Millner, N, Cunliff, AM, Mulero-Pázmány, M, Newport, B, Sandbrook, C and Wich, S

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Special Collection: Drone Ecologies

RESEARCH ARTICLE

Exploring the opportunities and risks of aerial monitoring for biodiversity conservation

Naomi Millner, naomi.millner@bristol.ac.uk
University of Bristol, UK

Andrew M. Cunliffe, a.cunliffe@exeter.ac.uk
University of Exeter, UK

Margarita Mulero-Pázmány, muleromara@hotmail.com
University of Málaga, Spain

Ben Newport, ben.newport@bristol.ac.uk
University of Bristol, UK

Chris Sandbrook, cgsandbrook@gmail.com
University of Málaga, Spain

Serge Wich, s.a.wich@ljmu.ac.uk
Liverpool John Moores University, UK

Drones are unoccupied aerial systems (UAS) whose technology has evolved rapidly over the past 15 years. Increasingly used in conservation to manage and monitor biodiversity, drones offer rich capabilities to observe in difficult terrain, have relatively affordable hardware costs and are likely to continue to proliferate rapidly in the years ahead. Drones are useful for tasks as diverse as monitoring wildlife poaching and illegal timber extraction, managing ecotourism and disaster responses, and tracking the regeneration or degradation of forests, and offer potential for more specialised tasks as their sensory payloads are developed. However, although associated technical issues and applications have been explored in wide-ranging ways within conservation science, there has been relatively little social-scientific engagement with drones to date. This leaves a gap surrounding the potential social benefits and risks of drones, as well as in interdisciplinary conversations. This introduction is the first of four papers under the heading 'Drone ecologies', building on an interdisciplinary workshop held under the same name at the University of Bristol in July 2021. Expanding from the plenary dialogues that opened this workshop, this introduction explores what interdisciplinary perspectives on drones can offer in addressing global social and ecological challenges, drawing on expertise from the fields of conservation biology, human and physical geography, rainforest ecology and environmental systems. Setting out the aims of the overall special collection, we review here the ways that drones are being used, and might be used, in biodiversity conservation, setting out important considerations to minimise risks of inadvertent harms.

Key words drones • biodiversity conservation • interdisciplinarity • monitoring technologies • digital governance

Key messages

- This paper opens the special collection 'Drones Ecologies', justifying the approach and introducing the theme.
- The paper argues for the importance of interdisciplinary perspectives on using drones in biodiversity conservation, which, until now, have been treated either in technical terms or in association with surveillance concerns.
- Drones present new opportunities to tackle global social and ecological challenges, including biodiversity loss and democratising conservation governance.
- Guidelines drawing on interdisciplinary perspectives are needed to mitigate potential harms to people and wildlife and ensure best practice.

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Introduction

Understanding the factors behind the current biodiversity loss crisis is an urgent task (Dirzo and Raven, 2003; Barnosky et al, 2011). Anthropogenic drivers of species extinction include habitat loss and fragmentation, pollution, invasive species, over exploitation of resources and climate change (Valiente-Banuet et al, 2015). Meeting global targets for reducing the harms of these drivers has prompted the development and adoption of new geospatial technologies to monitor biodiversity in habitats as diverse as forests and oceans (Adams, 2019). Considering how technologies like drones and Geographic Information System (GIS) mapping can be deployed is therefore vital for supporting efforts to meeting grand challenges of planetary environmental crisis, and to achieve more balanced human–environment relations. Within this special collection on Drone Ecologies, we focus on understanding the complexities, possibilities and limitations of drone use for biodiversity conservation within this broader context.

The incorporation of new technologies into everyday conservation also prompts important social and political debates. Technologies like drones, associated with surveillance practices, raise questions of safety, privacy, data security and power relations more broadly, but specifically in arenas of conservation practice (Sandbrook, 2015). Drones – also known as an unoccupied aerial system (UAS)[1] – can be useful to detect activities such as poaching or illegal logging, providing support to rangers in protected areas (Mulero-Pázmány et al, 2014). Yet the use of such technologies in conservation areas may amplify existing dynamics of fear, mistrust or conflict, or even be used to (unjustly) criminalise minority ethnic groups (Massé, 2018; Millner, 2020). On the other hand, rural and Indigenous communities have begun using drones as part of community-led conservation, and to protect communal land rights by producing evidence of incursions on their lands (Vargas-Ramírez and Paneque-Gálvez, 2019). In short, drones can alter the balance of power in meaningful ways and their incorporation into everyday conservation activities requires critical attention. This special collection opens interdisciplinary dialogue around the use of drones in biodiversity conservation in these terms, tempering fresh understanding of the capacities of drones with rigorous engagement with the risks and wider contexts of their use. Through such dialogues we aspire to optimise the use of drones to help address the major environmental challenges associated with biodiversity conservation while avoiding worsening global social challenges, including those concerning conflict and governance.

The authors involved in this special collection met virtually during the COVID-19 pandemic to begin this dialogue in a two-day interdisciplinary workshop called *Drone Ecologies: Exploring the Opportunities and Risks of Aerial Monitoring for Biodiversity Conservation* (July 2021). Funded by a British Academy / Leverhulme small grant, the event brought together 60 scientists from engineering, geography, anthropology, the arts, ecology and beyond, as well as technicians and strategists from non-governmental organisations (NGOs; see Amador et al, 2021 for a report). The premise of the meeting, consisting in plenaries, paper panels and roundtable discussions, was that the full potential of drones and associated sensors for conservation cannot be reached without inter- and transdisciplinary conversations, which, in turn, allow consideration of both the risks and the opportunities associated with these technologies. Because of their experience in distinct disciplinary contexts, participants were able to explore experiences from different perspectives. We discussed how drones can affect wildlife, especially birds, as well as human communities, and, if they are not introduced with sensitivity to ongoing social relations, may amplify existing forms of conflict. The social scientists in our workshop emphasised the importance of 'risk assessing' data flows to prevent conservation becoming unwittingly annexed to agendas of militarisation or securitisation. Biophysical scientists were able to complement these concerns with updates on recent efforts to improve and enhance open data science agendas.[2] Together, we noted the need for greater attention to possible risks and mitigation strategies in these open data efforts. These conversations inform what we call 'Drone Ecologies' within this special collection of papers: the wider arenas of best practice, limitations, social and political implications, and ethics that surround the use of drones within diversity conservation and environmental management.

The four papers of this special collection and the associated policy briefing [https://www.cifor-icraf.org/knowledge/publication/8851/] arose from the rich exchange of knowledge from the event. Through these collaborative, interdisciplinary contributions, we seek to avoid the general suspicion of drones that has been fostered within the social sciences through critiques of excessive policing and drone-based warfare, at the same time as recognising the value of empirical work in the social sciences for guiding future uses of drones. It is vital that communities living in areas where drones are used are properly informed and have influence over and access to the data produced, given the potential for drones to be used covertly or for surveillance purposes. On the other hand, because drones are relatively cheap to produce and easy to use, they can be vital tools to leverage spatial authority over land access and ownership (Paneque-Gálvez et al, 2014; Radjawali et al, 2017). As such they offer rich potential for the democratisation of data production, potentially countering new forms of dispossession associated with some conservation approaches and politico-security applications.

The authors of this introduction have all worked on questions of drone use in biodiversity conservation for some years. Authors Naomi Millner and Chris Sandbrook are human geographers who research the political ecologies of conservation with a focus on conflict and conservation technologies. Ben Newport is a geographer examining the role of accessible technologies, such as drones, in community-based forest management from an interdisciplinary perspective. Andrew Cunliffe is a physical geographer who uses drones extensively to understand predominantly non-forest terrestrial ecosystems and inform their management for wider societal benefit. Margarita Mulero-Pázmány is a conservation biologist focused on using new technologies for spatial ecology and biodiversity research, and Serge Wich is a biologist who focuses on primate behavioural ecology and conservation for which he increasingly uses conservation technologies. To open this special collection, we integrate our perspectives on conservation gleaned through our empirical and practical experience of wildlife conservation in forest, drylands, marshlands and high latitude tundra, in contexts including Europe, Latin America, North America, Eastern and Southern Africa, and South-East Asia.

In this paper, which also acts as an introduction to the special collection, we synthesise key insights emerging from our interdisciplinary dialogues. In doing so, we make the argument that social, political, ecological and technological understandings of biodiversity conservation *cannot be separated*. If geospatial technologies are to play an important role in future monitoring and conservation governance practices, then interdisciplinary spaces of exchange and collaboration are also vital. Specifically, the sociopolitical implications of technologies like drones cannot be predicted with any accuracy without a deep understanding of *what drones can do* in ecological and technical terms. Without this understanding, presumptions, and stereotypes about the (mis)use of drones, will continue to dominate social-scientific analysis. On the other hand, social and political analysis of the use of drones is vital for appreciating the ways that geospatial technologies interact with *contexts*, especially in terms of governance (who makes the rules and how spaces are ordered) and conflict (how and when conservation initiatives interact with existing forms of violence and mistrust). Incorporating insights from the social sciences will enable ecological interventions to address wider social challenges such as social exclusion and conflicts over access to resources.

We therefore focus here on informing best practice use of drones in biodiversity conservation towards democratic governance and conflict reduction. We set the use of drones in relation to other geospatial technologies, emphasising what can be done to ensure they are used to meet biodiversity challenges, but not abused or incorporated into undesirable new forms of control. The remainder of this introduction is structured as follows. In the next section we explore the technical specificities of drones in the context of the history of their application, and the requirements of several conservation scenarios. Next, we turn to the impacts on wildlife and important considerations relevant for using drones to meet the social and ecological challenges already described. This leads to the social and political implications of drones, which are summarised here and described in more detail by the other three papers in this special collection. To conclude we argue for the importance of interdisciplinary collaborations in future research to ensure that technical, social-scientific, ecological/biological and context-specific expertise informs cutting-edge and also socially informed conservation practices.

Drones and other geospatial technologies in biodiversity conservation

The emergence of drones in biodiversity conservation

Since its beginning in the late twentieth century, biodiversity monitoring has become an increasingly central aspect of conservation. Its major aim is to determine the richness, abundance and spatial distribution of species and how these vary over time so that conservation management can incorporate such information. During its history, biodiversity monitoring has incorporated a range of technologies to drive down costs of monitoring, get more accurate data and obtain observations over larger extents. Today, observation science relies on a variety of instruments and techniques to collect and analyse biodiversity data, including devices such as camera traps, bioacoustic sensors, drones, satellite and radio transmitters, software platforms, computing resources, algorithms and biotechnology methods that are collectively referred to as 'conservation technologies' (Lahoz-Monfort et al, 2019; Wich and Piel, 2021). Some of these technologies, such as camera traps, have been used for many years, but others are much more recent. Notably, since around 2008–10, drones have become popular for monitoring vegetation, animals and habitat, in part because they can gather fine spatio-temporal resolution information at relatively affordable effort and hardware costs[3] (Koh and Wich, 2012; Jiménez López and Mulero-Pázmány, 2019). Being smaller and quieter than fixed-wing aircraft or helicopters, which can also be used in surveying, drones can be used for conservation activities including counting of megafauna species and mapping of vegetation or forest cover. Meanwhile, because they can be used to navigate spaces normally inaccessible by ground and produce images far more detailed than satellite imaging, drones are transforming the monitoring and decision-making processes of everyday conservation. Complex forms of GIS mapping were mainstay monitoring technologies of conservation organisations until this point, but its tools are expensive, require a high degree of specialist knowledge, and cannot provide fine resolution of images of wildlife or vegetation. Drones offer complementary ways to revolutionise conservation monitoring and inform better decision making in biodiverse landscapes (Anderson and Gaston, 2013). While technical expertise limits the application of these options, drones are rapidly transforming the governance of biodiversity conservation globally.

The use of all these technologies nevertheless raises concerns, both in socio-scientific terms and in terms of the impact on wider ecologies. Many conservation technologies are installed or used *mainly* in nature-only scenarios (such as camera traps, acoustic sensors and drones), gathering images and sounds with the purpose of collecting information about wildlife. However, it can be difficult to implement such technologies without affecting other species – or accidentally involving humans (Sandbrook et al, 2018). This raises concerns around accidental or even deliberate surveillance, privacy concerns, and the potential to appropriate conservation technologies to intimidate or police communities. There are, additionally, safety elements to consider for those being observed by the drones (harassment, persecution and so on) *and* those using them (for example, intimidation by actors who do not want to be observed – see Paneque-Gálvez et al, 2017). There are therefore important reasons to consider carefully how and where drone technologies are implemented.

A drone is an airborne vehicle without an onboard pilot, primarily used to carry cameras and other sensors (Chabot et al, 2022). At the simplest level, a drone comprises a few fundamental components: an airframe; a power source and motor; a ground control station; and a few essential sensors, such as a global navigation satellite system (GNSS) receiver.[4] They can be piloted manually from the ground or via an autopilot and flight planning software. Drone technologies have existed for slightly more than a century and were initially developed for military purposes – the first pilotless vehicles were trialled during the First World War, using radio-control technologies (Keane and Carr, 2013). In the 21st century, however, the technology has become more available for non-military purposes, seeing adaptations for biodiversity monitoring, aerial photography and academic research.

In the early days of conservation drones, drones were mainly self-built by radio-control plane hobbyists, engineers and engineering-oriented conservationists but, more recently, off-the-shelf fixed-wing and multirotor systems have become widely available and are now much more commonly used. These drones differ significantly from military drones and evolved separately from them, being sophisticated radio-control planes that are smaller and lighter than military machines. Their small size mean that such drones are relatively cheap to purchase, maintain and repair; models used in conservation typically cost between £400 and £15,000, compared to military-grade drones which can cost tens of millions of pounds sterling. Despite these differences, a military association with drones is retained in some parts of the world, especially where aerial surveillance is already being employed by state security or military actors. Contributing to this is the deployment of civilian drones by military and law enforcement agencies across the globe (Enemark, 2021; Kesteloo, 2022), blurring these distinctions.

The development of drone technologies for biodiversity monitoring has led to a marked increase in the quality and type of sensors, both to well-resourced scientific research teams and to conservation and community organisations. These developments include the innovation of cameras that sample more specific sections of the electromagnetic spectrum, making it easier to differentiate between subjects such as different plants or animals (Assmann et al, 2018; 2020). There have even been studies using microphones to record soundscapes to understand the biological composition of different ecosystems (Frouin-Mouy et al, 2020). Such technical advances enable the pursuit of ever more creative lines of biological and ecological inquiry. For example, drones are being used to collect exhaled breath condensate from whales on a petri dish for genetic analysis to determine family relationships and health (Pirotta et al, 2017; Wolinsky, 2017) and to capture flying insects for entomological research (Mulero-Pázmány et al, 2022).

Understanding the limitations of drones

Drones are clearly useful tools for biodiversity monitoring, whose tasks are likely to multiply in the future. Nevertheless, it is important to be realistic about their constraints, both in technical and in sociopolitical terms. A common misconception lies in the definition of the extent of the areas drones can map. Mapping areas depend on the flight duration and flying height above ground level for all types of drones. For a flying time of 90 minutes (the upper limit of flight times of fixed-wing drones that conservationists use) the area that can be mapped with about 1.5 cm of spatial resolution will be about 500 ha,[5] and, within our experience, extends only to mapping up to 800 ha in a single day. It is thus important to realise that drones are not usually the best tool to map conservation areas of hundreds or thousands of square kilometres, although they can be useful in multiscale remote sensing frameworks to help inform appropriate interpretation of coarser scale satellite imagery (Assmann et al, 2020).

Another potential misconception is that drone surveys will be less costly than other methods. While this might be correct in some situations (Mesquita et al, 2020) it is essential to carefully consider the total costs of a survey and not only the hardware aspect. Drones are very effective at collecting large amounts of data in relatively short time periods, which can then be used for further analyses such as counting wildlife. However, given the large quantities of data acquired from even short flights, processing and analysis costs quickly accumulate. This can make drone-based surveys more expensive than surveys in which observers directly count animals. In addition, drone data collection and analysis often require specialist skill sets and software in order to derive the insights from the data to support conservation management. It is therefore essential to carefully think through complete workflows before starting to use drones (Cunliffe et al, 2022). It is also important to understand that there are important geographical disparities in terms of access to drone hardware, including spare parts, as well as the available skill-base for drone flying, drone maintenance, data collection, data processing and deriving insights from those that are useful for conservation. These access disparities were exemplified by the geographic range of those able participate in a recent global study of vegetation using drones (Cunliffe et al, 2022): despite discussions with hundreds of drone users in a study prioritising under-represented areas, contributing participants were still overwhelmingly from Europe and North America. These inequalities of access are of concern for the scalability of the technology for biodiversity monitoring and conservation management support, as for perpetuating biases in how different regions are represented in collections of scientific information.

Additionally, even though there are ever more drone data sets available for biodiversity monitoring, several technical constraints hamper their usage. First, there is a lack of user-friendly open-source software or web platforms for data processing. This ranges from computer vision to detect objects[6] to the processing of images to point clouds and orthomosaics.[7] Second, there are no established metadata standards to facilitate sharing drone data and make them usable for other users. Platforms like GeoNadir[8] help in this sense but could be developed much further. Third, we know that the downstream products and interpretations from drone surveys are sensitive to how data are (1) collected, (2) processed and (3) analysed, which hinders intercomparisons between surveys. While there have been some efforts to standardise protocols (for example, Cunliffe et al, 2022), more progress is needed to adopt common practice in user communities.

Because of such limitations, other geospatial technologies may be selected in place of drones, or their use may be discontinued after an initial trial period. For example, in Kruger National Park, South Africa, drones were employed for anti-poaching activities, but after a year-long trial period, no hunting parties had been detected (Massé, 2018). It was concluded that drones did not have the 'requisite payload needed for infra-red and thermal sensors or cameras that are necessary to […] detect people' (Massé, 2018: 62). It is important to recognise that, in many cases, drones cannot accomplish the tasks imagined for them. Meanwhile, beyond technical limitations, using drones in biodiversity conservation poses risks to drone users, wildlife, ecological flora and local communities. Table 1 presents a broad summary of these risks, drawing from our respective disciplinary perspectives and experiences. What is clear is that the concept of risk itself is differently conceptualised and assessed in different disciplines. Considering the different disciplinary emphases together is useful, however, showing 'hidden' risks that may be missed when one is looking primarily at human (or non-human) responses. Indeed, as Massé goes on to emphasise, we might even consider that the 'failure' of drones to detect illegal activities in the Kruger case points us away from large scale anti-poaching activities (which tend to abstract communities and deal with very large areas) and towards more 'community conservation' approaches that can incorporate attention to specific dynamics of exclusion and conflict.

The policy briefing linked with this special collection [https://www.cifor-icraf.org/knowledge/publication/8851/] attempts to synthesise these different risk areas in relation, leading to clear recommendations for reducing risks to all parties, including drone users themselves. Meanwhile, the following two sections unpack these risks in relation to wildlife and fauna, and to local communities.

Table 1: An interdisciplinary assessment of possible harms arising from drone use. Drone operators typically consider just one or two dimensions of 'risk', with inadequate consideration of the less obvious indirect interactions that potentially lead to harm

	Groups at risk			
Risk category	**Drone operators**	**Fauna**	**Flora**	**Local communities / bystanders**
Noise	Limited	Metabolic rates Behavioural	N/A	Nuisance or worse (intrusive)
Ecological disturbance	N/A	Risk of disturbed behaviours in protected areas	Disturbed ground, especially in repeat survey areas	N/A
Physical crashing	Risk of bodily harm	Fire risk (especially in arid areas)	Fire risk (especially in arid areas)	Generally limited risk to individuals (depending on context, but fire risk may apply)
Privacy	Limited	Accidental disclosure of precise location of threatened species at risk from poaching	Accidental disclosure of precise location of threatened species at risk from poaching	Images taken of individuals or their property Risk of perpetuating power imbalances
Reinforce conflict or social exclusion	Risk of physical threats in conflict areas, drug-trafficking zones, or if purpose misunderstood	N/A	N/A	Use of drones may increase fear or suspicion, especially if local people not consulted If data passed to state agencies, minorities may be falsely targeted

Impacts of using drones for wildlife and conservation ecologiesThe expansion of the professional and personal use of drones, often in areas of high biodiversity and flying at low altitudes, makes these small aircraft a new potential anthropogenic disturbance susceptible to impact local wildlife (Mulero-Pázmány et al, 2017). The effects caused by drones on animals can be compared with anti-predatory responses and are often like those produced by other stimuli such as predators, people or vehicles they perceive as a risk. Behaviourally, animals generally respond with vigilance, alert, alarm, fleeing responses or aggressive behaviour. In the long term, animals constantly exposed to disturbance may then either suffer from stress, potentially affecting reproductive success and causing space-use changes, or eventually become habituated to it (Tablado and Jenni, 2015). There is a growing body of literature assessing the effects of drone flights on animals, and the main factors associated with the type and intensity of response or lack thereof – are animal species, drone attributes and flight characteristics.

Animal species

Drone disturbance has been documented for several taxonomic groups inhabiting both terrestrial and aquatic habitats. Most studies assessing drone impact on wildlife are focused on birds, as interaction is more likely to take place in aerial environments. Different bird species groups have been reported to react to drone overflights in different ways, depending on the drone attributes and how the flights are performed. For example, penguins exposed to drones reacted with vigilance behaviour (Rümmler et al, 2016); seabirds raised alarm calls and showed flush behaviour (Brisson-Curadeau et al, 2017); Australian magpies showed aggressive reactions (Lyons et al, 2017); adult crows performed alarm calls and aggressive behaviour (Weissensteiner et al, 2015); and several seabird and waterfowl species exposed to drone flights did not show any observable responses (Weissensteiner et al, 2015; McEvoy et al, 2016; Brisson-Curadeau et al, 2017; Lyons et al, 2017). Terrestrial mammals such as bears reacted to close distance drone approaches with an increased heart rate (Ditmer et al, 2015); elephants showed fleeing responses (Hahn et al, 2016); and Tibetan antelopes and African rhinoceros did not show observable reactions when exposed to drone overflights (Mulero-Pázmány et al, 2014; Hu et al, 2018). Marine mammals such as killer and bowhead whales seemed undisturbed by drone flights (Durban et al, 2015; Koski et al, 2015); dolphins changed their behaviour with decreasing drone altitude (Giles et al, 2021); manatees fled the area when drones approached (Ramos et al, 2018); and seals showed nervous behaviour and moved to the water while being overflown (Pomeroy et al, 2015). Reptiles' reactions to drones have been less studied than for other animal groups but species such as turtles have not shown responses while crocodiles responded to drone approaches with head movements, fleeing or complete submergence (Bevan et al, 2018).

Animal-specific characteristics, such as age, reproductive status and level of aggregation – as well as historical experience of interaction with drones – have also been shown to influence animals' responses to drones (Tablado and Jenni, 2015). For example, king penguin adults incubating their young showed little signs of stress against drone approaches, while non-breeding adults and fledglings exhibited strong responses (Weimerskirch et al, 2018). Giles et al (2021) found that bottlenose dolphins' group size inversely increased the probability of behavioural changes during drone flights while Ramos et al (2018) found that these responded more to drones when they were alone or in small groups.

Drone attributes

Physical properties of drone models can affect wildlife in different ways. McEvoy et al (2016) tested various drone shapes and sizes including fixed and rotary wing models, finding that delta-wing design caused the greatest level of disturbance when it approached birds, probably because this silhouette resembles a larger raptor, while multicopters caused more subtle reactions. Noisier drones (such as those powered by fuel) tend to produce more animal reactions than electric ones because noise itself is a source of disturbance for wildlife (Mulero-Pázmány et al, 2017; Mesquita et al, 2022). Other physical drone attributes such as drone colour have not been found relevant for wildlife responses (Vas et al, 2015).

Flight characteristics

Flight altitude, angle of approach and speed changes of the drone importantly affect how animals react towards these aircrafts. Weimerskirch et al (2018) overflew 11 species of seabirds finding that while at 50 m altitude, only one reacted; most species showed strong stress responses below 10 m. Similarly, Rümmler et al (2016) found that almost all studied Adélie penguins showed vigilant behaviours with drones below 20 m altitude and stress remained elevated between 20 and 50 m. Some mammals, such as horses, have also been reported to show vigilance responses to drones flying at 20–30 m altitude, but ran away when the drone approached below 3 m (Howell et al, 2022).

The way a drone approaches wildlife also makes a difference. Flights conducted with a direct focus on animals, such as those intended to film them, produce more disturbance than other flying patterns likely because animals perceive the highest risk when the threat is on a trajectory facing towards them (Mulero-Pázmány et al, 2017). On the other hand, flights conducted at regular altitudes and following predictable patterns such as lawnmower paths (Assmann et al, 2018) – generally conducted for mapping and wildlife census – elicit fewer animal reactions (Mulero-Pázmány et al, 2017). Vertical drone approaches towards animals have also been shown to produce more negative impacts than horizontal ones (Vas et al, 2015; Rümmler et al, 2016). Brisson-Curadeau et al (2017) suggest that for cliff-nesting birds, where a vertical angle of attack may be less associated with predation, the angle of attack is apparently less important, but Mesquita et al (2020) found the diagonal distance explained 98.9 per cent of the variability of the disturbance caused by a drone approaching swift colonies located in waterfalls. The effects of drone speed on wildlife reactions have not been specifically assessed, but the general literature about wildlife disturbance suggests that fast and abrupt speed changes, that substantially affect drone trajectory and cause changes in the noise emitted by the aircraft, are likely to provoke more frequent and intense animal reactions than regular flight paths.

Other factors such as habitat characteristics can also affect wildlife responses to drones. For example, open habitats that allow for earlier detection (visually and by audition) favour wildlife-fleeing responses compared to closed habitats where drones are more difficult to perceive (Mulero-Pázmány et al, 2017). In a similar way, meteorological conditions such as wind may affect how drone noise is perceived by animals and therefore affect their reactions to the flights.

The social and political implications of using drones in conservation

Drones offer many potential advantages for conservation actors, including tools for onerous counting tasks, fine-grained detailed imaging and straightforward processes for monitoring fires. As the paper on community drones within this special collection shows (Sauls et al, 2023), they can be enormously useful to Indigenous and rural groups in community-led conservation and territorial defence strategies. Yet drones also pose risks to people: not understanding social or legal contexts could put drone users at risk. For example, long-term ecological monitoring sites in Mexico have been rendered inaccessible due to the risks of operating drones near areas now used for drug-trafficking. Regulations for drones vary significantly been regions and are often unclear, opening the possibility of legal (or even military) ramifications. Using drones may also have negative implications for the people living in and around conservation areas, if issues of privacy, social conflict and wider political context are not adequately considered. To date there has been comparatively little treatment of drones from this perspective in conservation applications (although see Sandbrook, 2015; Millner, 2020; Simlai and Sandbrook, 2021; Fish and Richardson, 2022), which is one reason this special collection fills an important gap. Here we review the areas that have begun to be explored within and beyond the social sciences, with a focus on issues of conflict and governance. The subsequent papers in this collection explore the value of drones to community conservation and territorial defence; the wider political ecologies of surveillance and monitoring in conservation; and policy recommendations for using drones responsibly.

Because some drone technologies were developed in military contexts for surveillance purposes, the ways that their use alters atmospheres and transforms contemporary warfare has already been explored within political geography (Gregory, 2011; Crandall, 2015). Such work applies directly to militarised approaches to policing (Wall, 2016) that are sometimes in play in protected areas, especially where conservation agendas are exploited to further state counter-insurgency or control agendas. In such cases – which are unpacked further in the paper on political ecology in this collection (Bersaglio et al, 2023) – the need to protect biodiversity is used as a pretext to justify racialised policing of certain demographics, usually those already perceived as 'risky' by state or other actors (Massé and Lunstrum, 2016).

As noted, the use of drones in conservation raises themes of privacy and data protection. In some extreme cases, drones have been one of a suite of technologies used by conservation park guards to maintain a regime of fear in protected areas. In the north Indian state of Uttarakhand, government drone security forces fly 'sorties' over protected tiger reserves, ostensibly to monitor illegal activities but which, in fact, aim to harass and deter certain castes from entering reserve buffer zones, despite their legal right to do so (Simlai, 2021). In most cases, drones are not used in this way. They are employed by conservation organisations or community organisations to collect data about biodiversity and conservation threats or to protect the areas from illegal activities. Nevertheless, as the policy briefing [https://www.cifor-icraf.org/knowledge/publication/8851/] linked with this collection makes clear, it is important to bear the privacy rights of local communities in mind when planning drone flights, and to avoid compounding conflict issues by flying drones over inhabited areas without consulting communities beforehand.

A contribution of the social science here is to observe that all technologies that produce visual data about humans have the potential to reinforce stereotypes about social groups or play into wider dynamics of social control, even where this is not intended. Drones offer unprecedented mobility and 'hyper-vision' to their users (see Gregory, 2011) – new ways of observing and photographing people from above that are difficult to escape. Meanwhile, alongside the deliberate imaging of people (for example, searching for illegal hunters; Bondi et al, 2018), footage of human actors may be captured by mistake. What Sandbrook et al (2018) refer to as 'human bycatch' describes the accidental capture of images of humans via procedures apparently designed to monitor non-human environments. In many cases this is unproblematic, but imaging of identifiable persons in apparently compromising situations, or breaking the law, *can* lead to a series of actions with implications for human communities. This is especially important in situations where ongoing conflict or negative stereotypes affect the balance of power, making it more likely that image-based evidence can be used to unjustly incriminate actors and communities. The policy briefing [https://www.cifor-icraf.org/knowledge/publication/8851/] emphasises the need to avoid collecting or storing data containing identifiable human characteristics for this reason, except where footage is being produced about a social context by or with those actors. An early process of socialisation is also crucial to involving communities and ensuring the data produced is useful to them.

In addition, the use of drones to 'see' when users cannot be seen (Crandall, 2015) may create fear in zones where there is unfamiliarity with drone technologies (see Sandbrook, 2015) or lack of clarity around the purpose of drone flights (Andrew Cunliffe, interviews, June 2020). Regardless of intent, drones have the potential to infringe upon communities' well-being, and undermine the fragile relationships between people and conservation organisations. However, the direction and magnitude of the social impacts of drone use are extremely dependent on who is using the drone, and for what.

When introduced with due process and concern, drones can, on the other hand, be important and enabling technologies as part of a wider repertoire of tools for participatory mapping, community conservation and/or territorial defence. Whether the drones are being used by scientists, conservation organisations and/or rural communities, they offer the potential to democratise conservation processes, both by enabling conservation decisions to be made at a more local level, and by supporting the production of data that reflects community perspectives. Millner (2020) notes how fine-resolution, georeferenced drone imagery enables communities to produce 'cartographic testimonies' in the 'language' of the state, which can then be used to counter state-based accounts of land use (see also de Vos, 2018). In one such example, a community NGO in Indonesia successfully contested a bauxite mine operating outside their concession by using drone imagery to document the illegal diverting of river tributaries (Radjawali et al, 2017). The impacts and benefits of community drone use are explored in greater detail in the second paper in this special collection (Sauls et al, 2023). Yet it is important to note that such uses can lead to retaliation from more traditionally powerful actors, such as extractive industries, with cases of intimidation and threats of violence levelled at community drone pilots (Paneque-Gálvez et al, 2017). This raises the importance of understanding the wider 'political ecology' of a context in connection with drone use, as the third paper in this collection argues (Enns et al, 2023). Political ecology is uniquely positioned to inform the questions raised in this introductory paper and special collection as an interdisciplinary subfield focused on exploring the relationships between political, social and economic processes and environmental transformations.

Integrating multidisciplinary perspectives on the regulation of conservation drones

The potential for drones to cause negative ecological and/or social effects at the same time as offering important new tools for meeting global social and environmental challenges has led to the development of various recommendations and guidelines, including those produced for the policy briefing [https://www.cifor-icraf.org/knowledge/publication/8851/] published alongside this special collection. In concluding this introduction, we note important areas of practical knowledge that we brought from our different disciplines that inform such guidelines, as well as noting the progress that has been made to date to integrate and publish such guidelines from an interdisciplinary perspective. This provides context for the policy brief authored by Drone Ecologies scientists, which is discussed further in the fourth paper of this collection (Jackman et al, 2023).

On the ecological side, observations of wildlife responses and close studies of drone impacts place emphasis on continuing to monitor the overflown animals. In practice this can result in cancelling flights or flying further away when animals react to the drone in a concerning way. There are some species-specific guidelines that are useful to follow when the target species is known in advance (for example, for dolphins and manatees see Ramos et al, 2018). In the absence of that information, the general principles suggested for flying in natural areas include: favour quieter and small drones against noisier and larger ones; operate the drone and take off further than 100 m from the target individuals and/or out of animals' sight or hearing range; conduct missions that are as short as possible; fly at the highest altitude possible feasible to get satisfactory data, such as 100 m above ground level; avoid abrupt changes of speed, altitude and direction, favouring lawnmower flight patterns over direct approaches; minimise flights over sensitive species or during breeding period; for nest inspections, fly at times in which eggs/chicks are out of risk; if the flights are around aggressive raptors' territories, perform them at times of day when the temperature is low and birds are less prone to fly (Vas et al, 2015; Hodgson and Koh, 2016; McEvoy et al, 2016; Mulero-Pázmány et al, 2017; Brisson-Curadeau et al, 2017; Giles et al, 2021).

This said, drones are less intrusive, smaller and quieter than many widely accepted wildlife monitoring methodologies. They offer more fine-grained detail than GIS technologies or other aerial technologies such as aeroplanes and helicopters, which present far higher risks in terms of noise and disturbances. Thus, the careful use of drones following the guidelines we have outlined constitutes a low-impact valuable tool for biological studies. In contrast, when animals are harassed directly, the disturbance levels can be far greater – as has been recorded in the use of drones for recreational filming (Rebolo-Ifrán et al, 2019). Therefore, the general recommendation is that drone flights are only performed when they constitute the least invasive option for necessary wildlife studies. Drone flights should also be discouraged in sensitive areas if they are performed just for leisure purposes (Mulero-Pázmány et al, 2017).

On the social side, guidelines are less fully developed. Some progress has been made towards the introduction of voluntary guidelines with recent discussions around the socially responsible use of environmental monitoring technology (for example, Sandbrook et al, 2021; Young et al, 2022). However, there has been little focus on drones, despite the unique concerns surrounding drones (such as the impact of a drone's physical presence) alongside general issues of data capture and management. This is why a number of scientists involved in the Drone Ecologies workshop in 2021 opted to produce a set of guidelines targeting conservation and environmental organisations using drones. The guidelines, which can be accessed online[9] are discussed in the intervention that concludes this special collection. This intervention explores the notion of interdisciplinary 'impact' more generally, as well as explaining how the policy briefing [https://www.cifor-icraf.org/knowledge/publication/8851/] was written, and some of the important surprises and areas of learning that resulted (Jackman et al, 2023). It is also important to note that, to date, guidelines to manage the ecological and social impacts of drones have been developed independently. Integrating these together into more holistic frameworks is an important area to which this special collection seeks to contribute.

However, it is also important that any new regulations are not too restrictive for communities unfamiliar with the many legal and regulatory sectors concerning aerial technologies such as drones. Protocols need to limit the negative impacts on communities and wildlife, without inhibiting uses that stand to benefit rural groups facing dispossession, or biodiverse landscapes. Issues around safety should not be downplayed (drones operating near airports can be very dangerous), but lengthy and expensive application processes for permits can render drones inaccessible for those without the financial resources nor ability to navigate multiple layers of bureaucracy. What is essential here is that training and learning materials are made accessible, to ensure that all drone-using communities are informed with best practice guidelines. Although there are many free online resources, these are predominantly English language, limiting their applicability outside the Anglosphere, as well as in rural areas with poor internet access. Local drone workshops are one potential solution (for example, Paneque-Gálvez et al, 2017) but communities may require continued external support for drone repair and maintenance. What must also be recognised is that *simply piloting a drone is only part of the equation*: equal attention must be paid to teaching skills in GIS and providing access to computers capable of processing and storing large amounts of drone imagery. A lack of these resources can be a serious impediment for potential drone users (Vargas-Ramírez and Paneque-Gálvez, 2019). Furthermore, despite the decreasing costs of drones, consideration should be given as to what constitutes 'affordability' for entities with different levels of resourcing. A failure to recognise these issues risks overestimating the real-world accessibility and potential benefits of drones while restricting their use to a select few conservation actors.

Rethinking drones through a multidisciplinary perspective has yielded fresh insights on the opportunities and risks of drones in biodiversity conservation. We summarise the range of different perspectives on the uses, advantages and potential problems with drones we have covered in this paper in Table 2. While the table overdraws the differences between disciplines (for example, political ecology places significant emphasis on non-human animals and more-than-human environments) this schematic overview helps underline the divergences in disciplinary foci.

Table 2: Multidisciplinary summary of different perspectives on the uses and potential impacts of drones

Discipline or area of practice	Area of concern	Advantages	Problems identified
Ecology	Wildlife	Fine spatial and temporal resolution data (Relatively) low impact Relatively low cost (if drone is equipped with basic payload)	Can affect animal behaviour Fire risk Requires technical knowledge Big data issues
Political ecology	Social and environmental justice for locally resident people; particularly those from marginalised and/or Indigenous groups	Drones may be used as a tool in struggles for land justice	Can cause fear or increase conflict Data may be used to support actions that disempower and harm local residents
Community conservation	Delineating cadastral boundaries Documenting sustainable forest management Documenting environmental crimes	More accessible than other remote sensing technologies Data is understood/acknowledged by authorities Autonomy over data collection and temporal resolution	Digital illiteracy and reliance on outsiders may limit use or potentially exacerbate local inequalities Negative reactions from extractive industries
Government conservation agencies	Enforcing conservation regulations; monitoring ecological conditions	Relatively cheap collection of data that can inform effective management decisions	Requires training of staff, new systems to manage equipment and data Concerns about using technologies developed in other countries Substantial overheads of archiving large data sets
Conservation organisations and NGOs	Wildlife Development Community resource management, often single-issue focus	Relatively cost-effective collection of data that enable fine-grained conservation decisions	Risk some organisations may be structured and motivated to ensure ongoing dependence on their support Some NGOs invest considerable effort working against other NGOs to protect their 'turf' rather than helping to solve problems If risk assessments are not conducted, wider adverse negative impacts on people and wildlife

Conclusion to the paper and introduction to the special collection

This article, which acts as an introduction to a special collection on Drone Ecologies, has outlined the technical capacities of drones for biodiversity conservation along with their limitations, highlighting insights drawn from a range of disciplinary perspectives. We have emphasised the value of drones in producing different forms of observations/data, and visual media for communicating why different landscapes/ecosystems/organisms matter. While they are not appropriate for all forms of monitoring, they can provide differentiated visual and cartographic information about environments that are difficult to capture using other geospatial technologies. On the other hand, we have made clear the risks and limitations of using drones, including privacy concerns, a potential for surveillance, and impacts on wildlife and local communities, which will be vital to grapple with as the use of the technology increases. Through this conversation we have also made clear the value of drones in meeting global *social* challenges such as democratisation (especially of unequal power relations in conservation spaces) and effective governance of biodiversity loss and degradation (enabling the protection of Indigenous territories, and informing community-led strategies for conservation). We have also highlighted issues of access, for not all communities or entities have equal access to drones, and regulatory jurisdictions may act as further barriers on drone use. What counts as 'accessibility' when it comes to conservation technologies warrants further discussion.

While exploring the important contributions of drone technologies to biodiversity conservation challenges, we have also emphasised that using drones in conflicted contexts, or where there is a history of surveillance and control, is not straightforward. As we argue in this paper, drones risk reproducing dynamics of securitisation and militarisation if they are not used with sensitivity to power relations and to questions of who is producing the data and why. These questions are developed further in the third paper in this collection (Bersaglio et al, 2023), which draws on the interdisciplinary field of political ecology to deepen understanding of these questions. On the other hand, the second paper of this collection (Sauls et al, 2023) makes clear that drones also offer fresh possibilities for ecologically sensitive and empowering conservation, and even the protection of Indigenous lands. Indeed, drones change the theatre of spatial authority, making it possible to rework the narratives told about communities and places, precisely by enabling new kinds of spatial stories. These innovations call, however, for new guidelines and protocols, as the fourth paper (Jackman et al, 2023) makes clear. While excessive or poor regulation of drone use may prevent effective use, some kinds of 'rules' are helpful. In the policy intervention that accompanies this collection, we lay out the recommendations established through our international workshop and what has been learned about the role of inter- or multidisciplinarity in transforming practice more generally. This dialogue between disciplines will be vital to ecologically sustainable and just implementation of drone technologies in the future.

Notes

[1] Other names are used – unmanned [sic] aerial vehicle (UAV); remotely piloted aircraft (RPA) – and we recognise that 'drone' can be a controversial term due to its military connotations (Paneque-Gálvez et al, 2014). It has been suggested that some academic disciplines therefore avoid the word in publications, despite using it colloquially (Sandbrook, 2015). However, in this paper we use 'drone' for brevity and clarity, given the term's common use in civilian and conservation applications.

[2] See, for example, https://geonadir.com.

[3] Nevertheless, many land management organisations still do not use drone data for routine monitoring because of the high costs of the hardware (such as computers and data storage) and the high costs of skilled time to derive useful outputs. These cost barriers are particularly relevant in many parts of the Global South.

[4] Drones are largely divided into two categories, fixed-wing or multirotor, although hybrid airframes are becoming more commonplace. In addition to the drone itself,

the infrastructure of a complete drone system includes a ground control station and a communications link, often comprising a tablet or smartphone and a remote controller.

[5] See: https://ageagle.com/drones/ebee-x/.

[6] See, for example, free: https://opendronemap.org, https://geonadir.com, https://www.conservationai.co.uk/; paid: https://picterra.ch/.

[7] For example, paid: Pix4D, professional photogrammetry and drone mapping software.

[8] https://geonadir.com.

[9] https://www.cifor-icraf.org/knowledge/publication/8851/.

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Data availability statement

The authors take responsibility for the integrity of the data and the accuracy of the analysis.

Conflict of interest

The authors declare that there is no conflict of interest.

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