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PERSPECTIVE

Existing and emerging uses of drones in restoration ecology

Jake M. Robinson[1,2] | Peter A. Harrison[3] | Suzanne Mavoa[4] | Martin F. Breed[2]

[1]Department of Landscape Architecture, The University of Sheffield, Sheffield, UK

[2]College of Science and Engineering, Flinders University, Bedford Park, SA, Australia

[3]ARC Training Centre for Forest Value and School of Natural Sciences, University of Tasmania, Hobart, Australia

[4]Melbourne School of Population and Global Health, University of Melbourne, Melbourne, Vic., Australia

Correspondence
Jake M. Robinson
Email: bio.jmr@gmail.com

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Abstract

1. In the absence of effective and scalable human intervention, up to 95% of the world's ecosystems will be affected by anthropogenic degradation by 2050. Therefore, immediate and large-scale ecological restoration is imperative to stem biodiversity loss and ecosystem decline. Ecologists must draw upon the most effective and efficient tools available to achieve successful restoration goals. Drones (i.e., unmanned aerial vehicles) are a valuable set of tools in the environmental, forestry, and agriculture sectors; however, there has been limited uptake in restoration ecology.
2. Here, we aim to highlight the existing and emerging uses of drones in restoration science and practice. We discuss the strengths and weaknesses of these applications and provide a roadmap for increasing the utilisation of drones to refine and enhance restoration objectives. Our article is presented with the restoration continuum in mind, including sections for restoration planning, implementation and monitoring. We also take a novel approach by describing how drones relate to a globally recognised restoration tool published by the *Society for Ecological Restoration*.
3. Drones are used in several restoration scenarios from mapping habitats and managing wildfires, to monitoring the effectiveness of restoration interventions. Many applications in other disciplines can also be transferred to restoration scenarios. However, the use of drones will be context-dependent, and several technical and practical constraints need to be addressed.
4. Drones have considerable potential to improve the science and practice of restoration at all stages of a restoration project, which is vital to realising the goals of the UN Decade on Ecosystem Restoration.

KEYWORDS
drones, ecological restoration, innovation, remote sensing, restoration ecology, UAVs, UN Decade on Ecosystem Restoration, unmanned aerial vehicles

1 | INTRODUCTION

To address the enormous task of restoring the world's degraded ecosystems, 2021 to 2030 was recently heralded as the UN Decade on Ecosystem Restoration (United Nations, 2020). In the absence of scalable interventions, it is expected that by 2050, 95% of Earth's land, up to 90% of coral reefs, and many other habitats will be affected by degradation (Foo & Asner, 2019; Yu et al., 2020). Against this backdrop of ecological crisis, practitioners must draw upon the most effective tools available to ensure large-scale restoration objectives are successful.

BOX 1 The two main types of drones

Fixed-wing: These are morphologically similar to aeroplanes and able to cover areas; they are now available with detachable wings for easier transportation/portability.

Multi-rotor: As the name suggests, these drones have multiple rotors. They typically range from four rotors (quadcopters) to eight (octocopters). They are designed for precision missions and large payloads.

Drones (also called unmanned aerial vehicles [UAVs]) have rapidly advanced over the last decade and are now primed to help tackle the complexities of ecological restoration. There are two main types of drones: (a) fixed-wing and (b) multi-rotor (Box 1). A diverse range of sensor units are now available for fully integrated and tailored drones, which can combine drones with artificial intelligence and provide greater autonomy, precision and efficiency of practice. Available sensors include active sensors, such as light detection and ranging (LiDAR) modules, which use laser-based technology to generate very high-density point clouds (e.g., >1,000 points/m^2) to detect objects at fine scales such as individual trees to model provenance performance differences (Camarretta et al., 2020). Passive sensors are also available, such as optical sensors, including high-definition cameras that can be used in combination with object recognition algorithms to monitor species and ecological communities (Dalla Corte et al., 2020; Hamylton et al., 2020; Harrison, Camarretta, et al., 2021; Harrison, Davidson, et al., 2021; Lu et al., 2020). In addition, drones can carry other payloads that are not sensors. These can include units that disperse fire extinguishing materials to help control wildfires, fire starting materials for prescribed burns, or specialised seed packages apparatus designed to disperse seeds and plant amendments (e.g., fertilisers) to meet revegetation objectives (Aydin et al., 2019; Droneseed, 2020; Rahman et al., 2019; Saikin et al., 2020).

The versatility of drones has positively impacted several fields, including environmental management, conservation biology, and agriculture (Hodgson et al., 2018; Jiménez López & Mulero-Pázmány, 2019). However, compared to these disciplines, the uptake of drones by the restoration sector has been limited, despite their increasing versatility and affordability (Buters, Bateman, et al., 2019; Camarretta et al., 2020). This lack of uptake could be attributed to several factors, including methodological ambiguity, a lack of standardised guidelines, and variations in policy frameworks––which may also compound the effects of more general concerns, such as perceptions around safety and intrusiveness (Buters, Bateman, et al., 2019; Rao et al., 2016). However, as the evidence base of the utility of drones grows (Brovkina et al., 2018; Buters, Belton, & Cross, 2019; Camarretta et al., 2020; Nuijten et al., 2021; Resop et al., 2019; Zahawi et al., 2015), so does their potential to contribute to restoration objectives.

To maximise the benefits of drones in restoration, it is important that end-users are aware of their strengths and weaknesses and the need for further innovation and development. To this end, we aim to (a) understand the extent to which drones are currently used in restoration and highlight emerging applications, (b) identify opportunities to transfer drone-based approaches from other disciplines (e.g., agriculture, conservation biology) into restoration, (c) examine key barriers to their broader adoption and (d) discuss how drones fit into the Society for Ecological Restoration's (SER) international principles and standards for the practice of ecological restoration (Gann et al., 2019). SER 'advances the science, practice, and policy of ecological restoration to sustain biodiversity, improve resilience in a changing climate, and re-establish an ecologically healthy relationship between nature and culture' (SER, 2022). Their standards guide restoration practitioners and help ensure that time and resources invested in restoration projects are well spent. We provide a restoration-centric narrative, focusing on the existing and potential uses of drones at three key stages of a restoration project: *planning*, *implementation* and *monitoring* (Figure 1), whilst anchoring to the SER ecological restoration 'recovery wheel'.

2 | THE SER RESTORATION RECOVERY WHEEL

The second edition of the international principles and standards for the practice of ecological restoration was released in 2019 (Gann et al., 2019). This publication guides the practice of ecological restoration and contains an ecological restoration 'recovery wheel' for assessing the success of a restoration project. The wheel measures the recovery of six distinct but interacting factors of an ecosystem—species composition, structural diversity, ecosystem function, external exchanges, absence of threats and physical conditions. Each of these components are scored between 1 and 5, where 1 indicates the lowest level of recovery outcome, and five the highest. While the recovery wheel provides a mechanism to track the progression of an ecosystem's recovery towards a desirable condition and the initiation of adaptive management options to re-set the trajectory, many of the factors that are assessed can be costly and time consuming to gather, especially as restoration is upscaled from local to landscape-scales. However, the rapid evolution of drone technology is now making it possible to assess these ecosystem factors at the required scale, and we highlight multiple examples of how drones could be used to support each of the six ecosystem recovery factor (Figure 2) through extensions of their applications in planning, implementing and monitoring restoration outcomes.

3 | RESTORATION PLANNING

Restoration projects require adequate planning to be successful. This planning phase typically involves baseline surveys (incl. Species/

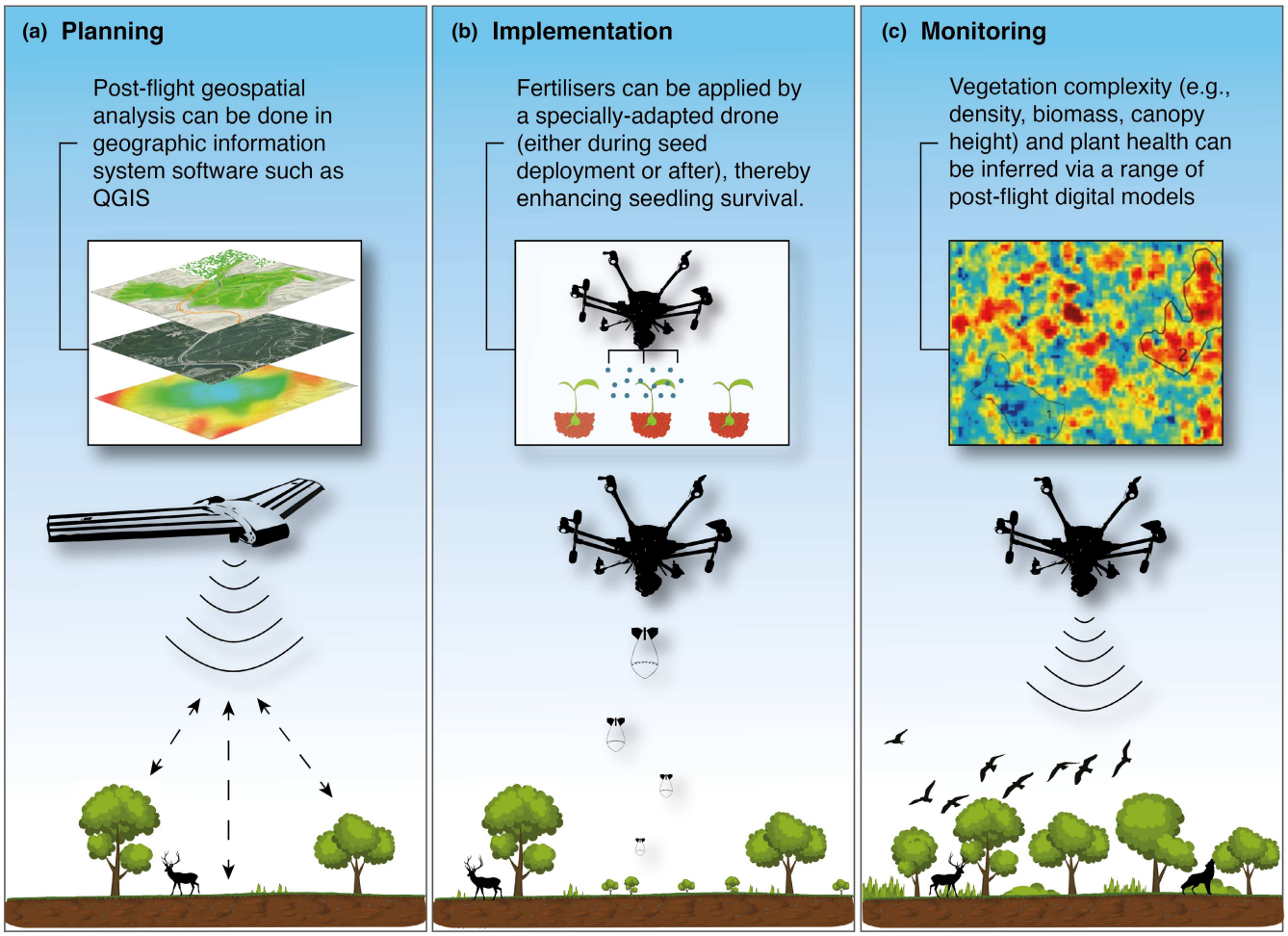

FIGURE 1 Examples of applications for drones along the restoration continuum from planning and implementation to monitoring and adaptive management. (a) Indicates a fixed-wing drone system able to collect baseline ecological and geophysical conditions over large spatial scales; (b) shows a multirotor drone able to deploy seed packages and fertilisers; and (c) indicates a multirotor drone able to conduct fine-scale assessments of vegetation complexity (e.g., via canopy height models, species counts).

ecosystem/vegetation surveys, abiotic condition surveys, characterisation of types and degrees of ecosystem degradation), reference ecosystem surveys, goal development (including scenario planning), restoration intervention option analysis, and mapping of associated logistical issues (Gann et al., 2019; Harrison, Camarretta, et al., 2021; Harrison, Davidson, et al., 2021). Drones can have a demonstrable role in each step, which we outline below.

3.1 | Image-based vegetation mapping

Producing maps to acquire information on baseline ecological conditions is fundamental to planning subsequent restoration strategies (European Environment Agency, 2016). However, this can be time-consuming and labour-intensive if traditional, on-ground surveys are undertaken. While satellite imagery can be used, it can have reduced temporal and spatial accuracy, and the resolution is sometimes not at the fine-scale required for restoration planning, however, drone-satellite synergies are being explored (Alvarez-Vanhard et al., 2021). The potential for other remote-sensing applications in planning restoration approaches are emerging, such as capturing drone-derived imagery that produce large-scale topographic and vegetation maps through photogrammetry approaches (Cruzan et al., 2016).

Drones can provide a means of reducing time expenditure by capturing real-time representations of land/seascapes. For example, to identify ecological units of conservation importance, Sierra-Escrigas et al. (2020) used an off-the-shelf, inexpensive DJI Phantom 4 drone with Pix4Dcapture™ software to generate a detailed orthomosaic (i.e., a composite image from multiple Red Green Blue [RGB] still-captured images) of a shallow coral reef community in the Caribbean at a spatial resolution of 1.4 cm/pixel. The ecological units we defined using the orthomosaic that covered a total area of 0.25 km^2 in conjunction with a supervised classification algorithm to identify pixels that correspond to the spectral signatures in each pre-defined class. In this case, the ecological units delimited areas that represented the most dominant organisms in the area and relevant physiognomic characteristics. Careful checking for sources of noise that could confound the classification of target units for restoration is essential. In the case of the above example, validating the classification was required by Sierra-Escrigas et al. (2020) as initial variability was detected due to signal similarity and

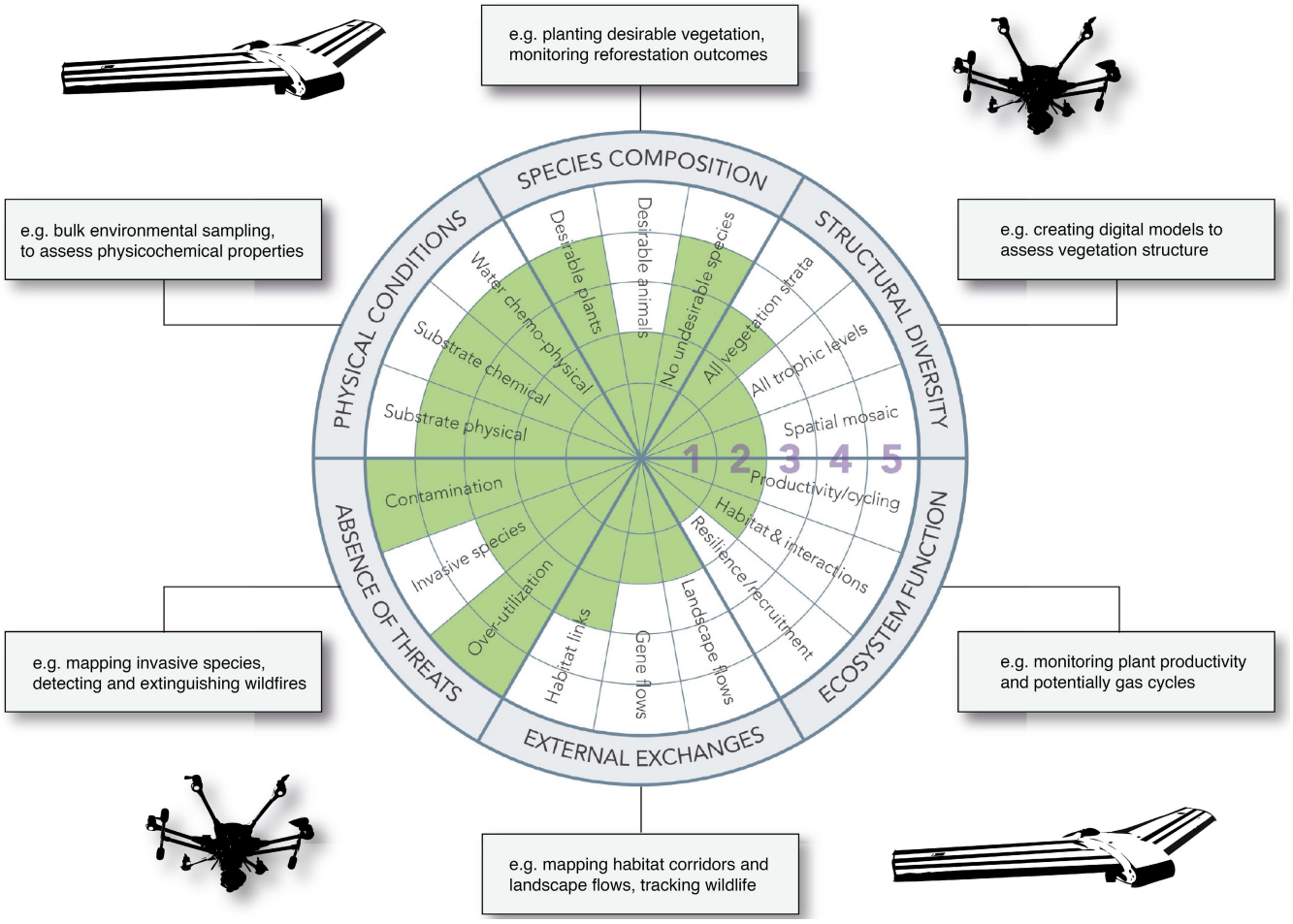

FIGURE 2 The SER recovery wheel and some examples of how drones could potentially contribute to assessing the recovery of each ecosystem factor. For instance, in the *Species Composition* segment, drones could be used to plant and monitor the development of plant composition and diversity against a goal.For the *Structural Diversity* segment, drones could be used to understand vegetation strata and spatial distribution by facilitating digital models. The figure provides examples of how drones can be used in each of the other segments of the recovery wheel. The 5-star scale represents a cumulative gradient from very low to very high similarity to a reference ecosystem. A restoration site can be assigned to one of the five recovery levels (1–5 stars) as indicated by the green subsegments.

interfering components of the atmosphere and water column. Although this study was carried out in a conservation context, the principles are transferable to restoration ecology for mapping baseline conditions and delineating ecological units. The application of mapping units of interest extends to the terrestrial landscape where drones have been used to detect plant species to delineate vegetation units (Baena et al., 2017; Villoslada et al., 2020). There is a clear, demonstrated approach on the utility of drones to assist in identifying invasive species and key ecological species that has extended applications in a restoration planning context. For instance, controlling invasive species is often vital to ecosystem restoration. Decisions about which control methods to use depend on the plant species' or growth forms and their spatial distributions. Drones could be used to map these taxonomic, structural and spatial elements and therefore aid in restoration decision-making. This contributes to several SER Recovery Wheel objectives (Figure 2), including providing a rapid assessment of the presence or absence of threats (*Absence of Threats*), or the baseline species composition and structural diversity of the ecosystem being restored.

Other studies have used off-the-shelf drones (e.g., DJI Phantoms) along transects to map intertidal, coastal (mangrove) and inland vegetation (Cruzan et al., 2016; Darmawan et al., 2020; Rossiter et al., 2020). Aerial images are collected by the drone and used to create orthomosaics and digital surface models (DSM) to map vegetation and landform elevation differences. The resulting orthomosaic can then be analysed using software such as ESRI ArcGIS 10.8 (ESRI, 2021), which has relevant processing tools and an 'Ortho Mapping' workspace. Similarly to the coral reef study mentioned above, ecological features displaying strong spectral or elevational differences allow for more accurate automated habitat delineation using DSMs.

These studies suggest that using drone-derived imagery can be valuable in a restoration context to, for example, acquire baseline ecological condition data and determine landscape prioritisation. Future research to improve the accuracy of imagery-based vegetation maps is needed. In particular, there is a need for methodological guidelines that restoration ecologists using drones can apply across

different ecosystems that detail the optimal approaches and associated pitfalls.

3.2 | LiDAR data fusion for rapid phenotyping

Drones can now support LiDAR sensors to measure the structural properties of an ecosystem (e.g., forests) at high spatiotemporal resolution (Camarretta et al., 2020; Jaakkola et al., 2010; Wallace et al., 2014, 2016). Drone-LiDAR platforms allow targeted surveys of small areas (~5 ha), though being dependent on the expenditure of batteries. De Almeida et al. (2021) developed approaches to assess the vegetation structure of twelve 13-year-old restoration plots. The plots (45×48 m) were experimentally established with 20, 60 or 120 native tree species in the Brazilian Atlantic Forest. The authors assessed (a) the complementarity of LiDAR and hyperspectral-derived variables, (b) their ability to distinguish differences in tree richness and (c) their ability to predict aboveground biomass. The authors analysed three structural attributes derived from LiDAR data, including canopy height, leaf area index and understory leaf area index. Additionally, 18 variables derived from hyperspectral data were acquired, including 15 vegetation indices. At the plot level, leaf area index and structural vegetation indices were found to increase with increasing species richness. LiDAR-derived canopy height better predicted aboveground biomass than hyperspectral-derived vegetation indices. However, the fusion of acquired hyperspectral and LiDAR data were the most effective at assessing forest structural attributes and tree species richness in restoration plots. Understanding the structural and compositional elements of an ecosystem is crucial to restoration planning. For instance, how many trees remain following a degradation period? What is their age and health status? Is unwanted vegetation encroaching on the target habitat? Drone-based LiDAR systems can help answer these questions, thereby aiding restoration planning objectives and contributing to the *Structural Diversity*, *Species Composition*, *and Ecosystem Function* objectives of the SER Recovery Wheel (Figure 2).

Neuville et al. (2021) also estimated forest structure using a drone-LiDAR platform and machine learning for point cloud processing. The authors used the hierarchical density-based spatial clustering of application of noise clustering algorithm (Ester et al., 1996) to segment tree stems. Following this, the authors used a principal component analysis to extract tree stem orientation for subsequent diameter at breast height estimation. This workflow was validated using LiDAR point clouds collected (using a maximum scanning angle Range of 75°) in a temperate deciduous closed-canopy forest stand during the leaf-on and leaf-off seasons. The results suggested that this approach detected ~82% of tree stems (with a precision of 98%) during the leaf-off season. The authors state that the point density within an approximately 1.3-m height above the ground was low within closed-canopy forest stands, thereby reducing the accuracy of diameter at breast height estimation. In summary, a LiDAR-based detection level of 82% for tree stems during the leaf-off season suggests improvements to the accuracy of LiDAR-based tree mapping are still needed. Yet, data fusion approaches that combine hyperspectral and LiDAR data seem to be the most effective approach to assess forest structural attributes and tree species richness for restoration planning in a forest environment. Additional research on the use of drone-based LiDAR platforms to gain baseline information for non-forest ecosystems, such as grasslands, is needed to ascertain the benefits of data fusion to remotely detect and classify vegetation composition in various restoration contexts, thereby aiding in restoration planning.

3.3 | Baseline plant stress/health assessments

Drones mounted with multispectral cameras can be used to acquire data on plant health via vegetation indices such as the Normalised Difference Vegetation Index (NDVI) and the Enhanced Vegetation Index (EVI) (Figure 3). A considerable amount of work has been done on this in the agricultural sector. For example, Kim et al. (2021) used the drone NDVI approach to assess crop damage after chemical exposure. NDVI is commonly used to detect changes in plant health derived from the difference between visible and near-infrared reflectance of vegetation cover. Rice crops were exposed to chemicals at five growth stages to four levels of the chemical toluene. The NDVI was measured 5 days after damage and 67 days after planting. NDVI of toluene-exposed rice was significantly lower at most growth stages. The authors suggested that this approach indicated that NDVI assessed at close range, as enabled by the drone, could detect plant responses to toluene exposure.

Drone-based vegetation assessments that exploit indices such as the NDVI or Photochemical Reflectance Index (PRI, derived from narrow-band reflectance at 531 and 570 nm and can show stress-induced changes in photosynthesis) (Cavender-Bares et al., 2020), can detect important baseline elements of plant health, thereby contributing to the *Physical Condition* and *Ecosystem Function* objectives on the SER Recovery Wheel (Figure 2). Moreover, these vegetation index methods can easily be transferred to a restoration planning context. There is value in using drones to mount cameras that provide information not available from satellite-based vegetation indices—for example, you can achieve higher resolution and real-time analysis than satellite imagery in certain contexts. For example, if mapping large-scale landscapes, satellites are highly effective, but if monitoring individual trees up to smaller-scale landscapes, then drones have important value and can provide data at higher resolution. A key pitfall to only using drones is the reduced spatial coverage compared to satellites. This is something to consider in a restoration context. For example, does the restoration project require higher resolution/targeted indices or broader spatial coverage? There may also be challenges for time series analyses, whereby data points are recorded at consistent intervals over a set period of time. Satellites do this consistently, whereas additional project planning and management is required for frequency data collection using drones.

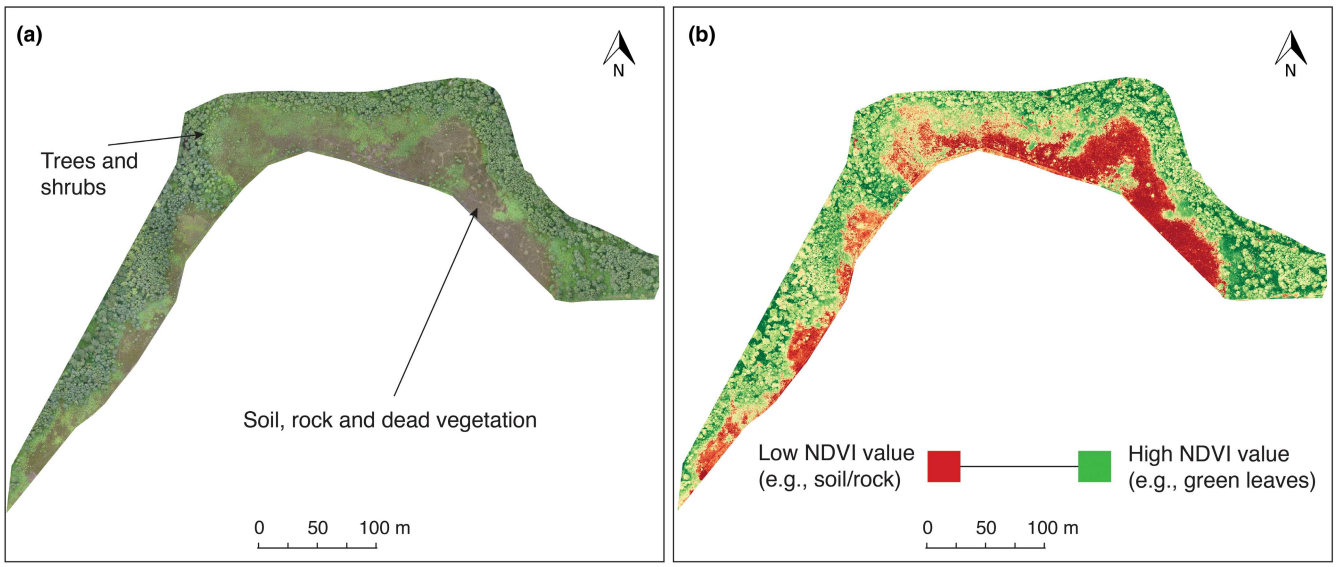

FIGURE 3 An example of how drones can monitor plant health is by utilising a modified multispectral camera to obtain normalised difference vegetation index (NDVI) values. Low NDVI values correspond to no or highly stressed vegetation, and high NDVI values correspond to higher levels of greenness as a proxy for relative chlorophyll output and therefore a proxy for high plant health. Panel (a) shows an orthomosaic image of a woodland-heathland ecotone in the Peak District, UK, and (b) visual representation of the NDVI—Where red indicates soil, rock and dead vegetation (Robinson, unpublished data using Pix4DMapper™, 2018).

3.4 | Counting wildlife

A considerable body of research has demonstrated how drones can be effectively deployed to remotely count wildlife. These data can be used to establish baseline conditions (e.g., determining species presence and abundance) for restoration projects. Francis et al. (2020) developed a semi-automated wildlife counting method, using drones and machine learning to identify and count waterbird species in the Okavango Delta, Botswana and the Lowbidgee floodplain, Australia. Their detection accuracy between the training and test data was 91% for the Okavango Delta colony and 98% for the Lowbidgee floodplain colony. In addition, their semi-automated method was 26% quicker, including development, and five-fold quicker without development than manual counting. This, as the authors emphasised, suggests that drone data of waterbird colonies can be collected rapidly and accurately, allowing for counting with minimal disturbance. This is corroborated by Davis (2021), who used a drone equipped with a thermal camera to detect deer in a range of habitats and to generate deer density estimates. The results showed that the drone outperformed ground observations regarding density, surveying efficiency, and area covered. Drones with thermal cameras are currently being used by the *Woodland Trust* in the UK for herbivore impact assessments. These assessments are vital in the planning stage of restoration projects. The drones allow forest restoration ecologists to efficiently count herbivore populations in the local area, and thus allow them to gauge herbivore pressure. This information is then used to formulate a tree protection plan, for example, do the saplings require tree guards, or is fencing enough? Drones can therefore contribute to several SER Recovery Wheel objectives (Figure 2), including *Absence of Threats* and *Species Composition*.

Many other studies have used drones to successfully count wildlife, from waterbirds to crocodiles (Aubert et al., 2021; Marchowski, 2021). Counting wildlife is an important facet of restoration ecology––for example, it can be part of measuring the composition, functionality and complexity of ecosystems prior to, during and following a restoration intervention. Drone surveys can provide advantages over traditional methods, including size estimation precision and the ability to cover remote areas (Díaz-Delgado et al., 2018). However, observer experience, field conditions (e.g., wind, sun), and site characteristics (e.g., vegetation complexity) can affect detectability.

Drones can also be less disturbing to wildlife (if species-specific protocols are followed) (Aubert et al., 2021; Gallego & Sarasola, 2021) and cover larger spatial extents than traditional field surveys. If protocols are not followed, drones can be detrimental to wildlife. For example, flying too close to animals can present a visual and acoustic disturbance that may adversely affect the animals' behaviour (Duporge et al., 2021). Disturbance outcomes can include behaviours that displace time and energy from primary survival functions such as breeding and foraging (Mulero-Pázmány et al., 2017).

4 | RESTORATION IMPLEMENTATION

The choice of restoration intervention will be context-dependent and generally should align with natural ecological processes, not cause any further degradation, and be compliant with local regulations (Gann et al., 2019). Here, we discuss how drones can and are used to implement restoration interventions.

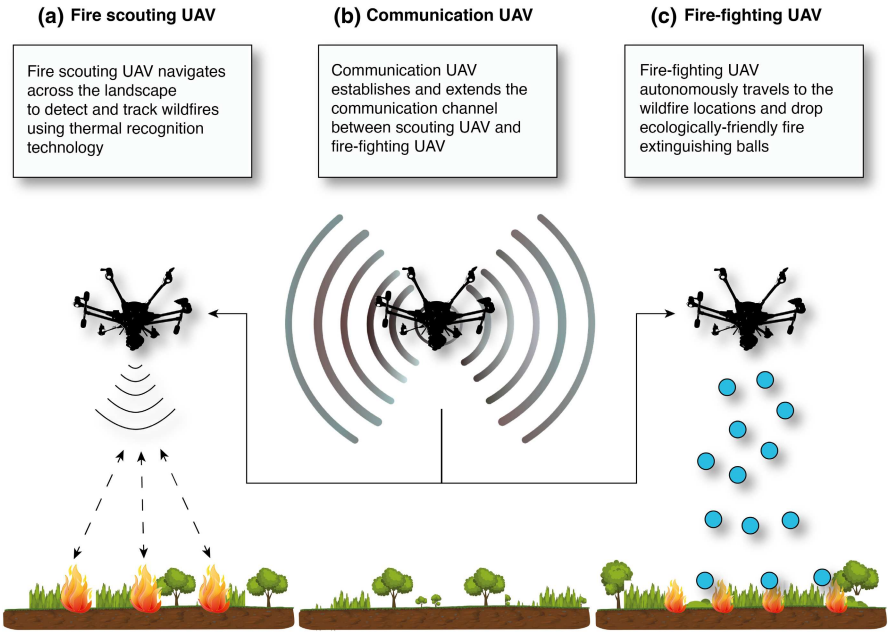

FIGURE 4 Proposed wildfire detecting, tracking and extinguishing drone system. (a) Fire scouting drone; (b) communication drone; and (c) fire-fighting drone by Aydin et al. (2019).

4.1 | Seed dispersal and pest management

Despite very few peer-reviewed studies on drone-based seed dispersal, there is great enthusiasm for its potential to assist in revegetation projects (Mohan et al., 2021). Dispersing seeds (along with fertilisers) using drones has been applied to help revegetate mangroves in Myanmar and the United Arab Emirates and has assisted in revegetation operations in Thailand, where the landscape is inaccessible or unsafe for humans (Mohan et al., 2021). However, a recent study demonstrated that the survival percentage of seeds dispersed by drone was low and ranged from 0% and 20% for certain conifer species (Aghai & Manteuffel-Ross, 2020). In this pilot study, numerous environmental factors (e.g., humidity, solar exposure and predation) limited the establishment of the seedlings. Still, this low survival level is comparable to some traditional seed-based restoration plantings (e.g., <25% survival; Woods et al., 2019), whilst others are considerably higher such as an 83% success rate for seedling establishment in a recent dryland restoration project (Shackelford et al., 2021). Given the paucity of peer-reviewed operational studies, it is difficult to compare the effectiveness and potential of drone-assisted seed dispersal to traditional seeding approaches. Nonetheless, drone-assisted seed dispersal does appear to have the potential to complement traditional planting efforts, particularly in dangerous or complex landscapes.

As pest species contribute heavily to biodiversity loss and degrade ecosystems, pest management is considered a key part of many restoration projects (Binny et al., 2021)—see *Absence of Threats* on the SER Recovery Wheel (Figure 2). In terms of drone-based pest management, most peer-reviewed studies come from the agriculture literature, but there is clear potential for adoption in restoration. For example, Li, Giles, Andaloro, et al. (2021) assessed drone-based application for alfalfa insect pest control. The authors used small-scale multirotor drones. They found that effective management of leaf-feeding insect pests was achieved when delivering chlorantraniliprole at the same labelled use rate in different spray volumes (46.8 and 93.5 L/ha) on commercially grown alfalfa. The results of their study show that multi-rotor drones were effective for pesticide application on agricultural crops and comparative to large-scale fixed-wing applications. Similar results were found in other agrarian studies, for example, on almond farms (Li, Giles, Niederholzer, et al., 2021) and cranberry farms (Luck et al., 2021). It could be valuable to use drones in this way to reduce the threats associated with seed predation—which is a considerable issue for drone-supported seed sowing activities.

4.2 | Wildfire tracking and control

Although wildfires managed for restoration can positively impact ecosystem recovery (Barros et al., 2018; White & Long, 2019), unprescribed and/or uncontrollable wildfires can have a detrimental ecological impact (Lewis, 2020). Therefore, innovative methods to help detect, track and extinguish certain types of wildfires are being developed. Further research into drone-assisted prescribed burning would also be beneficial (Beachly et al., 2016).

Detecting and tracking wildfires with drones via thermal detection (e.g., using infrared cameras) has considerable potential (Allison et al., 2016; Athanasis et al., 2018; Kumar et al., 2011; Pham et al., 2018) and therefore potential to contribute to the SER Recovery Wheel objective *Absence of Threats* (Figure 2). Drones can also supplement traditional wildfire-fighting methods. For example, Aydin et al. (2019) examined the potential use of fire extinguishing balls deployed by drones. The system consisted of (a) a scouting drone to detect spot fires, (b) a communication drone to establish and extend the communication channel between scouting drone and fire-fighting drone and (c) a fire-fighting drone that could

autonomously travel to the wildfire locations and drop ecologically friendly fire extinguishing balls (Figure 4). The experiments in Aydin et al. (2019) show that smaller sized fire extinguishing balls might be effective in extinguishing short grass fires (i.e., a ~0.5 kg ball effectively extinguished a circle of 1-m of short grass). This fire extinguishing potential of ball dispersing drones has been well-recognised, and many systems are currently being developed and tested (Bailon-Ruiz & Lacroix, 2020; Barua et al., 2020; Innocente & Grasso, 2019). We will likely have a much clearer picture of the effectiveness of drones to help extinguish wildfires in the coming years.

5 | RESTORATION MONITORING

Revegetation plantings must be monitored to evaluate whether the project's goals are being met and inform adaptive management strategies to potentially re-set the trajectory of projects towards the desired goals (Gann et al., 2019). Monitoring a restoration project involves evaluating outcomes, which typically includes the status of the intervention (e.g., plant health, community complexity) and the degrading processes or ecological threats (e.g., pest populations). Here, we discuss how drones can and are used to monitor restoration projects. Many drone applications and techniques used in the restoration planning and implementation stages (discussed above) can apply to restoration monitoring, and we only provide a relatively brief summary accordingly.

5.1 | Monitoring plant stress/health

Using the same methods to assess baseline plant health conditions (e.g., see Section 3.1.3), drones mounted with multispectral cameras, can be used in the restoration monitoring stage. The data collected in the planning and implementation stages can define reference states, allowing the practitioner/researcher to compare with subsequently collected post-intervention data. Data collected using drones in the monitoring stage can then help facilitate adaptive management strategies to reset the trajectory of the restored vegetation back towards the goal point and could potentially be used to monitor human impacts in sensitive areas (Ancin-Murguzur et al., 2020; Fernández-Guisuraga et al., 2018).

5.2 | Wildlife surveillance

Wildlife surveillance may be required as part of a restoration assessment—for example, to understand the wildlife responses to landscape repair (Jones & Davidson, 2016). Corcoran et al. (2021) found that automated wildlife detection using drones can be achieved for a wide range of species (e.g., koala *Phascolarctos cinereus*; glossy ibis *Plegadis falcinellis*) and under various ecological conditions (e.g., low dense eucalyptus forest, coastal wetlands). This is corroborated by several studies from different ecosystems, for example, coastal (Oosthuizen et al., 2020), marine (Dickens et al., 2021) and inland (Eori et al., 2020; Hui et al., 2021). Hollings et al. (2018) pointed out a potential constraint to using drones for automated wildlife detection is that accuracy often reduces over larger spatial scales, and the cost of high-resolution data is relatively high. Nonetheless, it has been estimated that using drones to survey 100 ha of land is ~10 times more efficient than surveys based on traditional field surveys (Filipovs et al., 2021). In addition, a recent study linked drone photogrammetry derived vegetation structural traits with animal tracking to understand the structural components required to elucidate animal behaviour (Harrison, Camarretta, et al., 2021; Harrison, Davidson, et al., 2021). Lee et al. (2021) pointed out that other approaches may be more efficient because automated detection systems require significant amounts of time to generate training data and train detection models. The authors proposed a real-time animal detection method based on the Sobel edge algorithm, which can detect animals in a single image without training data. In their feasibility study, the fastest detection time per image was 0.033 s. Target images were acquired at heights <100 m, and the maximum detection precision was 0.804. These studies highlight several ways of acquiring wildlife detection and counts that could be useful in a restoration context—that is, to understand the components of the ecosystem that has undergone a restoration intervention. Streamlining the analytical pipeline to make it easier for all operators (including non-specialists) to conduct automatic wildlife detection and interpretation will bring value to restoration ecology. Detecting wildlife using drones contributes to several SER Recovery Wheel objectives (Figure 2), including *Absence of Threats*, *Species Composition*, *External Exchanges* (e.g., gene flows) and *Ecosystem Function* (e.g., interactions and productivity).

5.3 | Bulk environmental sampling

Environmental sampling, such as collecting soil or water samples for downstream metagenomic or physicochemical analysis, can provide important information for restoration monitoring (Breed et al., 2019). A multirotor drone mounted with landing gear and a sampling device could be a valuable tool in this regard. Collecting water samples to acquire environmental DNA (eDNA), preceding polymerase chain reaction (PCR) and analysis, can provide detailed data on ecological community composition and target species presence (e.g., pest or conservation priority species) in a waterbody (Rees et al., 2014). Restoring an ecosystem might involve creating ponds to support aquatic wildlife. By using a drone-based water sampling system, eDNA samples can be collected from a given pond (particularly useful when the banks are steep or where marginal vegetation is dense, thus preventing on-foot sampling) to detect amphibians (Figure 5). This approach can help restoration practitioners to assess whether the pond restoration intervention has had the desired effect (e.g., *Ecosystem Function* and *Species Composition*; Figure 2). Invertebrate diversity surveys can also be conducted in this manner (Nguyen et al., 2020).

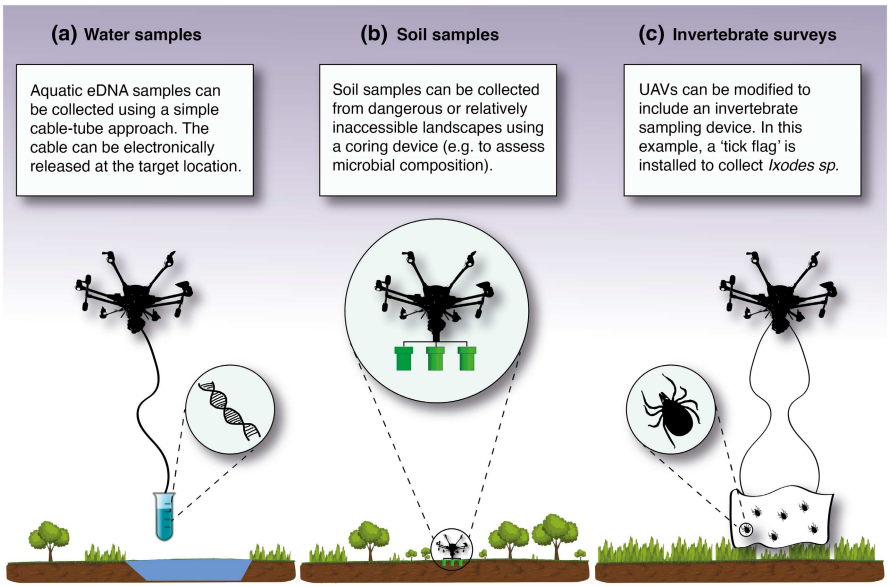

FIGURE 5 Modified drones can be used to collect samples in a range of environments—for example, (a) waterbodies, (b) soil, and (c) grasslands.

Similar sample collection devices can be attached to drones to potentially acquire other types of environmental samples in terrestrial habitats—e.g., soil and invertebrates. For example, in dangerous or relatively inaccessible landscapes, drones could be used to collect soil to assess the microbial composition and physicochemical properties, thus allowing soil health and biotic communities to be monitored following a restoration intervention. For example, the NIMBUS Lab at the University of Nebraska developed a drone soil drilling system that could be adapted to collect soil cores for this purpose. Ecological consultants have used drones with a tick (parasitic invertebrate) flagging systems attached to survey Ixodid ticks in a meadow habitat (unpublished). This enabled the operator to fly a drone across a grassland to survey ticks safely (i.e., removing the surveyor from vector hotspots) and efficiently as part of an invertebrate DNA surveying project to detect elusive species such as the European hedgehog *Erinaceus europaeus*. Notably, tick-borne diseases are increasing in some areas of the world, which has been linked to climate and land change (Gray et al., 2009; Madison-Antenucci et al., 2020). Our ability to reduce the likelihood of being infected in the field during restoration projects could be enhanced by employing drone-based preventative strategies. This sampling approach could be modified to survey other invertebrate species and communities as part of a restoration monitoring project.

5.4 | Air quality assessment

Similarly to using drones to sample soil and water samples, a drone can be mounted with an air sampling device to enable air quality assessments following a restoration intervention. Jumaah et al. (2021) developed a drone-based particulate matter at 2.5 μm (PM2.5) air quality monitoring system. The system included an air quality detector using Arduino sensors. The authors collected air PM2.5 data in a vertical flight path, which was similar to the ground truthed reference data. This could be useful for surveying large areas and collecting real-time air quality data following a restoration intervention (e.g., assessing whether a given restoration planting programme improves air quality). Several other researchers are developing drone-based air quality detection systems (Vijayakumar et al., 2020; Zhao et al., 2020). Hedworth et al. (2021) found that particle size distribution was unaffected by the drone and suggested that the area directly above the drone was optimal to mount an air quality sensor. A similar method could collect biogenic compounds such as pollen and microbial communities to assess restoration outcomes on these biotic components of air. Indeed, collecting airborne eDNA samples is an emerging area of research in ecology, for example, for monitoring terrestrial vertebrate communities (Lynggaard et al., 2022). Moreover, some researchers are assessing whether restoration interventions and aspects of habitat complexity can improve the aerobiome (microbiome of the air) with potential human health implications (Breed et al., 2021; Robinson et al., 2020; Robinson et al., 2021). Drones could potentially help facilitate the collection of airborne eDNA samples in different restoration settings. Research is required to determine if this is better than traditional and less mobile methods (e.g., sampling stations with Petri dishes or handheld samplers).

5.5 | Digital models to assess post-restoration vegetation complexity

Following a restoration intervention (e.g., a restoration planting scheme), drones with LiDAR modules can help assess the intervention's success, as highlighted in Section 3.2. Along with LiDAR models, structure from motion could be useful in assessing vegetation biomass and complexity to aid restoration monitoring (Swinfield et al., 2019). As discussed in Section 3.2, combining drone hyperspectral and LiDAR data seems to be the most effective approach to assess forest structural attributes and tree species richness for restoration planning in a forest ecosystem. This approach can therefore

contribute to several SER Recovery Wheel objectives (Figure 2), including *Species Composition* and *Structural Diversity*.

6 | SUMMARY OF POTENTIAL CONSTRAINTS

It is important to re-emphasise the constraints associated with using drones in restoration. These include potential risks to wildlife, particularly if the drone operator is inexperienced and fails to follow operating guidelines for given species or communities, for example, for birds (Rümmler et al., 2018; Vas et al., 2015). The cost of the hardware is also a potential constraint, where drones (and modules/sensors) themselves can be costly, particularly if damaged in the absence of insurance. Software, analysis and labour are also costly, plus methodological ambiguity can inhibit the generalisation of survey data (Buters, Bateman, et al., 2019). Public perception and opinion are also important factors; considering the social aspects of drone-assisted restoration, interventions will likely be critical to many projects' success and the continued development of drone-based methods in restoration. Research on the perception of drones in science in general has suggested that people can be apprehensive towards them, given their military origins (Markowitz et al., 2017). However, the same study showed moderate to strong public support for using drones for conservation purposes. This perception needs to be maintained—and potentially enhanced—if drones are to be used to help restore ecosystems in the long term. In many countries, a remote pilot licence and additional training are required by law to use drones and carry large payloads. These are important potential barriers that need consideration at the earliest stages. Drones often also need line of sight to the ground controller, which could prevent flight operations in certain ecosystems where prominent features obstruct this line. Moreover, countries (and ecosystems) have different legislations and flight rules that could constrain flight plans—for example, prohibited airspaces or flying near urban areas.

7 | CONCLUSIONS

Drones are a valuable tool in the environmental, forestry and agriculture sectors. Our article demonstrates that practical drone-based approaches can be—and indeed some have already been—transferred and potentially adopted in restoration, from mapping vegetation composition and structure to monitoring plant health and wildlife population dynamics. Drones can help to refine and enhance restoration objectives along the restoration continuum, from planning and implementation to monitoring and contribute to the SER Recovery Wheel objectives. Several technical and practical constraints need to be overcome, such as model accuracy, methodological ambiguity and perception of danger. Nonetheless, drones have considerable potential to revolutionise the science and practice of restoration at each stage of a restoration project, thereby contributing to the goals of the UN Decade on Ecosystem Restoration.

AUTHORS' CONTRIBUTIONS

J.M.R., M.F.B. and P.A.H. contributed to the conception and design of the article; J.M.R. M.F.B. and P.A.H. wrote the first draft of the manuscript; J.M.R. created the figures/visualisations; J.M.R., M.F.B., S.M. and P.A.H. contributed to critical review, manuscript revisions, and read and approved the submitted version.

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CONFLICT OF INTEREST

The authors declare that the research was conducted without any commercial or financial relationships that could be construed as a potential conflict of interest.

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ORCID

Jake M. Robinson https://orcid.org/0000-0001-8108-3271
Peter A. Harrison https://orcid.org/0000-0002-3502-0242
Suzanne Mavoa https://orcid.org/0000-0002-6071-2988
Martin F. Breed https://orcid.org/0000-0001-7810-9696

REFERENCES

Aghai, M., & Manteuffel-Ross, T. (2020). Enhanced direct seedling efforts with unmanned aerial vehicle (UAV) 'swarms' and seed technology. *Tree Planters Notes*, *63*, 32–48.

Allison, R. S., Johnston, J. M., Craig, G., & Jennings, S. (2016). Airborne optical and thermal remote sensing for wildfire detection and monitoring. *Sensors*, *16*(8), 1310.

Alvarez-Vanhard, E., Corpetti, T., & Houet, T. (2021). UAV & satellite synergies for optical remote sensing applications: A literature review. *Science of Remote Sensing*, *3*, 100019.

Ancin-Murguzur, F. J., Munoz, L., Monz, C., & Hausner, V. H. (2020). Drones as a tool to monitor human impacts and vegetation changes in parks and protected areas. *Remote Sensing in Ecology and Conservation*, *6*(1), 105–113.

Athanasis, N., Themistocleous, M., Kalabokidis, K., & Chatzitheodorou, C. (2018). Big data analysis in UAV surveillance for wildfire prevention and management. In M. Themistocleous & P. R. da Cunha (Eds.), *European, mediterranean, and middle eastern conference on information systems* (pp. 47–58). Springer.

Aubert, C., Le Moguédec, G., Assio, C., Blatrix, R., Ahizi, M. N. D., Hedegbetan, G. C., Kpera, N. G., Lapeyre, V., Martin, D., Labbé, P., & Shirley, M. H. (2021). Evaluation of the use of drones to monitor a diverse crocodylian assemblage in West Africa. *Wildlife Research*, *49*, 11–23.

Aydin, B., Selvi, E., Tao, J., & Starek, M. J. (2019). Use of fire-extinguishing balls for a conceptual system of drone-assisted wildfire fighting. *Drones*, *3*(1), 17.

Baena, S., Moat, J., Whaley, O., & Boyd, D. S. (2017). Identifying species from the air: UAVs and the very high resolution challenge for plant conservation. *PLoS ONE*, *12*, e0188714.

Bailon-Ruiz, R., & Lacroix, S. (2020). Wildfire remote sensing with UAVs: A review from the autonomy point of view. In *2020 international conference on unmanned aircraft systems (ICUAS)* (pp. 412–420). IEEE.

Barros, A. M., Ager, A. A., Day, M. A., Krawchuk, M. A., & Spies, T. A. (2018). Wildfires managed for restoration enhance ecological resilience. *Ecosphere*, *9*(3), e02161.

Barua, S., Tanjim, M. S. S., Oishi, A. N., Das, S. C., Basar, M. A., & Rafi, S. A. (2020). Design and implementation of fire extinguishing ball thrower quadcopter. In *2020 IEEE region 10 symposium (TENSYMP)* (pp. 1404–1407). IEEE.

Beachly, E., Higgins, J., Laney, C., Elbaum, S., Detweiler, C., Allen, C., & Twidwell, D. (2016). A micro-UAS to start prescribed fires. In D. Kulić, Y. Nakamura, O. Khatib, & G. Venture (Eds.), *International symposium on experimental robotics* (pp. 12–24). Springer.

Binny, R. N., Innes, J., Fitzgerald, N., Pech, R., James, A., Price, R., Gillies, C., & Byrom, A. E. (2021). Long-term biodiversity trajectories for pest-managed ecological restorations: Eradication vs. suppression. *Ecological Monographs*, *91*(2), e01439.

Breed, M. F., Cross, A. T., Wallace, K., Bradby, K., Flies, E., Goodwin, N., Jones, M., Orlando, L., Skelly, C., Weinstein, P., & Aronson, J. (2021). Ecosystem restoration: A public health intervention. *EcoHealth*, *18*(3), 269–271.

Breed, M. F., Harrison, P. A., Blyth, C., Byrne, M., Gaget, V., Gellie, N. J., Groom, S. V., Hodgson, R., Mills, J. G., Prowse, T. A., & Steane, D. A. (2019). The potential of genomics for restoring ecosystems and biodiversity. *Nature Reviews Genetics*, *20*(10), 615–628.

Brovkina, O., Cienciala, E., Surový, P., & Janata, P. (2018). Unmanned aerial vehicles (UAV) for assessment of qualitative classification of Norway spruce in temperate forest stands. *Geo-spatial Information Science*, *21*(1), 12–20.

Buters, T., Belton, D., & Cross, A. (2019). Seed and seedling detection using unmanned aerial vehicles and automated image classification in the monitoring of ecological recovery. *Drones*, *3*(3), 53.

Buters, T. M., Bateman, P. W., Robinson, T., Belton, D., Dixon, K. W., & Cross, A. T. (2019). Methodological ambiguity and inconsistency constrain unmanned aerial vehicles as a silver bullet for monitoring ecological restoration. *Remote Sensing*, *11*(10), 1180.

Camarretta, N., Harrison, P. A., Lucieer, A., Potts, B. M., Davidson, N., & Hunt, M. (2020). From drones to phenotype: Using UAV-LiDAR to detect species and provenance variation in tree productivity and structure. *Remote Sensing*, *12*(19), 3184.

Cavender-Bares, J., Gamon, J. A., & Townsend, P. A. (2020). *Remote sensing of plant biodiversity*. Springer Nature.

Corcoran, E., Winsen, M., Sudholz, A., & Hamilton, G. (2021). Automated detection of wildlife using drones: Synthesis, opportunities, and constraints. *Methods in Ecology and Evolution*, *12*(6), 1103–1114.

Cruzan, M. B., Weinstein, B. G., Grasty, M. R., Kohrn, B. F., Hendrickson, E. C., Arredondo, T. M., & Thompson, P. G. (2016). Small unmanned aerial vehicles (micro-UAVs, drones) in plant ecology. *Applications in Plant Sciences*, *4*(9), 1600041.

Dalla Corte, A. P., Rex, F. E., Almeida, D. R. A. D., Sanquetta, C. R., Silva, C. A., Moura, M. M., Wilkinson, B., Zambrano, A. M. A., Neto, C., Veras, H. F., & Moraes, A. D. (2020). Measuring individual tree diameter and height using GatorEye high-density UAV-lidar in an integrated crop-livestock-Forest system. *Remote Sensing*, *12*(5), 863.

Darmawan, A., Saputra, D. K., Asadi, M. A., & Karang, I. W. G. A. (2020). UAV application for site suitability mangrove replantation program, case study in Pasuruan and Probolinggo, East Java. In E3S Web of Conferences. *EDP Sciences*, *153*, 01009.

Davis, S. P. (2021). *Evaluating the use of drones to estimate deer density and count wildlife trails in bath nature preserve, Ohio* (Doctoral dissertation). University of Akron.

De Almeida, D. R. A., Broadbent, E. N., Ferreira, M. P., Meli, P., Zambrano, A. M. A., Gorgens, E. B., Resende, A. F., de Almeida, C. T., Do Amaral, C. H., Dalla Corte, A. P., & Silva, C. A. (2021). Monitoring restored tropical forest diversity and structure through UAV-borne hyperspectral and lidar fusion. *Remote Sensing of Environment*, *264*, 112582.

Díaz-Delgado, R., Cazacu, C., & Adamescu, M. (2018). Rapid assessment of ecological integrity for LTER wetland sites by using UAV multispectral mapping. *Drones*, *3*(1), 3.

Dickens, J., Hollyman, P. R., Hart, T., Clucas, G. V., Murphy, E. J., Poncet, S., Trathan, P. N., & Collins, M. A. (2021). Developing UAV monitoring of South Georgia and the South Sandwich Islands' iconic land-based marine predators. *Frontiers in Marine Science*, *8*, 630.

Droneseed. (2020). *Drone reforestation*. Retrieved from: https://www.droneseed.com/

Duporge, I., Spiegel, M. P., Thomson, E. R., Chapman, T., Lamberth, C., Pond, C., Macdonald, D. W., Wang, T., & Klinck, H. (2021). Determination of optimal flight altitude to minimise acoustic drone disturbance to wildlife using species audiograms. *Methods in Ecology and Evolution*, *12*(11), 2196–2207.

Eori, M. M., Barrow, E. J., Gehrke, V., Breeden, T., Kane, E. E., Susanto, T. W., & Knott, C. D. (2020). Assessing wild Bornean orangutan (*Pongo pygmaeus wurmbii*) populations with drone imagery. *American Journal of Physical Anthropology*, *171*(Supplement 69), 81.

ESRI. (2021). *ArcGIS Desktop: Release 10*. Environmental Systems Research Institute.

Ester, M., Kriegel, H. P., Sander, J., & Xu, X. (1996). A density-based algorithm for discovering clusters in large spatial databases with noise. *KDD*, *96*(34), 226–231.

European Environment Agency. (2016). *Mapping and assessment of ecosystems and their services*. Retrieved from https://ec.europa.eu/environment/nature/knowledge/ecosystem_assessment/pdf/3rdMAESReport_Condition.pdf

Fernández-Guisuraga, J. M., Sanz-Ablanedo, E., Suárez-Seoane, S., & Calvo, L. (2018). Using unmanned aerial vehicles in postfire vegetation survey campaigns through large and heterogeneous areas: Opportunities and challenges. *Sensors*, *18*(2), 586.

Filipovs, J., Berg, A., Ahlberg, J., Vecvanags, A., Brauns, A., & Jakovels, D. (2021). UAV areal imagery-based wild animal detection for sustainable wildlife management. In *EGU general assembly conference abstracts* (pp. EGU21-14137).

Foo, S. A., & Asner, G. P. (2019). Scaling up coral reef restoration using remote sensing technology. *Frontiers in Marine Science*, *6*, 79.

Francis, R. J., Lyons, M. B., Kingsford, R. T., & Brandis, K. J. (2020). Counting mixed breeding aggregations of animal species using drones: Lessons from waterbirds on semi-automation. *Remote Sensing*, *12*(7), 1185.

Gallego, D., & Sarasola, J. H. (2021). Using drones to reduce human disturbance while monitoring breeding status of an endangered raptor. *Remote Sensing in Ecology and Conservation*, *7*(3), 550–561.

Gann, G. D., McDonald, T., Walder, B., Aronson, J., Nelson, C. R., Jonson, J., Hallett, J. G., Eisenberg, C., Guariguata, M. R., Liu, J., Hua, F., Echeverria, C., Gonzales, E. K., Shaw, N., Decleer, K., & Dixon, K. W. (2019). International principles and standards for the practice of ecological restoration. Second edition. *Restoration Ecology*, *27*, S1–S46.

Gray, J. S., Dautel, H., Estrada-Peña, A., Kahl, O., & Lindgren, E. (2009). Effects of climate change on ticks and tick-borne diseases in Europe. *Interdisciplinary Perspectives on Infectious Diseases*, *2009*, 593232.

Hamylton, S. M., Morris, R. H., Carvalho, R. C., Roder, N., Barlow, P., Mills, K., & Wang, L. (2020). Evaluating techniques for mapping Island vegetation from unmanned aerial vehicle (UAV) images: Pixel classification, visual interpretation, and machine learning

approaches. *International Journal of Applied Earth Observation and Geoinformation*, *89*, 102085.

Harrison, P. A., Camarretta, N., Krisanski, S., Bailey, T., Davidson, N., Taskhiri, M. S., Turner, P., Turner, D., & Lucieer, A. (2021). From ecosystems to individuals: Using remote sensing to inform and monitor restoration plantings. *Ecological Management & Restoration*, *22*, 127–139.

Harrison, P. A., Davidson, N. J., Bailey, T. G., Jones, M., Gilfedder, L., Bridle, K., Bowman, D. M. J. S., Baker, T. P., Richardson, B. J., Wallis, L., & Potts, B. M. (2021). A decade of restoring a temperate woodland: Lessons learned and future directions. *Ecological Management & Restoration*, *22*, 164–174.

Hedworth, H. A., Sayahi, T., Kelly, K. E., & Saad, T. (2021). The effectiveness of drones in measuring particulate matter. *Journal of Aerosol Science*, *152*, 105702.

Hodgson, J. C., Mott, R., Baylis, S. M., Pham, T. T., Wotherspoon, S., Kilpatrick, A. D., Raja Segaran, R., Reid, I., Terauds, A., & Koh, L. P. (2018). Drones count wildlife more accurately and precisely than humans. *Methods in Ecology and Evolution*, *9*(5), 1160–1167.

Hollings, T., Burgman, M., van Andel, M., Gilbert, M., Robinson, T., & Robinson, A. (2018). How do you find the green sheep? A critical review of the use of remotely sensed imagery to detect and count animals. *Methods in Ecology and Evolution*, *9*(4), 881–892.

Hui, N. T., Lo, E. K., Moss, J. B., Gerber, G. P., Welch, M. E., Kastner, R., & Schurgers, C. (2021). A more precise way to localize animals using drones. *Journal of Field Robotics*, *38*, 917–928.

Innocente, M. S., & Grasso, P. (2019). Self-organising swarms of firefighting drones: Harnessing the power of collective intelligence in decentralised multi-robot systems. *Journal of Computational Science*, *34*, 80–101.

Jaakkola, A., Hyyppä, J., Kukko, A., Yu, X., Kaartinen, H., Lehtomäki, M., & Lin, Y. (2010). A low-cost multi-sensoral mobile mapping system and its feasibility for tree measurements. *ISPRS Journal of Photogrammetry and Remote Sensing*, *65*(6), 514–522.

Jiménez López, J., & Mulero-Pázmány, M. (2019). Drones for conservation in protected areas: Present and future. *Drones*, *3*(1), 10.

Jones, M. E., & Davidson, N. (2016). Applying an animal-centric approach to improve ecological restoration. *Restoration Ecology*, *24*(6), 836–842.

Jumaah, H. J., Kalantar, B., Mansor, S., Halin, A. A., Ueda, N., & Jumaah, S. J. (2021). Development of UAV-based PM2. 5 monitoring system. *Drones*, *5*(3), 60.

Kim, H., Kim, W., & Kim, S. D. (2021). Damage assessment of Rice crop after toluene exposure based on the vegetation index (VI) and UAV multispectral imagery. *Remote Sensing*, *13*(1), 25.

Kumar, M., Cohen, K., & HomChaudhuri, B. (2011). Cooperative control of multiple uninhabited aerial vehicles for monitoring and fighting wildfires. *Journal of Aerospace Computing, Information, and Communication*, *8*(1), 1–16.

Lee, S., Song, Y., & Kil, S. H. (2021). Feasibility analyses of real-time detection of wildlife using UAV-derived thermal and RGB images. *Remote Sensing*, *13*(11), 2169.

Lewis, D. (2020). 'Deathly silent': Ecologist describes Australian wildfires' devastating aftermath. *Nature*, *577*(7789), 304–305.

Li, X., Giles, D. K., Andaloro, J. T., Long, R., Lang, E. B., Watson, L. J., & Qandah, I. (2021). Comparison of UAV and fixed-wing aerial application for alfalfa insect pest control: Evaluating efficacy, residues, and spray quality. *Pest Management Science*, *77*, 4980–4992.

Li, X., Giles, D. K., Niederholzer, F. J., Andaloro, J. T., Lang, E. B., & Watson, L. J. (2021). Evaluation of an unmanned aerial vehicle as a new method of pesticide application for almond crop protection. *Pest Management Science*, *77*(1), 527–537.

Lu, J., Wang, H., Qin, S., Cao, L., Pu, R., Li, G., & Sun, J. (2020). Estimation of aboveground biomass of *Robinia pseudoacacia* forest in the Yellow River Delta based on UAV and backpack LiDAR point clouds. *International Journal of Applied Earth Observation and Geoinformation*, *86*, 102014.

Luck, B. D., Chasen, E. M., Williams, P. J., & Steffan, S. A. (2021). Drones that deliver: Pheromone-based mating disruption deployed via uncrewed aerial vehicles in us cranberries. *Journal of Economic Entomology*, *114*(5), 1910–1916.

Lynggaard, C., Bertelsen, M. F., Jensen, C. V., Johnson, M. S., Frøslev, T. G., Olsen, M. T., & Bohmann, K. (2022). Airborne environmental DNA for terrestrial vertebrate community monitoring. *Current Biology*, *32*, 701–707.e5.

Madison-Antenucci, S., Kramer, L. D., Gebhardt, L. L., & Kauffman, E. (2020). Emerging tick-borne diseases. *Clinical Microbiology Reviews*, *33*(2), e00083-18.

Marchowski, D. (2021). Drones, automatic counting tools and artificial neural networks in wildlife population censusing. *Authorea*, *11*, 16214–16227.

Markowitz, E. M., Nisbet, M. C., Danylchuk, A. J., & Engelbourg, S. I. (2017). What's that buzzing noise? Public opinion on the use of drones for conservation science. *Bioscience*, *67*(4), 382–385.

Mohan, M., Richardson, G., Gopan, G., Aghai, M. M., Bajaj, S., Galgamuwa, G. A., Vastaranta, M., Arachchige, P. S. P., Amorós, L., Corte, A. P. D., & de-Miguel, S. (2021). UAV-supported Forest regeneration: Current trends, challenges, and implications. *Remote Sensing*, *13*(13), 2596.

Mulero-Pázmány, M., Jenni-Eiermann, S., Strebel, N., Sattler, T., Negro, J. J., & Tablado, Z. (2017). Unmanned aircraft systems as a new source of disturbance for wildlife: A systematic review. *PloS One*, *12*(6), e0178448.

Neuville, R., Bates, J. S., & Jonard, F. (2021). Estimating forest structure from UAV-mounted LiDAR point cloud using machine learning. *Remote Sensing*, *13*(3), 352.

Nguyen, B. N., Shen, E. W., Seemann, J., Correa, A. M., O'Donnell, J. L., Altieri, A. H., Knowlton, N., Crandall, K. A., Egan, S. P., McMillan, W. O., & Leray, M. (2020). Environmental DNA survey captures patterns of fish and invertebrate diversity across a tropical seascape. *Scientific Reports*, *10*(1), 1–14.

Nuijten, R. J., Coops, N. C., Watson, C., & Theberge, D. (2021). Monitoring the structure of regenerating vegetation using drone-based digital aerial photogrammetry. *Remote Sensing*, *13*(10), 1942.

Oosthuizen, W. C., Krüger, L., Jouanneau, W., & Lowther, A. D. (2020). Unmanned aerial vehicle (UAV) survey of the Antarctic shag (*Leucocarbo bransfieldensis*) breeding colony at harmony point, Nelson Island, South Shetland Islands. *Polar Biology*, *43*(2), 187–191.

Pham, H. X., La, H. M., Feil-Seifer, D., & Deans, M. C. (2018). A distributed control framework of multiple unmanned aerial vehicles for dynamic wildfire tracking. *IEEE Transactions on Systems, Man, and Cybernetics: Systems*, *50*(4), 1537–1548.

Rahman, A. A., Jaafar, W. S. W. M., Maulud, K. N. A., Noor, N. M., Mohan, M., Cardil, A., Silva, C. A., Che'Ya, N. N., & Naba, N. I. (2019). Applications of drones in emerging economies: A case study of Malaysia. In *2019 6th international conference on space science and communication (IconSpace)* (pp. 35–40). IEEE.

Rao, B., Gopi, A. G., & Maione, R. (2016). The societal impact of commercial drones. *Technology in Society*, *45*, 83–90.

Rees, H. C., Bishop, K., Middleditch, D. J., Patmore, J. R., Maddison, B. C., & Gough, K. C. (2014). The application of eDNA for monitoring of the great crested newt in the UK. *Ecology and Evolution*, *4*(21), 4023–4032.

Resop, J. P., Lehmann, L., & Hession, W. C. (2019). Drone laser scanning for modeling riverscape topography and vegetation: Comparison with traditional aerial lidar. *Drones*, *3*(2), 35.

Robinson, J. M., Cando-Dumancela, C., Antwis, R. E., Cameron, R., Liddicoat, C., Poudel, R., Weinstein, P., & Breed, M. F. (2021). Exposure to airborne bacteria depends upon vertical stratification and vegetation complexity. *Scientific Reports*, *11*(1), 1–16.

Robinson, J. M., Cando-Dumancela, C., Liddicoat, C., Weinstein, P., Cameron, R., & Breed, M. F. (2020). Vertical stratification in urban green space aerobiomes. *Environmental Health Perspectives*, *128*(11), 117008.

Rossiter, T., Furey, T., McCarthy, T., & Stengel, D. B. (2020). UAV-mounted hyperspectral mapping of intertidal macroalgae. *Estuarine, Coastal and Shelf Science*, *242*, 106789.

Rümmler, M. C., Mustafa, O., Maercker, J., Peter, H. U., & Esefeld, J. (2018). Sensitivity of Adélie and Gentoo penguins to various flight activities of a micro UAV. *Polar Biology*, *41*(12), 2481–2493.

Saikin, D. A., Baca, T., Gurtner, M., & Saska, M. (2020). Wildfire fighting by unmanned aerial system exploiting its time-varying mass. *IEEE Robotics and Automation Letters*, *5*(2), 2674–2681.

SER. (2022). *The Society for Ecological Restoration*. Online. Retrieved from https://www.ser.org/

Shackelford, N., Paterno, G. B., Winkler, D. E., Erickson, T. E., Leger, E. A., Svejcar, L. N., Breed, M. F., Faist, A. M., Harrison, P. A., Curran, M. F., & Guo, Q. (2021). Drivers of seedling establishment success in dryland restoration efforts. *Nature Ecology & Evolution*, *5*(9), 1283–1290.

Sierra-Escrigas, S. L., Peluffo, D. R., & García-Urueña, R. (2020). Shallow coral reef community mapping and update on its ecological units using aerial images at Isla arena, Colombian Caribbean. *International Journal of Remote Sensing*, *41*, 1–18.

Swinfield, T., Lindsell, J. A., Williams, J. V., Harrison, R. D., Gemita, E., Schönlieb, C. B., & Coomes, D. A. (2019). Accurate measurement of tropical forest canopy heights and aboveground carbon using structure from motion. *Remote Sensing*, *11*(8), 928.

United Nations. (2020). UN decade on ecosystem restoration. Retrieved from https://www.decadeonrestoration.org/

Vas, E., Lescroël, A., Duriez, O., Boguszewski, G., & Grémillet, D. (2015). Approaching birds with drones: First experiments and ethical guidelines. *Biology Letters*, *11*(2), 20140754.

Vijayakumar, P., Khokhar, A., Pal, A., & Dhawan, M. (2020). Air quality index monitoring and mapping using UAV. In *2020 international conference on communication and signal processing (ICCSP)* (pp. 1176–1179). IEEE.

Villoslada, M., Bergamo, T. F., Ward, R. D., Burnside, N. G., Joyce, C. B., Bunce, R. G. H., & Sepp, K. (2020). Fine scale plant community assessment in coastal meadows using UAV based multispectral data. *Ecological Indicators*, *111*, 105979.

Wallace, L., Lucieer, A., Malenovský, Z., Turner, D., & Vopěnka, P. (2016). Assessment of forest structure using two UAV techniques: A comparison of airborne laser scanning and structure from motion (SfM) point clouds. *Forests*, *7*(3), 62.

Wallace, L., Musk, R., & Lucieer, A. (2014). An assessment of the repeatability of automatic forest inventory metrics derived from UAV-borne laser scanning data. *IEEE Transactions on Geoscience and Remote Sensing*, *52*(11), 7160–7169.

White, A. M., & Long, J. W. (2019). Understanding ecological contexts for active reforestation following wildfires. *New Forests*, *50*(1), 41–56.

Woods, M. J., Cobb, M., Hickle, K., & McEwan, R. W. (2019). Assessing the efficacy of seedling planting as a Forest restoration technique in temperate hardwood forests impacted by invasive species. *Forests*, *10*(8), 699.

Yu, Y., Zhao, W., Martinez-Murillo, J. F., & Pereira, P. (2020). Loess plateau, from degradation to restoration. *Science of the Total Environment.*, *738*, 140206.

Zahawi, R. A., Dandois, J. P., Holl, K. D., Nadwodny, D., Reid, J. L., & Ellis, E. C. (2015). Using lightweight unmanned aerial vehicles to monitor tropical forest recovery. *Biological Conservation*, *186*, 287–295.

Zhao, Y., Shi, P. Y., & Guo, W. H. (2020). Design of Urban air Quality Monitoring System Based on big data and UAV. In S. Liu & L. Xia (Eds.), *International conference on advanced hybrid information processing* (pp. 159–169). Springer.

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