

REVIEW

SmallSats: a new technological frontier in ecology and conservation?

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Abstract

We are in the midst of a revolution in satellite technology, with the rapid development and advancement of small satellites (or SmallSats, i.e., satellites <180 kg). Here, we review the opportunities and challenges that such technology might afford in the field of conservation and ecology. SmallSat constellations may yield higher resolutions than those that are currently available to scientists and practitioners, increasing opportunities to improve environmental-monitoring and animal-tracking capabilities. They may cut access costs to end users, by reducing operational costs and bringing increased competition to the existing market. Their greater flexibility and affordability may moreover enable the development of bespoke constellations for specific conservation and ecological applications, and provide greater interoperability with ground-based sensors, such as tracking devices and camera traps. In addition, SmallSats may serve as cost-effective research and development platforms for new components and products. Combined, these benefits could significantly improve our ability to monitor threats to the environment as they unfold, while enhancing our understanding of animal ecology and ecosystem dynamics. However, significant hardware and software developments are required before such technology is able to produce, process and handle reliable and cost-effective data, and the initial research and development costs still represent a major challenge. Further, we argue that much remains to be done to ensure these new data products become accessible, equitable and sustainable.

Introduction

Satellites are a vital tool for ecologists and conservationists to monitor ecosystem structure, composition and functioning (Pettorelli, Laurance, et al., 2014; Pettorelli, Safi, et al., 2014); track human activities and impacts on the natural world (Biermann et al., 2020; Kroodsma et al., 2018); and relay data from instruments deployed on animals (e.g., Barkley et al., 2019; Curnick & Fearn, 2020;

Doherty et al., 2017). Continual increases in the spatial and temporal resolution of data freely available to researchers are being brought about by initiatives such as the Landsat, MODIS and Copernicus missions (Pettorelli, 2019; Williamson et al., 2019). These platforms provide valuable long-term geospatial coverage (Hansen & Loveland, 2012; Traganos et al., 2018; Wessels et al., 2004), but can still lack the required spatial resolution for site- or organism-level analyses (Williamson et al., 2019) and

may have limited spectral resolution or ranges (Asner et al., 2015; Marvin et al., 2016). For instance, the Sentinel-2 multispectral mission only captures 13 bands across the visible, near-infrared and short-wave infrared portions of the electromagnetic spectrum, at a resolution of 10 to 60 m over land and coastal waters with 5-days revisit frequency. Higher spatial resolution data, up to approximately 30 cm, can be provided by commercial satellites, but often at a prohibitive cost (Pettorelli et al., 2018; Turner et al., 2015), effectively constraining ecological research and conservation monitoring opportunities.

In some instances, researchers have used drones to obtain higher spatial resolution data (e.g., Koh & Wich, 2012; Wich & Koh, 2018) or motes (a wireless transceiver combined with a sensor) to enhance data recovery from satellite-tagged animals (Jeanniard-du-Dot et al., 2017). Yet, their applications can be limited by power constraints (i.e., battery life); relatively high costs per unit area; and low temporal continuity and geographical availability. The recent development of smaller satellites, known as ‘SmallSats’, may represent a unique opportunity to complement existing satellite infrastructure and enhance the spatial, temporal and spectral resolution of data available at a fraction of the cost, increasing both the scope and scale of research questions that can be feasibly explored.

SmallSats are small satellites weighing <180 kg; they include femtosatellites (0.001–0.01 kg), picosatellites (0.01–1 kg), nanosatellites/cubesatellites (1–10 kg), microsatellites (10–100 kg), and minisatellites (100–180 kg). They are relatively cheap to design, build (open-source kits are available at www.cubesatkit.com), and launch (Venturini et al., 2017) compared with traditional commercial satellites. SmallSats can be installed in large constellations (orbitally synchronised satellites) and in lower orbits (typically 450–700 km above the Earth) (Polat et al., 2016) thus potentially reducing the power consumption of animal-borne tags, for example, as they communicate with SmallSats from the earth’s surface. Over 1400 nanosatellites have so far been deployed (to January 2021), with thousands more planned (nanosats.eu). Most constellations deployed thus far have been for optical earth observation and data communication network services, with a few having hyperspectral (e.g., Satellogic) and synthetic aperture radar capabilities (see www.newspace.im for up-to-date catalogue of constellations deployed and in planning). For possible environmental science applications (Table 1), Planet Labs (San Francisco, CA, USA) have deployed two SmallSat constellations: ‘PlanetScope’ capable of imaging the entire Earth daily at approximately 3.7 m resolution, and ‘SkySat’, providing

Table 1. Examples of SmallSat constellations with the potential to generate data for ecological or conservation applications.

Organisation/constellation	Year of initial deployment	Constellation size (launched/planned)	Mission objectives	Sensors/spectral bands	Website
Planet (SkySat)	2013	21	Earth observation	RGB, NIR, PAN	http://developers.planet.com/docs/data/skysat/
Spire	2013	141/150	Weather system, AIS, ADS-B	UHF/VHF	https://spire.com
Planet (PlanetScope)	2016	~130	Earth observation	RGB, NIR, RedEdge	http://developers.planet.com/docs/data/planetscope
Satellogic	2016	18/300	Earth observation	PAN, RGB, NIR, Hyperspectral, Thermal Infrared	https://satellogic.com
Capella space	2018	6/36	Earth observation (SAR)	SHF	https://www.capellaspace.com
Hiber	2018	4/48	IoT	UHF	https://hiber.global
Astrocast	2018	10/100	IoT	UHF	https://www.astrocast.com
ICEYE	2018	10/18	Earth observation (SAR)	SHF	https://www.iceye.com
SpaceX (Starlink)	2018	1664/41493	Internet	SHF/EHF	https://www.starlink.com
Lacuna space	2019	5/240	IoT	UHF	https://lacuna.space
Kinéis	2022	0/25	IoT and AIS	UHF	https://www.kineis.com

Mission objectives include Internet of Things (IoT), Automatic Dependent Surveillance–Broadcast (ADS-B) and automatic identification systems (AIS). Sensors and spectral bands include red, green and blue (RGB), near-infrared (NIR), panchromatic (PAN) synthetic aperture radar (SAR), Adapted from www.newspace.im (accessed July 2021). Radio bands include very high frequency (VHF), ultra high frequency (UHF), super high frequency (SHF) and extremely high frequency (EHF).

HD video capability and multispectral imagery at 0.5 m resolution (Marta, 2018). Traditional satellite providers are also phasing in SmallSat constellations to replace existing decaying infrastructure. For example, KinéS, with the support of the French Space Agency CNES, plans to launch a constellation of 25 SmallSats by late 2022 to enhance Argos coverage and ultimately upgrade the existing Argos-2/3 system (the network of satellites operated and maintained by Collecte Localisation satellite (CLS) – www.argos-system.org).

Currently, satellite monitoring in the field of ecology and conservation is still dominated by traditional satellite infrastructure. Indeed, a search of the Web of Science Core Collection between 2000 and 2020 revealed just 135 papers have been published to date with SmallSats within the ‘Topic’, compared with 4956 with MODIS, 4365 with Landsat and 1923 across the Copernicus programme (Fig. 1). However, with such rapid advances and uptake in SmallSats (nearly all of which have been published in the last three years, 2018–2020), the technology is expected to become ever more accessible to ecologists and conservation biologists. At this important stage in their development and deployment, we review the opportunities and possible challenges associated with SmallSats and

highlight the technological, ethical and policy considerations needed to ensure that they become a valuable addition to the research toolbox.

Opportunities Associated With SmallSats

Increased resolution

Since 2014, medium-high spatial (up to 10 m) and temporal (up to 2–3 days revisit time) resolution imaging data have been available through the Copernicus programme (www.copernicus.eu). This development has afforded opportunities to detect seasonal variations across landscapes and finer-scale characteristics of landscapes (see e.g., Defourny et al., 2019). SmallSat constellations represent an opportunity to access potentially higher resolution for site-specific applications. Analysis of high temporal resolution optical imagery has been restricted in many instances, predominantly due to the presence of clouds (Asner, 2001). The development of temporal gap-filling methods (Grizonnet et al., 2017) and the fusion of the Copernicus optical and radar products (see e.g. Lopes et al., 2020) have overcome some of these challenges.

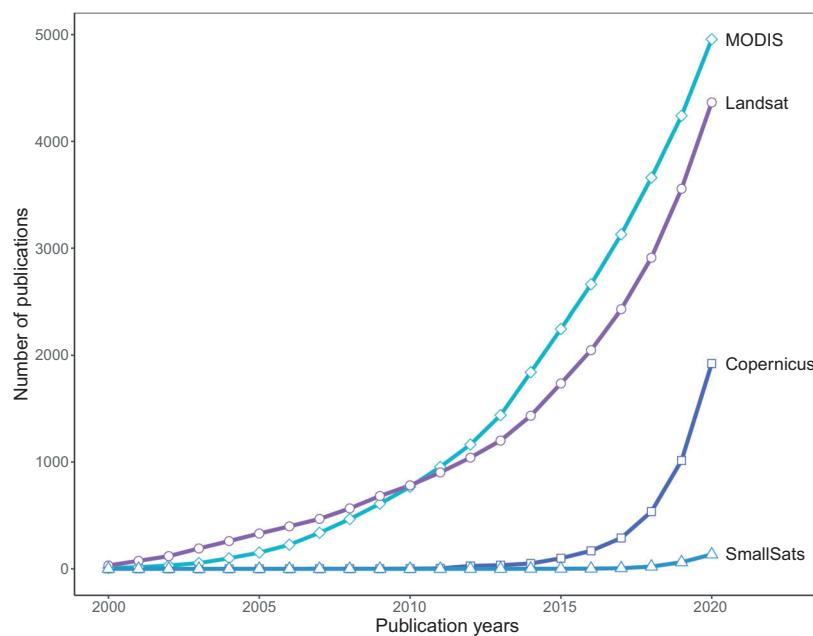


Figure 1. The cumulative number of publications between 2000 and 2020 using SmallSats (triangles) compared with traditional satellite infrastructures MODIS (diamonds), Landsat (circles) and Copernicus (squares). Searches for publications were conducted through the Web of Science Core Collection, within the category of Environmental Sciences. For SmallSats, abbreviated names and sub-categories of small satellites (smallsat* OR cubesat* OR nanosat* OR femtosat* OR picosat*) and major constellations (SkySat or PlanetScope) were included within the ‘Topic’ field. For MODIS and Landsat, searches contained the satellite name and ‘satellite’ within the ‘Topic’ field. For Copernicus, we searched for ‘satellite’ and the satellites across the programme (‘sentinel-1’ OR ‘sentinel-2’ OR ‘sentinel-3’ OR ‘sentinel-4’ OR ‘sentinel-5’ OR ‘sentinel-6’). Web of Science Core Collection accessed 23rd September 2021.

However, higher spatial resolution earth observation products (e.g., WorldView) are often single-date or temporal composites where much temporal information is lost (Crowson et al., 2019; Erinjery et al., 2018; Griffiths et al., 2013; Harcourt et al., 2019). Biotelemetry studies can also suffer from a lack of data retrieval due to infrequent passes (Breed et al., 2011), as tags often have a single attempt to transmit data and rarely have two-way communication links. This is a particular issue in remote regions, where satellite coverage is less frequent or in-situ environmental data are commonly lacking (Williamson et al., 2019).

More frequent satellite passes will increase the probability of returning cloud-free optical imagery in earth observation studies (McCabe et al., 2017), reducing the requirement to apply spatial, temporal and spatio-temporal gap-filling methods (e.g., Buttlar et al., 2014; Jönsson & Eklundh, 2002; Kang et al., 2005; Zhang et al., 2007) or data fusion techniques (Moreno-Martínez et al., 2020). For ecosystem monitoring, access to such high temporal resolution data would, for example, facilitate the near real-time and local detection of changes in ecosystem features, enabling researchers to better detect acute ecosystem shifts or novel threats in a timely manner. In addition, SmallSats could provide opportunities to track animals more continuously and at greater spatial resolution, both optically (e.g., daily distributions of wild populations [penguin colonies; Fretwell & Trathan, 2020]) and through data relaying from animal-borne devices (e.g., satellite tags). By combining data from multiple SmallSats within a constellation, it will indeed be possible to obtain information from a specific location at higher temporal resolutions, such as hourly, that are currently only available from in-situ instrumentation (Reising et al., 2015; Ruf et al., 2013). Further, SmallSats could facilitate a greater interoperability between satellite-derived data and animal-borne devices. For example, environmental data could be collected at higher spatiotemporal resolutions – without the temporal lag or spatial aggregation – to better elucidate environmental drivers of animal movement patterns and distributions. Access to higher spatiotemporal resolutions may thus have important implications for advancing our understanding of the dynamic relationship between species and their habitats, and subsequently for informing conservation actions: for example, SmallSats could reliably track fine-scale forest fragmentation and degradation as they happen, information that could be used to assess and/or revise assessments of dispersal capabilities for threatened forest species (Descals et al., 2017).

SmallSats are advantageous over drone applications that may be spatially restricted (e.g., geo-fenced no-fly zones) or temporally limited by battery life, range, flying conditions, costs and fieldwork logistics (Oleksyn et al.,

2021). They could revolutionise fisheries surveillance by improving the detection of illegal, unreported and unregulated (IUU) fishing (Agnew et al., 2009; Tickler et al., 2019) and drifting gears (Curnick et al., 2020). Detecting vessels in a vast ocean is inherently difficult due to the sheer scale involved. Although traditional satellite remote sensing already plays a role in monitoring illegal activity at sea (Kurekin et al., 2019; Oozeki et al., 2017), the detection of small wooden vessels often involved in IUU fishing (Collins et al., 2021) remains particularly difficult, especially considering the infrequent acquisitions of medium-high resolution earth observation data over the oceans. A SmallSat constellation targeted on specific water masses (e.g., a marine protected area) with greater spatial resolution could better detect small vessels operating illegally (Kanfir et al., 2016; Lazreg et al., 2018), especially if combined with artificial intelligence (Soldi et al., 2020). These could be further coupled with animal-borne devices detecting IUU (Weimerskirch et al., 2018, 2020), with SmallSats acting as a relay to transmit the data to managers in a timely manner.

Reduced power consumption

SmallSats are generally placed in lower orbits (Polat et al., 2016), reducing the attenuation of the signal between the satellite and the ground. All else being equal, it requires almost three times less transmission power to communicate with a satellite at 500 km altitude than it does with one at 850 km. While bandwidth, frequency and antenna characteristics also play significant roles, lower orbits make it easier to close the link with the satellite from a low-power radio. This could have significant implications for the taxonomic breadth of biotelemetry studies, in particular where battery size and weight are still major limiting factors to deployment (Portugal & White, 2018; Wikelski et al., 2007). Reductions in battery requirements could facilitate an increase in onboard sensor capacity (i.e., more sensors on one device), the addition of bidirectional communications or further advances in tag miniaturisation, opening up new swaths of species that could be tracked electronically (Kays et al., 2015).

Increased sensor capacity

An increase in sensor capacity onboard satellites could mean SmallSats are being able to collect information over a larger number of spectral bands. Hyperspectral sensors offer a number of opportunities to inform ecology and conservation: the data they collect can, for example, be used to map plant species and plant diversity from space, enabling the tracking of invasive species (He et al., 2011). However, access to hyperspectral data is currently limited

to a few missions, such as PRISMA (Candela et al., 2016) and DESIS (Müller et al., 2016). The development of SmallSat constellations equipped with hyperspectral sensors would therefore represent a significant advancement in our ability to monitor the impacts of environmental change on biodiversity and the delivery of ecosystem services.

Reduced costs and greater accessibility of very high-resolution data

One of the greatest opportunities afforded by SmallSats is the potential cost reduction to end users in need of very high resolution data through increased market competition and reduced operational costs (Dyer & McClelland, 2017; Poghosyan & Golkar, 2017). Given that conservation is chronically underfunded (McCarthy et al., 2012), any reductions in data provision costs could dramatically increase conservation outcomes. Some initiatives, such as Planet Labs Norway's International Climate & Forests Initiative, offer free access to researchers and non-profit organisations, although data are not available for all applications and there are restrictions on the spatial and temporal resolutions that are freely available. Other commercial initiatives tend to offer a very limited amount of freely available data to researchers. SmallSat-induced cost reductions would significantly increase accessibility for

developing and emerging nations, where conservation efforts are focussed (Bookbinder et al., 1998; Lenzen et al., 2012).

Additionally, the reduced costs of SmallSat development and launch could enable the advancement of bespoke constellations within a connected 'Internet of Things' ecosystem (Fig. 2). This could be of great benefit to the research community as networks can be tailored to specific projects and research questions or even reprogrammed in-situ, such as through software-defined radios (Wangsa et al., 2019). Indeed, we are already seeing institutions beginning to establish their own satellite systems (both conventional and SmallSats) with specific application to ecological research and conservation; for example, the ICARUS (International Cooperation for Animal Research Using Space) antenna (<https://www.icarus.mpg.de/en>), the GEDI Ecosystem Laser (<https://gedi.umd.edu/>), and PandaSat, a SmallSat constellation spearheaded by the World Wide Fund For Nature, are in early development.

Innovation and effective remote sensing networks

SmallSats have the potential to become important accessible platforms for proof-of-concept tests of new components and sensors, reducing risk before full roll-out.

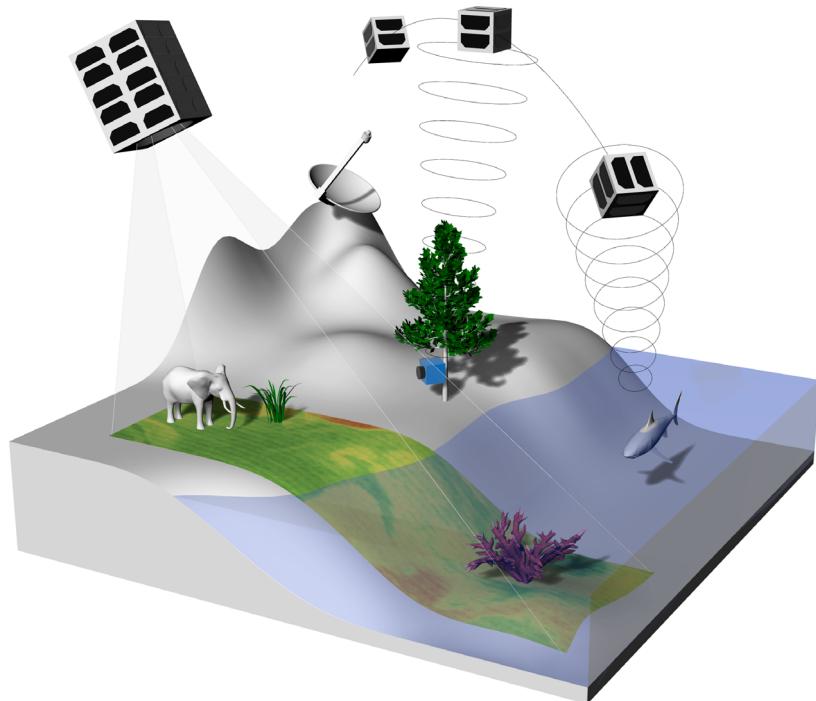


Figure 2. An example of a connected SmallSat constellation collecting earth observation data and an associated ground sensor network of animal-borne devices or camera traps.

SmallSats could indeed drastically enhance sensor innovation research-and-development loops, cutting timeframes to technological advancements. For example, the development of relay satellites (Perea-Tamayo et al., 2018) and laser downlinks (Welle et al., 2018) could provide crucial communication and data transfer functions between other remote sensing platforms (e.g. WamCAM – Wildlife Advanced Monitoring Camera; www.business.esa.int/projects/wamcam). SmallSats could enable communication with networked camera traps and acoustic recorder grids, offering real-time alerts of poaching or animal detection events, and continuous ‘health-checks’ (e.g., battery life, memory status). This could address some of the significant user-reported constraints for these technologies (Glover-Kapfer et al., 2019), thereby greatly enhancing the efficiency of camera trap and acoustic surveys in terrestrial environments. Currently, wireless- and cellular-enabled camera traps are available, but many areas in need of conservation attention do not have cellular signal. Advances within embedded machine learning (TinyML) have moreover started to unlock access to inference ‘on the edge’ (i.e., onboard processing). This would enable the transfer of inferred results within smaller processed data packets, such as species recognition or acoustic signature detections. Penguin Watch’s open source time-lapse camera deployed on the Antarctic Peninsular supports this technique, embedding Google’s Tensorflow machine learning framework to process image data (Vaswani et al., 2018). Camera traps with satellite connectivity (hereafter, satellite-enabled camera traps) to wirelessly send data from remote locations could help to overcome these problems and is a desire of the research community (Glover-Kapfer et al., 2019). However, these are not currently available off-the-shelf, likely because the data transmission costs make them commercially unviable. Emerging solutions to this, such as the Instant Detect 2.0 camera trap and the TrailGuard AI camera trap, are relatively expensive, bespoke designs, and rely on the goodwill of commercial satellite companies (Iridium and Inmarsat, respectively). The rise of SmallSat technology could decrease the transmission costs to a point at which mass-produced and economical satellite-enabled camera traps finally become widely available.

Satellites have already been used to monitor multiple species from space at the individual level, such as whales (Cubaynes et al., 2019; Fretwell et al., 2014) and seals (LaRue et al., 2011; McMahon et al., 2014), and at the population level, such as emperor penguins (*Aptenodytes fosteri*) (Fretwell et al., 2012), but require labour-intensive post-hoc analyses of the large volumes of transmitted data. This can limit their effectiveness for real-time monitoring. On-board artificial intelligence and embedded machine learning could reduce satellite data transfer costs

and enable larger projects that were previously unfeasible or unrealistic. Importantly, edge processing could quickly provide the summary data needed to dramatically reduce response rates to conservation emergencies. For example, near real-time on-board processing by SmallSat computing platforms have been previously used for ship detection (Yao et al., 2019). Such processing could facilitate more rapid responses to illegal fishing events (Greidanus et al., 2017; Kurekin et al., 2019) or illegal logging in protected areas (Lynch et al., 2013; Wyniawskyj et al., 2019).

Limitations and Considerations

By reducing data transfer costs, increasing spatial and temporal data coverage and providing new technologies for imaging and asset tracking, SmallSats have the potential to fill an important gap in earth observation (Gregorio et al., 2018). However, before this potential can be realised, there are several issues that must be addressed.

Significant developments still required

Although hundreds of SmallSats have already been deployed, we are still in the research-and-development phase of the technology and initial investments can be high and risky. For example, Kinéis have reportedly invested €100 m into launching the Kinéis constellation (25 SmallSats). This may lead risk-adverse consumers to remain with traditional providers and infrastructure in the immediate future, until market confidence builds in SmallSat technology and upfront costs are reduced. This reaction was observed before: early adopters of drones for conservation applications were decades behind the military who drove technological development Ivošević et al., 2015). Many of the perceived benefits of SmallSats then come from their increased number; yet, as of January 2021, only two nanosatellite constellations (PlanetScope and Spire) containing more than a dozen satellites (nanosats.eu) could be identified (although other microsatellite commercial organisations plan to enrich their constellations, such as ICEYE and Capella Space (Synthetic Aperture Radar) and Satellogic (Hyperspectral)). Moreover, although SmallSats provide a platform for greater data access, their ability to capture, process and transmit large amounts of data is currently restricted due to their relatively small antennae and limited power budgets. Thus, significant areas of development are still needed, especially given that it is highly likely that SmallSat constellations will facilitate a rapid increase in the volume of data available. In order to handle, manage and process such large volumes of data, computational and analytical capacity amongst conservationists and ecologists will also need to increase concurrently.

Here, we can learn from other recent explosions in technological advancements, such as drones, camera traps and electronic tags. Drones and camera traps have facilitated new distinct eras for remotely sensing of wildlife (Burton et al., 2015; Kays et al., 2015; López & Mulero-Pázmány, 2019; Pimm et al., 2015). Yet, the sheer volume of information now gathered by survey and monitoring technologies poses several issues for researchers working with ‘big data’, such as storage infrastructure and processing, data sharing, and analysis of complex data (Fan et al., 2014; Jin et al., 2015; Wang et al., 2016). Many of these technologies have already adapted to utilise cloud computing, and MapReduce programming and processing techniques (Fan et al., 2014; Wang et al., 2016) can be utilised to aid the development of SmallSats. However, these too can come with their own challenges (Marx, 2013; Wearn et al., 2019). Further development of statistical methods that can handle complex, noisy and dependent data is therefore still required (Fan et al., 2014; Smith & Nichols, 2018; Wang et al., 2016). For example, SmallSat data quality and utility may be reduced if they are not well-calibrated (compared with traditional satellite data) and without the radiometric or geometric corrections required (Descals et al., 2017). There are also legal issues surrounding privacy, licencing and regulations that should be proactively discussed and addressed now, while the technology of SmallSats is still emerging, rather than reactively in response to the technology becoming mainstream (Jin et al., 2015; Wang et al., 2016).

Commercially available SmallSat earth observation imagery has been largely limited to visible optical data (e.g. Planet Labs: Red, Green and Blue and near-infrared wavelengths). In recent years, however, the utility of radar and hyperspectral missions to inform ecology and conservation has dramatically increased (Pettorelli, 2019). The miniaturised sensors necessary to bring radar and hyperspectral capabilities to SmallSat platforms are in various phases of research and development (see Stephens et al., 2020 for a review of sensor capabilities). If successful, these new sensors could substantially increase opportunities for SmallSats to inform science and management in the coming years.

The emergence of SmallSats cannot be considered in isolation, as they will still be dependent on ground-based infrastructure or animal-borne devices. Associated devices will therefore need to be developed at the same speed in order to prevent data uplink (tags per unit area) and down-link (total data to ground station) bottlenecks forming. Such infrastructure will need to be low cost or open-source in order to maintain accessibility. For tracking studies, this requires the development of associated hardware, such as open-source tracking hardware (e.g., OpenCollar.io) or transmitter chips. Currently, Hiber and Lacuna

(LoRaWAN) aim to produce cheaper designs, and Argos launched a competition to design their new open-source Argos Transceiver Integrated Chipset (ARTIC – www.argos-system.org/chipset-contest), leading to the Arribada Initiative developing an open-source reference design that is ARGOS Artic R2 certified (www.arribada.org/horizon).

Equitability and accessibility

As many SmallSat constellations are backed by private companies, the data can be harder to access than readily available, government backed infrastructure. Further, although some new constellations such as AstroCast, Kinéis, Swarm and Lacuna are offering cheaper rates for data acquisition compared with some traditional platforms, there are no guarantees that the reduced costs incurred will be directly passed down to consumers, as established, large companies will likely continue to set fair market rates in the near future. Indeed, any per unit cost savings may be offset by greater data volume, resulting in similar costs to the end-user.

SmallSats moreover have the potential to exacerbate inequities in the global distribution of technological access and power. They could provide an increased availability of surveillance data and monitoring capacity that subsequently poses significant national security issues. For example, >80% of the nanosatellites launched by January 2021 were launched by the European Union and the United States of America. Regulatory frameworks exist within the USA (e.g., NOAA-NESDIS-2018-0058). However, multilateral agreements will be needed for data spanning other territories, potentially at a higher resolution than currently available to the governments in those territories. The societal costs of increased surveillance also need to be considered. Whether intentional (e.g., for anti-poaching purposes) or as ‘bycatch’ in non-human-targeting conservation applications (Sandbrook et al., 2018), such surveillance allows for increasingly detailed profiling of humans, as well as animals, raising a series of ethical and political issues (Resnik & Elliott, 2019; Sandbrook et al., 2021). Moreover, any impacts are unlikely to be equitable, with negative consequences more likely to be borne by marginalised and disempowered groups (e.g., indigenous peoples; Sandbrook et al., 2021). In addition, SmallSats may fuel an ongoing arms race, providing greater information to extractive industries (e.g., fishing), or illegal activities (e.g., poaching), as well as conservationists and managers (Pimm et al., 2015).

Sustainability

There are significant concerns over the economic and environmental sustainability of SmallSats. First, the

relatively limited lifespans of SmallSats might make it difficult for users to plan long-term studies and monitoring frameworks reliant on these technologies. Second, with thousands of deployments planned over the coming years, extensive trajectory analyses need to be undertaken and the spectrum and orbit allocation carefully managed in order to prevent overcrowding. Given that the average SmallSat mission is about 9–24 months (Allan et al., 2018) compared with Sentinel-2 and Sentinel-3s lifespans of about 7 years, significant orbital debris could be produced if the mean time to failure is greater than the time for a satellite to deorbit and burn up. Indeed, there are concerns around the impact of the proposed Starlink megaconstellation of nearly 42 000 satellites (Massey et al., 2020), which may deposit sufficient aluminium into the atmosphere upon re-entry to alter the Earth's albedo (Boley & Byers, 2021). The 'cluttering' of space with many small objects may also inhibit or damage existing satellite systems and providers by adding to the space debris problem (Shan et al., 2017). Thus, comprehensive waste management plans would need to be implemented before rapid scaling of SmallSat deployments and constellations. Mechanisms using nets and hooks are being developed to deorbit SmallSats, but they remain largely untested in the space environment. Interestingly, SmallSats themselves may provide an opportunity for removing and limiting space debris, with technologies such as the RemoveDEBRIS programme already being developed (Forshaw et al., 2016).

Conclusion

SmallSat technology could serve as a fantastic vehicle for innovation, shaping the future conservation science landscape. However, despite the significant opportunities these small satellites could open to practitioners and scientists, there remains a considerable list of open challenges associated with the use of this technology in ecology and conservation. These include:

- 1 Establishing whether there is a net benefit to the development of conservation SmallSats after their economic and ecological footprint are considered. Should we direct crucial conservation funds into further SmallSat developments or refine traditional satellite products? Will these data actually enable us to better answer today's critical conservation questions?
- 2 Identifying relevant entities that are able to help the conservation community tackle the issues associated with storage, processing, ethics, sustainability and security considerations posed by the potential explosion of data provided by SmallSats.
- 3 Developing the needed legal and ethical regulatory frameworks to manage the deployment and application

of conservation SmallSats and ensure equitable data access.

SmallSats will undoubtedly form a part of the future remote sensing conservation toolbox and, alongside existing commercial and civilian programmes, could lead to significant increases in data resolution and accessibility, dramatically increasing the accuracy and power of wildlife and natural resource monitoring. Yet, if we as conservationists and ecologists are to maximise the potential for this technology, we need to ensure that the regulatory frameworks, associated systems and technologies are 'in place' before their application really takes-off.

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Author Contribution

DJC and NP conceived the manuscript and lead on its design and scope. DJC, DMPJ, CD, ORW and AD secured funding that supported the production of this paper. All co-authors made significant contributions towards reviewing available literature, collating relevant information and specifications, and drafting the manuscript.

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