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Review

Unmanned aircraft systems for protected areas: Gadgetry or necessity?

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ABSTRACT

The ease of use and availability of unmanned aircraft systems (UAS) recently pervaded a wide range of topics and applications. In nature conservation and for the management of protected areas (PAs), UAS are still not an established approach compared to other methods such as satellite-based remote sensing, although several research articles have already discussed their use. In this context, UAS are even denoted as 'conservation drones', suggesting that their use is beneficial in terms of accomplishing various tasks such as land-cover mapping, vegetation monitoring, biomass estimation, and animal detection. However, although disturbance of wildlife or other issues caused by UAS are debated and guidelines for the use of UAS in wildlife studies suggest precautionary measures, the implications of the use of UAS in PAs has not been analyzed in detail yet. Therefore, by reviewing research articles, the present paper aims to show whether the use of UAS in PAs is relevant or irrelevant for the PA management in terms of biodiversity conservation, considers a controversial debate of the potential threats, and investigates whether the type of PA concerned matters in this context. We showed that a majority (73%) of selected articles (89) report the use of UAS in PAs as relevant for the PA management in terms of biodiversity. However, most of these studies did not consider impacts of UAS on wildlife or the environment. The possibility of disturbances was discussed in 15 (approx. 17%) of the reviewed works, of which most concluded that the effects were negligible or non-existent. Only in three articles (approx. 3%) an impact has been demonstrated. While most research studies discussing UAS in PAs do not report nor mention any impacts, UAS are banned in many PAs. Therefore, the use of UAS in PAs as 'conservation drones' and the related pros and cons need to be carefully considered by the PA managers and stakeholders concerned.

1. Introduction

Unmanned aircraft systems (UAS) have been frequently introduced in protected areas (PAs). However, the application of this technology produces emissions and potential waste. Consequentially, there is a looming danger of impacting the observed environment, which is of particular concern in PAs. This article addresses potential challenges with an emphasis on the risks and opportunities of applying UAS in PAs.

There are different ways to address the definition of PAs. The term 'PA' comprises different types of (geographically defined spaces of) water, forest and open landscape that are incidentally valuable for biodiversity and nature conservation and/or are perceived unique due to their cultural and/or scenic value. PAs describe a legally defined form of land use intended for conservation of nature, which typically requires management (IUCN, 1994; Eagles et al., 2002; Dudley, 2008). In order to find global standards and to facilitate communication between managers, scientists and politicians as well as the general public, the International Union for Conservation of Nature (IUCN) put forward a system consisting of six categories of PAs in total (IUCN, 1994; Eagles et al., 2002): 'Ia: Strict nature reserve', 'Ib: Wilderness area', 'II: National park', 'III: Natural monument or feature', 'IV: Habitat/species management area', 'V: Protected landscape/seascape', 'VI: Protected area with sustainable use of natural resources'. These categories do not follow a simple hierarchic scheme in terms of quality, importance or naturalness, but they are based on the areas' management objective (Dudley, 2008). The term 'naturalness' in the context of IUCN protected areas means that all PA categories are typically characterized by natural conditions compared to outside their boundaries (Dudley, 2008). This is also

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important from a recreation or tourism perspective, since the protection status and the connoted nature experience have proven more important to visitors than the respective PA category itself (Pröbstl-Haider & Haider, 2014). The management objectives of the IUCN categories cover a range of different topics and tasks such as the conservation of species and genetic diversity (biodiversity) and the contribution to regional conservation strategies (Eagles et al., 2002; Dudley, 2008; Schoville et al., 2018). However, all PA categories should aim (Dudley, 2008; Eagles et al., 2002) but not exclusively to

- conserve biodiversity,
- maintain diversity of landscape or habitat and of associated species and ecosystems and,
- operate using a management plan including a monitoring program to enable adaptive management.

PAs should also enable the conservation of landscape features, ecological monitoring, a visitor management as well as a sustainable use of resources (Dudley, 2008). They should also facilitate low-impact scientific research activities and provide education opportunities (Eagles et al., 2002; Dudley, 2008) and control the effectiveness of management actions and to decide upon their adaptation. Despite the different terms, definitions and categorizations in use, PAs should overall facilitate conservation and minimize threats to conservation goals. A crucial point to meet these goals is the acceptance of conservation areas by the landowners (Prutsch et al., 2008; Depraz & Laslaz, 2017; Von Ruschkowski & Mayer, 2011). To some extent they may also contribute to regional development, e.g., eco-tourism. In order to support the various management tasks, today, different methods and technologies are in use, e.g., remote sensing.

Ecological research for nature conservation requires integrating multiple technologies and methods in order to effectively reduce threats to ecosystems and endangered species (Marvin et al., 2016). In this context, UAS are perceived as a valuable asset in situations where the acquisition of cloud-free satellite data is impractical (Goebel et al., 2015) and complement other remote sensing methods. During the last decade, UAS have been increasingly employed not only for leisure and commercial activities, e.g., precision farming (e.g., Zhang & Kovacs, 2012), but also for research, monitoring and nature conservation purposes (e.g., Linchant et al., 2015; Wich & Koh, 2018; Pajares, 2015; Bhardwaj et al., 2016). The use of UAS is often motivated and justified by the demand of covering inaccessible areas (Sanderson, 2008) and because these devices facilitate high resolution (spatial, temporal, spectral dimension) image data acquisition at low cost and time (Weissensteiner et al., 2015; Manfreda et al., 2018). However, drawbacks of UAS applications are rarely reported, which is probably partly due to the short period of time since their introduction and related to the quite recent development of UAS regulations. This applies, e.g., to Europe, where UAS-related regulations became harmonized recently (EASA, 2020). Challenging aspects of UAS include legal aspects and impacts of their use, which is particularly of relevance when PAs are concerned. In the context of nature conservation and monitoring, the use of UAS is seen from two opposing standpoints: while monitoring of inaccessible areas facilitates a sound basis for the management of animal populations (McMahon et al., 2014), the disturbance of wildlife by UAS may counteract the undisturbed development of the monitored species (e.g., Laborie et al., 2021). The discussion of limitations and potential threats has recently increased (Smith et al., 2015; Borrelle & Fletcher, 2017; Mulero-Pázmány et al., 2017). Today, UAS are widely used in conservation and the related literature can roughly be divided into two main categories, of which one emphasizes the benefits of UAS-based data acquisition and monitoring in conservation, whereas the other discusses drawbacks and impacts of UAS to the wildlife concerned.

Satellite- and airborne remote sensing applications are widely established in ecological and biological research activities and UAS are increasingly used in this context as a complement (Ancin-Murguzur et al., 2020; Anderson & Gaston, 2013; Hodgson & Koh, 2016; Wang et al., 2019). For several years, UAS have been recognized as essential tools in wildlife and vegetation monitoring, for managing wildlife and to fight poaching (e.g., Schiffman, 2014; Ogden, 2013; Pajares, 2015). Several authors (e.g., Sandbrook, 2015; Wich & Koh, 2018) have even identified UAS as 'conservation drones' and recommended their use in applied conservation (Wich & Koh, 2018). Müllerová et al. (2017) highlighted the potential of low-cost UAS solutions for species monitoring and provided suggestions for practical management of plant invasions. UAS are a vital biodiversity-related remote sensing approach, since not only individual animals but even entire populations and endangered plant species can be studied (Guo et al., 2018; Hu et al., 2020; Rominger & Meyer, 2019). The cost-effectiveness and safe operability of UAS in conservation was, e.g., shown by Sykora-Bodie et al. (2017) by assessing a population of sea turtles, which is of prime importance in managing coastal marine ecosystems. However, a main challenge of using UAS in wildlife-related research remains the risk of potential disturbance. Reintsma et al. (2018) found UAS to have little influence on water birds compared to conventional methods due to the ability of faster work procedures. McEvoy et al. (2016) studied disturbance effects of UAS on wild waterfowl and found no apparent impact. The study by Vas et al. (2015) is another example for applying UAS without impacting wildlife. In contrast, Bennitt et al. (2019) showed that UAS used below 60 m above ground can affect mammals and therefore UAS-related regulations were called for. In some cases, UAS provoke at least short-term behavioral changes on wildlife (Ditmer et al., 2015; Rümmler et al., 2016). Another impact is the possibility of collisions with wild birds, a risk also known from manned flights (e.g., Jenny, 2010). UAS are recognized as an appropriate tool for wildlife surveys overcoming drawbacks of traditional methods, e.g., for wild waterfowl (McEvoy et al., 2016). Apart from technical specifications of the UAS and the mode of use, wild animal reactions depend on the individual itself and the animal type, e.g., birds in general show more severe reactions as compared to other animals, which is why specific guidelines for using UAS around wildlife are recommended (Mulero-Pázmány et al., 2017). However, the lack of an obvious reaction does not necessarily mean that the animals are not affected as they may still react on a physiological level, e.g., by the release of stress hormones, an increased heartrate or energy consumption (Romero & Wingfield, 2016; Wich & Koh, 2018).

In line with the many papers highlighting the significant support of so-called 'conservation drones', critical aspects and threats, e.g., collision with birds or disturbance of wildlife in general have already been addressed (Wich & Koh, 2018). However, the specific implications of using UAS in PAs have not been widely addressed yet. Against this theoretical background, the present article aims to review the use of UAS in PAs. Through an exemplary case study in a national park, a critical view on UAS applications and their challenges is sought. We want to show whether scientific studies based on UAS in PAs

(i) present the use of UAS as either relevant or irrelevant for the PA management in terms of biodiversity by assessing the respective study's aims,
(ii) discuss the use of UAS with respect to potential threats, and
(iii) display that the type of PA concerned matters in this context.

2. Methods

The article at hand provides an in-depth literature review on the use of UAS in PAs. Objectivity is obtained by following a consistent query approach that was conducted on 12 April 2021 via the standard scientific databases Web of Science and Scopus and that included all types of documents published before 2021. In order to analyze the articles dealing with UAS in PAs in a consistent manner and in relation to the IUCN management categories mentioned in Section 1, we queried the scientific databases with the search terms 'UAS', 'UAV' (for unmanned aerial vehicle), 'unmanned', 'drone', 'RPAS' (for remotely piloted aircraft systems), and 'remotely piloted'. Additionally, the terms 'protected area', 'nature reserve', 'wilderness area', 'national park', 'natural monument', 'habitat management', 'species management', 'protected landscape', and 'protected seascape' were used. In total, the number of keyword combinations, which was realized using Boolean operators, was 54. Following PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) recommendations (www.prisma-statement.org), the total number of references found (n = 852) was reduced to 673 after removal of duplicates. These references were then screened, which revealed some cases in which the search term had a different meaning from the one prior assigned to it. For instance, the search term 'UAS' was found to be used as an abbreviation for 'user accuracies'. With this first screening, the number of publications was further reduced to 226. Finally, after eligibility tests of full text contributions, a total of 89 references were included in the subsequent analysis and 137 references were excluded due to different reasons, e.g., being a review article or not fitting the precondition PA (e.g., Koh & Wich, 2012 reported the use of UAS adjacent to a PA). A visual overview of this selection procedure is provided in the appendix. Another crucial precondition to include a study in the subsequent analysis was that the PA concerned must be available in the World Database on Protected Areas (WDPAs) or in the database on Other Effective Area-Based Conservation Measures (OECMs) accessible via the website www.protectedplanet.net, which is provided by the IUCN and the United Nations Environment Programme World Conservation Monitoring Centre (UNEP-WCMC). These databases were last accessed on 26 April 2021.

In a next step, the selected articles were assessed for whether the respective study aims were relevant for the PA management in terms of biodiversity conservation. The main criterion for this assessment was whether biological organisms were relevant to the studies' goals, given that the conservation of biodiversity is a primary purpose of PAs. In addition, studies dealing with landscapes and habitats or suggesting UAS as a monitoring tool, all of which are related to biodiversity and the aims of PAs in general (see Section 1), were also assessed as relevant for the PA management. For instance, detecting animals or mapping their habitats was assessed as highly relevant in terms of PAs. If, in contrast, a study yields no obvious implications for biodiversity, because the respective study was aimed at abiotic processes or components, UAS use was considered irrelevant in terms of PA management and conservation. For example, the geomorphic changes studied by Schraml et al. (2015) could potentially inform management actions, but the study's intention (which is the investigation of debris-flow activity) is not relevant for PA management in terms of biodiversity conservation. Finally, the articles were analyzed concerning disturbance caused by UAS use and the IUCN categorization.

3. Results

3.1. Time of publication and type of PA

The literature search based on the aforementioned criteria resulted in 89 publications (Table 1). Apart from a few earlier pioneer studies, most of the publications examined were published from 2015 onwards with a noteworthy increase after 2017 (Fig. 1, Table 1). Concerning the PA category, the results show that all IUCN management categories are represented except the category Ib (Fig. 1). Furthermore, the articles are dominated by studies conducted in national parks (IUCN category II) followed by studies in habitat/species management areas (category IV) and in PAs for which IUCN categories are not reported or for which a categorization is not applicable, such as World Heritage Sites (natural or mixed), Wildlife Management Areas, Sites of Special Scientific Interest, Ramsar Sites (Wetlands of International Importance), Special Protection Areas (under the European Union Birds Directive), Sites of Community Importance (European Union Habitats Directive), Natura 2000 areas (European Union), UNESCO-MAB Biosphere Reserves. Although these PA categories were not part of the database query, they turned up as a result of using the general search term 'protected area' and were therefore also considered in the analysis. Whenever multiple categories for the same PA were found, the IUCN category was used for classification if available.

3.2. Spatial origin of the studies, UAS type and methods used

Fig. 1 shows a clear majority of investigated studies from Europe followed by a high number of studies from Asia. Remarkably, among the studies that met the search criteria only a few studies were conducted in Africa and Antarctica. Concerning the type of UAS used it can be noted that multirotor solutions predominate by far (60) over fixed-wing UAS (24 studies) and over a minor number of helicopters, kites, blimps, and undefined UAS types (Fig. 1). Among the multirotor solutions, the low-cost and easy-to-use solutions of the Chinese technology company DJI (battery-powered Phantom, Inspire or Mavic) prevail (36 studies). Some studies (5) also relied on higher budget devices and more professional DJI models/products (Matrice, S1000, S800). From a methodological point of view, it can be noted that most of the studies used photographs to generate photogrammetric results such as orthophotos and digital elevation models (DEMs).

3.3. Linkage between categories

Focusing on the linkage between the analyzed categories (Fig. 1), it becomes apparent that the PA category and the year of publication tend to match the above-mentioned pattern, e.g., most studies in national parks were published after 2017. However, for studies conducted in IUCN category III, no such clear correlation concerning the year of publication can be found, which is probably owed to the comparably low number of studies included (Fig. 1). By considering both the continent and IUCN management category, Fig. 1 also reveals that all category V-related studies were conducted in Europe. No remarkable correlations between UAS type and continent can be deduced.

3.4. Main purpose of the study and potential disturbance of UAS

Out of the 89 studies selected (Table 1), 73% (65) were assessed as relevant for PA management in terms of biodiversity (Fig. 2). The remaining 24 articles (27%) were classified as irrelevant for PA management (Fig. 2), which discussed neither issues nor consequences of UAS use for wildlife or the environment. Remarkably, among the 65 studies with relevance for PA management in terms of biodiversity, 77% of articles (50) did not discuss or even mention potential disturbance of UAS.

3.5. Actual impacts caused by UAS

Among the 15 articles (23%) dealing with potential issues related to the use of UAS in PAs, most (n = 9) did not notice any or only minor disturbance. Four articles reported no disturbance: two dealing with birds in general (Afán et al., 2018; Ivošević et al., 2015), one with terns (Chabot & Bird, 2015), and one with crocodiles (Thapa et al., 2018). Minor disturbance was expressed in different ways or recommendations: observable disturbance on orangutans was minimized by the use of small LEDs (Abdul Mutalib et al., 2019), potential effects of UAS should be minded as elephants do react to UAS (Hahn et al., 2017), the reactions of sika deer were negligible (Liang et al., 2020), cattle and other ungulates did not noticeably react to UAS (Mulero-Pázmány et al., 2015), and in one case hippopotamus did not show any reactions (Linchant et al., 2018), which was owed to the UAS shape resembling a bird (Fig. 2). Three further articles recommended disturbance-minimizing use of UAS, one of which studied the optimum flying height aimed at reducing the influence of UAS on black-faced spoonbill (Liu et al., 2015), one article mentioned appropriate flight planning and choice of device (Ancin-Murguzur et al., 2020) and another one mentioned that UAS are

Table 1
List of 89 selected publications addressing the use of UAS in PAs.

Authors and year of publication	Name of protected area, country	IUCN category[1]	Study aims / intention
Abdul Mutalib et al., 2019	Semenggoh Nature Reserve, Malaysia	II	To examine the feasibility of thermal imaging for orangutan mapping
Afán et al., 2018	Parque nacional de Doñana, Spain	II	Integrating UAS in the long-term monitoring of waterbird population censuses
Aldous et al., 2020	Parc national de Loango, Gabon	–	Establishing an accurate baseline map for adaptive management and monitoring future change in wetland habitats
Alexander et al., 2018	Gunung Leuser National Park, Indonesia	II	To assess the suitability of UAS data for locating emergent trees and potential sleeping trees for hylobatids
Ancin-Murguzur et al., 2020	Jotunheimen nasjonalpark, Norway	II	To assess the accuracy and reliability of UAS data for monitoring impacts derived from recreational use
Asbridge et al., 2019	Kakadu National Park, Australia	II	To determine local drivers of expansion within areas that had experienced dieback in the context of broader climate and sea-level change
Balková et al., 2020	Žďárské vrchy, Czech Republic	V	To describe the vegetation development of a place that has been influenced (by humans or by natural processes)
Barasona et al., 2014	Parque nacional de Doñana, Spain	II	Modeling the spatial pattern of abundance for each potential host species and evaluating the predictions of host abundance obtained from UAS data
Barnas et al., 2018	Wapusk National Park, Canada	II	To quantify the behavioral responses of nesting waterfowl to UAS surveys
Brooke et al., 2015	Papahānaumokuākea Marine National Monument, USA	–	Integrating UAS into effective management of vital marine resources
Cagnazzo et al., 2020	Bosco Pantano di Policoro e Costa Ionica Foce Sinni, Italy	IV	Assessing the health of the coastal environment in a natural protected area
Castellanos-Galindo et al., 2019	Parque nacional natural Ensenada de Utría, Colombia	II	Improving the knowledge of conservation targets and facilitating the monitoring process in Marine Protected Areas
Castillo et al., 2018	Reserva de Producción de Fauna Chimborazo, Ecuador	–	Estimating the photosynthetic activity by means of vegetation indices and characterizing the spatial features of the forest
Chabot and Bird, 2015	Kouchibouguac National Park, Canada	VI	Comparing UAS-based with ground counts and assessing sources of variation and error in detection rates as well as the estimation of the number of nests in a tern colony
Chio & Lin, 2017	Yangmingshan National Park, Taiwan	II	The thermal image collection of a quadcopter UAS for volcanic geothermal monitoring
Clarke et al., 2019	Poole Harbour Special Protection Area (SPA), England/UK	IV	Quantifying the spatial extent and intensity of shellfish dredging in intertidal mudflats in a designated PA
Cody et al., 2020	Aoraki Mount Cook National Park, New Zealand	II	The understanding of how geological structures precondition paraglacial rock slope failures and influence their response to contemporary glacier retreat
Cwiakala et al., 2018	Tatrzański Park Narodowy, Poland	II	To document the selected linear hiking trails between the lower subalpine zones and alpine glades
Dabski et al., 2020	Western Shore of Admiralty Bay, Antarctica	–	Determining the area and spatial distribution of glacial landforms
Dai et al., 2018	Yancheng Rare Birds Nature Reserve, China	–	Exploring the evolution of muddy tidal flat and to quantify change rates
Dale et al., 2020	Medmerry, England/UK	IV	To investigate the erosion and accretion of sediments of a creek system
De Luca et al., 2018	Area Naturale Marina Protetta Capo Caccia Isola Piana, Italy	IV	Producing overlapping maps to control the evolution of biocenoses in real time
Díaz-Varela et al., 2018	Serra Do Xistral, Spain	–	The integration of photogrammetric image reconstruction techniques and object-based image analysis for the automatic estimation of vegetation types
Dimitrov et al., 2019	Gornata Koria Reserve, Chuprene Biosphere Reserve, Bulgaria	Ia	Integration of UAS and traditional entomological and phytopathological methods for investigating the sanitary status of two PAs
Edmonds, 2019	Axmouth to Lyme Regis Undercliffs, England/UK	IV	Detailed mapping of the foreshore in front of great undercliff landslides
Eugenio et al., 2020	Las Dunas de Maspalomas, Spain	V	Monitoring of a complex water inner lagoon including water quality parameters to support the sustainable management of natural resources
Fürstenau Oliveira et al., 2017	Parque Estadual Do Cantão, Brazil	II	Detecting and counting dolphins and groups of dolphins compared to observations using a canoe
Fugazza et al., 2015	Parco Nazionale Dello Stelvio, Italy	II	The feasibility of UAS for mapping several glacier features
Fugazza et al., 2018	Parco Nazionale Dello Stelvio, Italy	II	To compare the different methods and select the most appropriate ones for monitoring glacier hazards
Gallik & Bolesova, 2016	Tatranský národný park, Slovakia	II	To demonstrate benefits of small UAS in inaccessible areas and unfavorable weather conditions
Goncalves et al., 2016	Serra D'Arga, Portugal	–	Assessing complex, dynamic vegetation mosaics composed of several European Union habitat types of high conservation value in terms of monitoring habitat types
Gray et al., 2019	Refugio de vida silvestre Ostional, Costa Rica	VI	The feasibility of using deep-learning techniques to increase the efficiency of an aerial image-based population assessment of sea turtles
Ha & Yang, 2020	Xinjiang Tianshan, China	–	To find out the spatial suitability of different types of monitoring tools in landscape monitoring
Hahn et al., 2017	Burunge Wildlife Management Area, Tanzania	–	Testing the efficacy of UAS operated by trained wildlife managers to move elephants out of conflict zones
Hamylton et al., 2020	Five Islands Nature Reserve, Australia	IV	To evaluate how a machine learning algorithm can be used to detect Lomandra and how this relates to other commonly used approaches for vegetation mapping
Hese et al., 2019	Nationalpark Hainich, Germany	II	To examine the potential of small UAS for detailed multi-seasonal tree canopy mapping
Ivošević et al., 2015	Chiaksan National Park, Taeanhaean National Park, Republic of Korea	II	To obtain photographs and videos of monitoring areas and to assess if UAS are suitable under different conditions
Johnston et al., 2016	Christmas Island, Australia	II	To determine the proportion of baits that would be caught in vegetation or be otherwise inaccessible to feral cats if aerial baiting was to be undertaken
Kapetanović et al., 2020	Nacionalni park Plitvička jezera, Croatia	–	UAS-based orthophotos as basis for automatic bathymetric measurements
Klouček et al., 2019	Krkonoše, Czech Republic	–	Distinguishing healthy and infested trees in the green attack stage and performing a detailed spatial analysis at the level of individual trees

(continued on next page)

Table 1 (*continued*)

Authors and year of publication	Name of protected area, country	IUCN category[1]	Study aims / intention
Kohv et al., 2017	Selisoo, Estonia	IV	To measure pool bank heights with different methods and to construct a (semi-)automatic workflow in a GIS for bog pool delineation
Koucká et al., 2020	Jizerské Hory, Czech Republic	V	To identify the extent of historical and current mining areas of sapphires and iserines in order to increase protection of these sites
Lehnert et al., 2018	Pan de Azúcar National Park, Chile	II	To unveil the fog dynamics in austral autumn in a typical fog oasis
Lendzioch et al., 2016	Národní park Šumava, Czech Republic	II	Snow depth patterns of two different environments such as open area and dead spruce forest stand
Lendzioch et al., 2019	Národní park Šumava, Czech Republic	II	To introduce a workflow for efficient UAS-based snowpack monitoring
Liang et al., 2020	Kenting National Park, Taiwan	II	Conducting the first assessment of Formosan sika deer herd composition, reproductive activity, and social behavior
Linchant et al., 2018	Parc nat. de la Garamba, Dem. Rep. of Congo	II	Determination of the optimal parameters for estimating accurate hippo population sizes with UAS
Liu et al., 2015	Taijiang National Park, Taiwan	II	To investigate the feasibility of supporting the annual international black-faced spoonbill census with a low-cost UAS system
López-Jiménez et al., 2019	Reserva de la biosfera Tehuacán-Cuicatlán, Mexico	VI	A deep learning-based approach for recognizing cactus species
Mallmann et al., 2020	Parque Estadual Quarta Colônia, Brazil	II	To evaluate vegetation indices extracted from multispectral images based on UAS in terms of managing invasive species
Miranda et al., 2020	Fildes Penins., King George I., Areas Bey. Nat. Jurisdiction	–	To accurately detect recent changes on vegetation covers in Antarctica through remote sensing
Miřijovský et al., 2015	Národní přírodní rezervace Ramena řeky Moravy, Czech Republic	III	To quantify the historical evolution of the anastomosed/meandering river system modified by river regulation
Mohd Razali et al., 2020	Tanjong Piai National Park, Malaysia	II	To map mangrove density based on vegetation indices for health area identification
Mulero-Pázmány et al., 2015	Parque nacional de Doñana, Spain	II	To test the suitability of UAS images for modeling spatial distribution patterns of animals as compared to widely used methods
Nahirnick et al., 2019	Pacific Rim, Gulf Islands, Gwaii Haanas National Park Reserve and Haida Heritage Site, Hakai-Luxvbalis Conservancy, Canada	II	To understand the limitations of UAS-based mapping of seagrass extent across a temperate coastal region
Natesan et al., 2020	Petawawa Terrace Provincial Park, Canada	Ia	Identification of individual conifer tree species of economic value occurring in mixed-wood set-up
Ngo et al., 2020	Ngoc Linh, Vietnam	IV	To analyze the characteristics of vegetation types based on plant indicators obtained from UAS
Popa et al., 2016	Blocurile De Calcar De La Bădila, Romania	III	To analyze the areal distribution of limestone blocks and to evaluate the textural features of the block assemblage
Prošek & Šímová, 2019	Doupovské hory, Czech Republic	–	To find out if the fusion of multispectral information and vertical data can significantly improve the classification accuracy of shrubland vegetation
Rivas-Torres et al., 2018	Galápagos National Park, Ecuador	–	To fill knowledge gaps in the spatial distribution of native and invasive-dominated vegetation units on tropical islands
Röder et al., 2018	Bayerischer Wald, Germany	II	To compare the performance of UAS- and aerial photo-based stand-structure data and to explore the accuracy over a range of forest sites
Ruessink et al. 2018	Nationaal Park Zuid-Kennemerland, Netherlands	II	To quantify and interpret the geomorphic dynamics of a (fore)dune system
Safonova et al., 2019	Mininskie Stolby, Russia	III	Testing the possibilities of neural networks as a new approach to detect bark beetle outbreaks in fir forests
Sandino et al., 2018	Cape Range National Park, Australia	II	Creating a global approach for the surveillance of invasive grasses and related biosecurity applications
Scher et al., 2020	Morton Arboretum, USA	–	To investigate how high-resolution multispectral imagery and volume estimates correlate with field-based estimates of grassland productivity
Schiefer et al., 2020	Nationalpark Hainich, Germany	II	To map tree species in heterogeneous forests
Scholefield et al., 2019	Moor House-Upper Teesdale, England/UK	IV	To explore the potential of high spatial resolution imagery obtained from a UAS platform for mapping an upland blanket bog
Schraml et al., 2015	Nationalpark Gesäuse, Austria	II	Investigation of debris-flow activity in steep channels and to obtain a time series
Seier et al., 2020	Nationalpark Gesäuse, Austria	II	To detect intra- and multiannual sediment changes of a gravel-bed channel and to reveal consequences of methodological issues
Smigaj et al., 2019	Loch Lomond and The Trossachs, Scotland/UK	IV	UAS-borne thermal imagery for detecting disease-induced canopy temperature increase and exploring the influence of the imaging time and weather conditions
Somers et al., 2016	Huascarán National Park, Peru	II	To combine heat tracing and dye tracing methods to quantify the groundwater contributions
Sona et al., 2014	Parco Naturale Dell'Adda Nord, Italy	V	Validating vector-sensor systems and optimizing the UAS survey for 3D modelling and to compare different software packages
Stark et al., 2018	Lower Kinabatangan Wildlife Sanctuary, Malaysia	IV	Assessing the effectiveness of UAS-based data combined with satellite tracking data of an endemic, endangered species to facilitate policy changes regarding riparian habitat destruction
Suo et al., 2019	Buckroney-Brittas Dunes and Fen SAC, Ireland	–	Vegetation mapping of a coastal dune complex
Takayama et al., 2020	Common fishery right area (Tottori), Japan	VI	To analyze the spatial distribution of sand movement and the vegetation cover ratio to investigate changes
Thapa et al., 2018	Bardia National Park, Nepal	II	To count gharials (a critically endangered crocodilian species) along a river stretch
Urban et al., 2019	Tatranský národný park, Slovakia	II	To analyze and evaluate the overall suitability of low-cost UAS photogrammetry for the needs of monitoring selected geohazards
Van Andel et al., 2015	Parc national de Loango, Gabon	–	To detect chimpanzee nests, and which conditions increase the detection rate as well as to locate and identify fruit tree species to characterize a chimpanzee habitat

(*continued on next page*)

Table 1 (*continued*)

Authors and year of publication	Name of protected area, country	IUCN category[1]	Study aims / intention
Ventura et al., 2018	Parco Nazionale Dell' Arcipelago Toscano, Italy	II	Evaluating the utility of small UAS in the field of marine ecology for monitoring benthic-sensitive habitats
Weimerskirch et al., 2018	Réserve Naturelle Nationale des Terres Australes Française, France	IV	To examine the sensitivity of different seabird species breeding on a sub-Antarctic island to UAS disturbance and to examine whether the individuals of different status react differently to UAS
Witczuk et al., 2018	Drawieński Park Narodowy, Poland	II	To explore the feasibility of a UAS and TIR imaging system for ungulate surveys in forests
Witt et al., 2020	Gir-um-bit, Australia	II	To test a survey protocol and to assess the effectiveness and efficiency of UAS thermal imaging sensors for detecting koalas
Woellner & Wagner, 2019	Ammergebirge, Germany	IV	To demonstrate how a low-cost UAS was used to easily acquire all relevant monitoring data outlining the dynamic processes of the ecosystem and to document short-term habitat changes
Wright et al., 2018	Bosque de protección del Alto Mayo, Peru	VI	To highlight an integrated forest monitoring system that leverages cutting edge technology to empower rangers to stop deforestation
Yin & Wang, 2019	Shankou National Mangrove Nature Reserve, China	–	To explore the possibility of identifying individual mangrove trees using high point density UAS-LiDAR data
Zapico et al., 2020	Parque natural del Alto Tajo, Spain	II	To quantify global earth movements due to mining activity in a stream catchment and to characterize the shape and displacement of a landslide
Zhang et al., 2016	Dinghushan National Nature Reserve, China	–	To explore the utility of using lightweight UAS as a flexible, cost-effective, and accurate method for mapping forest stand characteristics
Zhang et al., 2020	Paramos de Guantiva y la Rusia, Colombia	VI	Mapping frailejones across the páramos to enhance the current monitoring of the park authorities and other agencies responsible for the conservation
Zhu et al., 2019	Zhanjiang Mangrove National Nature Reserve, China	–	Exploring mangrove-inundation spatial patterns across a subtropical estuarine wetland in order to quantitatively evaluate the role of inundation regime

[1] Categories according to IUCN (1994) and Dudley (2008). In case of multiple categories only the category with most natural conditions (Dudley 2008) is mentioned. If no IUCN category was reported or if the IUCN categorization did not apply to the PA concerned, then this was marked with a hyphen.

generally less invasive than drive counts (Witczuk et al., 2018; Fig. 2). In contrast, only three articles proved the behavioral impact of UAS: Barnas et al. (2018) found disturbance on nesting waterfowl, Brooke et al. (2015) found impact on birds in general, while sea turtles and monk seals were not affected, and Weimerskirch et al. (2018) found that the reaction of birds highly depended on the bird species (Fig. 2). However, due to different UAS models, survey configurations (flying height etc.) and wildlife, general statements on behavioral changes or disturbance are hardly possible. Also, wildlife response to UAS need not manifest itself in easily observable changes in behavior but might entail physiological consequences (e.g., Ditmer et al., 2015). Moreover, while less than 50% (41) of the investigated studies were carried out in national parks, approx. 73% of the articles mentioning possible disturbance were conducted in national parks (11 out of 15), which illustrates this PA category's high relevance in this context.

3.6. Summary of findings and lessons learned

Overall, the literature review can be summarized by seven main lessons learned, which are relevant for PA management:

1. The application of UAS should be based and or justified by a scientific monitoring concept. However, within this concept the application of non-disturbing research approaches such as remote sensing should be preferred (e.g., Afán et al., 2018; Castellanos-Galindo et al., 2019).
2. The literature review revealed a high suitability of UAS for the mapping of wildlife and vegetation and for monitoring of natural resources and landscape change (e.g., vegetation coverage, glacier retreat, geological or geomorphological features, see, e.g., Asbridge et al., 2019; Balková et al., 2020).
3. The review also shows that possible impacts on wildlife depend on many different influencing factors such as the type of UAS, the monitored or affected species and the overall conditions (e.g., presence of other species, size of the group, see, e.g., Barnas et al., 2018; Weimerskirch et al., 2018).
4. A research or monitoring concept applying UAS should include the discussion of possible mitigation and adaptation measures. Mitigation may be achieved by considering appropriate vehicles (size, shape) and flight plans to reduce potential impact (e.g., Barnas et al., 2018; Linchant et al., 2018).
5. To support PA management, UAS should be applied in a multidisciplinary manner, including different approaches and topics, e.g., aspects of outdoor recreation (e.g., Ancin-Murguzur et al., 2020; Cwiakala et al., 2018).
6. PA management may profit from the application of UAS due to a significant cost reduction compared to other inventory methods (e.g., Liu et al., 2015; Zhang et al., 2016).
7. Finally, the application of UAS facilitates visualization and mapping (e.g., 3D modelling and vegetation mapping, e.g., Sona et al., 2014; Suo et al., 2019).

4. Discussion

4.1. Methodological considerations

The review tried to be as inclusive as possible. However, although the search query was based on common scientific databases and used search terms covering a wide range of obvious keywords, not all relevant documents were found, e.g., the study by Seier et al. (2017) was conducted in a national park and was mainly based on UAS, but the PA was not mentioned in this article apart from the acknowledgements and thus the article was not found in the search query. This example shows the limitations of a search query approach in general. Apart from potential biases resulting from the search query, other issues arise with studies relating to PAs in general. For instance, as PAs and their implementation are not uniformly defined and/or realized it cannot be guaranteed that all articles found are really about well-established PAs and not dealing with so-called 'paper parks' instead, that have no effective management and therefore only exist on a legislation level or 'on paper', so to speak (Rife et al., 2013; Di Minin & Toivonen, 2015; Pieraccini et al., 2017; cf. Castellanos-Galindo et al., 2019). In addition, a national park as defined by the legislation in one country might not qualify as such in another. Therefore, the WDPA-based IUCN management categories were used instead of simply adopting the PA categories provided by the cited publications.

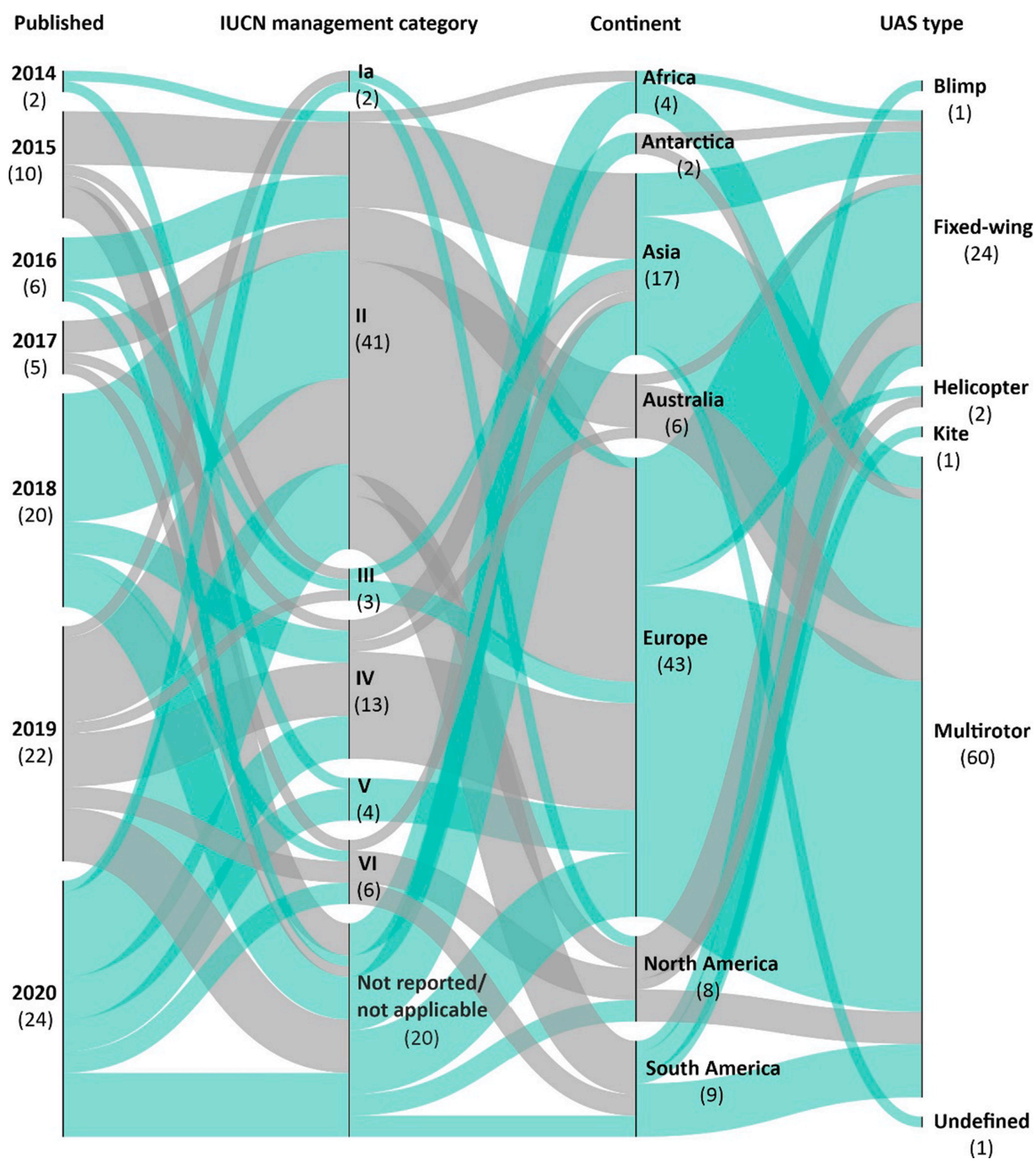

Fig. 1. The investigated studies (n = 89) classified by year, IUCN management category, continent, and UAS type.

4.2. Case study of the Gesäuse National Park (GNP) in Austria

In order to discuss the main findings, an Austrian national park was used as a case study, which also serves as a benchmark to scrutinize a discussion solely based on literature. Against this background, the relevance and applicability of the lessons learned (Section 3.6) are evaluated:

The GNP management defined the recording and long-term observation of natural processes as a research priority (Maringer & Kreiner, 2016), with a special focus on species and habitats. In the last decades, research in the GNP mostly dealt with bioscientific or management-oriented studies, whereas long-term (i.e., multi-annual) and interdisciplinary studies dedicated to processes and monitoring remained few (Maringer & Kreiner, 2016). This may change by increasingly using UAS for GNP-related research in the future. Although the use of UAS in the GNP is prohibited for commercial and leisure activities (Nationalpark Gesäuse, 2020), UAS can be used for research purposes. However, from the perspective of the GNP management, the methods of choice should be non-intrusive and minimally invasive (Maringer & Kreiner, 2016). The guidelines for research therefore confirm the necessity of a research concept before applying UAS and the consideration of other non-invasive methods such as remote sensing data analyses (see Section 3.6 (1)).

In the GNP, one site of ongoing research is an alluvial channel with high sediment yield and intermittent discharge (Lieb & Premm, 2008; Rascher et al., 2018; Fig. 3). Using UAS, it was possible to quantify related sediment changes over the course of several months in 2015 (Schöttl, 2017) and multi-annual (2015–2019) erosional and depositional changes of several meters (Seier et al., 2020). The UAS-based acquisition required a special license issued by the GNP in order to declare the research-related activity. During the assessment as to whether a special license can be issued and the definition of requirements, the GNP management pointed out the location of an eagle's nest in the vicinity of the study area, which had to be considered during flight planning. For each individual case, the GNP management balances all relevant arguments and situations in order to minimize potential disturbance while supporting research. The application of UAS in the GNP confirms the high suitability of UAS for the inventory and monitoring of environmental changes (see Section 3.6 (2) and Fig. 3). Because the breeding status of birds of prey from the accipitrid family is of particular concern when it comes to disturbance, UAS use was restricted to specific time slots and short-term notification of the GNP

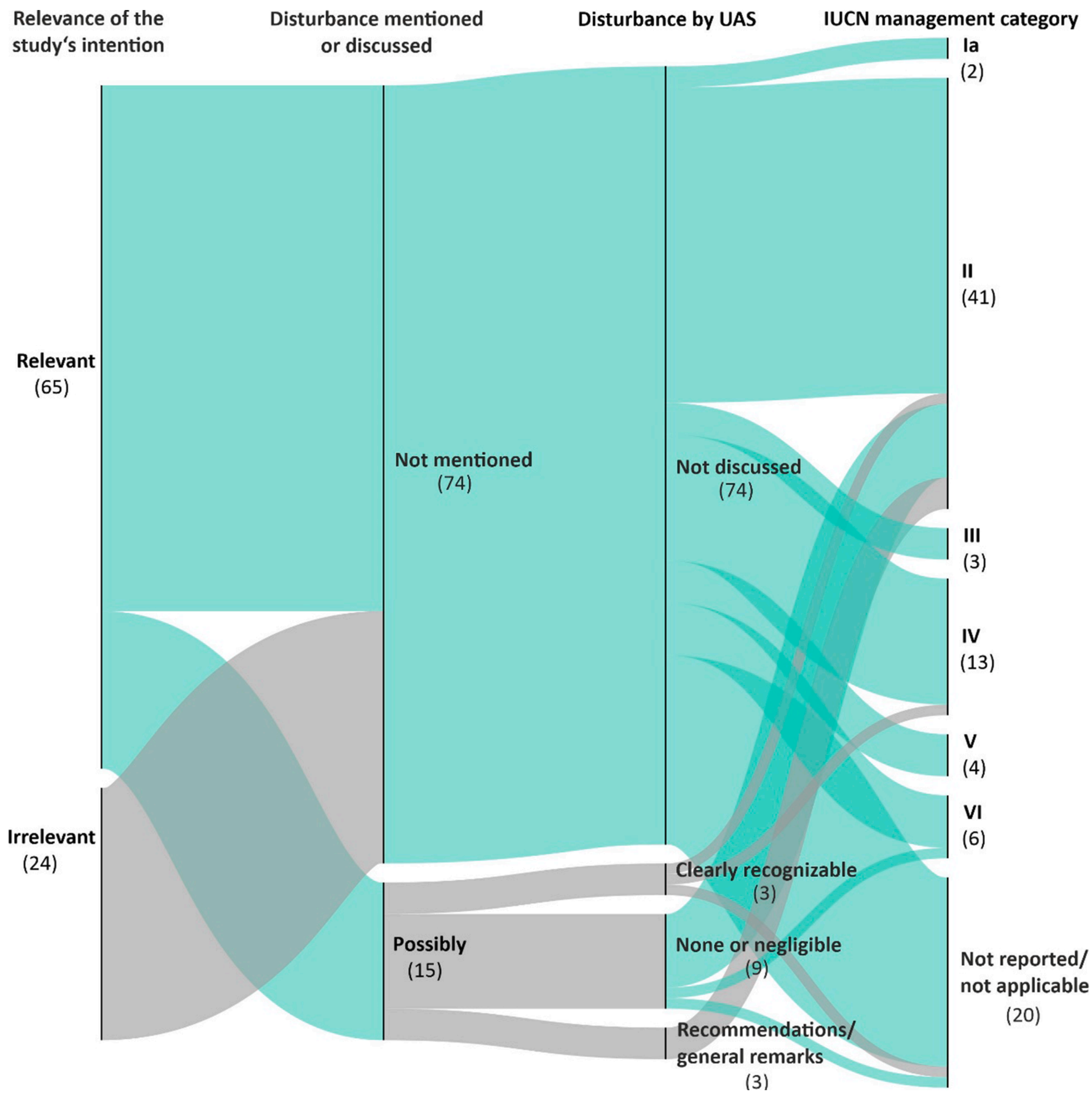

Fig. 2. The investigated studies (n = 89) categorized by the relevance of the study's intention for the PA management in terms of biodiversity conservation, disturbance or issues related to UAS, description of how disturbance was mentioned, and the IUCN management category.

management by the flight operators was required. This example shows that communication and cooperation of all stakeholders is essential to ensuring minimally invasive UAS operation in PAs, that, in addition to the scientific output, informs management decisions. In contrast, but in line with the fact that privately owned UAS have become popular, the GNP management recorded several incidents: raptor bird nests were dangerously encroached by UAS from climbers surveying their routes and by a group using their UAS to take photos; in other cases, pilots were stopped operating their UAS by intervention of GNP employees; in another case, the publication of UAS-acquired videos via an internet platform was prohibited and later taken offline (Maringer, personal communication 2021). Apart from the above-mentioned study of an alluvial channel that was initiated and carried out by researchers not affiliated with the GNP, the GNP has commissioned UAS-based research for vegetation mapping and long-term observations of natural processes (e.g., Hecke et al. 2017, see Section 3.6 (6)).

Overall, this case study confirms the main findings of the literature review. The application in the GNP is a good example for mitigation and a wise use of UAS. In addition, the GNP management is convinced that the use of UAS is likely to play a major role in long-term observations of natural processes and in terms of vegetation mapping, which is in line with the review findings. The development of UAS use in PAs shows similarity to other technology-based activities in PAs such as geocaching (Hödl & Pröbstl-Haider, 2017), which is likely to lead to negative effects for the environment if the activity is not regulated. Therefore, a multidisciplinary application of UAS might be necessary in the future to survey also certain outdoor recreation activities (see Section 3.6 (5)).

4.3. UAS in conservation research

The articles investigated discussed a broad variety of topics such as vegetation, wildlife and habitats, geomorphology and hydrology, methodological aspects, and anti-poaching. Only a minority of investigated articles discuss the topic of wildlife disturbance caused by UAS. General statements on behavioral impacts induced by UAS cannot be made due to the diversity of UAS models currently available (Barnas et al., 2018). Nevertheless, disturbance induced by UAS is not necessarily detrimental from a management perspective. For example, since it was found that elephants react to small UAS (lights, noise), they became a means to dislodge elephants from conflict zones (Hahn et al., 2017). However, 83% of investigated studies did not discuss disturbance, although the research was conducted in PAs, which is in contrast to the

Fig. 3. A photograph acquired by a small UAS, which shows the eastern section of an alluvial channel located in the GNP (approx. direction of view: east-northeast), photo acquisition: 17 October 2019, G. Seier/N. Landl/S. Kostka.

fact that numerous articles have already examined UAS-induced wildlife disturbance outside PAs (e.g., Mulero-Pázmány et al., 2017). For instance, Barr et al. (2020) investigated disturbance of mixed-species waterbird colonies caused by a UAS (quadcopter) at different flying heights and found no evidence of increasing colony-wide escape behavior except for the lowest flying height. A species-specific reaction to UAS was also shown by Brisson-Curadeau et al. (2017) for seabirds, and they emphasized that UAS provide a comparably less hazardous and potentially more accurate method for surveying wildlife than conventional methods. However, both studies (Barr et al., 2020; Brisson-Curadeau et al., 2017) recommended further research on wildlife response, e.g., for the purpose of defining species-specific flight distances to reduce or mitigate impact. Goebel et al. (2015:629) emphasized that UAS are promising for ecological applications and assessed noise-induced impact as minimal as "[…] even at close range during takeoff and landing, noise levels are typically exceeded by background noises from animals, ocean waves, and wind." In their review of UAS for wildlife monitoring, Linchant et al. (2015) underline that UAS are an adequate solution for monitoring animal populations and to assist wildlife protection, as these vehicles enable records with high spatial resolution at low costs, while also reducing the risk for operators (compared to ultralight motorized aircraft). In addition to the potential impacts of UAS on the object of study such as animals, conservation is particularly challenging in situations where people live within the boundaries or in the vicinity of PAs, using the local resources, e.g., for fuelwood (Humle et al., 2014). In such cases, UAS may be perceived as threatening by local people (Humle et al., 2014). This is likely counterproductive since local people and their participation play a key role in the conservation of endangered habitats and species (e.g., Pröbstl, 2003). Applying UAS may have positive social impacts, e.g., UAS are in many regards safer than manned aircraft (Jones et al., 2006) and are perceived socially empowering if local people are enabled to collect their own data (Paneque-Gálvez et al., 2014). In contrast, UAS could entail a range of potential concerns, e.g., in terms of privacy and data security (Sandbrook, 2015). Therefore, there is the need for more empirical research on the social effects of UAS and on good ethical practices minimizing the risk of unintended consequences (Sandbrook, 2015) as well as on the values of societies living close to critical biodiversity (Manfredo et al., 2017). Using UAS in conservation can work well in some settings, whereas in other cases they might distract attention from conservation issues (Sandbrook, 2015). Also, misuse of UAS is an issue, necessitating so-called anti-drone services disrupting UAS operations. To this end, Noh et al. (2019) developed an improved solution that enables safe hijacking in the sense of remotely removing UAS from an area.

Although general effects of UAS are difficult to determine, measures can be taken to reduce the potential impact of UAS on wildlife and expand the use of UAS for wildlife population research and ecological monitoring (e.g., Mangewa et al., 2019). Starting and landing the vehicle beyond the animals' field of vision, as well as flying trajectories that do not follow the investigated species' movement pattern, are some easily implementable measures, as McEvoy et al. (2016) discovered in their study of waterfowl. They also proposed determining fixed flying heights and conducting flight maneuvers with considerable distances from the animals to prevent any disturbance.

UAS are now widely employed in sciences and conservation, allowing for insights that would otherwise be impossible to gain (e.g., Schofield et al., 2017; Jiménez López & Mulero-Pázmány, 2019; Strumia et al., 2020). Nevertheless, the rationale behind using UAS in some cases may be related to the question whether UAS have already been effectively employed for the desired research purpose or may also simply be owed to a researcher's desire to test this new technology hands-on. Against this backdrop, our findings suggest the consideration of possible UAS-caused impacts by PA stakeholders and UAS users, in particular in PAs.

5. Conclusions

In this review article we discuss the potential, limitations, and challenges of UAS use in PAs. For most (73%) of the investigated studies ($n = 89$) the use of UAS was assessed as relevant for the PA management in terms of biodiversity. Among these, about 77% did not report impacts caused by UAS which probably reflects a low awareness of UAS users for possible impacts. Therefore, it is not surprising that among the remaining 23% (i.e., the studies mentioning possible effects) only three (approx. 3% of the investigated studies) articles highlighted clearly detectable disturbance effects. One major outcome of this study is that the likelihood of possible impacts and disturbances are insufficiently considered in PA-related applications. Consequently, PA managers and study designers should carefully assess, and if possible, initiate and support further investigations in order to minimize controversial use of UAS.

About 74% of the investigated studies were published after 2017, indicating that the use of UAS in PAs is a comparably new and emerging scientific field. Moreover, we found slight indications that the type of PA is relevant for the disturbance mentioned, as less than a half of all the investigated studies were conducted in national parks (IUCN category II) but 73% of those studies reporting possible disturbance.

The paper at hand delivers arguments to carefully use this new opportunity, to enhance UAS users' and PA managers' awareness of the possible impact of these devices on wildlife, to initiate suitable mitigation measures, and to provide a clear concept of giving flight permissions, which should be limited to a necessary level.

The review also reveals research fields and crucial aspects which may be suitable to guide the use of UAS in PAs. The application of UAS should be based and/or justified by a scientific monitoring or management concept considering non-disturbing research methods. Advantages due to multidisciplinary applications should be tested and further researched. Future applications should carefully consider possible impacts in advance including possible mitigation measures and adaptation processes. Finally, the literature review and applications worldwide highlight advantages of UAS for PAs in terms of cost reduction and time saving as well as for mapping and monitoring.

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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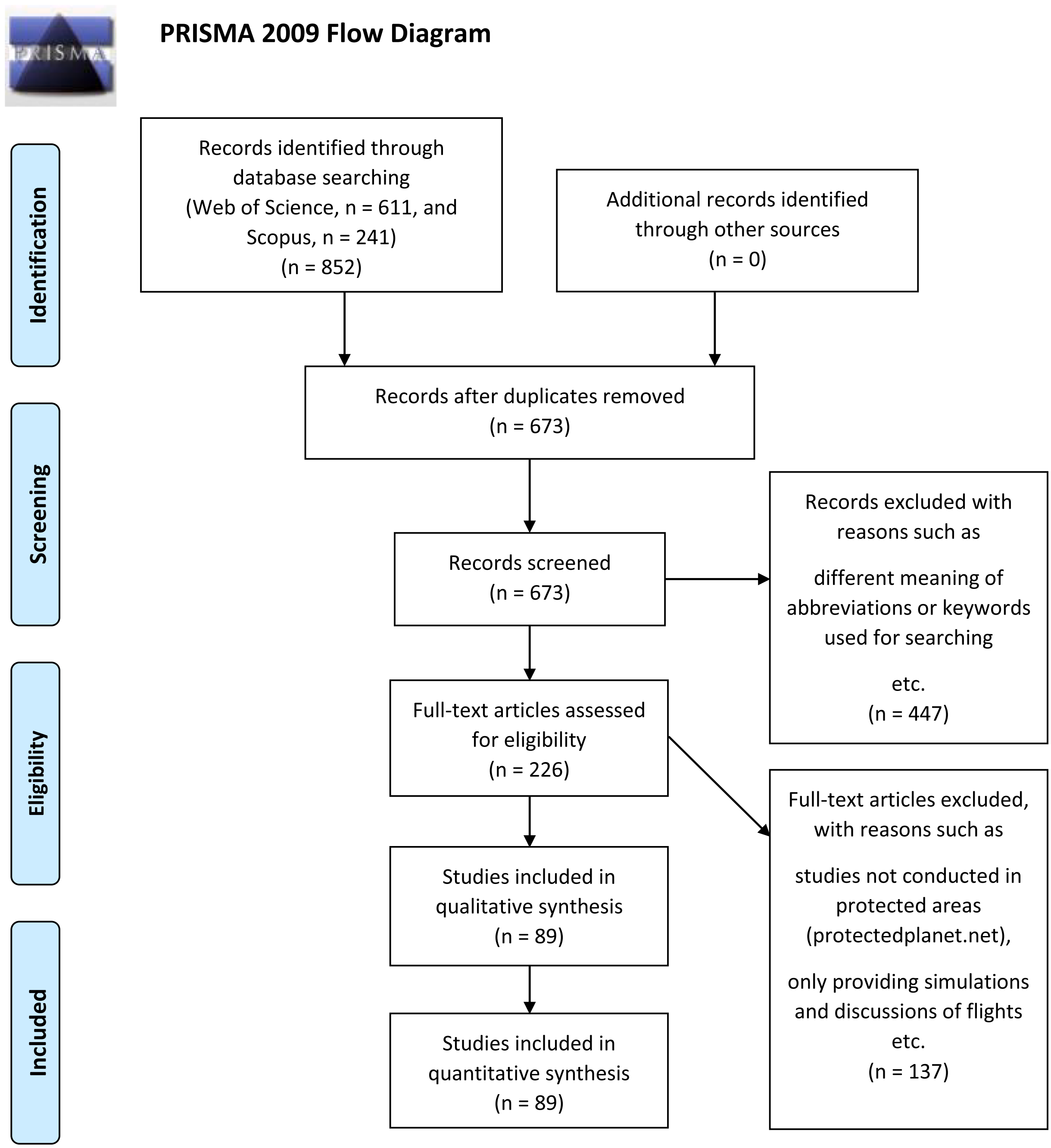
Appendix



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