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PRACTICE INSIGHTS

Innovation in Practice

The conservation impact of botanical drones: Documenting and collecting rare plants from vertical cliffs and other hard-to-reach areas

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Abstract

1. A high percentage of island floras are at risk of extinction and have been reduced to relic populations, often in remote hard-to-reach areas. Uncrewed aircraft systems (UAS aka drones) are now being utilized to assist in the survey and collection of rare plants in inaccessible areas or vertical cliff habitats.
2. Here, we test the application of this technology for conservation of 23 plant taxa in three oceanic island hotspots: Hawai'i, Madeira and the Republic of Palau. We collect high-resolution imagery using a small UAS to document the distribution and abundance of vascular flowering plants. Location information is then used to map and assess plant populations. Depending on the terrain, collections are completed using either traditional rope techniques or newly developed remote drone-based collection methods.
3. Over the course of 6 years, we have greatly expanded our knowledge of rare and endangered species, while increasing survey efficiency and staff safety. Most importantly, this work has had a large impact on the conservation of critically endangered plants. Although using drones for botanical conservation comes with limits and challenges, we see great potential in the continued employment of these techniques wherever plants are growing on cliffs or in other hard-to-reach areas.

KEYWORDS
endangered plants, Hawaii, island flora, Madeira, Palau, plant distribution, remote sensing, sampling techniques, uncrewed aircraft systems

1 | INTRODUCTION

Hard-to-reach areas present challenges for the documentation and conservation of plants that occur there. Baseline data on species distribution and abundance is difficult and can be dangerous to collect, leaving many areas either completely unexplored or under-explored (Larson et al., 2000). These areas are often characterized by excessive steepness of terrain, sometimes vertical cliffs, or thickness of vegetation that may prohibit movement and line of sight.

Forests or forest patches surrounded by cliffs or steep slopes (ex. tepuis) have long-evaded detailed botanical exploration (Huber & Rull, 2019). For example, areas with steep, highly eroded terrain, as is common across the Hawaiian Islands, can be difficult or impossible to survey on foot, though they may contain many rare plant species (Chapin et al., 2004). Similarly, rocky-off-shore islets without safe moorings or docks have remained understudied (Ellenita et al., 2020), though they often harbour diverse and unique biotic assemblages free from mainland threats and degradations (Lorence & Wood, 1994; Wood, 2008). Likewise, tropical forest canopies are one of the last frontiers for botanical exploration (Lowman & Rinker, 2004), as thickness of the vegetation prevents any meaningful observation of the tree canopies (Anderson, 2009; Muul & Liat, 1970).

Steep rocky environments have been centres for plant evolution and now host diverse native lineages (Fernández-Palacios et al., 2021), though due to their inaccessibility, these areas have also been referred to as “botanical black holes” (Lichter-Marck, 2022). Many of these unique and narrowly endemic plant taxa are critically endangered (Larson et al., 2000) and urgently require ex-situ conservation to prevent extinction (Foster et al., 2022).

The European Union has classified at least 90 distinct cliff ecosystems as protected landscapes in the Natura 2020 accord (Devillers & Devillers-Terschuren, 1998), while others have suggested cliffs are priority areas worthy of further protection globally (March-Salas et al., 2023).

Scientists are now deploying uncrewed aircraft systems (UAS also called drones) to gather data from hard-to-reach areas including for DNA studies of whales from drone-based respiratory blow samples (Atkinson et al., 2021), assessment of cliff-dwelling seabird colonies (Bishop et al., 2022), and monitoring canopy infestations in palm trees (Kadethankar et al., 2021). Plants growing in hard-to-reach areas have also been studied using these emerging technologies including, for example, the study of water holding capacity of bromeliads in Brazil (Lehmann et al., 2022), systematic vertical transects to assess floristic abundance in China (Zhou et al., 2021), and in-depth imaging and modelling of one specific cliff section in Italy (Strumia et al., 2020). Here we test the application of UAS for exploratory survey, detailed inventory and collection of critically endangered cliff plants across three oceanic island hotspots in a range of habitat types and geographic locations.

2 | MATERIALS AND METHODS

Over the course of 6 years, we conducted 136 field days surveying and documenting plants in hard-to-reach areas of Kaua'i. Additional UAS surveys were completed in Madeira (eight field days) and Palau (two field days). During this time period, we collected over 24,000 photographs across a wide range of habitats and geographic locations. The estimated time for post-processing involved in this study was ca. 600 h.

In an effort to make this system easily replicable by botanists in other localities, we have compiled a series of recommendations and considerations for deploying UAS for botanical surveys (Appendix S1). While we are focused on the botanical survey of inaccessible areas, we found the work of Duffy et al. (2018) helpful in the general planning and executing of any type of drone operations. It is important to mention the regulatory framework set-up to manage airspace for this type of work and acknowledge our permits that allow botanical survey via drone; State of Hawaii Permit I5371.

2.1 | Survey area

A majority of this study was carried out on the island of Kaua'i, in the Hawaiian Archipelago. Due to its remoteness, the Hawaiian Islands are a global biodiversity hotspot, with 90% endemism of vascular plants (Wagner et al., 1990). As the oldest of the high Hawaiian Islands (Fleischer et al., 1998), Kaua'i is also the most floristically diverse, with 256 single-island endemic species (Rønsted et al., 2022), including 67 extremely rare taxa that are at or near extinction (plants having 50 or fewer individuals remaining in the wild, Plant Extinction Prevention Program, 2023). We have prioritized steep north-facing slopes for our surveys, as they have shown an affinity to harbour rare plant populations (Yang et al., 2020). In some cases, we will use local ecological knowledge (LEK; Charnley et al., 2007) to select specific sections on which to focus the field operations. Target species for Kaua'i include all U.S. federally listed and State of Hawaii listed endangered plant taxa (U.S. Fish and Wildlife Service (USFWS), 2023) that occupy steep, hard-to-reach areas or cliff habitats. We rank targets based on known levels of endangerment and focus on the most critically rare taxa first. However, these surveys are exploratory and will often lead to unexpected discoveries.

Survey work outside of Hawai'i included islands located in both Macaronesia and Micronesia. The Macaronesia region of the Atlantic Ocean (Canary Islands, Madeira, Salvages, Azores, Cabo Verde) is similar to Hawai'i in its volcanic origins, highly varied terrain, and diversity of endemic plant lineages (Jardim & Menezes de Sequeira, 2008). The Madeira Archipelago, located 795 km SW of mainland Portugal, is composed of the islands of Madeira, Porto Santo and Desertas. With the aid of local experts, we selected several target species of conservation importance that would have a distinctive form (size and shape) that could be easily observed remotely with the use of a drone. These targets included species such as *Cheirolophus massonianus* (Lowe)

FIGURE 1 *Cheirolophus massonianus* (Lowe) Hansen & Sund. A comprehensive inventory of the Madeira-endemic *Cheirolophus massonianus* (a) was conducted in surveys of populations on Madeira Island (b) and Porto Santo (c).

A.Hansen & Sunding (Figure 1a), *Monizia edulis* Lowe and *Geranium maderense* Yeo. The surveys included vertical cliffs and other difficult-to-access areas where these rare endemics had historically been collected, with the aim of increasing our knowledge of population numbers and species distributions.

As part of an ongoing more extensive floristic study of the flora of Micronesia (Wagner et al., 2012), our team conducted both on-the-ground and in-the-air surveys in the Republic of Palau. This section of the Caroline Islands Archipelago hosts 807 native plant species of which 18% are endemic (Kitalong, 2008). Surveys in Palau were focused on canopy trees in thick tropical forests, mirroring similar challenges in Hawaiʻi with forest patches in steep terrain. While these areas in Palau are not extremely steep, the work is included here to illustrate the application and impact of UAS in the survey of hard-to-reach areas more generally. The study focused specifically on aerial survey for *Parkia parvifoliola* Hosok. (Figure 2b), an endangered tree that is endemic to the island of Babeldaob. This species was estimated to have a total population of 50 individuals and occurs in dense tropical forests, making ground surveys extremely difficult and time-consuming.

For each of the target species for which we present data, at each of the sites that were surveyed, a baseline estimate of population size had been ascertained prior to the UAS survey. We either referenced recent assessments on the IUCN Red List of Threatened Species (IUCN, 2024), or, for those taxa that did not have updated assessments available, utilized a very similar process (a combination of direct observation, herbarium vouchers, agency biological/natural resource databases, and some extrapolation and habitat modelling) to obtain demographic approximations.

2.2 | Data acquisition

All data for this study was collected using a consumer-grade UAS. The model selected for these aerial surveys was the DJI Phantom 4 Pro quadcopter (DJI, Shenzhen, China) (Figure 3a). It offers a 20-megapixel one-inch RGB sensor that delivers clear, high-resolution imagery. This UAS is remotely controlled and all flight operations are conducted manually. The pilot manoeuvres the UAS into position approximately 5 m from the cliff surface using readings from the onboard obstacle

FIGURE 2 *Parkia parvifoliola* Hosok. With an estimated 50 known individuals, Parkia parvifoliola is a species at risk of extinction. Its stature and habitat (a, arrows showing individuals) in dense tropical forest makes survey difficult and time-consuming. The species is distinct from surrounding forest in shape (b) and colour (c), making aerial survey effective in identification.

FIGURE 3 Survey equipment. (a) DJI Phantom 4 Pro in use. (b) Remote control displaying video feed. (c) Visual observer aiding flight operations with spotting scope.

avoidance sensors. When additional resolution is necessary for plant identification, we may approach the surface at 2.5–3 m. To standardize resolution and minimize unusable data, the camera is aimed squarely at the surface in both vertical and horizontal orientations (Appendix Figure S2). Still images are collected with GPS location information embedded into the Exif data of each image.

The initial selection of survey sites is completed using Google Earth (or similar) to highlight target areas, access points, and ideal UAS launch and landing locations. When arriving in the field, we conduct a pre-flight assessment using a Vortex Razor HD 20-60× 85 mm spotting scope (Vortex Optics, Barneveld, Wisconsin) mounted on a full-size tripod (Figure 3c).

Survey plans are developed in the field for the target area to maximize survey efficiency, increase spatial awareness and help locate target plants (Figure 4 and Appendix S1—Section 3). In this process, we prioritize areas with conspicuous native species that

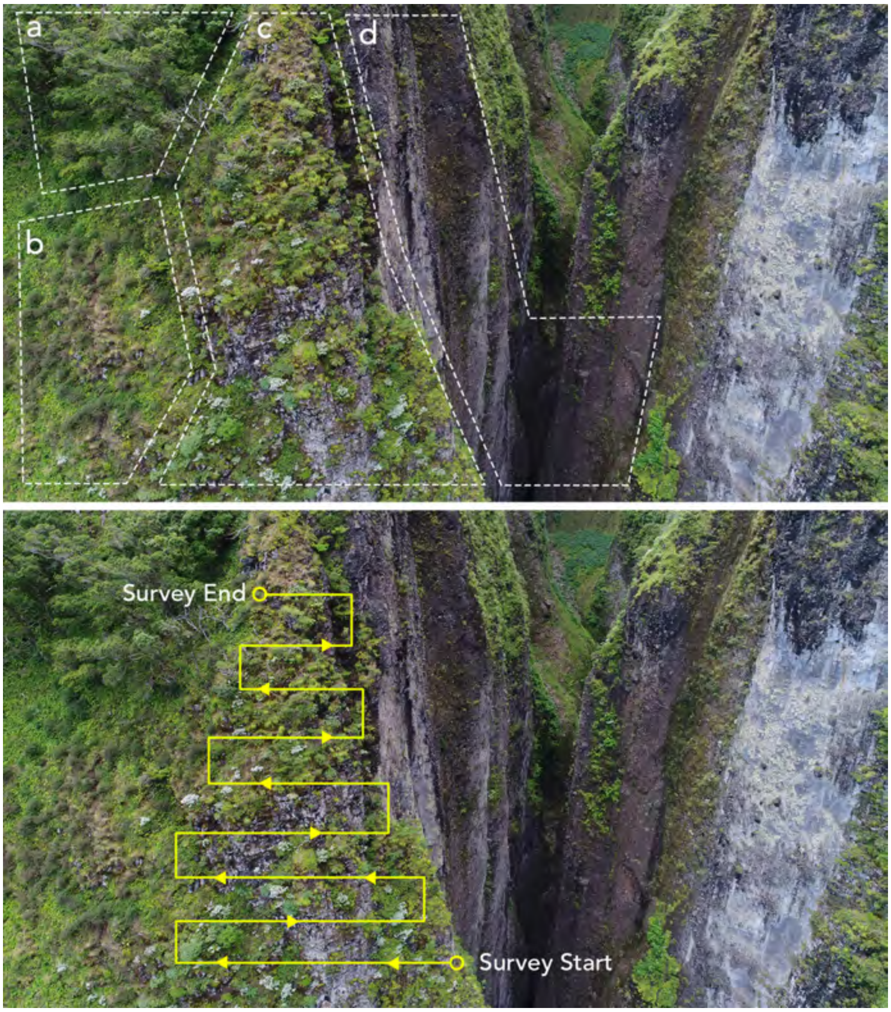

FIGURE 4 Flight planning. (Top) Vegetation classes—(a) forested, (b) non-native, (c) diverse native target area and (d) bare rock (Bottom). Proposed survey path to effectively image the target area.

serve as key indicators of habitat health and intact native communities. For example, in steep cliff areas of Kaua'i, we have found that *Wilkesia gymnoxiphium* A. Gray and *Nototrichium sandwicense* (A. Gray) Hillebr., and a variety of native bunch grasses indicate a lack of ungulate herbivory and thus are important visual indicators for sections on which we may want to focus (Figure S1).

In initial field trials, we tested and categorized four basic survey approaches, based on the field of view and the operator's perspective with regard to the target survey area (Figure 5). The extra effort that may be required to access an ideal survey site can be well worth it for the advantages gained in perspective, efficiency and amount of area that can be safely covered. A more detailed description of these approaches can be found in the Supplementary document (Appendix S1).

2.3 | Data processing

Post-processing of the imagery is completed on a large high-definition computer screen using Adobe Lightroom Classic; a desktop-based photo management software (Adobe, San Jose, California). The classification process is fully manual and involves tagging photos with plants of interest, including those that need further review or are undetermined (see Appendix S1, Section 7, and Figure S3). Phenology can also be noted at this step and specific individuals with reproductive material can be highlighted for potential collection. Geographic coordinates in each image file (latitude, longitude, and elevation) can be mapped within Lightroom; however, we use Geographic Information Systems (GIS) software (ESRI, 2023) for geospatial data management. When photos are exported from Lightroom into ArcGIS, the data can then be plotted on a map for future analysis or sharing with conservation partners. Additionally, rare plant points are uploaded to botanists' mobile devices to enable offline navigation to the remote field locations.

2.4 | Collection methods

Traditional rappelling techniques have been used to access plants from above for collection of seeds, cuttings, and voucher specimens. UAS can assist in this type of field operation by selecting helicopter landing zones, identifying rope anchor points that are positioned above the target plants, locating individual plants that may be out of the collectors' field of vision, and estimating the amount of rope required to reach the area of interest.

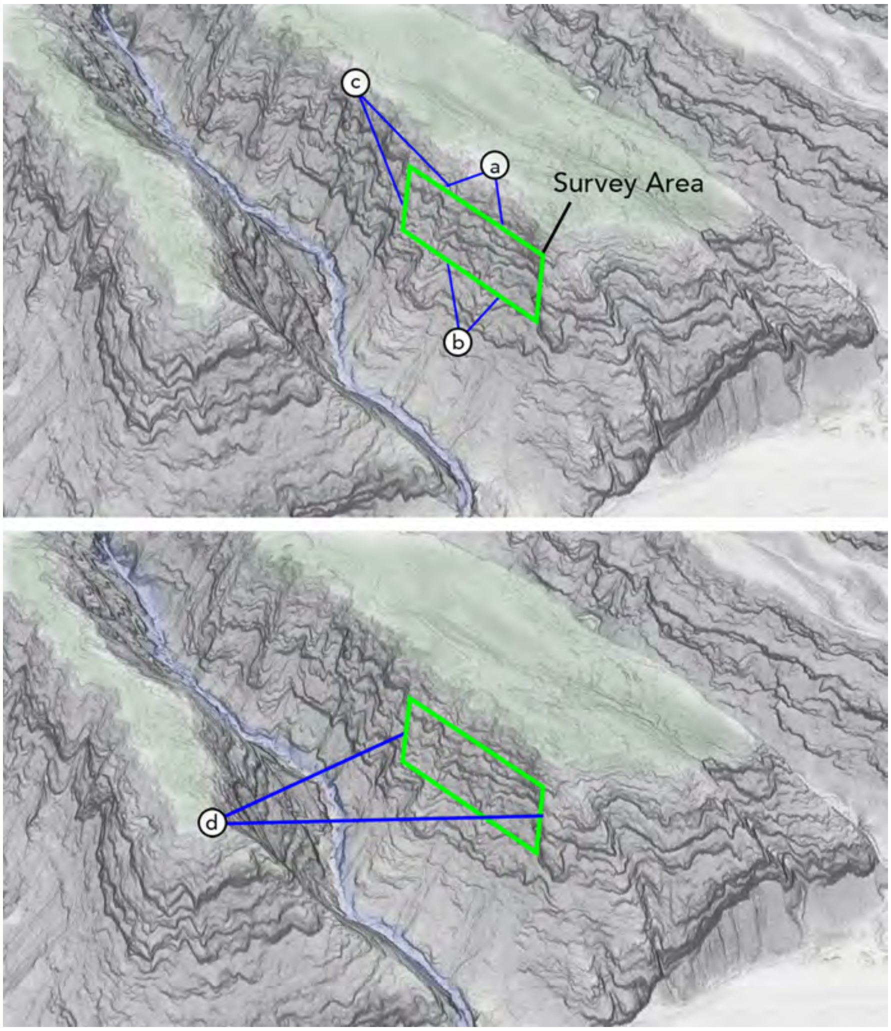

FIGURE 5 Survey perspectives. (Top) Potential survey perspectives—(a) "Top-Down", (b) "Bottom-Up" and (c) "Side View". (Bottom) Ideal survey perspective—(d) "Wide Angle".

Sometimes target plants are found on areas of cliff that are prohibitively difficult to access, even using ropes and rappelling techniques. This challenge has given rise to new UAS-based remote collecting tools (La Vigne et al., 2022; Perroy et al., 2022). For this study, we deployed the Outreach Robotics Mamba (Outreach Robotics, Sherbrooke, Canada), a robotic collecting arm suspended under a larger carrying drone. This mechanism was developed specifically for sampling plants in inaccessible areas or growing on vertical cliffs, with feedback from our team and field testing in the Hawaiian Islands (La Vigne et al., 2022).

3 | RESULTS

Our survey and inventory results revealed higher-than-estimated plant sub-populations and total individuals for 23 threatened plant taxa (18 Critically Endangered, three Endangered, and two rare taxa not formally assessed according to IUCN Red List criteria) compared to pre-survey population estimates, as illustrated in Table 1. Partial survey results for *Gouania meyenii* Steud., *Hibiscadelphus woodii* Lorence & W.L.Wagner, and *Silene lanceolata* A.Gray have been reported previously (Nyberg et al., 2023).

We observed similar results in each of the study areas. *Cheriolophus massonianus* went from 250 individuals to 1250 individuals (Madeira, Figure 1), including a newly located sub-population on Madeira Island and a five-fold increase in the population on Porto Santo. In addition, surveys uncovered remote populations of *Geranium maderense* and *Vicia ferreirensis* Goyder—both species are critically endangered with fewer than 50 individuals.

Parkia parvifoliola went from 50 individuals to 415 individuals (Palau, Figure 2). In a single day of UAS survey we documented 385 trees. The plants were numerous and not every visible tree was photographed in an effort to establish the population's extent. Further surveys will likely uncover additional individuals.

Lysimachia scopulensis K.L. Marr from just two individuals to 77 individuals (Kaua'i, Figure 6). Through the reported surveys, we have expanded the known range of this species which was thought-to-be extremely narrowly endemic to the north shore of Kaua'i. In some cases, for example *Euphorbia eleanoriae* (D.H.Lorence & W.L.Wagner) Govaerts, the number of known individuals increased ten-fold compared to pre-UAS survey estimates (Table 1).

In addition to the inventory results, UAS have proved valuable in documenting botanical anomalies including new island records,

TABLE 1 Survey and collections results.

Species	Family	IUCN status[a]	Pre-UAS sub pops	New sub pops	New total pops	Pre-UAS indv.	New indv.	New total indv.	Increase indv (%)	Seeds	Cuttings	Drone collected
KAUAI												
Cyanea asarifolia H.St.John	Campanulaceae	CR	3	1	4	90	95	185	106			
Euphorbia eleanoriae (D.H.Lorence & W.L.Wagner) Govaerts	Euphorbiaceae	CR	1	8	9	40	500	540	1250	Y	Y	Y[c]
Gouania meyenii Steud.	Rhamnaceae	CR	1	1	2	2	13[b]	15	650	Y	Y	
Hibiscadelphus distans L.E.Bishop & Herbst	Malvaceae	CR	1	1	2	15	100	115	667		Y	Y[c]
Hibiscadelphus woodii Lorence & W.L.Wagner	Malvaceae	CR	0	1	1	0	3[b]	0	NA			
Isodendrion pyrifolium A.Gray	Violaceae	CR	0 (on Kauai)	3	3	0 (on Kauai)	19	19	NA		Y	Y[b]
Kadua st-johnii (B.C.Stone & Lane) W.L.Wagner & Lorence	Rubiaceae	CR	4	2	6	18	10	28	56	Y		Y
Lepidium orbiculare H.St.John	Bassicaceae	CR	1	4	5	61	190	251	311			
Lysimachia filifolia C.N.Forbes & Lydgate	Primulaceae	CR	0 (on Kauai)	1	1	0 (on Kauai)	10	10	NA			
Lysimachia iniki K.L.Marr	Primulaceae	CR	1	2	3	50	275	325	550	Y	Y	Y
Lysimachia scopulensis K.L.Marr	Primulaceae	CR	1	4	5	2	75	77	3750	Y	Y	
Plantago princeps Cham. & Schltdl. var. *anomala* Rock	Plantaginaceae	CR	1	2	3	25	74	99	296	Y	Y	Y
Silene lanceolata A.Gray	Caryopyllaceae	CR	0 (on Kauai)	1	1	0 (on Kauai)	17[b]	17	NA	Y	Y	
Wilkesia hobdyi H.St.John	Asteraceae	CR	10	4	14	809	6000	6809	742			Y[c]
MADEIRA												
Andryala crithmifolia Aiton	Asteraceae	CR	2	0	2	200	16	216	8			
Cheirolophus massonianus (Lowe) A.Hansen & Sunding	Asteraceae	EN	2	1	3	250	1000	1250	400		Y	
*Geranium maderense*Yeo	Geraniaceae	CR	3	2	5	50	140	190	280		Y	
Helichrysum monizii Lowe	Asteraceae	Not listed	1	1	2	50	81	131	162			
Monizia edulis Lowe (*Daucus edulis* (Lowe) Wojew., Reduron, Banasiak & Spalik)	Apiaceae	CR	3	1	4	50	8	58	16			
Marcetella maderensis (Bornm.) Svent.	Rosaceae	EN	10	2	12	75	11	86	15			
Pericallis menezesii R.Jardim, K.E.Jones, Carine & M.Seq.	Asteraceae	Not listed	3	4	7	30	23	53	77			
Vicia ferreirensis Goyder	Fabaceae	CR	2	2	4	50	6	56	12			

TABLE 1 (Continued)

Species	Family	IUCN status[a]	Pre-UAS sub pops	New sub pops	New total pops	Pre-UAS indv.	New indv.	New total indv.	Increase indv (%)	Seeds	Cuttings	Drone collected
PALAU												
Parkia parvifoliola Hosok.	Fabaceae	EN	1	1	2	50	385	435	770			

Note: Indv.—individuals; Pop.—populations; Collection events—Y (successful collection).

[a] IUCN Red List Ranking—CR (Critically Endangered), EN (Endangered).

[b] Nyberg, B., Wood, K. R., Deans, S. M., Heintzman, S., Williams, A. (2023). Recent notable plant records and rediscoveries from Kauaʻi, Hawaiian Islands. *Bishop Museum Occasional Papers. 148*, 163–168.

[c] La Vigne, H., Charron, G., Rachiele-Tremblay, J., Rancourt, D., Nyberg, B., & Desbiens, A.L. (2022). Collecting critically endangered cliff plants using a drone-based sampling manipulator. *Nature Scientific Report*, *12*, 14827.

thought-to-be-extinct species (Nyberg et al., 2023) and led to the discovery of two previously undescribed taxa of *Schiedea* (Weller et al., unpublished data); and *Euphorbia* (Williams et al., unpublished data). Botanists rappelled to sites identified by UAS survey to make conservation collections and document the flora of these intact cliff habitats (Figure 6b).

Seeds, cuttings and DNA material collected as part of this work have been deposited at the National Tropical Botanical Garden (NTBG, herbarium PTBG) seed bank and nursery, the University of Hawaiʻi's Lyon Arboretum Seed Bank, the University of Madeira, as well as the rare plant nursery of the Kauaʻi district of the State of Hawaiʻi Division of Forestry and Wildlife. Seven species were accessible by rappel and are now represented in ex-situ collections.

For some sites, our team has utilized the Mamba (Figure 7b), a remote plant collection platform attached to UAS (La Vigne et al., 2022). To date, we successfully collected plant material from 11 threatened taxa on Kauaʻi using the Mamba, four of which have been reported previously (Table 1; *Euphorbia eleanoriae* (D.H.Lorence & W.L.Wagner) Govaerts, *Hibiscadelphus distans* L.E.Bishop & Herbst, *Wilkesia hobdyi* H.St.John (La Vigne et al., 2022); *Isodendrion pyrifolium* A.Gray (Nyberg et al., 2023)). Most recently, we remotely collected three cuttings and 240 mature seeds of *Lysimachia iniki* K.L. Marr, some of which are now growing in the NTBG nursery and awaiting reintroduction. All previous collections of this species were opportunistic discoveries of broken pieces lying on the ground at the base of its cliff habitat. *Plantago princeps* Cham. & Schltdl. var. *anomala* Rock populations had been reduced to only 25 known individuals, when drone survey uncovered ca. 75 plants growing on the inaccessible slopes of Limahuli Valley, Kauaʻi (Figure 7a). The Mamba device was deployed in March 2022 to successfully collect from this population and the cutting that was collected has rooted at NTBG nursery, flowered and produced seeds which are now in cultivation (Figure 7c–e).

4 | DISCUSSION

As with many fields of study, individual research objectives and their unique challenges give rise to varying methodologies. Many approaches have been developed to conduct UAS botanical surveys in hard-to-reach environments. For some researchers, a photogrammetry method has been used to create complete orthomosaics of the surface of interest to inventory specific species using a single pass (De Simone, 2020; Strumia et al., 2020) or double pass approach (Gao et al., 2024; Li et al., 2022). Others have conducted vertical transects to create checklists of floral components across elevational gradients (Zhou et al., 2021). One drawback of our system outlined above is that we leave some areas unsurveyed, however, we have found that the application of LEK and indicator species helps us identify diverse target areas and locate plants of conservation importance.

We have found that imagery from this type of high-resolution remote sensing can be used to identify a range of species, from small herbaceous plants to large trees.

FIGURE 6 *Lysimachia scopulensis* K.L. Marr. Believed to be down to only two individuals, *Lysimachia scopulensis* (a) was on the verge of extinction. As part of surveys for another critically endangered plant, we located four new populations totalling nearly 75 individuals. Authors rappelled to the locations (b) and collected seeds from two of the populations (c).

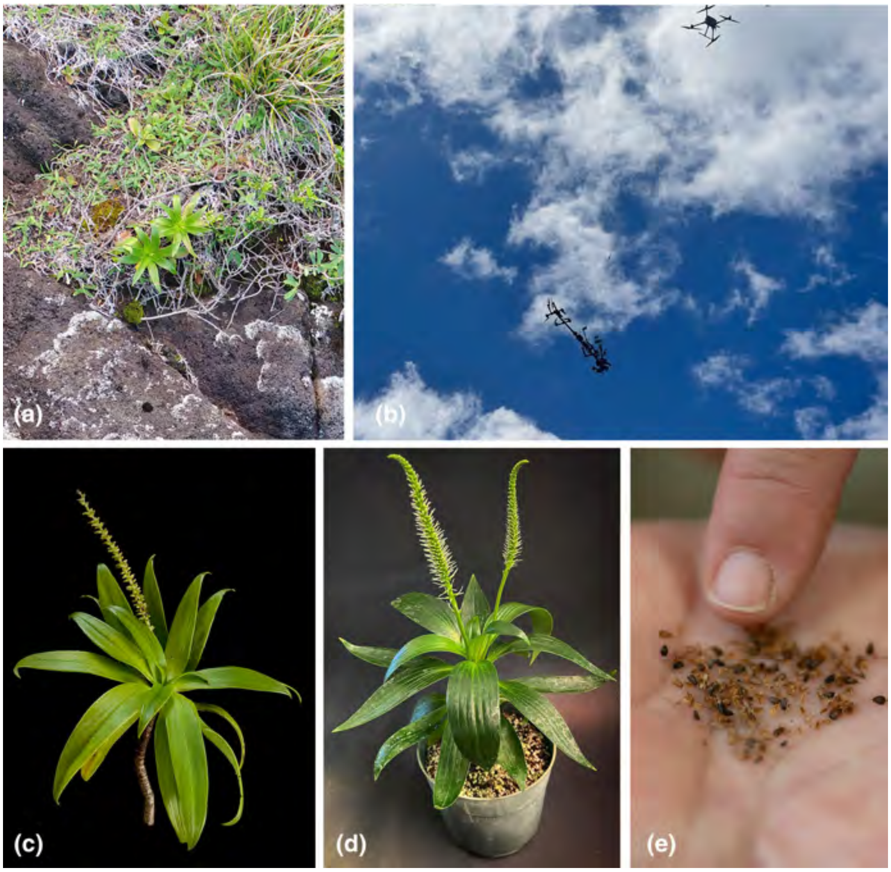

FIGURE 7 *Plantago princeps* Cham. & Schltdl. var. *anomala* Rock. Early in this study, ca. 75 individuals of *Plantago princeps* var. *anomala* were discovered on the rock spires above Limahuli Valley, Kauai (a). This represented the largest known population of the taxa and a significant increase in known distribution. The area is inaccessible on foot which made it necessary to attempt remote collection (b). In March 2022, the robotic arm was utilized to make a collection and that material is now growing at NTBG nursery (c). In addition, that cutting has rooted, flowered and fruited ex-situ (d), making seed available for storage and propagation (e).

Users can expect to achieve a ground sampling distance (GSD) or pixel size of approximately 1 mm, using the specific camera on the DJI Phantom 4 at five meters from the surface. GSD can be improved to sub-mm when the UAS is positioned within 2.5–3 m from the target species.

Drone development cycles lead to frequent new releases and added features. Continued improvement of onboard camera sensors and zoom lenses will unlock even further resolution which could see applications in the imaging of cryptograms or small herbaceous plants. The authors are now deploying the DJI Mavic 3 Pro equipped with a high-resolution zoom lens allowing for the imaging of minute floral characteristics. In addition, improved battery life increases flight time and the amount of imagery that can be collected.

The manual flight method described above was developed to keep the drone away from uneven, rugged terrain and hard-to-detect obstacles (i.e. single branches, overhanging trees) while maximizing imagery collection in intact survey regions and minimizing unusable imagery (i.e. bare rock, areas dominated by invasive weed species). A time-consuming, yet effective two-pass method has been developed to allow for safe, high-resolution, automated botanical surveys (Gao et al., 2024). With the addition of zoom lens technology, we may be approaching a system where the UAS can be safely away from obstacles, while also collecting the high-resolution imagery necessary for plant identification. Improved camera sensors may also increase the resolution or the type of data that is collected by these systems (e.g. Thermal—Hoffrén & García, 2023; Hyperspectral—Chan, 2020).

Studies examining the functionality of automated image classification have been insightful as we consider methods for reducing post-processing effort. Reckling et al. (2021) found that neural networks were not successful at identifying endangered *Geum radiatum* Pursh plants from UAS imagery. Recent work (Soltani et al., 2023) indicates that convolutional neural networks can now accurately identify plants from high-resolution UAS images when citizen science records are used as training data. The necessity of large training sets when applying automated approaches has made us cautious as we are searching for extremely rare, cryptic, or undescribed species that generally have limited reference imagery. Classification work carried out during this study has produced an extensive library of classified images that may be useful in future studies employing automated techniques.

The findings of this work highlight the importance of identifying intact native habitats in hard-to-reach areas and prioritizing their on-the-ground survey. Each specific finding is critical to the conservation of these species and may uncover yet unknown information about their unique ecologies and phytogeography in addition to providing an opportunity for making conservation collections from previously unknown populations. There have been instances where botanists, working on rope near target plants discovered by the UAS, have made new and novel discoveries of rare plants that were not observed by the drone. For example, critically endangered *Silene lanceolata* was not seen for 150 years on Kaua'i and was assumed to be extirpated, when botanists on rope discovered a large colony while accessing plants identified by drone survey (Nyberg et al., 2023).

Remote plant collection is a new and rapidly developing field that will have an immense impact on plant research. Other than the applications mentioned above, remote drone collection techniques are now being employed to monitor the spread of forest pathogens on Hawai'i Island (Perroy et al., 2022). In agricultural settings, non-flying robots are being utilized to recognize and harvest fruits for human consumption (Tang et al., 2020), and it likely will not be long before this type of technology is available for aerial applications. While aerial exploration and manipulation via drone is still a developing field, oceanic explorers have been using remotely operated vehicles to collect and document biodiversity from inaccessible ecosystems for many years (Baco, 2007).

In addition to the positive impacts of UAS for plant conservation, there are a range of additional benefits. In the face of ongoing biodiversity loss, especially across island ecosystems (Wood et al., 2017), video and image records of floristically rich regions will be extremely valuable in highlighting change over time. The temporal resolution allowed by UAS survey may help elucidate important studies of phenology or demographics. Ultimately, these snapshots of inaccessible areas and cliff ecosystems provide ample data for future scientific studies, for example, vegetation studies (Fraser et al., 2016), climate change impacts (Luber et al., 2023) or microclimate niche modelling (Hoffrén & García, 2023).

5 | CONCLUSIONS

As we see the continuing decline of native plant populations paired with increasing threats to their environments, it is critical to expedite our plant conservation work. This includes gathering baseline data on species distribution and abundance, describing organisms that occur in these areas and establishing diverse ex-situ collections. New drone tools have been instrumental in each aspect of the process, especially in hard-to-reach or vertical cliff habitats. We recommend expanding the deployment of the toolkit outlined above so other locations may see the benefit we have. These tools may be especially effective in oceanic islands (e.g. Canary Islands, Juan Fernandez Islands, Mascarene Islands), steep canyon environments (e.g. Copper Canyon, Grand Canyon) or large rock outcrops (e.g. Tepuis, Inselbergs, Sky Islands).

AUTHOR CONTRIBUTIONS

Ben Nyberg and Adam M. Williams conceived the idea and led the studies on Kaua'i with Marcela Brimhall, Susan M. Deans, Scott Heintzman, and Kenneth R. Wood. Ben Nyberg, Sholeh Hanser, Ann Hillmann Kitalong, Niro Nobert and Naito Soaladaob designed and conducted the studies in the Republic of Palau. Ben Nyberg, Célia Bairos and Miguel Menezes de Sequeira designed and conducted the studies in Madeira. Ben Nyberg and Adam M. Williams drafted and revised the manuscript and all authors read, contributed to and approved the manuscript for submission.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflict of interest.

PEER REVIEW

The peer review history for this article is available at https://www.webofscience.com/api/gateway/wos/peer-review/10.1002/2688-8319.12318.

DATA AVAILABILITY STATEMENT

Available data is presented in Table 1. Exact location information is held at the institutions and only available through request due to the sensitivity of sharing rare plant collections and the regulatory conditions of permits. Please contact the corresponding author.

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SUPPORTING INFORMATION

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

Appendix S1. Recommendations and considerations for deploying UAS for botanical surveys.

Figure S1. Key Indicator Species (Hawaii).

Figure S2. Flight angles.

Figure S3. Post-processing in Adobe Lightroom.

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