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Biologist's Toolbox

Harnessing the full potential of drones for fieldwork

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Abstract

Field-based research in the biological sciences encounters several challenges, including cost, accessibility, safety, and spatial coverage. Drones have emerged as a transformative technology to address these challenges while providing a less intrusive alternative to field surveys. Although drones have mainly been used for high-resolution image collection, their capabilities extend beyond mapping and image production. They can be tailored to track wildlife, measure environmental parameters, and collect physical samples, and their versatility enables researchers to tackle a variety of biodiversity and conservation challenges. In this article, we advocate for drones to be integrated more comprehensively into field-based research, from site reconnaissance to sampling, interventions, and monitoring. We discuss the future innovations needed to harness their full potential, including customized instrumentation, fit-for-purpose software and apps, and better integration with existing online databases. We also support leveraging community scientists and empowering citizens to contribute to scientific endeavors while promoting environmental stewardship via drones.

Keywords: unpiloted aircraft systems, unmanned aerial vehicles, remotely piloted aircraft, environmental management, ecological restoration

Field work is integral to the biological, natural, and environmental sciences, but traditional field approaches face increasing limitations surrounding cost, site accessibility, time, safety, and spatial coverage (Reichenborn et al. 2024). Drones, also called *unpiloted aircraft systems* or *unmanned aerial vehicles*, have emerged as a potential technology to overcome some of these challenges. Compared with traditional field surveys, drones can offer a less intrusive approach for minimizing disturbances in sensitive environments or can reduce the need to capture and handle animals (Pirotta et al. 2017, Zemanova 2020). They can also improve researcher safety by providing access to challenging or hard-to-reach areas and minimizing the need to enter dangerous areas, allowing professionals to gather data and monitor previously inaccessible environments (Reichenborn et al. 2024). There has been an uptick in the use of drones for environmental studies over the past two decades (Singh and Frazier 2018, Singh et al. 2024), but they remain underused in their capacity for aiding many other aspects of the research process from site reconnaissance and data collection to interventions and monitoring.

To date, drones have primarily been used in the biosciences to collect high spatial resolution (e.g., less than 5 centimeters) imagery (Anderson and Gaston 2013, Singh et al. 2024). Historically, the imagery used in biological studies has been collected through government-funded satellite platforms such as Landsat, which have fixed data collection parameters and schedules, or more recently by private organizations such as Planet, which capture imagery more frequently but still have limitations (Frazier and Hemingway 2021). In contrast, drones have democratized the image collection process by allowing researchers to collect imagery at their own desired spatial resolutions and on time frames tailored to the particular study or site (Choi-Fitzpatrick 2020). These images are used for a variety of purposes, including censuses of terrestrial and marine wildlife (Seymour et al. 2017, Hodgson et al. 2018), taking morphological measurements of large aquatic animals (Johnston 2019), and assessing vegetation health (Sun et al. 2021), but most often, they are used to create land cover maps or other types of vegetation maps (Singh et al. 2024). Sometimes, if the data collection design permits, the images are used to develop 3D models, such as digital terrain and digital surface models, using structure from motion techniques (Westoby et al. 2012), which leverage overlapping camera perspectives to reconstruct site or vegetation structure (James and Robson 2012). Open source software for flight planning, mission control, and image capture, as well as structure from motion processing, have facilitated widespread and prolific adoption of drones for these purposes (Singh and Frazier 2018, Dash et al. 2019, Robinson et al. 2022).

However, capturing images for mapping is a relatively narrow opportunity set given the flexibility of drones to be customized and fit for purpose in terms of their sensors or equipment payload and deployed on demand across different landscape types and geographies (Anderson and Gaston 2013). We argue that drones are underused across the entire field research lifecycle and have the potential to contribute to more than simply land cover mapping, alleviating many of the challenges currently hindering in-person fieldwork. We discuss how drones are a valuable tool in the biologist's toolbox that can be integrated into field-based workflows to alleviate labor-intensive activities, minimize the overall cost of a project, supplement sampling efforts, and enable comprehensive biodiversity assessments and monitoring. By harnessing the versatility of drones, we contend that researchers can achieve scientifically rigorous and detailed ground data collections, craft survey protocols that are reproducible, repeatable, and scalable, and

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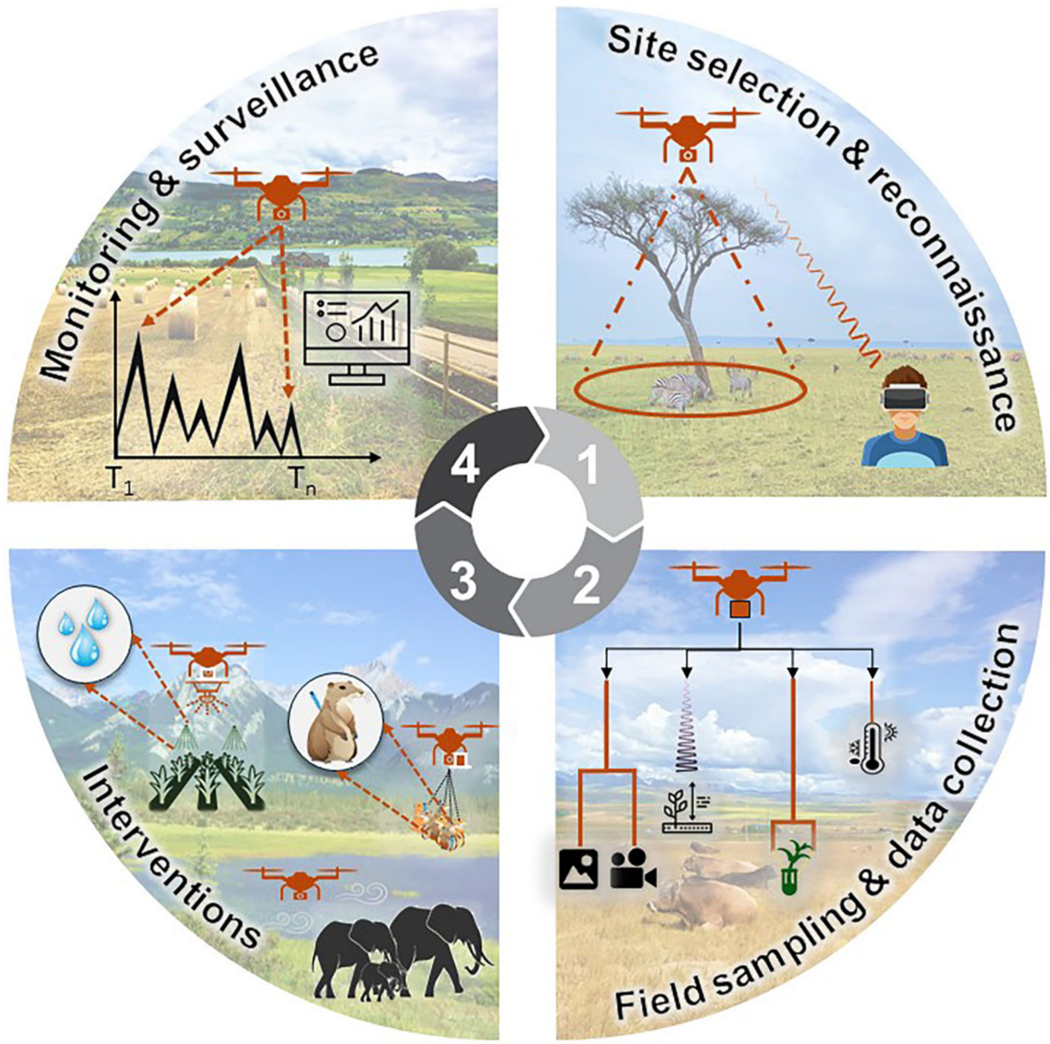

Figure 1. Drones can facilitate many aspects of the biology research lifecycle, including site reconnaissance and selection; data collection and sampling, including imagery capture but also physical or biological samples (e.g., soil, water, or vegetation) and measuring physiochemical properties (e.g., substrate temperature); management interventions such as fertilizer and agrochemical applications, vaccine distribution, or threat abatement; and monitoring to assess site changes or improvements over time.

overcome some of the limitations of traditional field methodologies.

Leveraging drones across the field research lifecycle

Field-based activities are often required or warranted at multiple stages in a research project (figure 1). These stages include the initial selection or reconnaissance of research sites, followed by systematic sampling or data collection. After data have been analyzed and recommendations have been made, there may then be a need for site-specific interventions or regular or repeated monitoring and assessment. At each of these four stages, there is an opportunity to leverage drones to alleviate the burdens of in-person site visits, saving time and money and reducing possible harm to people and disturbances to the environment. In addition, drones can broaden the spatial and temporal breadths of data collection, thereby boosting the volume of robust data sets essential for rigorous statistical data analysis and other computations. We detail the exciting potential and state-of-the-art capabilities that are emerging for drones in each of these stages.

Site selection and reconnaissance

The initial step in a research project often involves site selection or preliminary surveys and reconnaissance. In-person surveying efforts can require considerable human capital and resources and can also lead to site selection bias, whereby sampling sites are identified in easy-to-access areas (e.g., near roads) or in areas where surveyors know there is high species richness or abundance. These biases can influence analyses and exaggerate effects (Mentges et al. 2021). Even when systematic or random site selection schemes are implemented, there can be accessibility challenges from terrain, land cover, or land tenure. Drones can be deployed to reconnoiter sites of interest and allow researchers and land managers to efficiently explore or tour these sites without physical presence *in situ*, which can also make these activities inclusive for those with physical or other limitations. Drone-captured still images or 360-degree video footage can provide researchers with comprehensive visual data not only to assess site accessibility and feasibility but also to carry out retrospective reanalysis. The integration of augmented reality headsets can elevate the experience and allow surveyors to control the drone's movement simply by turning their head while seeing what the camera is sensing. Video and augmented reality surveillance can also help reduce the human footprint associated with site visits (McIntosh et al. 2018, Gallego and Sarasola 2021).

Once a site has been located, there are several ways in which drone technology can continue to be leveraged. First, preliminary data on site characteristics, including vegetation communities, topographical and hydrological features, or physical barriers can be captured to help refine research questions, optimize sampling strategies, or develop data collection protocols (Baena et al. 2018). Drones are well suited for image capture and 3D model creation, which facilitates the acquisition of detailed information on environmental conditions, habitat structure, morphological traits of plants and animals, and many other factors (Johnston 2019, Frazier and Singh 2021, Frazier 2022). The use of wearable augmented reality technology can also be used to guide researchers or land managers to the identified sampling units, and even assist with sampling (Huuskonen and Oksanen 2018). The same wearable technology can also facilitate virtual site visits by students or research assistants who otherwise might not be able to travel there to gain the benefits of place based learning (Klippel et al. 2019), creating spillover benefits of investments in the technology.

Field sampling and data collection

As was noted above, the use of drones for capturing high resolution optical imagery is well documented across a diverse range of ecosystems, but their capacity for collecting other types of data is underdeveloped (Frazier et al. 2017). A natural extension of optical imagery applications is using thermal sensors for wildlife detection and population counts. Thermal sensors, or microbolometers, produce images on the basis of the amount of heat emitted by objects, and machine learning models can be employed to interpret these images and videos to identify animals that are warmer than their surroundings (Corcoran et al. 2021). Thermal sensors have been found to provide accurate and reliable wildlife population surveys in a safe and cost-effective manner compared with traditional aerial surveys (Hodgson et al. 2018, Beaver et al. 2020) and can also be used to derive measurements of the size, mass, and morphology of larger animals. They are especially effective for tracking nocturnal species (Anderson and Gaston 2013, Kays et al. 2019). For ecologically cryptic, small, or wide ranging animals that have historically evaded conventional survey techniques, drones with thermal imaging sensors can also be deployed in places where it has historically been difficult to visually detect species (Karp 2020, Lahoz-Monfort and Magrath 2021). These same techniques have also proven useful for marine species (Johnston 2019). Thermal sensors can be used to capture data related to water stress and other health indicators of plants (Berni et al. 2009), or they can be used to identify thermal refugia for vegetation communities—for example, in wetlands (Watts et al. 2023). They can also be used to detect pollutant sources affecting coastal and freshwater ecosystems (Lega et al. 2012).

Beyond imagery, a promising application is to outfit drones with receivers to help locate radio tagged or collared animals, track wildlife, and assess their surrounding environments (Wilmers et al. 2015). Drones equipped with ultra-high frequency or radio frequency identification technology have demonstrated efficacy in monitoring the movements of large mammals, resulting in considerable cost reductions compared with traditional satellite and ground-based methods of collaring and tracking (Marvin et al. 2016). It should be noted that the effects of the drones themselves on wildlife are largely unknown for most species, but studies on this topic have been increasing (Rebolo-Ifrán et al. 2019, Raoult et al. 2020), and in cases where drones do create a disturbance, researchers are working to minimize those disturbances through best practices and codes of conduct (Hodgson and Koh 2016, Bevan et al. 2018, Weston et al. 2020).

For measuring properties of soil, water, vegetation, and atmosphere directly, drones can be equipped with a range of other nonremote sensors. For instance, weather and climate variables often factor into biological studies, but researchers are often reliant on measurements from a single nearby tower (e.g., from a mesonet; Van der Veer Martens et al. 2017) or must construct their own eddy towers to deploy sensors at the appropriate height and location (Goulden et al. 2006). These types of sensors can instead be affixed to the drone to capture temperature, humidity, pressure, wind speed, wind direction, and many other atmospheric variables across wide areas, giving researchers the flexibility of where in space and time to capture these variables (Frazier et al. 2017). Studies have assessed the precision, bias, and time response of many atmospheric sensors, providing guidance on how and where to attach them to the drone for optimal performance and when to capture data (Barbieri et al. 2019). Similarly, miniature sensors for capturing environmental chemistry measurements, including carbon dioxide, methane, oxygen, and many others, have been tested on drones (Burgués and Marco 2020).

The discussion so far has primarily been focused on variables that are sensed, either remotely (i.e., imagery) or directly (i.e., atmospheric measurements). However, drones can also be used for capturing physical and material samples directly for use in biochemical or metagenomic studies (Johnston 2019, Lally et al. 2019). For example, water sampling devices can be attached to a cable that is lowered when the drone reaches the specified coordinate (Hanlon et al. 2022) to measure real-time water quality parameters, such as temperature, pH, and turbidity (Lally et al. 2019). Coring devices can be affixed to the drone to collect soil or scat samples in place where a drone lands, and sticky paper or flags can be used for insect collection (Robinson et al. 2022). Other examples of physical and material sampling by drones include leaf and stem cutting devices such as the DeLeaves sampling tool (Charron et al. 2020) or the Flying Tree Top Sampler (Käslin et al. 2018), which are being tested to sample tall trees. Airborne, waterproof drones have been engineered to collect whale and dolphin blow, enabling noninvasive sampling for genetic and viral analyses (Geoghegan et al. 2018, Keller and Willke 2019, Raudino et al. 2019). In short, there is massive potential for researchers to think creatively about how drones can stimulate new sampling opportunities and collaborate with other scientists and engineers to design novel, fit-for-purpose sampling devices that can be affixed to a drone.

Interventions

Broadly, interventions are actions that result in changes to the physical environment. Interventions are often initiated to improve a situation or outcome (e.g., reseeding), but they can also have negative impacts such as habitat alteration or disturbances to wildlife. In agriculture, irrigation and fertilizer application are examples of interventions to improve crop yield or quality. In natural landscapes, the removal of invasive species or pests is an example of interventions aimed at restoring ecosystems and services. The use of drones for interventions in the biosciences is lagging behind their use in other phases of the research process, but there are some notable examples and opportunities. For instance, in precision agriculture, drones have been employed for aerial pesticide spraying and fertilizer applications, as well as supplementary pollination (Spoorthi et al. 2017, Broussard et al. 2023). In aquatic environments, they are being proposed as part of an integrated system of robots for invasive species mapping and removal (Mekuria et al. 2021). In the context of ecological restoration, drones have been suggested for seed dispersal (Robinson et al. 2022), and although there are ongoing debates about the efficacy of spreading seeds via drones (Castro et al. 2023), there are examples where these technologies have been successfully used for afforestation and reforestation, especially in areas where the landscape was inaccessible or unsafe for humans (Mohan et al. 2021).

In conservation contexts, drones are being tested as an antipoaching tactic to directly intervene to protect threatened and endangered wildlife (Mulero-Pázmány et al. 2014). A case in Africa used the drone itself as a stimuli to manipulate the movement of endangered white rhinoceros (*Ceratotherium simum*) away from areas where they may be in danger of poaching and toward safer territory (Penny et al. 2019). It was found that the noise produced by drones could resemble a swarm of bees, prompting the animals to change their course away from farms, villages, and poaching hotspots, thereby reducing crop damages while mitigating human–wildlife conflicts (Penny et al. 2019). In that study, the drones were found to be more effective at deterring the animals than were other methods such as sirens, because they were capable of moving with the targeted wildlife and have long transmission ranges.

Drones also offer promise for intervention in animal health through delivering vaccines, larvicides, and pesticides. In the western United States, the US Fish and Wildlife Service and Arizona Game and Fish are using drones to distribute edible vaccine pellets in prairie dog colonies (genus *Cynomys*) to ward off sylvatic plague and, in turn, help protect the critically endangered black-footed ferret (*Mustela nigripes*), which relies on prairie dogs as their primary prey (Fritts 2020). The drones are able to distribute the pellets across larger geographic areas than can be done through manually distribution, and they can do so without the damage to habitat caused by off-road vehicles. Similarly, drones can facilitate interventions to control zoonotic and vector-borne diseases such as malaria, dengue fever, and Zika virus by releasing sterile insects or delivering larvicides and insecticides (Mechan et al. 2023). An indirect benefit of using drones for this type of delivery is minimizing human exposure to these chemicals and using precision GPS to minimize off-target applications, promoting sustainable pest and pathogen management practices.

Monitoring and surveillance

One of the most promising uses of drones in field research is for automated monitoring to detect and measure landscape changes over time while also permitting timely responses and interventions if needed (Baena et al. 2018). Long-term data also provide important insights into climate change and complex ecological systems. Regular monitoring is valuable for a range of ecosystem functions (Lindenmayer and Likens 2010), including tracking ecosystem restoration, assessing agricultural evolution, catching illicit deforestation, mitigating human–wildlife conflicts, and understanding ecosystem resilience and recovery, among others. Ideally, longer-term monitoring tasks can be automated to increase efficiency and reduce human labor costs. Although the potential exists for drones to be used for real-time environmental monitoring, existing applications have largely consisted of single data collection events (Singh et al. 2024), and their use for longer-term or regular monitoring is limited (Zhang et al. 2016). In the present article, we provide examples of how drones can be leveraged for regular monitoring and surveillance.

Restoration sites are particularly well suited for drone monitoring, because they are typically small in size, are often characterized by a fine-scale mosaic of different habitat patches (Woellner and Wagner 2019), and usually have a clear observation objective (e.g., seedling establishment). Monitoring for restoration can involve evaluating the outcomes of interventions or assessing ecological threats (Robinson et al. 2022). Drones equipped with multispectral sensors or live cameras are valuable for both pre- and postrestoration monitoring, particularly in assessing plant health to understand the baseline ecological status, as well as ecological responses to restoration interventions (Robinson et al. 2022). These assessments provide crucial insights into stressors such as disease or chemical exposure, aiding restoration planning by capturing plant responses effectively and providing insights into the efficacy of different restoration strategies. Underwater monitoring is also being facilitated by the use of fluid lensing technology on aerial drones to sense objects below the water surface, such as coral reefs (Chirayath and Earle 2016).

Given their flexibility for on-demand deployment, drones can be used for regular surveillance of protected areas or vulnerable ecosystems to monitor key species or illicit activities (Koh and Wich 2012, Jiménez López and Mulero-Pázmány 2019). Antipoaching surveillance tasks have traditionally been done by rangers in person and require lots of time, vehicle mileage, and fuel (Mulero-Pázmány et al. 2014). Drones can be flown regularly to supplant some of those costs and monitor signs of illicit activity or security signals such as breached fences. In marine environments, they can be used to monitor fishing vessels, providing critical data for enforcement against illegal fishing operations (Toonen and Bush 2020). First-person view capabilities can be leveraged for enforcement to identify violators or intervene when suspicious behavior is detected. In forested ecosystems, drones have the potential to be used for long-term monitoring to overcome the high costs, spatial site biases, and data gaps that often characterize *in situ* monitoring (Zhang et al. 2016). Drones have been proposed for community-based forest surveillance programs to monitor deforestation and degradation locally (Paneque-Gálvez et al. 2014), and drones are being introduced to indigenous communities to monitor agriculture productivity, aboveground biomass, and carbon sequestration potential on vulnerable lands (Cummings et al. 2017). These programs have the added benefit of putting control of the data directly into the hands of those stewarding the land and strengthening local decision-making.

Drones offer a promising solution for monitoring human–wildlife conflicts, which often occur in close proximity to human settlements. Obtaining information on feeding frequency, foraging patterns, and habitat use by large mammals and wildlife of management concern via drones can enable informed management strategies, particularly in areas with high human–wildlife interactions (Yang et al. 2023). This proactive approach allows for early detection of wildlife presence in areas frequented by humans, enabling timely intervention or warning systems to be implemented, thereby reducing the risk of encounters and enhancing safety for both humans and wildlife.

In the atmospheric sciences, researchers are working to develop a 3D mesonet concept, in which a coordinated network of drones could be deployed to automatically capture measurements of temperature, humidity, carbon dioxide, and other variables at regular, designated intervals (Chilson et al. 2019). This concept, in which the drones are nested at a docking station, could be extended to the FLUXNET (i.e., a global network of micrometeorological tower sites) network of eddy covariance towers (Baldocchi et al. 2001) to extend those measurements of the energy exchanges between the biosphere and the atmosphere at more dense spatial locations via drones. The drones would carry similar instrumentation as the tower and would be programmed to go on regular data collection missions to key locations around the tower. A fleet of drones could be docked at an existing FLUXNET tower, which could serve as a ground station from which drones can be launched, recovered, and recharged with minimal human intervention and where other digital infrastructure could allow the data to be uploaded automatically to the cloud for dissemination.

Future innovations needed to optimize drones in field research

Although there are many places where drones can be leveraged more effectively in field-based research activities, there are also areas that are currently ripe for innovation to optimize the effectiveness of drones for these purposes. We envision three areas of progress that could help harness their full potential, including specialized open-source software that is fit for purpose, customized instrumentation, integration with existing online databases that leverage artificial intelligence and machine learning, and enhanced community science initiatives (figure 2). In some cases, the technology needed to move science forward already exists but is commercialized and beyond the price point for most academics. In other cases, novel inventions are needed to push the boundaries of the uses of these tools in the biosciences.

There is a growing need for specialized hardware and open-source software that is engineered to be compatible with drone electronics and tailored to field applications beyond image collection. For instance, drones equipped with telemetry systems have been developed that can automatically locate and track wildlife that have been tagged with radio collars (https://wildlifedrones.net). These systems are valuable, but the technology is proprietary and often prohibitively expensive for research purposes. Similarly, drone systems exist for distributing seeds for agriculture or restoration projects and releasing biocontrol agents to mitigate pest infestations or control invasive species, but open-source versions have not yet been released. In terms of software, the development of smartphone applications that interface with drone hardware to facilitate real-time data collection could advance all types of sampling. These applications could ideally enable the measurement of variables in preprogrammed locations or carry out a predetermined experimental design. By integrating expertise across disciplines, these applications could also facilitate spatial planning to ensure appropriate geographic representation of sampling locations, depths, heights, or timeframes. Such applications could also integrate data management systems for real-time analysis and reporting, further aiding in the comprehensive assessment of environmental conditions.

Most of the small drones being used in research have limited payload capacity and, therefore, require specialized, lightweight, miniaturized equipment. Sampling equipment for drones is in its infancy, and there is still a need to create instruments that can be integrated into drone payloads to receive commands to deploy remotely from the ground control station. Developing universal mounting platforms that can support interchangeable sensors and instruments (e.g., water and soil sample collecting harnesses) and connect to multiple types of drones will enhance modularity, helping to keep costs down and barriers to use low. Incorporating open-source hardware designs (e.g., through 3D printing) can further empower researchers to tailor their drone configurations to specific survey needs. In addition, innovating drone technology to include adaptations for environmental applications—such as improvements that mitigate acoustic disturbance through quieter

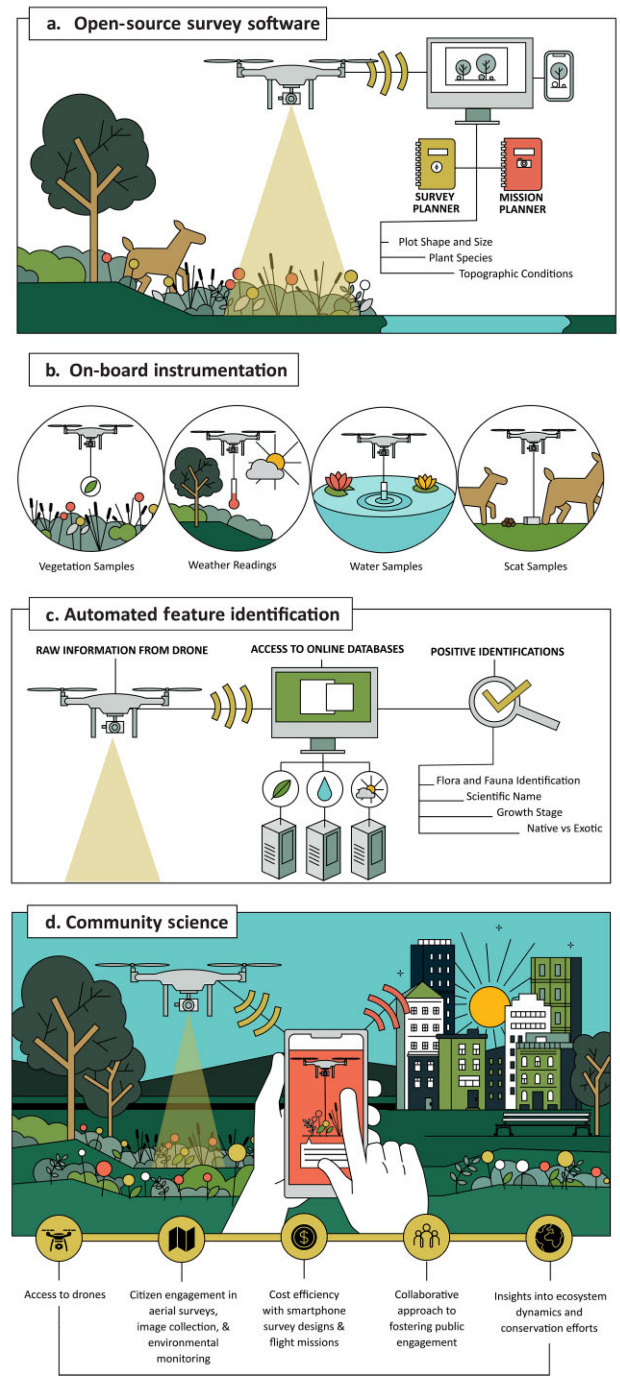

Figure 2. The key innovations needed to advance drone-based field research include (a) the development of open-source software compatible with drone onboard electronics for diverse field applications beyond image collection; (b) the production of lightweight, miniaturized equipment that can be integrated into drone payloads using universal mounting platforms, facilitating ground sample collection (e.g., vegetation, water, weather conditions, and scat); (c) the integration of species recognition applications with drone-mounted cameras for real-time and automated species identification; and (d) enhanced engagement of community scientists in drone-based data collection to enhance public participation in scientific research and environmental monitoring while minimizing costs.

or brushless motors, advanced propeller designs, and more compact configurations—could foster their use in sensitive habitats. Targeted, species-specific studies to better understand the impact of drones on wildlife behavior will be needed to guide these types of innovations.

A plethora of online databases and smartphone applications exist to identify species (e.g., iNaturalist, eBird, iMapInvasives) that could be integrated with drone sensors and software to consolidate data collection and interpretation tasks. For example, AI and machine-learning algorithms trained on those open databases could be used to automatically detect species in the images captured by drone mounted cameras, allowing researchers to immediately identify whether a site contained certain rare, endangered, or invasive species. Along with this type of on the fly automated object identification, functionality within these apps could automatically compute plant morphological characteristics, such as tree height, canopy architecture, or leaf arrangement, further advancing rapid insights into ecosystem structure and health.

Engaging community scientists in data collection tasks empowers communities to contribute to scientific endeavors while minimizing research costs associated with field surveys (Kobori et al. 2016). Drones offer a versatile platform for community science projects, enabling volunteers to participate in aerial surveys, image collection, and environmental monitoring activities (Pucino et al. 2021). Providing preprogrammed survey designs and flight mission details could enhance the accessibility and participation of science enthusiasts in drone-based data collection efforts. This type of collaborative approach fosters public engagement in scientific inquiry, promotes environmental stewardship, and facilitates the generation of valuable insights into ecosystem dynamics and conservation efforts.

Challenges and solutions for integrating drones into bioscience research

Although drones hold significant promise for advancing bioscience research, there are constraints. High platform and software costs remain a barrier, especially in low-income nations with limited access to advanced technologies. Lower cost options have been suggested for conservation (Koh and Wich 2012), including building platforms from parts together with local partners (Cummings et al. 2017), which can also help build trust in the technology. Blueprints for drone construction are publicly accessible (Lim et al. 2012), and open-source development platforms often provide flexible and modular frameworks that allow interchangeable parts, such as battery packs, motors, or sensors, thereby extending the operational lifespan and lowering long-term maintenance costs. Recycling and repurposing components from older drone systems or other electronics can also reduce material costs and resource demands. Finally, cross-disciplinary partnerships with engineering and technology-focused research groups can facilitate the development of low-cost prototypes tailored to bioscience applications. For example, innovations such as 3D-printed drone components or lightweight carbon fiber structures could significantly reduce production costs without compromising drone performance.

We also suggest building collaborative funding models and partnerships among academic institutions, governmental agencies, nonprofit organizations, and the aviation industry across both the Global North and South to mitigate the financial barriers. Funding mechanisms for international biodiversity conservation, such as those mediated through the United Nations, World Bank, or regional development banks, could play a pivotal role in subsidizing costs for low-income nations. Industrial sponsorship and grant programs focused on technology transfer can further reduce financial burdens. Such initiatives represent strategic investments in the for-profit sector, because they open new markets for drone technology, particularly in emerging economies and research-focused applications.

Another challenge limiting who is able to partake in drone work is training not only for pilots but also for building the requisite skills for data processing and analyses (Frazier and Singh 2021). To that end, universities and research institutions can establish cost-effective drone training programs tailored to regional needs, incorporating hands-on instruction focused on bioscience applications. These programs can be embedded within existing curricula or offered as nontraditional learning opportunities. Open educational resources, such as online courses and instructional videos (Cañas et al. 2020), can further enhance accessibility by covering both the technical aspects of drone operation and best practices for bioscience research—benefiting researchers in resource-limited settings. Cross-disciplinary partnerships with engineering, computer science, and data science departments can again bridge knowledge gaps, fostering a comprehensive understanding of drone technology. This approach ensures that researchers gain the necessary skills to effectively integrate drones into their studies and advance bioscience applications.

From a regulatory perspective, strict operational or airspace laws can pose significant hurdles, particularly in politically fragmented or sensitive areas (Floreano and Wood 2015). Even in protected areas, drone use may conflict with stewardship mandates aimed at minimizing human activities. Researchers can advocate for region-specific drone regulations that balance research needs with safety concerns. Public–private partnerships, such as automated drone traffic management systems, could lower the regulatory barriers by streamlining flight permission processes in restricted areas, especially in urban and conservation settings. Employing geofencing technology that automatically restricts drone operations to sensitive areas (e.g., Boselli et al. 2017) could help mitigate regulatory concerns and without compromising compliance.

From an operational perspective, the challenges related to different platform designs, including maneuverability, power, endurance, actuation, control, and sensing systems have been well documented (Floreano and Wood 2015, Duffy et al. 2018), as have the challenges of flying in different and challenging environments (Duffy et al. 2018). Improvements in battery technology, such as the use of lithium–sulfur batteries or solar-powered drones, could extend flight times and operational range. Developing lighter, more efficient sensors or modular payload systems that can be interchanged depending on the specific research needs could help drones carry a broader range of instruments without compromising flight time. Extrinsic conditions such as weather, high winds, rain, and reduced visibility can adversely affect drone performance, flight schedules, and data quality, thereby restricting operational timeframes (Gao et al. 2021, Frazier 2022). Complex and challenging terrains may necessitate multiple drone flights or the use of multidrone swarms, which increase operational complexity (Floreano and Wood 2015, Duffy et al. 2018) but allow researchers to cover larger areas, which would be beneficial for large-scale studies or monitoring remote ecosystems. Finally, privacy concerns and public perception can lead to resistance or opposition to drone use, highlighting the importance of proactive stakeholder engagement and transparent communication to address these concerns and facilitate smooth operational deployment (Altawy and Youssef 2017).

Conclusions

Drones offer tremendous potential for overcoming many of the limitations of traditional field-based research in the biological sciences. Although they have been widely used for image acquisition, they remain underused in other aspects of the research lifecycle. We argue for expanding their use in four parts of the research lifecycle where they can transform field activities related to site reconnaissance and systematic data collection to interventions and long-term monitoring. By integrating them into these workflows, researchers can mitigate logistical challenges, enhance safety, and reduce the environmental footprint of research activities while also crafting reproducible and scalable protocols for scientifically rigorous data collection. However, to fully leverage their full potential, further development of specialized open-source software, miniaturized instrumentation, and community science initiatives will be essential. Engaging interdisciplinary collaborations to create tailored drone technologies will enhance their utility and accessibility in field research. We also recognize that widespread adoption still faces challenges such as access to equipment, technical, or skill limitations; regulatory constraints; and even privacy concerns. Continuing to push the boundaries of how these systems can be used in research and development while also balancing associated ethical and societal concerns will also help the field advance and address critical, global-scale environmental challenges. Although drone technology offers significant potential for advancing bioscience research, its widespread adoption faces challenges, including high costs, time-intensive training for technical expertise, and strict airspace regulations. Operational issues such as adverse weather, limited battery life, complex data processing, and public resistance further constrain drone use, particularly in sensitive or restricted areas. Overcoming these limitations requires cost-effective solutions, regulatory navigation, technical advancements, and proactive stakeholder engagement to address environmental and logistical barriers.

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Data availability

No data were used or produced in the development of this manuscript.

Author contributions

Thilina D. Surasinghe (Conceptualization, Funding acquisition, Investigation, Writing - original draft, Writing - review & editing), Kunwar K. Singh (Conceptualization, Funding acquisition, Investigation, Writing - original draft, Writing - review & editing), and Amy E. Frazier (Conceptualization, Funding acquisition, Investigation, Writing - original draft, Writing - review & editing).

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