammetry to study individual plants and may revolutionize and begin a new era for investigating and studying cliff flora.

However, it is currently difficult to perform UAV-based photogrammetry in windy and extremely hostile environments. To address such issues, we introduce the use of a smart remote-controlled unmanned aerial system (UAS) to spatially investigate flora on cliffs with hostile environments that are difficult to reach. With the proposed method, we identified vascular plant species from high-resolution visible imagery and studied the floristic patterns of the identified cliff flora, aiming to accelerate botanical and ecological research on unreachable cliff flora.

Materials and Methods

Study area and data collection

We conducted the study over a stone (cliff) forest with a size of approximately 200 km² in the Wulingyuan area, Zhangjiajie National Forest Park, Hunan Province, China (Fig. 1). It has been a UNESCO World Heritage Site since 1992 and is classified as a category VI IUCN-protected area. In the Wulingyuan region, there are many sandstone cliffs, with an estimated number of greater than 3000, and the cliffs are commonly shaped such as narrow pillars and peaks (Figs. 1C–E), with heights varying from tens of meters to approximately 400 m (Chen & Li, 2003). The climate is generally mid-subtropical, with an annual precipitation and average temperature of approximately 1400 mm and 16 °C, respectively. Elevations change from approximately 300–1260 m above sea level (a.s.l.). Biodiversity in the Wulingyuan area is relatively high and unique because the secondary primeval forest is rich in rare and native endemic species (Chen & Li, 2003; Koponen et al., 2000).

Field experiments were performed with the help of a smart remote-controlled UAS during sunny and relatively windless days from July to August 2019. The relatively windless days were categorized by a general description at ground level, which does not necessarily represent the conditions on cliff faces (or between cliffs). It is well known that greater wind speeds and greater turbulence occur on cliff faces than in the surrounding habitat; thus, cliff edges can have exceptionally high local wind speeds (Larson et al., 2000a), whereas rocky surfaces, high ridges and sheer cliffs all combine to produce unpredictable flow patterns and turbulence, especially between cliffs, making local distortion of the airflow even more severe. These conditions increase the difficulties related to the control of a UAS and the crash risks of a UAS. Nonetheless, visible imageries, with a very high resolution and ground sampling distance (GSD) <2 cm, were captured by a 20-megapixel camera (L1D-20c, Hasselblad Inc., Sweden) and stored automatically. The aperture of the camera, adjustable between f/2.8 and f/11, can provide quality images in both strong- and weak-light environments. The camera was carried on a Mavic 2 Pro (DJI Co., Ltd., China) (Fig. 2). The drone had a weight of approximately 900 g, and its battery could last for a maximum flight time of 30 min at a consistent speed of 25 km/h. The drone could hover and fly stably due to advanced omnidirectional and infrared sensing systems. The geographic location and posture of the drone were recorded by inertial measurement units (IMUs) onboard the platform using a dual navigation system, specifically the global positioning system (GPS) and the Global Navigation Satellite System (GLONASS). Because the horizontal
hovering accuracy of the drone is relatively high, with values ranging from ±0.3 m to ±1.5 m at varied GPS signals (Mavic 2 Pro User manual, DJI Co., Ltd.), and the distance between the drone and the target image was within 3–6 m, the geographic location of the image was assumed to be the location of the drone. For sheltered areas with weak or no GPS signals, where a few images had no geographic records, the locations were estimated using the sampling interval and the adjacent vertical location with accuracy of ±0.5 m (Mavic 2 Pro User manual, DJI Co., Ltd.).

Considering national park protection rules and drone safety, our flight surveys were mainly performed along roadsides (within a buffer zone of approximately 2 km). However, cliffs were not randomly selected and the 197 sampled cliffs were systematically distributed in the study area (Fig. 1B). Before each flight, an open and flat area with strong GPS signals was chosen to place and start the drone in positioning (P) mode, which allowed the drone to fly at a maximum speed and approach the target cliff as quickly as possible. When the distance between the drone and the target cliff was close enough to take a visible imagery picture of the entire cliff (e.g., approximately 100 m), the drone was switched to tripod (T) mode, in which the omnidirectional sensing system was turned on and the horizontal flight speed slowed to a maximum value of 1 m/s to prepare a stable condition for close-range photogrammetry. When the distance was 3–6 m (a safe distance for protecting the drone) horizontal to the target cliff, the drone hovered and stabilized to perform close-range photogrammetry with a shooting frequency of 2–3 photos (Fig. 2). Thereafter, the drone flew vertically upward 15 m,
hovered and stabilized again for photogrammetry. Such close-range photogrammetry was repeated until the drone reached the top of the cliff to ensure systematic sampling.

Species identification

The best quality image for each sampling site was selected and ordered, and high-resolution images covering the 197 cliffs were selected for analysis. Three professional botanists, who are familiar with plant species in the entire Wulingyuan area, identified the plant species in each image independently. The botanists tried to classify each plant into a specific species. Most of the arbors, shrubs and vines could be identified, and related information was recorded (Fig. 3); however, species under a canopy, such as herbs, were difficult to identify. For some plant species that were difficult to identify (e.g., those with no distinct characters, such as a flower and fruit), we classified the plant only into a specific genus, which accounted for approximately 0.2% of the samples. For some plants that may be new and could not be identified currently, we only labeled the plant. If different results were obtained for a given species, the botanists would compare the species with the database in the Plant Photo Bank of China (PPBC) provided by the Institute of Botany, Chinese Academy of Sciences and discussed the results to make a final decision. Such processes ensured the accuracy of the identified results.

Data analyses

Based on the abovementioned database, we obtained statistics, such as the number of species and frequency, defined as the number of occurrences for a given species in the entire selected images. Nonetheless, for this analysis, we counted a species only once even if it was distributed at different locations in a given photo due to unavailable root information (Fig. 3). We analyzed floristic patterns of the identified cliff flora as well as the relationship to radiation conditions, elevation and water gradients. For radiation conditions, we used south- and north-facing cliffs to describe the possible differences. A north-facing cliff was defined where the yaw angle of a UAV ranged from 90 to 270°, whereas this angle ranged from 270 to 360° and 0 to 90° for a south-facing cliff. For the elevation gradient, we used 50 m, approximately a distance of three sampling sites, as the statistical interval. For water conditions, we focused on a river approximately 13 km long and defined a 6-km gradient starting from the river and moving outwards (on both the north and south sides of the river) (Fig. 1B). We used a buffer zone of 50 m to select the cliffs along the river and finally
20 cliffs were obtained as a group representing close to water conditions (group0) (red dots in Fig. 1B). Increasing the distance away from the river, three additional cliff groups of 20 each were collected, defined, respectively, as group1 (cliffs within the overlapping areas of 500-m and 1000-m buffer zones), group2 (cliffs in the buffer zone of 2000 m) and group3 (cliffs in the buffer zone of 3000 m), representing decreased water gradients. Thereafter, we performed statistics on different conditions.

### Results

**Fundamental statistics of cliff flora**

Based on the 197 investigated cliffs and approximately 9200 records, we identified 267 vascular plant species, belonging to 140 genera and 58 families. Of the 267 species, shrubs, arbors and vines accounted for 49%, 36% and 15%, respectively (Fig. 4A). Four abundant species made up 65% of the arbors, that is, *Pinus tabuliformis var. henryi* (26.6%), followed by *Daphniphyllum oldhamii* (18.6%), *Acer cordatum* (12.7%) and *Toxicodendron succedaneum* (7.1%) (Fig. 4B). For the shrubs, five species comprised 65% of the flora; specifically, *Quercus phillyreoides* (23.9%), *Rhododendron mariesii* (17.0%), *Itea omiensis* (9.7%), *Vaccinium* (8.3%) and *Rhododendron latoucheae* (6.3%) (Fig. 4C). Eight species made up 65% of the vine species, and the three most abundant were *Trachelospermum jasminoides* (15.4%), *Celastrus orbiculatus* (11.7%) and *Actinidia rubricaulis* (8.8%) (Fig. 4D). Of the 267 identified species, 15 were represented by 113–1223 individuals, 52 were represented by 10–97 individuals, and the remaining 200 species (approximately 75%) were represented by one plant or fewer than 10 individual plants.

Of the 140 identified genera, only one genus, *Ilex*, had 10 species, and each of the remaining 139 genera had fewer than 10 species; 79 genera were represented by a single species. The top 15 genera, with more than 3 species each, comprised 30% of the flora (Fig. 4E). Of the 58 families, six families, accounting for 35% of the flora, had more than 10 species each (Fig. 4F). The family with the highest diversity was Rosaceae (26 species), followed by Ericaceae (17 species), Lauraceae (14 species), Fabaceae

| Photo ID | No. | Species               | Genus      | Family | Cliff types | Lat (°) | Long (°) | Alt (m) |
|----------|-----|-----------------------|------------|--------|-------------|---------|----------|---------|
| 201908081339 | 1   | *Quercus phillyreoides* | *Quercus*  | Fagaceae | cliff face  | 110.416586 | 29.358075 | 1022.7  |
|          | 2   | *Pinus tabuliformis var. henryi* | *Pinus*  | Pinaceae | cliff face  | 110.416586 | 29.358075 | 1022.7  |
|          | 3   | *Daphniphyllum oldhamii* | *Daphniphyllum* | Daphniphyllaceae | cliff face  | 110.416586 | 29.358075 | 1022.7  |
|          | 4   | *Itea omiensis* | *Itea* | Iteaeeae | cliff face  | 110.416586 | 29.358075 | 1022.7  |
|          | 5   | *Vaccinium bracteatum* | *Vaccinium* | Ericaceae | cliff face  | 110.416586 | 29.358075 | 1022.7  |
|          | 6   | *Acer cordatum* | *Acer* | Sapindaceae | cliff face  | 110.416586 | 29.358075 | 1022.7  |

**Figure 3.** An example showing how cliff flora in terms of vascular plant species were identified and recorded using high-resolution visible imageries taken by our smart remote-controlled unmanned aerial system (UAS). We index different species in a given visible image and count each species only once even if it appears at a different location in the photo (top left), and an enlarged species for a clear identification (top right).
(13 species), and Fabaceae and Rubiaceae (12 species) (Fig. 4F). The 40 other families were each represented by 2–10 species, and the remaining 12 families were represented by only a single species. These results mean that the maximum diversity was attributable to a few dominant families and genera, and most of the genera and families were represented by only a few species.

**Spatial dynamics of cliff flora**

We found that there are special dynamics between the cliff flora and the elevation gradient in our study area: the numbers of species exhibited a mid-elevation peak change trend along the vertical altitudinal gradients from low to high elevations (Fig. 5A). Specifically, the number of species gradually increased from 400 to 800 m a.s.l., with values varying from 48 to 120. The highest plant diversity appeared between 750 and 800 m a.s.l., with 120 species belonging to 79 genera and 49 families. Thereafter, the number of species generally decreased from 800 to 1100 m a.s.l., with variations between 80 and 1000 m a.s.l. It is interesting that the number of species in the final 50-m segment (1050–1100 m) was comparable to that in each of the first three 50-m segments (400–550 m) (Fig. 5A). Similar trends were found for genus and family (Fig. S1).

However, the number of species collected from 4 groups of 20 cliffs were 131, 99, 78 and 74, indicating a decline in species number along a 3-km gradient starting from the river and moving farther north (or south) (Fig. 5B). Moreover, the relationship between the number of species and the elevation for the group alongside the river (group0) was different from that of the other three groups farther from the river; namely, the species peak in group0 occurred at a relatively low elevation (600–650 m), whereas the species peak was much higher (1000–1050 m) for the other three groups (Fig. 5C). Interestingly, the number of species in group0 was lower than that in the other three groups starting at 800 m (Fig. 5C). In other words, the farther away the cliff was from the river and the higher the elevation, the greater the number of plant species.

The species on south- and north-facing cliffs made up 56% and 44% of the total species, respectively, and the difference was nonsignificant (Fig. 6A). The nine most abundant species that comprised approximately 65% of...
the flora were the same on both south- and north-facing cliffs, although three species shifted in the order of abundance (Figs. 6B and C). However, it is interesting that a few species appeared on only the south or north side. Species that appeared on only the south side represented 38% of the species that appeared on the south side; 14.5% of the species that were unique to the south side were trees, 18.5% were shrubs and 4.8% were vines (Fig. 6D). Species that appeared on only the north side represented 22% of the species that appeared on the north side; 6.1% of the species that were unique to the north side were trees, 10.5% were shrubs and 5.5% were vines (Fig. 6E). Although we could not distinguish any obvious differences between most species that appeared on both sides, we did find that certain species grew much better on south-facing cliffs than on north-facing cliffs (Fig. S2A), and on the same south-facing cliff, the leaves and size of a given understory species were much smaller than those of the same species growing in the canopy (Fig. S2B).

**Discussion**

We have shown that 267 species were identified from 197 cliffs. Compared to statistics in recent studies, which indicated that there are 1468 species, 742 genera and 171 families of seed plants in Wulingyuan district (Liao et al., 2004), the number of cliff flora identified in our study is...
relatively small. Nonetheless, considering the extremely harsh environment on cliffs and the difficulty of seed dispersal to cliffs, the ratio of the number of identified cliff species within the 200 km\(^2\) study area to the total number of seed plants in Wulingyuan district, covering 550 km\(^2\), was 18.2%, which can be considered rather high as well as promising. Moreover, we argue that new species may exist in the unidentified plant species in this study (approximately 2% of the samples were not identified due to a lack of distinct identifiers such as flowers or fruits) because cliff species can alter their physiology and morphology to adapt to the extremely harsh habitats. In addition, because the heights of the horizontal field of view varied between 1 and 2 m (Fig. 2D) and there was no overlap between images sampled at adjacent sites vertically, a sampling interval of 15 m may miss some rare species as 37% of the identified species were represented by only one plant.

We found that the combination of elevation and water gradients may impact the floristic pattern because the farther away the cliff is from a river and the higher the elevation is, the greater the number of plant species. It is likely that water (or water vapor) from the river promotes vegetation growth and species diversity below a certain altitude. Nonetheless, at high altitudes, the physical conditions of the microsites where cliff flora live, rather than water availability, may limit plant growth (Larson et al., 2000a). This phenomenon may be further suggested by the facts that although no obvious differences existed between most species that appeared on both south- and north-facing cliffs, the leaves and sizes of certain species that appeared on south- and north-facing cliffs or even on the same side but growing in the canopy and understory, exhibited large differences. Such discrepancies are likely caused by radiation conditions because the vertical orientation markedly affects the microclimate and energy balance on cliffs (Larson et al., 2000a).

It should be noted that the height and size of cliff flora differed not only within species but also from those of vegetation on level ground or slopes. Cliff vegetation endures harsh conditions due to soil, water and nutrient limitations; thus, cliff flora grows slowly and remains small (Larson et al., 1999). Taking species in the Pinus genus as an example, an individual tree can typically grow up to 20 m in a mid-subtropical climate, whereas such species were commonly shorter than 2 m in our investigation (Fig. 7). Species growing at the tops of cliffs, especially trees, are morphologically more similar to noncliff species, because there are no obstacles above the canopy, whereas species growing on the cliff face encounter obstacles and are much smaller in height and size (Fig. 7). In addition, the cliff top can provide platforms and allow litter (or other mass) to accumulate, thereby providing a more favorable habitat than the cliff face. Another problem that should also be
noted is that if a cliff is wide enough, species composition might be different as well. However, most of the cliffs investigated in this study were usually narrow, which could not support such analysis.

To the best of our knowledge, this is the first study to propose a systematic sampling method for spatially investigating cliff flora in hostile environments and difficult-to-reach regions with the help of a smart UAS. The study of cliff flora is necessary for the following reasons: (1) cliff flora, which are recognized as being mainly distributed in temperate climatic zones (Larson et al., 2000b) (Fig. S3), are among the least understood types of terrestrial vegetation and contain ancient and unique species in completely natural unreachable habitats; these areas require conservation to achieve the Convention on Biological Diversity’s goals (Joppa et al., 2013; Pimm et al., 2014), but no comprehensive and systematic information or database is available for cliff flora; (2) climate-related local extinctions are already widespread among plant species (Wiens, 2016), and species at high elevations are especially vulnerable to global warming (Freeman et al., 2018); the existing undisturbed cliff flora may serve as a sensor (Dralle et al., 2020) and a guide for adapting to climate change (Nichols et al., 2020) and (3) the high tolerance of cliff flora in extremely harsh conditions may provide valuable insights for applications such as selecting species for restoring degraded rocky and karst ecosystems. We call on the relevant global research communities to actively participate in the study of cliff flora and suggest the following (yet incomplete) research priorities: (1) develop computer-aided methods to identify plant species by solving the difficulties encountered in automatic species recognition, such as the variations in the shape, color and texture of the leaf (or flower/fruit) in the target plant at different stages of the life cycle (Wildchen & Mäder, 2018); (2) investigate and identify cliff flora globally and then establish a corresponding floristic database; (3) develop new sensors and technologies based on a UAS to detect the composition of microhabitats, physiological characteristics of cliff flora and sample organisms for

**Figure 7.** Morphological comparisons between cliff and noncliff flora. The top, middle and bottom panels are life forms of *Pinus tabuliformis* var. *henryi*, *Juniperus formosana* and *Pseudotaxus chienii*, respectively. Note: the left column shows cliff flora growing on the cliff face, the middle shows cliff flora growing on the cliff top and the right shows noncliff flora cited from the Plant Photo Bank of China provided by the Institute of Botany, Chinese Academy of Sciences.
supporting further ecological studies and (4) determine the mechanism of plant species dispersal strategies in extremely harsh cliff environments. These studies will broaden our understanding of these unreachable cliffs and the ‘Last Unknown’.

In summary, we proposed a novel method based on high-resolution visible imagery and smart UAS close-range photogrammetry to investigate cliff flora, which is one of the least understood vegetation types due to its inaccessibility to humans. Our preliminary results from 197 cliffs in the Wulingyuan global cultural heritage area, a mid-subtropical region of China, identified 267 species of cliff plants, belonging to 140 genera and 58 families of trees, shrubs and vines. We found unique floristic patterns as well as unique morphology on these cliffs that warrant further study.

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Authors’ Contributions

DKM motivated and designed the study; DKM, JXZ and HZ performed the field experiment; JXL and YFX identified the plant species; HZ, JXZ, QL, EPY, SHZ and YJX conducted the data analysis; and YJX, DKM, HZ and JXZ wrote the paper. All authors contributed to the analysis and presentation of the results, and read and approved the final manuscript.

Conflict Interest

The authors declare no competing financial interests.

Data Availability Statement

All data used in this study are available within the paper and any raw data can be obtained from the corresponding author upon reasonable request.

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**Supporting Information**

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

**Figure S1.** Number of species, genera, and families versus elevation in meters above sea level (a.s.l.). The statistics are based on the 197 investigated cliffs.

**Figure S2.** Morphological comparisons between *Quercus phillyraeoides* on south- and north-facing cliffs.

**Figure S3.** Spatial distribution of the studied cliffs based on published studies in the literature (dots with different colors, see texts for details) at the global level and our study site in China (blue triangle).