



Raptor research during the COVID-19 pandemic provides invaluable opportunities for conservation biology

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ABSTRACT

Research is underway to examine how a wide range of animal species have responded to reduced levels of human activity during the COVID-19 pandemic. In this perspective article, we argue that raptors (i.e., the orders Accipitriformes, Cariamiformes, Cathartiformes, Falconiformes, and Strigiformes) are particularly well-suited for investigating potential ‘anthropause’ effects: they are sensitive to environmental perturbation, affected by various human activities, and include many locally and globally threatened species. Lockdowns likely alter extrinsic factors that normally limit raptor populations. These environmental changes are in turn expected to influence – mediated by behavioral and physiological responses – the intrinsic (demographic) factors that ultimately determine raptor population levels and distributions. Using this population-limitation framework, we identify a range of research opportunities and conservation challenges that have arisen during the pandemic, related to changes in human disturbance, light and noise pollution, collision risk, road-kill availability, supplementary feeding, and persecution levels. Importantly, raptors attract intense research interest, with many professional and amateur researchers running long-term monitoring programs, often incorporating community-science components, advanced tracking technology and field-methodological approaches that allow flexible timing, enabling continued data collection before, during, and after COVID-19 lockdowns. To facilitate and coordinate global collaboration, we are hereby launching the ‘Global Anthropause Raptor Research Network’ (GARRN). We invite the international raptor research community to join this inclusive and diverse group, to tackle ambitious analyses across geographic regions, ecosystems, species, and gradients of lockdown perturbation. Under the most tragic of circumstances, the COVID-19 anthropause has afforded an invaluable opportunity to significantly boost global raptor conservation.

1. Introduction

Restrictions introduced to control the spread of COVID-19 have resulted in a significant global reduction (and some pronounced shifts) in human activity. Brought about by the most tragic of circumstances, this ‘anthropause’ (Rutz et al., 2020) affords unprecedented opportunities to gain deep mechanistic insights into human–wildlife interactions, by comparing animal biology across time periods (before,

during, and after ‘lockdown’) and areas (affected and unaffected by lockdown) (Rutz et al., 2020). Perhaps most importantly, lockdowns allow researchers to separate the effects of direct human interference from those of anthropogenic landscape modifications at a global scale (see Doherty et al., 2021). Many projects are underway to investigate the consequences of this extraordinary perturbation, collating data for a vast range of species and environmental contexts (e.g., Bates et al., 2020; Corlett et al., 2020; Bates et al., 2021; Rutz et al., 2020).

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Governments are taking drastic steps to stem the spread of COVID-19, including lockdowns affecting billions of people (Bates et al., 2020; Diffenbaugh et al., 2020; Doherty et al., 2021). This has reduced air, water, light, and sound pollution (Chowdhury et al., 2021), travel and trade, and human visitation to many (but not all recreational) areas (Rutz et al., 2020; Venter et al., 2020). All of these changes may affect wildlife behavior, distribution, productivity, and survival (Kowarik, 2011). Preliminary results indicate a mix of positive and negative effects on wildlife (Bates et al., 2021), such as an increase in species richness in temporarily less-disturbed areas (Manenti et al., 2020), and hampered conservation activities triggering a surge in the illegal killing of animals in some localities (Lindsey et al., 2020). For birds, first studies have reported, among other things, altered singing behavior in unusually calm urban areas (Derryberry et al., 2020), reduced fear responses towards people wearing face masks (Jiang et al., 2020), and shifts in abundance levels due to changing anthropogenic food availability (Soh et al., 2021).

Here we argue that raptors (orders Accipitriformes, Cariamiformes, Cathartiformes, Falconiformes, and Strigiformes; Iriarte et al., 2019; McClure et al., 2019) are a taxonomic group of exceptional research promise for evaluating the impacts of the COVID-19 anthropause, and that these insights will provide much-needed impetus for global conservation efforts. First, although raptors vary greatly in their adaptability to human disturbance (and human activities more generally), many species are expected to exhibit a particular sensitivity to the environmental changes that occurred during the pandemic. Second, raptors attract intense research interest, with many professional and amateur researchers running long-term monitoring programs, often incorporating community-science components, advanced tracking technology and field-methodological approaches that allow flexible timing, thus ensuring continued data collection under challenging lockdown conditions. Third, raptors provide critical ecosystem services (Donazar et al., 2016; Markandya et al., 2008), and are routinely used as indicators of environmental health (Sergio et al., 2008) and biodiversity (Sergio et al., 2005; Sergio et al., 2006). They typically have large home ranges (Newton, 1979; Peery, 2000; Schoener, 1968) and generalist species can ‘sample’ a wide variety of prey species (from insects to medium-sized vertebrates) across the landscape. They also occupy high trophic levels, acting as bio-accumulators and bio-magnifiers of toxins (Gómez-Ramírez et al., 2014), making them important bio-indicators in human-dominated landscapes. Fourth, some raptors occasionally prey on livestock and game birds (Redpath et al., 2013), resulting in their persecution through shooting, poisoning, and nest destruction (Madden et al., 2019; Murgatroyd et al., 2019), while others are trapped for trade or poisoned unintentionally (Ogada et al., 2012; Ogada et al., 2016b). In summary, raptors are particularly vulnerable to anthropogenic disturbance, land-use change, environmental pollutants, and persecution (Buechley et al., 2019), all of which are affected (at least locally) by COVID-19 lockdowns – and data availability for documenting impacts is likely better than for most other taxa.

Perhaps most importantly, raptors offer an outstanding opportunity for conducting comparative analyses across extensively-researched taxa that are relatively similar in terms of their basic morphology, yet exhibit significant variation in ecological needs, life-history strategies and a wide range of other factors. By leveraging well-resolved recent phylogenies (McClure et al., 2019; McClure et al., 2020; Mindell et al., 2018; Suh et al., 2011) and large numbers of comparable datasets collected across different species and environmental contexts, it will be possible to conduct powerful comparative analyses to examine why some raptors are sensitive to (changes in) human presence and activity, while others are not, or lack the ability to adapt quickly to change. Understanding which particular traits, environmental conditions and historical contingencies make a species either resilient or vulnerable, and which aspects of human activity have the most profound impacts (both positive and negative), is of critical importance for informing global conservation efforts and, ultimately, for developing models capable of predicting

future impact. This matters, since the group sadly includes a disproportionately high number of globally threatened species, whose status reflects their vulnerability to several of the factors discussed above.

The worldwide decline of predator populations is contributing substantially to the biodiversity crisis (Ritchie and Johnson, 2009), specifically in human-dominated landscapes (Lamb et al., 2020), with potentially extensive cascading effects on ecosystems (Estes et al., 2011). Where predators have been retained or restored, they can buffer against globally threatening processes, including the impacts of biological invasion (Wallach et al., 2010) and disease transmission (Pongsiri et al., 2009). Recent advances have highlighted ways in which human activities influence such ecosystem regulation by predators (Dorresteijn et al., 2015). In raptors, some species are able to take advantage of human-dominated landscapes, including urban areas (Bird et al., 1996; Boal and Dykstra, 2018; Mak et al., 2021; McPherson et al., 2021), but on a global scale, we observe worrying population declines. Of the world’s over 500 raptor species, 52% are in decline and 19% are currently classified as threatened with extinction (Buechley et al., 2019; McClure et al., 2018). Agriculture and logging are the most frequently identified threats to raptors overall (McClure et al., 2018), but direct persecution is a problem for a range of endangered species. Many vulture populations have collapsed across Asia, due to secondary poisoning with the veterinary drug diclofenac (Green et al., 2004; Naidoo et al., 2009; Oaks et al., 2004; Shultz et al., 2004), and others are declining rapidly across Africa, due to deliberate poisoning linked to human-wildlife conflict, poaching, and trade (Buij et al., 2016; Ogada et al., 2012; Ogada et al., 2016a). At the same time, people’s perception of raptors is highly relevant (Soga and Gaston, 2020), as they are common symbols of national strength (Lorimer, 2007), are used in falconry and for pest control, and serve as umbrella or flagship species for conservation initiatives (Donazar et al., 2016). Even for scavenging raptors, there is increasing recognition that they play an important role that goes beyond disease control and carcass removal, providing aesthetic enjoyment and valuable recreational experiences (Aguilera-Alcalá et al., 2020).

Environmental changes caused by COVID-19 lockdowns will allow us – for the first time across multiple species and across large geographic areas – to separate the effects of human activity and infrastructure on raptor biology. Pinpointing mechanistic pathways requires landscape-level experimental manipulations, which are not normally feasible (Bates et al., 2020; Corlett et al., 2020; Rutz et al., 2020), especially with protected (and wide-ranging) species like raptors. Analyses of lockdown effects may reveal, for example, that susceptibility to human disturbance is affected by foraging mode (e.g., specialist vs. generalist; active vs. scavenging), habitat preferences (e.g., urban vs. non-urban), or past exposure to human persecution. As top-predators, raptors are fairly unique in occupying the full gradient of human-dominated landscapes (Francis and Chadwick, 2012). Knowledge gained through the COVID-19 anthropause would not only help inform global raptor conservation efforts (Buechley et al., 2019; Buechley and Şekericioğlu, 2016; McClure et al., 2018), but it would also pave the way for identifying possible vulnerabilities in under-studied taxa.

For all these reasons, raptors are an exceptionally useful taxonomic group for mapping lockdown-related responses and impacts. In the following section, and in Table 1, we discuss specific opportunities that have arisen during the COVID-19 pandemic to study the nature and consequences of human–raptor interactions, and highlight a range of emerging conservation challenges. This is followed by a brief discussion of how raptors could be used to monitor broader environmental impacts of lockdowns. Finally, building on these analyses, we introduce our vision for a global raptor research network, which could integrate the work of amateur and professional researchers, creating a platform for ambitious collaborative analyses.

Table 1

Selected aspects of raptor biology that may be influenced by lockdowns during the COVID-19 pandemic (see Fig. 1 for a conceptual framework), together with predicted effects, evidence required to test predictions, and an indication of potentially useful data types. This is a non-exhaustive list, and effects are expected to be highly context-dependent: examples may apply only to certain taxonomic groups, species, or localities.

Characteristic	Predictions	Evidence required to test predictions	Data types
Behavior			
Movements and activity	<p><i>Changes in human activity may alter temporal and spatial patterns of raptors' avoidance behavior and use of landscape types</i></p> <ul style="list-style-type: none"> Changes in space use by humans produce corresponding changes in space use by raptors, depending on whether they avoid or are attracted by human activity and/or infrastructure (spatial distribution) Fewer humans visit protected areas and human activity is reduced in peripheral areas during periods of hard lockdown, allowing raptors sensitive to human disturbance greater range of movement More humans visit protected areas and human activity is increased in peripheral areas during partial lockdowns (with shops closed and restricted travelling options abroad, people seek recreation in urban parks and nature reserves) Reduced road traffic leads to increased presence of disturbance-sensitive raptors near roads with less traffic Reduced road-kill and reduced provisioning at vulture restaurants limit carrion availability for scavengers Urban raptors are active at different times of day (diel timing) 	<ul style="list-style-type: none"> Increased or decreased time spent in areas where the intensity of human activity has changed (e.g., urban areas, hiking trails, national parks) Increased movement of large raptors beyond protected area boundaries Overall larger home range sizes and extended activity times More disturbance for sensitive species evident from smaller home range sizes (avoiding areas of pedestrian and vehicle traffic) and restricted activity times (avoiding human presence/encounters) Traffic volume impacts raptor ranging and feeding Dispersal of scavengers away from roads and vulture restaurants Increased time spent hunting by acoustic hunters (i.e., owls) during periods normally labelled as 'rush hours' Decreased activity by visual hunters (i.e., diurnal raptors) after dark, due to reduced light pollution (less vehicle traffic; fewer illuminated closed shops and businesses) 	<p>Bio-logging data;</p> <p>Presence data (including from community science);</p> <p>Road-kill data (road-kill apps);</p> <p>Camera traps at feeding locations such as abattoirs;</p> <p>Acoustic monitoring data (for owl species).</p>
Diet choice	<p><i>Changes in human activity may impact food availability and raptors' foraging behavior and foraging success</i></p> <ul style="list-style-type: none"> Human activity influences prey activity/behavior and distribution Prey species change behavior due to increased availability of provisioned food (e.g., at bird feeders) Changes in road-verge maintenance influence prey availability 	<ul style="list-style-type: none"> Raptor diet composition is affected by changes in noise and light pollution and anthropogenic disturbance Increased foraging success and efficiency of avian specialists (particularly hawks and small falcons) Changes in diet composition resulting from changes in prey distribution and spatial/temporal availability Increased road-side feeding by raptors sensitive to disturbance; decreased road-side feeding by species that typically hunt in short grass alongside roadways 	<p>Examination of prey remains and pellets;</p> <p>Nest cameras;</p> <p>Intensive nest monitoring;</p> <p>Feather samples for isotopic determination of diet;</p> <p>Bio-logging data.</p>
Physiology	<p><i>Changes in human activity and use/disposal of toxicants may induce physiological changes in raptors</i></p> <ul style="list-style-type: none"> Decreased or increased exposure to anthropogenic stressors affects raptors' stress hormone levels and body condition Anthropogenic shift in use or disposal of chemical pollutants is reflected in contaminant loads in environmental sentinel species Large quantities of disinfectants, including chlorine-releasing agents, accumulate in food chains and have negative impacts on urban wildlife, including raptors Reduced provisioning at vulture restaurants limits food availability for scavengers 	<ul style="list-style-type: none"> Changes in corticosterone levels in urban raptor populations Reduced or increased incidence of fault bars in new flight feathers Decreased or increased concentrations of contaminants in plasma samples Increased levels of chlorine or their metabolites in urban raptors Reduced food intake resulting in deteriorating body condition 	<p>Blood, feather, and excreta samples;</p> <p>Morphometric data from nestlings;</p> <p>Body condition data from adults.</p>
Demography	<p><i>Human activities and human-induced changes in raptor diet and physiology may affect breeding success and productivity</i></p> <ul style="list-style-type: none"> Synanthropic scavengers have reduced breeding success due to reduced food availability Urban owls have greater breeding success due to increased foraging opportunities and foraging efficiency In some tropical areas, unemployment and economic insecurity lead to increased illegal logging, reducing habitat for tropical forest raptors and limiting their movements and reproductive rates 	<ul style="list-style-type: none"> Fewer breeding attempts, reduced clutch size, slower nestling growth rate, reduced weight at fledging, more nest failures, lower productivity, and reduced post-fledging survival More breeding attempts, increased clutch size, higher nestling growth rate, increased weight at fledging, larger fledged brood sizes, and increased post-fledging survival Reduced use of deforested areas, limited dispersal due to habitat fragmentation, and reduced breeding success Higher reproductive rates, and more young birds breeding 	<p>Breeding data, including number of breeding attempts, clutch size, breeding success, productivity, nestling growth and condition;</p> <p>Long-term data including post-fledging survival, recruitment records, specifically of marked populations;</p> <p>Estimates of age at first breeding (e.g., based on plumage, eye color or molted feathers).</p>

(continued on next page)

Table 1 (continued)

Characteristic	Predictions	Evidence required to test predictions	Data types
Mortality	<ul style="list-style-type: none"> Raptors sensitive to anthropogenic disturbance have greater breeding success where human activity levels drop during lockdowns, and more individuals breed at an earlier age Changes in human activity may affect some sources of raptor mortality Lower traffic volumes result in fewer road-killed raptors Persecution and poaching pressure change as law enforcement wanes, and recreation in protected or remote areas decreases, leading to changes in raptor mortality Changes in human hunting pressure (depending on the strength and timing of lockdown measures) at migratory pinch points 	<ul style="list-style-type: none"> Lower proportion of ringing recoveries attributed to traffic collisions Fewer reports of raptor mortalities submitted through road-kill apps (though this could reflect lower observer effort) Increased numbers of persecution incidents reported from remote areas and/or private land Potentially, reduced persecution in areas subject to increased footfall, as more people participate in outdoor recreation, deterring would-be persecutors Increased or decreased raptor mortality due to illegal killings Increased mortality of avian scavengers in association with retaliatory poisoning by pastoralists, deliberate poisoning by ivory poachers, killing for bushmeat or belief-based traditional uses during hard lockdowns More or less raptor mortality during migration (e.g., at sites around the Mediterranean and other migration bottlenecks) 	Road-kill data; Poisoning databases; Persecution databases; Mortality records from national ringing/ banding programs; Bio-logging data.

^a Following the terminology proposed by Steenhof (2017).

2. Research opportunities and emerging challenges

A productive way of identifying lockdown-related effects on raptors is to consider how their populations are limited (Newton, 1979; Rutz et al., 2006). A range of environmental (extrinsic) factors (including food and nest-site availability, pollution, disease, and disturbance or killing by humans) influence – mediated by behavioral and physiological responses – demographic (intrinsic) factors, which ultimately determine population levels and distributions (Fig. 1). COVID-19 related restrictions most likely affected the limiting factors of many raptor populations, and it should be possible to document the resulting impacts. Specifically, human activities (notably human mobility, recreation, and traffic), which can hamper access to critical resources, were significantly reduced during lockdowns in many areas, but spiked in others. Habitat management, pollution, and persecution have also changed in intensity, potentially affecting raptor behavior and demographics. Rather than exploring all potentially limiting factors one-by-one, we have decided to spotlight here what we perceive as promising avenues (Table 1; Fig. 2), but a more exhaustive evaluation may be warranted in the future, once data availability is clearer and more field evidence has accumulated.

2.1. Human disturbance

COVID-19 restrictions provide an opportunity to assess, under unusually controlled conditions and across different spatio-temporal scales and species, the impacts of routine human-raptor encounters. We will first review the large body of literature on the effects of human recreational activities, as it provides important insights into how raptors may respond to changes in activity levels that are short-term and/or occur in relatively remote areas, before considering the special case of urban-breeding raptor populations, which present especially valuable research opportunities.

Many people living in urban areas use weekends and holidays to spend time in nature, resulting in a temporary increase in outdoor recreation. This ‘weekend effect’ (e.g., Barrieto et al., 2014) is known to shape raptor activity and movement. For example, during weekends (and holidays), the occurrence of Spanish imperial eagles (*Aquila adalberti*) and vultures decreased near roads when traffic volume was highest (Bautista et al., 2004), and Bonelli’s eagles (*Aquila fasciata*) ranged more widely in response to lower human disturbance (Perona et al., 2019). In light of these findings, we predict significant changes in raptor ranging (and foraging) behavior during the pandemic where humans were initially confined to their homes, followed by local spikes of activity as restrictions eased, allowing brief periods of outdoor activity. COVID-19 lockdowns therefore allow us to examine if, and how quickly, raptors respond to both decreases and increases in human activity levels (whilst human infrastructure remains effectively unchanged). Such analyses would require tracking data collected before, during, and after lockdown, and under different lockdown regimes, which seems eminently feasible, given that at least 42 individual datasets from 30 different raptor species (from North- and South America, Europe, Africa and India) have already been offered to the COVID-19 Bio-Logging Initiative for collaborative analyses (Rutz et al., 2020). Many of these studies are ongoing and will generate data covering multiple cycles of hard lockdowns and relaxed restrictions.

Beyond the weekend effect on raptors’ ranging behavior, there are indications that human recreation can disrupt nest attentiveness, cause abandonment of breeding territories, reduce productivity, and affect foraging, habitat use, and energy budgets (Knight and Skagen, 1988; Martínez-Abraín et al., 2010; Richardson and Miller, 1997). Nesting activities may be especially sensitive to human disturbance. For example, in northern Finland, fewer golden eagles (*Aquila chrysaetos*) nest near tourist resorts than in undisturbed areas, with disturbance levels measured as the length of skiing slopes and snowmobile routes (Kaisanlahti-Jokimaki et al., 2008). Similarly, pedestrian activities

Table 2

Examples of raptor organizations that coordinate large-scale research or conservation programs and/or host long-term datasets. This is a non-exhaustive list, and we would be most grateful if readers could bring to our attention any other relevant initiatives that may be interested in contributing to GARRN.

Raptor research organizations	Region	Link
GRIN - Global Raptor Impact Network	Global	https://globalraptors.org/grin/indexAlt.asp
ARDB - African Raptor Databank	Africa	http://www.habitatinfo.com/african-raptor-databank/
EWT - Endangered Wildlife Trust: Bird of Prey Programme	Africa	https://www.ewt.org.za/
The Mara Raptor Project	Africa	https://www.mararaptorproject.org/
VISA - The Vulture Initiative for sub-Saharan Africa	Africa	https://www.visa4vultures.org/
ARRCN - Asian Raptor Research & Conservation Network	Asia	http://www5b.biglobe.ne.jp/~raptor/
Batumi Raptor Count	Asia	https://www.batimiraptorcount.org/
Himalayan Nature	Asia	https://www.himalayannature.org/
Philippine Eagle Foundations	Asia	https://www.philippineaglefoundation.org/
Russian Raptor Research Conservation Network	Asia	http://rrrcn.ru/en
The Flyway Foundation	Asia	https://www.theflywayfoundation.or.th/
BirdLife Australia Raptor Group (formerly Australasian Raptor Association)	Australasia	https://ausraptorgroup.org/
Society for the Preservation of Raptors	Australasia	http://www.raptor.org.au/
Wingspan National Bird of Prey Centre	Australasia	https://www.wingspan.co.nz/
BRRI - Belize Raptor Research Institute	Central America	https://belizebirdconservancy.org/
Dutch Working Group on Birds of Prey	Europe	http://www.werkgroeproofvogels.nl/
EURAPMON - Research and Monitoring for and with Raptors in Europe	Europe	https://www.eurapmon.net/
Fundación migres	Europe	https://www.fundacionmigres.org/
International Association for Falconry and Conservation of Birds of Prey	Europe	https://iaf.org/falconry-and-conservation/
International Centre for Birds of Prey	Europe	https://www.icbp.org/
International Wildlife Consultants Ltd.	Europe	https://www.iwicons.co.uk/
IRSG - Irish Raptor Study Group	Europe	http://irsg.ie/
Medraptors	Europe	http://www.raptormigration.org/
MEROS - Monitoring Greifvögel und Eulen Europas	Europe	http://www.greifvogelmonitoring.de/
Natural Research Group	Europe	https://www.natural-research.org/
SRMS – Scottish Raptor Monitoring Scheme	Europe	http://raptormonitoring.org/
Vulture Conservation Foundation	Europe	https://www.4vultures.org/
World Working Group on Birds of Prey and Owls	Europe	http://www.raptors-international.de/
ArcticRaptors.ca Nunavut's Raptor Study	North America	http://www.arcticraptors.ca/
Coastal Raptors	North America	https://coastalraptors.com/
George Miksch Sutton Avian Research Center	North America	https://www.suttoncenter.org/
Golden Gate Raptor Observatory, Sausalito, California	North America	https://www.parksconservancy.org/programs/golden-gate-raptor-observatory
Hawk Conservancy Trust	North America	https://www.hawk-conservancy.org/
Hawk Migration Association of North America	North America	https://www.hmana.org/
Hawk Mountain Sanctuary	North America	https://www.hawkmountain.org/
Hawk Watch International	North America	https://hawkwatch.org/
Hawks Aloft	North America	http://hawksaloft.org/
High Arctic Institute	North America	http://www.higharctic.org/
Raptor Research Foundation	North America	https://www.raptorresearchfoundation.org/
Raptor View Research Institute	North America	https://www.raptorview.org/
The American Kestrel Partnership	North America	https://kestrel.peregrinefund.org/
The Canadian Peregrine Foundation	North America	http://www.peregrine-foundation.ca/
The Peregrine Fund	North America	https://peregrinefund.org/
The Raptor Center	North America	https://raptor.umn.edu/
Wildlife Research Institute Inc.	North America	https://www.wildlife-research.org/
World Center for Birds of Prey	North America	https://peregrinefund.org/visit
CECARA - Center for the Study and Conservation of Birds of Prey in Argentina	South America	http://www.cecara.com.ar/
ECA - Eagle Conservation Alliance	South America	http://www.eagleconservationalliance.org/
Neotropical Raptor Network	South America	http://www.neotropicalraptors.org/
Parque Cóndor	South America	https://www.parquecondor.com/

(mainly of hunters, campers, and ecotourists) cause more flight reactions from the nest in Spanish imperial eagles (González et al., 2006) than vehicles; and nest failure associated with forestry and other human activities is common in Egyptian vultures (*Neophron percnopterus*; Zuberogitia et al., 2008). In some species, flush responses are age-dependent: a study on disturbance effects of (unmotorized) recreational boating on bald eagles (*Haliaeetus leucocephalus*) showed that flush distance was greatest for adults, smallest for juveniles, and intermediate for subadults, and breeding adults were less likely to flush than nonbreeding adults (Steidl and Anthony, 1996). Noise from recreationists can also negatively affect birds within protected areas (Levenhagen et al., 2021), causing nest abandonment, especially during sensitive breeding stages (i.e., around egg laying and incubation; Richardson and Miller, 1997), and even local population declines (Craighead and Mindell, 1981; Martínez-Abraín et al., 2010; Swenson, 1979).

Because many raptor species are sensitive to human disturbance during breeding, or prey on species that are more abundant or accessible

when human activity is restricted, we expect a positive influence on raptor reproductive rates where human outdoor activities were reduced at critical stages of the breeding cycle during lockdowns – especially for young, inexperienced birds. The larger the species, the later sexual maturity is reached, the more experience is required to reproduce successfully, and the fewer young are produced during each cycle (Newton, 1979). Because individuals breed at an earlier age when environmental conditions are unusually favorable, we predict – for populations that are not currently at capacity level – a change in breeding age structure during (or after) the pandemic, with more young birds attempting to breed and, if given the opportunity, breeding with greater success, compared to pre- and post-lockdown ‘control’ periods. Where human visitation rates to nature reserves, urban parks, and other raptor nesting habitats increased during lockdowns, the opposite pattern is expected. For these kinds of analyses, long-term datasets, especially those involving individually marked or otherwise identifiable birds, are needed, and should be available through country-wide raptor ringing and monitoring schemes (Table 2). If breeders are not marked,

researchers can evaluate the percentages of breeding birds in immature plumage and/or molt stage, which can be done reliably for most raptor species (Ferguson-Lees and Christie, 2005).

Recreational and other human activities can also impact raptor foraging behavior, resulting in increased energy expenditure, due to avoidance flights, and decreased energy intake rates (Stalmaster, 1983; Stalmaster and Kaiser, 1998). For example, bald eagles, which are now generally considered to be a fairly human-tolerant species, spent more time on riverbanks scavenging when anglers were absent (Knight et al., 1991), while harpy eagles (*Harpia harpyja*), which were long thought to be highly susceptible to human disturbance, have recently been documented targeting prey that occur mainly in disturbed areas close to humans (Bowler et al., 2020). Both the type of disturbance and its context matter: foraging raptors are often more likely to flush when approached by pedestrians than by vehicles, and large raptors are more easily flushed by pedestrians than are smaller ones (Holmes et al., 1993). In some species, individuals can habituate to high levels of human activity and do not seem to suffer negative effects on foraging, or at least a subset of birds that has greater tolerance limits is able to occupy heavily disturbed areas (Buehler et al., 1991; McGarigal et al., 1991). It is possible that a larger number of raptor species have temporarily visited areas they were not (routinely) using before the pandemic, in response to changing levels of human activity, such as urban parks, beaches, or waste management centers during operating hours. A recent example from a seabird colony in the Baltic Sea revealed a previously unknown human 'shielding effect': the absence of tourists in 2020 from the island was associated with a sevenfold increase in the presence of white-tailed eagles (*Haliaeetus albicilla*), which in turn appeared to cause a 26% reduction in common murre (*Uria aalge*) productivity compared to the long-term average (Hentati-Sundberg et al., 2021). This provides a striking example of how seemingly benign tourist activity can render a potentially attractive foraging area unsuitable for a raptor.

Overall, raptor populations vary widely in their tolerance of human presence. Falcons, such as peregrines (*Falco peregrinus*) and Eurasian kestrels (*Falco tinnunculus*) (e.g., Cade et al., 1996; Sumasgutner et al., 2020; Sumasgutner et al., 2014), and many accipiter species (e.g., Rutz, 2008; Suri et al., 2017), are often drawn to urban areas by abundant food and nest sites, apparently coping well with high human disturbance levels, while non-urban conspecifics often maintain greater vigilance and exhibit stronger disturbance responses (e.g., Palmer et al., 2003; Merling de Chapa et al., 2020). Urban raptor populations provide a valuable opportunity to examine – in a quasi-experimental manner – how baseline habituation levels affect responses to changes in human activity during the pandemic. It seems reasonable to predict that well-habituated urban populations exhibit weaker responses (to both increasing and decreasing levels of human activity) than their non-urban counterparts, but the discovery of strong responses during COVID-19 lockdown could uncover substantial 'hidden costs' of exposure to high levels of human disturbance in urban environments. In other words, urban raptors may appear stress tolerant but could, in fact, be highly stressed, possibly affecting survival and reproductive rates. It would also be interesting to examine behavioral data from lockdown periods for species like black kites (*Milvus migrans*) that face trade-offs in urban environments in terms of defending their young against humans, while exploiting anthropogenic food sources (Kumar et al., 2018).

Finally, human presence may impact raptors indirectly, through effects on their prey. Prey availability can be affected at smaller scales by changes in human activity levels, and at larger scales, by changes in landscape management practices. We explore these issues in more detail below.

2.2. Habitat loss and landscape management

Raptor breeding is likely to be directly affected by increased levels of habitat loss. A surge in (illegal) logging activity has been reported from throughout the tropics since the start of the COVID-19 anthropause

(WWF, 2020). Preliminary evidence suggests that most of this activity has been prompted by increased unemployment and poverty driving people to exploit forest resources, combined with a lack of monitoring by enforcement authorities.

One study using satellite data from 18 countries in Africa, Asia, and South America showed that deforestation in March 2020 was 150% higher than the March average for the years 2017–2019 (WWF, 2020). This is a significant concern for raptor conservation, given that 59% of tropical forest raptors are already in decline, and 21% are classed as globally threatened (Buechley et al., 2019; McClure et al., 2018). Since these raptors' current status is largely the result of forest loss, the reported surge in deforestation is likely to accelerate declines among this under-studied group. Worryingly, some of the highest rates of forest loss have been reported from countries with some of the richest, most threatened, and least known raptor communities, such as Indonesia (WWF, 2020). Because the negative impacts of the pandemic on people's livelihoods and forestry law enforcement are likely to be felt for many months or longer, the overall rates of illegal logging may continue to rise. As such, we expect the anthropause to lead to steepening declines among tropical forest raptors, although this can of course be detected only if suitable baseline data are available from pre-pandemic years.

Raptor foraging is also likely to be affected by changes in management programs. For example, local pauses in desert locust control (Bates et al., 2020) could have temporarily increased food supplies for insectivorous raptors (e.g., harriers, kites, falcons). In contrast, a reduction in the burning of grasslands has likely reduced the availability of insects and other prey for opportunistic, migratory, and small raptors. In Africa, south of the equator, where 130 million ha of grasslands and savannas are burned annually (FAO, 2000), a widespread reduction in burning could depress insect prey availability, with measurable impacts on the survival or subsequent productivity of small raptors, including many well-studied Palearctic migrants (e.g., lesser kestrel *Falco naumanni*, Eleonora's falcon *F. eleonorae*, black kite). Vegetation burning is also used as a form of land management in parts of Europe (Newton, 2020). In Scotland, for example, the burning of moorland to 'improve' upland areas for gamebird shooting was suspended during the lockdown period in 2020 to avoid the risk of triggering wildfires, and hence the need to call out emergency services. This occurred towards the end of the 'muirburn' season, potentially reducing disturbance levels for moorland raptors returning to re-establish breeding territories, and affecting prey availability (Ratcliffe, 2010; Werritty et al., 2019).

2.3. Anthropogenic pollution

In urban ecology, a common approach is to collect data along a gradient of physical development (e.g., building density or proportion of sealed/unproductive area) to evaluate potential impacts on wildlife. However, the presence of physical structures is usually correlated with human activity (Nickel et al., 2020) and associated pollution levels, including artificial light at night (ALAN), anthropogenic noise, and chemical pollution due to traffic fumes and other sources. Importantly, this situation changed during lockdown, when structures such as buildings and roads remained, but human activity and pollution levels dropped (at least locally), enabling researchers to disentangle the effects of these factors (see for example Nickel et al., 2020; Ulloa et al., 2021). One aspect of particular interest for urban raptor research is the effects of sensory pollution caused by vehicle traffic (Dominoni et al., 2020), which are usually inseparable from those of the traffic infrastructure itself.

During the COVID-19 pandemic, environmental sound pollution has dropped significantly (Ulloa et al., 2021; Zambrano-Monserrate et al., 2020), as has traffic volume, which usually adds to ALAN levels, especially away from urban centers (Bará et al., 2019). ALAN and noise can disrupt raptors' sensory perception (e.g., Scobie et al., 2016; Senzaki et al., 2016) and their 'biological clocks' (Swaddle et al., 2015) – mechanisms that program the behavior and physiology of organisms

based on input from daily and seasonal cues (Dominoni et al., 2013). The effects of ALAN on nesting phenology and reproductive success are mediated by the light-gathering ability of the avian eye (Senzaki et al., 2020), and we believe that raptors would offer a good system for investigating potential responses to lockdown-induced changes in light pollution levels.

Diurnal raptors can use ALAN to hunt at night (Eleonora's falcon, Buij and Gschweg, 2017; peregrine falcons, DeCandido and Allen, 2006, Kettel et al., 2016; lesser kestrel, Negro et al., 2000). In some contexts, they take advantage of increased light levels to hunt their typical prey (DeCandido and Allen, 2006; Negro et al., 2000), while in others, they hunt more unusual species, such as bats (Mikula et al., 2016; Sumasgutner et al., 2013). Artificial light sources often encourage concentrations of arthropod prey, which in turn can attract predators such as lesser kestrels (Tella et al., 1996) and burrowing owls *Athene cunicularia* (Rodríguez et al., 2020); indeed, burrowing owls are known to select nest sites that are close to street lights (Rodríguez et al., 2020). It is still unclear how exactly COVID-19 lockdowns affected ALAN, but we may expect a drastic reduction in the number of vehicle headlights in some urban areas, even though levels of street-light emissions may have remained largely unchanged.

Acoustic hunters like owls will likely profit from reduced sound pollution. In fact, traffic noise is known to reduce foraging efficiency (Senzaki et al., 2016); the hunting success of saw-whet owls (*Aegolius acadicus*), for example, drops by 8% per dB increase in anthropogenic noise (Mason et al., 2016). Because traffic noise hampers acoustic communication in other bird species (Derryberry et al., 2020; Leonard and Horn, 2005; Mockford and Marshall, 2009), with negative impacts on their reproductive success (Halfwerk et al., 2011), similar fitness consequences are expected for owls, which use acoustic communication to find mates and defend territories. We therefore predict improved reproductive success in owl species living and foraging in close proximity to roads and in urban areas during lockdown.

Effects of anthropogenic noise on diurnal raptors are less well studied, and are difficult to separate from effects of disturbance by vehicles and pedestrians. Traffic noise is thought to negatively affect some species, even those considered relatively tolerant of disturbance. For example, American kestrels (*Falco sparverius*) nesting near noisy roads with high traffic volumes or in other high-disturbance areas exhibited higher levels of stress (as measured by corticosterone concentrations), higher levels of nest abandonment, and lower reproductive rates compared to those nesting further away from large, busy roads and developed areas (Strasser and Heath, 2013). Among non-urban raptors, noisy agricultural work (such as cork harvesting) near the nest was associated with elevated rates of nest abandonment and failure in cinereous vultures (*Aegypius monachus*; Margalida et al., 2011); lower levels of noise did not have the same effect. Another example stems from long-term breeding data of golden eagles, where a dramatic increase in off-highway vehicle use from 1999 to 2009, was associated with a decline in the occupancy and success of territories in close proximity to recreational trails and parking areas, and the proportion of these territories producing young differed significantly from territories not impacted by increased traffic volumes (Steenhof et al., 2014). For species negatively influenced by traffic noise, COVID-19 lockdowns may provide a respite allowing greater reproductive success, particularly in the northern hemisphere where the most significant reductions in vehicle traffic coincided with raptor breeding periods.

Changes in chemical pollutant levels during lockdowns can potentially have a range of direct and indirect effects on raptors (González-Rubio et al., 2021; Saaristo et al., 2018). Short-term fluctuations in pollutants were for example detected in white-backed vultures (*Gyps africanus*) in a pre-pandemic study, where blood lead levels were closely linked to the hunting season (Garbett et al., 2018). While these effects are not further explored here, we will revisit the topic of environmental pollution below when discussing how raptors can be used for effective biomonitoring.

2.4. Collisions with anthropogenic obstacles

Road-kill rates are expected to correlate with the nature and timing of mobility restrictions imposed by governments in response to COVID-19. Specifically, a reduction in road-traffic volume during lockdowns (Marchat, 2020) should affect the hunting and scavenging behavior of some raptor species, as well as their vulnerability to collisions with vehicles. Traffic volume is a major driver of raptor distributions along roads (Planillo et al., 2015). Many species feed on road-kill (Lambertucci et al., 2009), roadside garbage, and garbage-associated prey (like pigeons and rats; Kumar et al., 2014), making them susceptible to vehicle collisions (Dean et al., 2019).

Since scavenging raptors quickly capitalize on pulsed carrion resources (Schlacher et al., 2013), a swift response to any downturn in carrion availability during lockdowns is expected. Early evidence of such an effect stems from anecdotes of red kites (*Milvus milvus*) suffering starvation during the pandemic in the UK (Garlick, 2020). Such negative impacts are expected for many road-side raptors, such as Australasian harriers (*Circus approximans*; Baker-Gabb, 1981), pale chanting-goshawks (*Melierax canorus*), yellow-billed kites (*Milvus migrans parasitus*), and jackal buzzards (*Buteo rufofuscus*; Dean and Milton, 2009). Depending on the dietary importance of road-kill, a lockdown-related decline in food availability may in some cases have affected survival rates, breeding success, and ultimately, local population levels.

Species that scavenge for road-kill are especially vulnerable to being struck by vehicles (Arnold et al., 2019; Erritzoe et al., 2003), as are those that hunt small mammals and other prey in the grassy verges along roads (Sabino-Marques and Mira, 2011). In South Africa, Accipitridae and Falconidae are primarily attracted to roads by available perches in the form of fences, poles, and wires that can be used to survey for prey, and by the relatively productive road verges, rather than by the abundance of road-killed animals (Dean and Milton, 2009). A review of mortality causes of urban raptors in North America found that vehicle collisions were reported for most diurnal species (73%), specifically for those that forage along roads, and that nearly a third of owls found dead had collided with a vehicle (Hager, 2009). Road mortality of barn owls (*Tyto alba*) increases with traffic volume (Arnold et al., 2019), even to the point that it can depress local population levels (Boves and Belthoff, 2012). Spanish barn owl populations decreased by 70% over a 10-year period, apparently in large part due to road casualties (Fajardo, 2001). Population-level consequences have also been reported for tawny owls (*Strix aluco*) and little owls (*Athene noctua*) (Silva et al., 2012). For burrowing and great horned owls (*Bubo virginianus*), collision with vehicles is the most important source of mortality in urban populations (Lynch, 2007; Millsap, 2002). Given this body of evidence, we expect the number of road-killed raptors, specifically owls, to have decreased in areas where strict travel restrictions caused a significant drop in traffic volume.

We see a valuable research opportunity arising from the large number of community-science projects that quantify vehicle collisions with easy-to-use apps (e.g., Roadkill App from Spotteron; Vercaayie and Herremans, 2015), and from raptor satellite tracking projects. However, results need to be interpreted cautiously: road-kills are more likely to be reported when vehicle traffic is high and from built-up areas. However, lockdowns required most participants to spend more time at home, which resulted in a lower volume of vehicle traffic but more individuals seeking out wildlife experiences within urban areas. Additionally, we see regional differences in community-science data collection. While reporting rates in the South African Bird Atlas Project dropped (Rose et al., 2020), a greater proportion of eBird observations were made in urbanized landscapes (Hochachka et al., 2021), and there was an overall increase in reporting rates in eBird and iNaturalist in the United States (Crimmins et al., 2021).

Collisions with energy infrastructure, windows, and buildings also kill or injure many raptors, including urban species (Boal and Mannan, 1999; Hager, 2009; Merling de Chapa et al., 2020). Window strikes are a

cause of mortality for 45% of urban North American raptors, and the primary cause of death for 12% of diurnal raptor species, including falcons and Accipiter hawks (Hager, 2009). Although collisions with vehicles are generally thought to be more important than window strikes (Hager, 2009; Thompson et al., 2013), in many studies different sources of trauma or collision are not differentiated (Al Zoubi et al., 2020; Cianchetti-Benedetti et al., 2016; Montesdeoca et al., 2016; Morishita et al., 1998; Rodríguez et al., 2010). Importantly, COVID-19 lockdowns should enable an evaluation of whether the physical presence of humans contributes to the risk of colliding with windows and buildings. For example, it is conceivable, that birds hit obstacles occasionally as a result of avoiding humans.

2.5. Supplementary feeding

Some urban raptor populations depend on anthropogenic food resources. Kites are good examples: red kites in Reading, UK, are non-resident in urban areas but frequently forage on provided meat scraps in gardens (Orros and Fellowes, 2015), while one of the world's densest black kite populations, in Delhi, India, is supported by a practice of ritualized subsidized feeding (Kumar et al., 2019; Kumar et al., 2018). Given the extent of the COVID-19 pandemic in India, food provisioning suffered abrupt declines, coinciding with the imposition of lockdown measures (Mishra and Rampal, 2020). Since kite habitat choice, territory occupancy, and breeding success were closely linked to human activities during pre-pandemic times (Kumar et al., 2019), we expect significant lockdown effects in this system (Kumar et al., 2018; NK, unpubl. data).

Another example of large-scale supplementary feeding is that of vulture restaurants, which have become a popular conservation tool. They are used to provide food to declining vulture populations, and to draw birds away from potentially poisoned carcasses associated with wildlife poaching (Brink et al., 2020). Additionally, vulture restaurants are an increasing attraction in ecotourism and for wildlife photography (Shannon et al., 2017) – an industry severely affected by the pandemic. We suspect that the provisioning of carrion resources by some programs may have been compromised when conservation practitioners were affected by movement restrictions, which might have led to a decline in the numbers of vultures using these feeding sites, in turn impacting on survival rates; this issue deserves further investigation.

We further predict an increased presence of hawks and other bird-eating raptors in urban areas, profiting from an increased number (and/or increased provisioning) of garden bird feeders during lockdown periods (Brock et al., 2020) leading to an accumulation of prey at predictable sites. In the Global North, the provisioning of anthropogenic food usually peaks during the winter months, which partly explains an increased abundance of some hawk species (*Accipiter nisus*, *A. cooperii*, and *A. striatus*) in urban areas at that time (Roth et al., 2008; Schütz and Schulze, 2018) and might contribute to persistent breeding populations (Estes and Mannan, 2003; McCabe et al., 2018).

We are confident that valuable data on the effects of supplementary feeding in urban areas and other aspects of raptor biology exist, not least because people affected by lockdown measures were seeking wildlife encounters. This was evident in several 'lockdown challenges' in community-science projects, such as the BirdLasser Lockdown Garden Surveys in South Africa (Rose et al., 2020) and the British Trust for Ornithology's Garden BirdWatch Project. For example, there was a documented increase in submitted kestrel observations in the Vienna Kestrel Project, although this was likely due to an observer effect, with people spending more time at home and being more likely to detect a kestrel in their neighborhood (PS, pers. obs.). It is important to note more generally that the places sampled as part of community-science programs may be biased through the increased collection of data from urban areas, as many contributors were confined to their homes (Hochachka et al., 2021; Randler et al., 2020). While interpretation of findings will require stringent data quality control and some caution,

community science may have captured invaluable data on raptor presence at unusual rates and/or in unusual areas.

2.6. Persecution

Persecution has been a long-standing concern for raptor conservation, from historic to recent times (Madden et al., 2019; McClure et al., 2018), and is implicated in the population declines of some species, such as red kite and golden eagle (Newton, 2021; Pedrini and Sergio, 2002; Smart et al., 2010; Whitfield et al., 2004b). Persecution refers to mostly illegal intentional killing through shooting, trapping, or poisoning. Many different species are shot at migration bottlenecks for recreational purposes or to produce animal fodder (Brochet et al., 2016; Hoekstra et al., 2020; Sollund, 2019; Van Maanen et al., 2001), while harriers, hawks, and eagles are killed when they are perceived as predators of pets, livestock (Reynolds et al., in press), or game species (Murgatroyd et al., 2019; Restrepo-Cardona et al., 2020). In some regions of the world, raptors are captured or killed for human consumption, trade, or belief-based use (Buij et al., 2016; Wyatt, 2009). In addition, raptors are frequently killed unintentionally, through retaliatory poisoning directed at carnivores (Richards, 2011).

Persecution levels may be reduced by increased appreciation of raptors, as witnessed across Europe during the last few decades (e.g., Martínez-Abraín et al., 2008; Mayhew et al., 2016). There are indications that the COVID-19 anthropause has boosted the public's attention and compassion for wildlife (Lemmey, 2020; Rousseau and Deschacht, 2020), which may include raptors. Where spatially explicit baseline data from before the pandemic are available, such changes in people's appreciation of raptors could be quantified. A greater appreciation of nature in general may also benefit raptors indirectly, for example if it leads to afforestation (e.g., in urban areas), and hence the creation of nesting habitats (see Kumar et al. 2019).

Where persecution levels drop, raptors may behaviorally habituate to human presence (Galeotti et al., 2000; Holmes et al., 1993) and select more exposed nest sites. For example, the proportion of Bonelli's and golden eagles nesting in trees (compared to more secure cliff sites) increased, while Spanish and Eastern imperial eagles (*Aquila heliaca*) are increasingly nesting in exposed places outside protected areas or in areas of high human density, suggestive of increased fearlessness (Martínez-Abraín et al., 2019). For other species, the recent colonization of urban areas is probably partly explained by reduced persecution levels (e.g., northern goshawk *Accipiter gentilis*, Rutz, 2008), and the same is true for the recolonization of more rural landscapes (Lensink, 1997; Sim et al., 2000). Therefore, if lockdowns caused reductions in persecution (which remains to be confirmed), we might expect raptors to respond favorably over time, by (re-)using areas that they previously avoided. Global observation records, such as those collated by eBird, as well as local GPS tracking studies could provide useful information on changes in habitat use or foraging behavior (e.g., Linssen et al., 2019; Sánchez-Clavijo et al., 2021; LeTourneux et al., 2021). These could be combined with routinely performed spring and autumn migration counts, which were in some cases possible despite the pandemic. Examples are long-term datasets hosted by Hawk Mountain Sanctuary, Hawk Watch International, and Batumi Raptor Count. The latter is also a known hot spot for raptor persecution (Sándor and Anthony, 2018; Sándor et al., 2017) in the form of targeted shooting.

At the same time, there are concerns that raptor persecution increased with ongoing restrictions on human mobility, because illicit activities are more difficult to detect and combat. Under normal circumstances, the mere presence of people for recreational or research activities may deter criminals, especially in unprotected areas with minimal surveillance (Piel et al., 2015). For example, there are concerns that in remote areas of the UK, persecution levels may have increased during lockdown because there were fewer people watching out for criminal activities (Whitehead, 2020). Indeed, after lockdown began in March 2020, the Royal Society for the Protection of Birds (RSPB)

received 3–4 reports of raptor persecution per day, compared with 3–4 per week, pre-lockdown (Marshall, 2020; Wordley, 2020). Among the species shot or poisoned in the UK were white-tailed eagle, hen harrier (*Circus cyaneus*), peregrine falcon, red kite, goshawk, common buzzard (*Buteo buteo*), and barn owl (Marshall, 2020), while white-tailed and eastern imperial eagles were reported killed in Central and Eastern Europe (Hollenstein and Lucius, 2020; Marshall, 2020). At least 27 raptors were illegally killed in Austria, Hungary, Czech Republic, and Slovakia in March 2020 alone, while several other suspected cases are still being investigated.

Where lockdowns persist and lead to higher levels of persecution, we expect a decrease in survival rates compared to baseline levels (Smart et al., 2010), a reduction in the age of first breeding, and an increase in territory vacancies and the use of territories by non-breeding immatures (Whitfield et al., 2004a). In addition, areas that suffer elevated levels of persecution during lockdowns, such as those with high densities of game species, are likely to exhibit disproportionate declines of raptors and higher rates of disappearance of satellite-tagged individuals (Murgatroyd et al., 2019; Villafuerte et al., 1998).

Illegal killing of raptors may be especially problematic in tropical countries, such as in Africa, where fewer anti-poaching teams were operational during lockdown, due to reduced funding (typically derived from tourism revenues) and tighter restrictions (Lindsey et al., 2020). This is likely to trigger increased levels of poaching, which may impact species such as African vultures – some of the most severely persecuted birds on the planet today (either intentionally or unintentionally; Ogada et al., 2012). In southern Africa, vultures are often poisoned by elephant and rhino poachers because they enable anti-poaching teams to pinpoint the locations of carcasses (Ogada et al., 2016a; Ogada et al., 2016b). As such, vultures would be vulnerable to an increase in poaching intensity (Roth, 2020), which may be only partly offset by recent restrictions on wildlife trade imposed by Asian countries that source ivory from Africa (Lindsey et al., 2020). In West and Central Africa, where the trade in vultures for belief-based use and bushmeat is concentrated (Buij et al., 2016), hunting pressure linked to the trade is likely to increase due to a rise in poverty and a movement to rural areas resulting from the pandemic (McNamara et al., 2020). Under such conditions, we expect increased levels of trade in threatened species, and a decline in their abundance, due to elevated mortality rates.

3. Raptors as sentinels of broader environmental impacts

Some raptor species can be used as ‘sentinels’ (e.g., Henny et al., 2010; Kelly et al., 2011; Espín et al., 2016), with changes in their population levels, contaminant loads, and diets indicating environmental conditions. For example, the osprey (*Pandion haliaetus*) has been proposed as a sentinel of aquatic contaminants (Henny et al., 2010), and blood lead levels of turkey vultures (*Cathartes aura*) were used to test the efficacy of California’s ban on lead ammunition (Kelly et al., 2011). Monitoring of raptors might therefore reveal effects of the anthropause that are not apparent at lower trophic levels, or readily detectable via other methods.

3.1. Biodiversity

There is growing recognition of the important roles played by predators, including raptors (e.g., Salo et al., 2008; Lyly et al., 2015), in shaping ecosystems and sustaining biodiversity (Ritchie et al., 2012; Ritchie and Johnson, 2009), because of their top-down regulation of trophic systems (Faeth et al., 2005). The high trophic levels occupied by raptors make them generally useful as indicators of biodiversity (Sergio et al., 2005). Indeed, within forests of the Italian Alps, sites containing nesting raptors (northern goshawks and several owl species) had up to twice the biodiversity of random control sites (Sergio et al., 2005; Sergio et al., 2006), and within the Cape Floral Kingdom of South Africa, areas occupied by black harriers (*Circus maurus*) were associated with higher

bird and mammal species richness than unoccupied ones (Jenkins et al., 2013). Although there is a clear pattern of raptors being associated with areas of high biodiversity, this relationship may not generalize across all ecosystems (Estrada and Rodríguez-Estrella, 2016), and more research is needed. For example, in urbanized Kanagawa, Japan, breeding northern goshawks serve well as indicators of bird species richness and functional diversity (Natsukawa, 2020), but this does not hold true for non-urban areas elsewhere in Japan (Ozaki et al., 2006). It is therefore possible that the utility of the goshawk as an indicator species is mediated by anthropogenic factors that are only present within cities (Natsukawa, 2020). The COVID-19 anthropause presents an opportunity to study correlations between raptors and biodiversity during a period of significantly reduced human activity, although it is possible that lockdowns were too short in duration to cause measurable perturbation.

3.2. Contaminants and pollutants

Raptors are also particularly useful as indicators of environmental pollutants (Gómez-Ramírez et al., 2014). Raptor monitoring can provide early warnings of the potential impacts of contaminants on humans and the environment, as well as a means of tracking the success of associated mitigation measures. During lockdowns, we would for example expect reduced emissions of NOx from traffic (large effects; Sanderfoot and Holloway, 2017), industry, and power generation (smaller effects; Ghosh and Ghosh, 2020). This should reduce levels of lead, mercury, and other typical contaminants in the environment – toxic agents known to negatively affect raptors (Franson and Russell, 2014; Redig and Arent, 2008). Significant lockdown reductions in groundwater pollutants, such as reported from India for selenium (42%) and lead (50%) (Selvam et al., 2020), may also be beneficial to raptors (Gil-Sánchez et al., 2018; Wiemeyer and Hoffman, 1996). On the other hand, large quantities of disinfectants were sprayed in some urban public areas in an attempt to contain the spread COVID-19 in China, South Korea, and Italy (Palmer et al., 2020; Service, 2020). This includes chlorine-releasing agents that accumulate in food chains (Barghi et al., 2018), and may have negative impacts on urban wildlife, including raptors (Nabi et al., 2020; You, 2020). Although active raptor monitoring (e.g., trapping birds and accessing nests) was likely restricted during the pandemic in most areas, some passive approaches (e.g., collection of carcasses and feathers) may have been feasible, perhaps even at increased levels due to intensified recreational outdoors activities.

3.3. Prey species and diet composition

Many generalist raptors sample prey from diverse communities, exhibiting significant responses to landscape-level changes in prey abundance, relative availability, and vulnerability (Masoero et al., 2020; Reif et al., 2001; Rutz and Bijlsma, 2006; Terraube and Arroyo, 2011). This means that their diet composition can in principle be used to track changes in the levels of prey populations, and sometimes, in the composition of entire prey communities. Northern goshawks, for example, have diverse diets across a wide range of landcover types, from forested areas to city centers (Rutz et al., 2006). This species could therefore provide a productive study system for research on COVID-19 impacts. Goshawk diets are easily assessed by collecting prey remains around active nests (Rutz, 2003) – a field method widely used by professional and amateur raptor researchers. Importantly, it can provide reliable results from relatively few site visits (e.g., Suri et al., 2017), so post-lockdown collections could enable inferences about lockdown diets. Comparing breeding season diets from 2020 with data from pre-pandemic ‘baseline’ years (and possibly future years) may reveal significant shifts in diet composition, and hence prey communities (see Rutz and Bijlsma, 2006).

4. The Global Anthropause Raptor Research Network (GARRN)

To take full advantage of the COVID-19 anthropause for advancing the scientific investigation and conservation of the world's raptors, the research community must mobilize and establish innovative modes of pooling data for large-scale analyses, across species, geographic regions, ecosystems, and disturbance regimes (see Rutz et al., 2020). Here, we announce the launch of a new collaborative initiative – the Global Anthropause Raptor Research Network (GARRN) – to achieve this ambitious goal.

4.1. A vision for collaborative research and community building

Our vision is that GARRN will act as an umbrella organization to coordinate global research efforts. As outlined in the preceding sections and Table 1, a broad range of metrics is of interest when assessing potential lockdown effects, including data on ranging behavior and activity patterns, diet composition, individual health, reproductive performance, mortality rates, and population levels. For most analyses, it will be essential to compare data collected during COVID-19 lockdown periods with baseline data from prior (and ideally subsequent) years, to formally assess impacts (Bates et al., 2020; Rutz et al., 2020). Raptor research is often conducted in the context of long-term monitoring programs, providing an ideal foundation for such longitudinal analyses. For some commonly studied raptor species, it may even be possible to make comparisons across multiple populations that experienced varying levels of COVID-19-related perturbation, enabling powerful 'before-after-control-impact' (BACI) study designs (Rutz et al., 2020; Wauchope et al., 2021).

GARRN will be founded on the principles of inclusion, diversity, transparency, and fairness. Because some groups, including (but not limited to) ethnic minorities, women, and persons with disabilities, are underrepresented in STEM fields in general (Hamrick, 2019) and in natural resource management in particular (Kern et al., 2015), GARRN will work hard from the outset to promote inclusion and diversity by tackling key obstacles to participation, such as financial and language barriers, and lack of role models and mentors (Balcarczyk et al., 2015). Active recruitment and support for underrepresented participant groups will help tackle systemic biases (Batavia et al., 2020), build a welcoming community, produce better research outcomes, and ultimately, increase GARRN's relevance to global conservation efforts and natural resource management. All raptor experts are encouraged to participate: this includes not only professional biologists and conservation scientists, but also keen amateurs, who often conduct outstanding monitoring work.

We recognize that, to date, research effort has focused overwhelmingly on a number of widespread, north temperate raptor species (Amar et al., 2018; Buechley et al., 2019), many of which are well adapted to disturbed, anthropogenic environments. The launch of a new global research network provides a valuable opportunity to redress this imbalance, by forging new collaborations with established raptor monitoring initiatives at tropical latitudes and by initiating new programs with full support from the wider community.

Emulating an approach developed by other consortia, such as the COVID-19 Bio-Logging Initiative (Rutz et al., 2020), GARRN will ask researchers to contribute data to a shared database, which can then be leveraged to pursue a broad portfolio of self-contained projects, focusing on specific hypotheses, taxonomic groups or species, or geographic regions (see Table 1). Importantly, researchers will retain full ownership of their hard-won data, and will be able to opt in and out on a project-by-project basis. Contributions of data providers will be formally recognized through co-authorship on publication outputs (as appropriate), following guidelines of the International Committee of Medical Journal Editors (ICMJE).

A significant amount of work lies ahead, in terms of developing robust governance, administrative, and data-handling infrastructure, and timely implementation will require support from dedicated

volunteers, partner organizations, and funders. As GARRN's Steering Committee is formed over the coming months, we will investigate suitable funding opportunities and build partnerships with relevant stakeholders.

4.2. Existing infrastructure and collaboration opportunities

Fortunately, significant infrastructure and expertise already exists that could provide critical support for GARRN's mission. For example, there is a large number of well-established raptor research and conservation organizations (for a non-exhaustive list, see Table 2), which we hope will join GARRN as collaboration partners, and help advertise it among their members and wider networks. Some of these organizations work at a regional or country level, like the 'Monitoring Greifvögel und Eulen Europas' (MEROS) (a long-running program curating raptor population monitoring data across Europe), while others operate across countries, like the Vulture Conservation Foundation (an international NGO focusing on research, environmental education, and providing advice to various stakeholders).

As with any research network, a major challenge will be to build local capacity across countries, to facilitate large-scale participation and data standardization. Here again, there is abundant existing knowledge within the international raptor research community, which we hope GARRN can utilize and advance. For example, the European Raptor Biomonitoring Facility already coordinates best sampling practices and data exchange for contaminant monitoring; their recently published guidelines can be adopted worldwide, to ensure appropriate sample quality, and to maximize the reliability, comparability, and interoperability of data (Espín et al., 2021). In Africa, the African Raptor Data-Bank (ARDB) was an effort to collect and organize spatial data for African raptors to determine their conservation status, which played an integral role not only in developing a multi-species action plan to conserve African-Eurasian vultures (Botha et al., 2017) but also in launching The Peregrine Fund's Global Raptor Impact Network (GRIN) – the first initiative to monitor the world's raptors.

Via the GRIN mobile application, raptor researchers can enter data from across the globe on breeding, mortality, and population levels among other information. GRIN also contains many local long-term datasets spanning several decades preceding the COVID-19 pandemic. The principal goal of GRIN is to inform conservation assessments of the world's raptors (McClure et al., in revision), whereas GARRN will coordinate collaborative testing of hypotheses about human-raptor interactions and their impacts. GRIN's infrastructure for data collection, storage, and analyses will be leveraged to support GARRN's objectives, while data collated by GARRN for anthropause research will support efforts to monitor the conservation status of raptors worldwide. In fact, since the bulk of data within GRIN are from the African Raptor Data Bank and many GRIN partners are located in the Global South, GARRN can make valuable contributions to addressing north-temperate bias. These two programs – GRIN and GARRN – are thus perfectly complementary, and we look forward to collaborating on realizing the full potential of these synergies.

Other repositories, like Movebank, eBird, and iNaturalist, were set up with a broader taxonomic remit, but could provide invaluable additional raptor datasets. There is also scope for fruitful collaboration with other consortia that are exploring the effects of COVID-19 restrictions on animal movements and activity patterns (Rutz et al., 2020), and on ecosystems more generally (Bates et al., 2020; Bates et al., 2021).

While we launch GARRN as the Global Anthropause Raptor Research Network, to tackle time-sensitive research opportunities arising from the COVID-19 anthropause, our plan is to gradually transition towards addressing questions about human-raptor interactions in the Anthropocene more generally. The community we strive to build over the coming months and years will then continue to collaborate as the Global Anthropocene Raptor Research Network, retaining the original acronym GARRN.

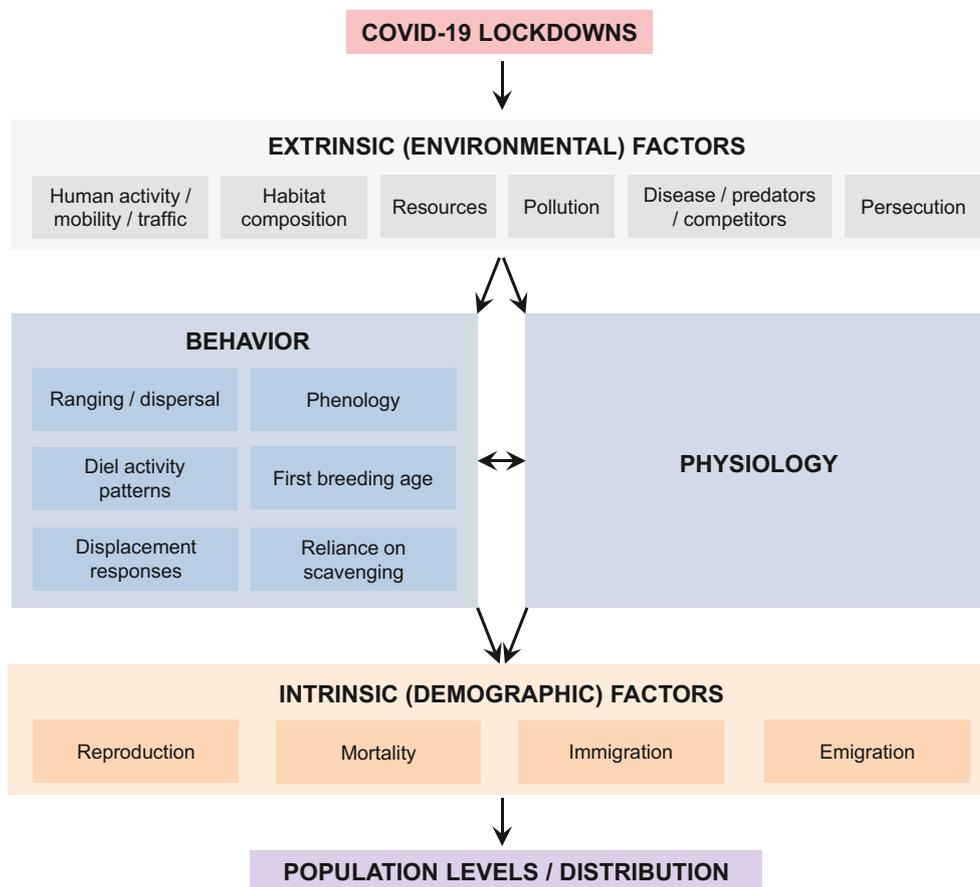


Fig. 1. A conceptual framework for guiding studies on the effects of the COVID-19 anthropause on raptors and other taxa. COVID-19 lockdowns likely altered many of the extrinsic factors that are limiting raptor populations. These environmental changes are in turn expected to affect – usually mediated by behavior and physiological responses – the intrinsic factors that ultimately determine population levels and distributions. Causal pathways, and strengths of effects, will likely vary significantly across raptor species and regions. Large-scale collaboration is required to document the impact of the COVID-19 pandemic on global raptor populations and derive conservation recommendations. This is the stated goal of the Global Anthropause Raptor Research Network (GARRN).

4.3. Data availability and quality

We acknowledge that GARRN faces considerable challenges in terms of collating datasets of sufficient quality. Restrictions imposed on human movement during the pandemic have significantly constrained raptor fieldwork activities, including during time periods where continuous data collection is most required. That said, we are aware of many field projects that managed to continue despite local lockdowns. For example, several of The Peregrine Fund's international research and conservation programs were able to continue by employing modified field protocols (CJWM, pers. obs.). Many other studies will have benefitted from automated data-collection methods (e.g., from satellite tags or camera traps deployed pre-lockdown), or will have been able to collect critical data after movement restrictions were eased or lifted (e.g., fledgling production, adult:juvenile ratio, abundance, diet composition). While we are confident that globally available datasets will enable a robust investigation of lockdown effects, we acknowledge that data deficiency may hamper some of the proposed analyses.

Many of GARRN's projects will focus on the question of whether a particular type of change in human behavior, at a particular intensity, had a measurable effect on raptor behavior and demography. For studies from areas affected by lockdowns, it will be essential to define a spatially and temporally explicit window within which human movement restrictions were imposed. The information used to define this period is expected to fall into two categories. First, documentary evidence of the types of restrictions applied, their location, and their start and end dates, will be required as a minimum, to apportion a time series of observations into before, during, and after periods. Second, corroborative evidence should be sought, where possible, that these restrictions were sufficiently intense to alter aspects of the environment that are known to influence raptor biology. Clearly, in some cases, areas may have been

subject to human movement restrictions, yet significant impacts on the lives of local raptors would not be expected, because local compliance, or baseline levels of human presence, were low. A range of data products is available that can be used to measure changes in human activity either directly or indirectly, to inform analyses of animal data (Ellis-Soto et al., manuscript in preparation). It is important to note that data are also required for study areas where there were no (or only minimal) restrictions and effects on human mobility, to enable critical comparisons between raptor populations that did, and did not, experience pandemic-induced perturbation (see Rutz et al., 2020; Bates et al., 2020; Wauchope et al., 2021).

The timespan over which observations were made will also influence the robustness of any conclusions that can be drawn. Ideally, the same types of observations should have been made before, during, and after the imposition of restrictions, within the same study area and following the same protocols. The type of data and research question under investigation will determine the most appropriate time scale. For example, while it is possible to meaningfully analyze movement and activity data (e.g., collected by tracking devices) collected just during 2020, comparisons across years are necessary to evaluate possible impacts on demographics. For all analyses, long-term datasets spanning several years, where time periods can be matched exactly to remove any effects of natural seasonal cycles, are of particular value, and we strongly encourage fieldworkers to continue data collection post-pandemic where possible.

We conclude this section by emphasizing that GARRN welcomes all data contributions – from lockdown-affected and -unaffected areas, from short- and long-term studies, on any aspect of raptor biology, and of course, from all species and geographic regions. This will allow GARRN to develop a database that can support a strong portfolio of complementary anthropause-focused research projects, to contribute to GRIN's

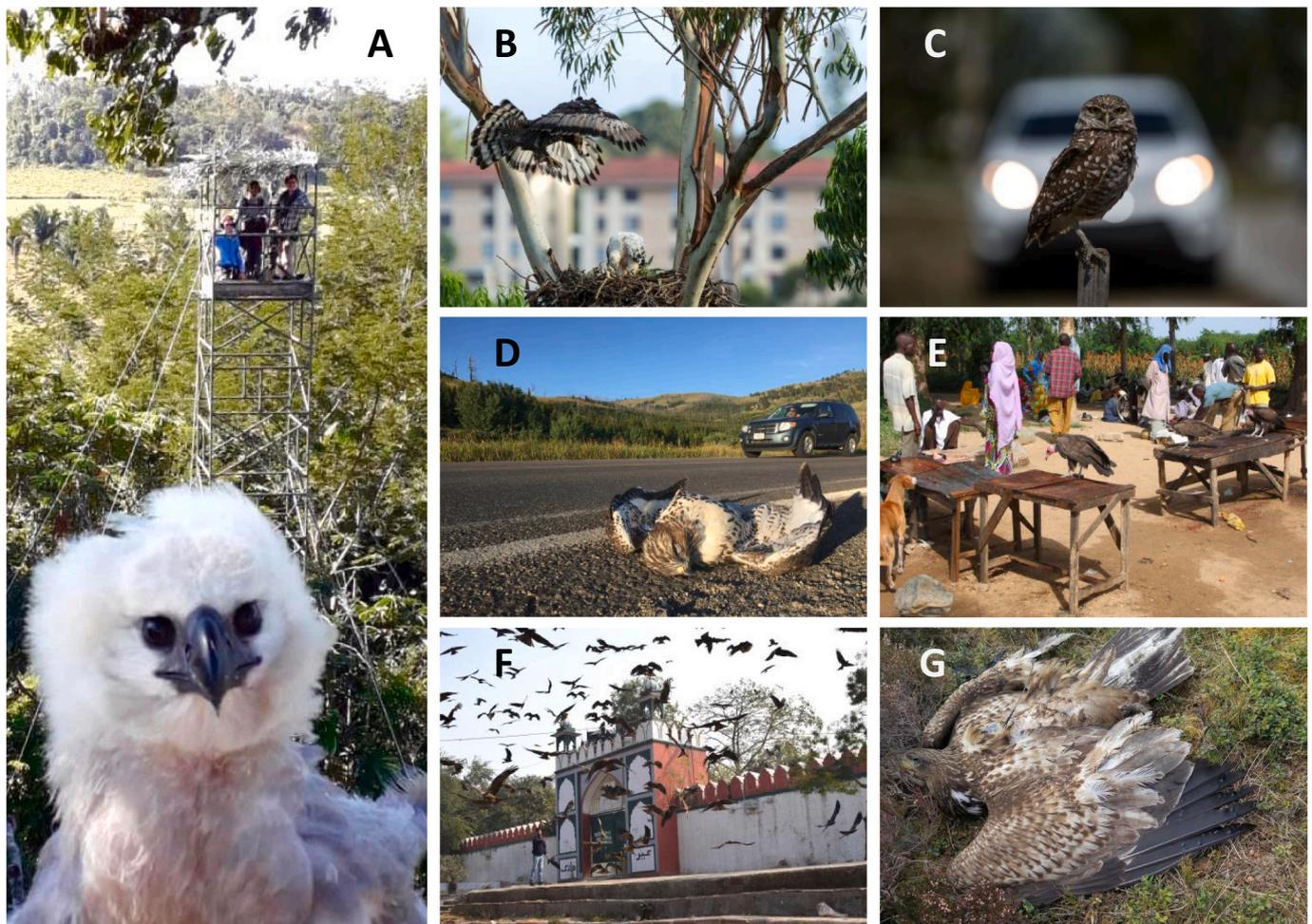


Fig. 2. Examples of human–raptor interactions during the COVID-19 anthropause, and the Anthropocene more generally, as discussed in the main text. **(A)** Recreational activities: A film crew on an observation tower overlooking a harpy eagle nest in the Arc of Deforestation, Southern Amazon Forest, Mato Grosso, Brazil. While human recreation can cause significant disturbance to raptors, this is a good example of how it can provide valuable funding for conservation work, which has been badly affected during lockdowns in many areas. **(B)** Habitat loss and landscape management: A crowned eagle nest in a Durban suburb, South Africa, where gardens and Eucalypts have replaced native forest. **(C)** Reduced traffic volume: Reduced noise and light pollution levels may have benefited nocturnal raptors, such as this burrowing owl in the USA. **(D)** Road-kill: A reduction in road-kill during the COVID-19 anthropause may have affected scavenging species, such as common buzzards, by reducing both foraging opportunities and collision risk. **(E)** Unintentional or **(F)** deliberate supplementary feeding: Hooded vultures gleaning meat scraps at a slaughter house in Cameroon, Central Africa, and black kites foraging on food subsidies offered for religious reasons in Delhi, India. **(G)** Increased persecution: A satellite-tagged white-tailed eagle found poisoned on a Scottish grouse moor during lockdown in April 2020. Photos reproduced with permission – A: E. Miranda; B/C: M. Graf and C. Sonvilla; D/E: R. Buij; F: G. and H. Singh; G: Police Scotland.

raptor conservation efforts, and ultimately, to help build an inclusive global raptor research community that will continue to collaborate long after the COVID-19 pandemic has come to an end – for the benefit of both raptors and humans.

5. Concluding remarks

The COVID-19 anthropause has created an unprecedented opportunity to gain deep mechanistic insights into human–raptor interactions, informing urgent ongoing conservation efforts. GARRN aspires to use datasets gathered before, during, and after COVID-19 lockdown (and potentially additional lockdowns in future years) to address important, long-standing questions in fundamental and applied raptor biology. With this article, we would like to initiate a conversation with all relevant stakeholders, to explore how GARRN could harness pre-existing infrastructure, expertise and data, as well as the power of community science, indigenous knowledge, and cutting-edge technology, to make the most of the extraordinary conditions that were so tragically created by the pandemic, and to build a strong research community.

From a scientific perspective, this is an invaluable opportunity to separate the effects of human presence (and disturbance) from those of human-made landscape modifications, with quasi-experimental control and outstanding population-level replication. To guide research efforts, we offer a conceptual framework (Fig. 1) as well as a non-exhaustive set of predictions that can be examined with the kinds of datasets that are routinely collected by raptor researchers (Table 1; Fig. 2). This includes both traditional methods, such as nest and diet surveys, as well as more recent approaches, including GPS tracking and community science. Given the paucity of data on tropical raptors (compared to temperate species), and the greater proportion of globally threatened species in the tropics, GARRN will seek to redress this imbalance where possible, for example by inviting data contributions from any ongoing tracking studies of vultures and large eagles in Africa, South and Central America, and Southern Asia. By pooling datasets across large numbers of species globally, it will be possible to investigate comparatively whether certain traits or ecological contexts are associated with an ability (or inability) to cope well with human disturbance and environmental perturbation, providing critical data for informing conservation interventions.

Finally, we stress the importance of tact when conducting scientific studies in the face of great human suffering. Raptor researchers must remain sensitive to the health and economic consequences of the pandemic that underlie these potential research opportunities. We also agree with earlier commentaries that, although the study of lockdown impacts should be well-funded to reap potential conservation benefits, competition with schemes focused on human health must be avoided (Rutz et al., 2020).

Given the importance of raptors to environmental health, and their sensitivity to human disturbance, we must continue to monitor and study them throughout the COVID-19 pandemic and beyond, to help safeguard their populations in the Anthropocene.

Declaration of competing interests

The authors declare that there is no conflict of interest.

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CRedit authorship contribution statement

CR conceived the initial idea for GARRN, which was developed further in close collaboration with PS; PS and CR initiated and coordinated manuscript preparation, and developed the conceptual framing; PS produced a first draft to which all authors contributed text sections, ideas and critical feedback; CR and PhS prepared Fig. 1; PS collated images for Fig. 2; RB, CJWM, CRD, PhS and PS prepared Table 1; PS prepared Table 2; and all authors edited and approved the manuscript.

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