Biological Conservation 263 (2021) 109175

Contents lists available at ScienceDirect

Biological Conservation

journal homepage: www.elsevier.com/locate/biocon

Global COVID-19 lockdown highlights humans as both threats and custodians of the environment

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https://doi.org/10.1016/j.biocon.2021.109175
Received 4 May 2021; Accepted 7 May 2021
Available online 20 May 2021

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ARTICLE INFO

Keywords:
Pandemic
Biodiversity
Restoration
Global monitoring

ABSTRACT

The global lockdown to mitigate COVID-19 pandemic health risks has altered human interactions with nature. Here, we report immediate impacts of changes in human activities on wildlife and environmental threats during the early lockdown months of 2020, based on 877 qualitative reports and 332 quantitative assessments from 89 different studies. Hundreds of reports of unusual species observations from around the world suggest that animals quickly responded to the reductions in human presence. However, negative effects of lockdown on conservation also emerged, as confinement resulted in some park officials being unable to perform conservation, restoration and enforcement tasks, resulting in local increases in illegal activities such as hunting. Overall, there is a complex mixture of positive and negative effects of the pandemic lockdown on nature, all of which have the potential to lead to cascading responses which in turn impact wildlife and nature conservation. While the net effect of the lockdown will need to be assessed over years as data becomes available and persistent effects emerge, immediate responses were detected across the world. Thus, initial qualitative and quantitative data arising from this serendipitous global quasi-experimental perturbation highlights the dual role that humans play in threatening and protecting species and ecosystems. Pathways to favorably tilt this delicate balance include reducing impacts and increasing conservation effectiveness.

1. Introduction

Human-driven alterations of atmospheric conditions, elemental cycles and biodiversity suggest that the Earth has entered a new epoch, the Anthropocene (Crutzen, 2002; Steffen et al., 2007). Negative impacts associated with human activities include a much warmer Earth state, marked expansion of urbanization, and accelerating species extinctions (Schipper et al., 2008). The perspective that the main role of humans is a source of threats on species and ecosystems leads to the prediction that the global human lockdown to mitigate COVID-19 health risks may alleviate human impacts, with resulting positive environmental responses (Derryberry et al., 2020; Rutz et al., 2020). Indeed, early reports indicate that restrictions led to immediate decreases in air, land, and water travel, with similar declines in industry, commercial exploitation of natural resources and manufacturing, and lower levels of PM_{10}, NO_2, CO_2, SO_2, and noise pollution (Bao and Zhang, 2020; March et al., 2021; Millefiori et al., 2021; Otmani et al., 2020; Santamaria et al., 2020; Thomson and Barclay, 2020; Terry et al., 2021 [this issue]; Ulloa et al., 2021 [this issue]).

Yet a more comprehensive consideration of the links between human activities, species and ecosystems also acknowledges the role of humans as custodians of nature, who engage in conservation research, biodiversity monitoring, restoration of damaged habitats, and enforcement activities associated with wildlife protection (Bates et al., 2020; Corlett et al., 2020; Evans et al., 2020; Manenti et al., 2020; Rondeau et al., 2020; Zambrano-Monserrate et al., 2020; Kishimoto and Kobori, 2021 [this issue]; Miller-Rushing et al., 2021 [this issue]; Vale et al., 2021 [this issue]; Sumasgutner et al., 2021 [this issue]). Indeed, the global

COVID-19 human confinement has disrupted conservation enforcement, research activities and policy processes to improve the global environment and biodiversity (Corlett et al., 2020; Evans et al., 2020; Zambrano-Monserrate et al., 2020; Quesada-Rodriguez et al., 2021 [this issue]). The lockdown has also created economic insecurity in rural areas, which may pose biodiversity threats as humans seek to support themselves through unregulated and illegal hunting and fishing, and conservation spending is reduced. In particular, declines in ecotourism in and around national parks and other protected areas lowered local revenue, park staffing, and funding to enforce hunting restrictions and invasive species management programs (Spenceley et al., 2021; Waithaka et al., 2021). In many areas, restoration projects have been postponed or even cancelled (Bates et al., 2020; Corlett et al., 2020; Manenti et al., 2020).

Here, we consider the global COVID-19 lockdown to be a unique, quasi-experimental opportunity to test the role of human activities in both harming and benefiting nature (Bates et al., 2020). If the negative roles of humans on species and ecosystems predominate, we would expect overwhelmingly positive reports of responses of nature to human lockdown. We integrate 30 diverse observations from before and during the peak lockdown period to examine how shifts in human behavior impact wildlife, biodiversity threats, and conservation. We first analyze the mobility of humans on land and waterways, and in the air, to quantify the change in human activities. Second, we compile qualitative reports from social media, news articles, scientists, and published manuscripts, describing seemingly lockdown-related responses of nature, encompassing 406 media reports and 471 observations from 67 countries. Third, we map the direction and magnitude of responses from wildlife, the environment and environmental programs, using data collected before and during lockdown provided by scientists, representing replicated observations across large geographic areas. We collated data from 84 research teams that maintained or accessed existing monitoring programs during the lockdown period, reporting 326 responses analyzed using a standardized analytical framework. We accounted for factors including autocorrelation and observation bias using mixed-effects statistical models, and selected the most robust available baselines for each study to report lockdown-specific effect sizes (see methods). We empirically describe the type, magnitude, and direction of responses for those linked with confidence to the lockdown, and offer integrated outcomes supported by examples drawn from our results. Finally, we use these results to provide recommendations to increase the effectiveness of conservation strategies.

2. Materials and methods

Here we interpret data and qualitative observations that represent a non-random sample of available information comprising diverse response variables. Thus, we make inferences about the geographic scope of observations and focus on what integrated understanding can be gained from considering the evidence of both positive and negative effects of the lockdown and their linkages.

From diverse data sources and analyses, we compiled a high-level view of how the lockdown influenced four major categories of responses or shifts in (1) human mobility and activity, (2) biodiversity threats, (3) wildlife responses, and the (4) social structures and systems that influence nature and conservation (described in further detail in Appendix 1, Table A1). In brief, human mobility and activities included recreational activities such as park visits and boating, commuting, and activities related to industry, such as shipping. Biodiversity threats included categories which were linked directly to a possible negative wildlife response, such as hunting, fishing, mining, vehicle strikes, wildlife trade, environmental pollution, and deforestation. Wildlife responses represented observations related to biodiversity and species, such as community structure, animal performance (e.g., reproduction, health, foraging) and habitat use (i.e., abundance and distribution). Environmental monitoring, restoration programs, conservation, and enforcement were grouped as representing social systems and structures that influence and support conservation.

2.1. Human mobility data

Data on government responses to COVID-19 across countries and time were retrieved from the Oxford COVID-19 Government Response Tracker (Hale et al., 2021), which also reports where the restrictions on internal movement apply to the whole or part of the country. The global population under confinement of internal movement was calculated by adding up the population of countries where the restriction is general, and 20% of the population of countries where the restriction is targeted, as an estimate of the fraction of the population affected. Population data by country corresponding to year 2020 have been obtained from the Population Division of the Department of Economic and Social Affairs of the United Nations (United Nations, 2018). Note that the data about restrictions contain missing information for some countries and dates. Therefore, the calculated number of human confinement does not take into account the population of countries with missing information and may thus underestimate the actual number of humans under restriction.

Changes in human mobility data were recorded by a number of agencies globally, and combined, describe how the lockdown affected movements on land, at sea, and in the air. Data on the restriction of individuals in residential areas and to parks were derived from Google Community Mobility Reports (https://www.google.com/covid19/mobility/). Data on driving were obtained from the Apple Maps Mobility Trends Report (https://www.apple.com/covid19/mobility). Marine traffic and air traffic data were derived from exactEarth Ltd. (http://www.exactearth.com/), and OpenSky Network (https://openskynetwork.org/) respectively. Google Community Mobility Report data are based on anonymized data representing how long users stay in different types of localities, and are aggregated to regional scales (usually country). Each regional mobility report reflects a percentage change over time compared to a 5-week baseline (Jan. 3 to Feb. 6, 2020). Similarly, Apple Maps Mobility Trends Reports are based on Apple maps user data and aggregated by region to reflect the percent change in time Apple maps users spent driving relative to a baseline (Jan. 12, 2020). The percent change in the responses of human mobility through time allows identification of extreme inflections related to human behavior. For Google and Apple data, we extracted the overall mobility trends for each country until May 1st, which was selected from a sensitivity test and before relaxation of confinement measures were introduced in most countries. We further excluded within-country variations in mobility, and removed all countries with extensive data gaps and countries that did not show a response to lockdown.

The first step to quantifying the effect due to the lockdown on community mobility (residential and parks) and driving data was identifying the date of greatest change in each time-series (data and script files are here: https://github.com/rjcommand/PAN-Environment). Because each country had differing lockdown dates and multiple types of lockdown, we identified critical transition dates which best explained the change in mobility for each country. To do so, we used Generalized Additive Models (GAM (Wood, 2011)) on daily mobility levels in each country, using the Oxford Covid-19 Government Response Tracker database of country-level containment policies (C1-C7) to define a variable for the before and after lockdown periods, running up to 15 models per country depending on the number of different kinds of lockdown measures imposed. From these models, we selected the lockdown date that explained the greatest amount of change. We manually identified the confinement dates in cases where the models did not converge or when multiple unexplained inflection points were detected ($N = 10$ countries). Percent change was calculated as the mean percentages after implementation of the confinement measure selected from the models.

For marine traffic mobility, satellite AIS (S-AIS) data for April 2019 and 2020 were obtained from exactEarth Ltd. (http://www.exactearth.

com/), a space-based data service provider which operates a constellation of 65 satellites to provide global AIS coverage at a high-frequency rate (< 5 min average update rate). The latest upgrade in the constellation entered into production in February 2019 and S-AIS coverage was equivalent for both periods (exactEarth Ltd., pers. comm.). Values represented the monthly number of unique vessels within grid cells of 0.25×0.25 degrees. We calculated the vessel density as the number of vessels per unit area, considering the difference of cell size across the latitudinal gradient (March et al., 2021). Grid cells from the Caspian Sea and with <10% ocean area were removed from the analysis, based on the GADM Database of Global Administrative Areas (version 3.6, https://gadm.org/). Further quality control procedures were provided in more detail in a complementary publication. We calculated the percentage change in marine traffic density between April 2019 and April 2020 per country and Exclusive Economic Zones (EEZ, Figs. S6 & S7) using a Generalized Linear Model (GLM (R Core Team, 2020; Pinheiro et al., 2021)).

For air traffic mobility, data were downloaded from the OpenSky network (https://openskynetwork.org). OpenSky uses open-source, community-based receivers to receive air traffic data from around the world and makes these data available in an online repository. The online database consists of latitude and longitude of departure and landing for all flights detected where receivers are available. Data are limited in some areas, including Africa and parts of Asia. We downloaded daily data for 129 countries where data were available in April 2019 (1,302,282 flights) and the same period in April 2020 (316,609 flights, when most countries included in the analysis had imposed international travel restrictions) to compare the total volume of traffic departing from, or arriving to, all countries where data were available for both years. We aggregated these flights by country, then ran a GLM on the daily number of flights in each country, accounting for the day of the week and comparing 2020 (countries in lockdown) to 2019. We used this model to calculate a t-statistic for the lockdown effect in each country, and then calculated a percentage change in flight volume based on numbers of flights per country in April 2019 versus the lockdown period in April 2020.

2.2. *Qualitative observations*

Observational evidence of the impact of the first four months of the COVID-19 lockdown on society, the environment and biodiversity was collected and collated through: (1) internet searches with the keywords nature, conservation, environment and COVID-19; (2) calls on social media for personal observations and for volunteers to contribute from our networks; (3) Web of Science general search for papers (terms: nature, conservation, environment, COVID-19) released between May to August 2020 that also used qualitative evidence to investigate the lockdown effect, and (4) through volunteer contributions from our global PAN-Environment working group of over 100 scientists. Each qualitative observation ($N = 877$ observations) was assigned a geographic location (latitude and longitude) and classified by observation type (described in Appendix 1, Table A1), including a description and details on the species impacted (where relevant). Reports that listed several impacts (e.g., independent observations, species, or locations) were entered as multiple lines. Following entry to our dataset, each observation was assigned an effect score from 0 to 10 (as described in Appendix 1, Table A2) to distinguish between observations with ephemeral effects with unknown impacts from those that will have widespread or persistent outcomes with strong effects in positive or negative directions. Qualitative data were recorded for all continents, except Antarctica, representing 67 countries. Non country-specific observations were also included, representing 20% of all anecdotes. The majority of countries were represented by fewer than five observations (51 countries), while South Africa submitted approximately one third of the total observations (total = 297). This high representation in South Africa was a known bias due to the use of African birding forums to collect citizen science data which were organized to communicate and engage widely as lockdown measures were implemented. Similarly, other known biases included high relative representation of charismatic species and those that were easily observed during lockdown by humans (e.g., giant pandas and garden birds). Most reports were gathered from English sources, however, over 100 observations were translated from Italian, and another 50 and 10 were from Spanish and Afrikaans, respectively. We interpreted our results in this context by focusing on the inferences that can be made in spite of these biases, and in combination with the empirical data. See Appendix 3 (Table S3) for the full dataset.

2.3. *Empirical data*

We further assembled a global network of scientists and managers to download, interpret, and analyze quantitative information investigating the negative, neutral, and positive effects resulting from the lockdown. We made use of ongoing monitoring programs for comparisons before, during, and after the lockdown confinement period, or in similar time windows in previous unaffected years. Seven example scripts were provided to represent different types of considerations for analyses for each team to match with the types of response data, biases, references, study durations, and complexity (covariates, spatial and temporal autocorrelation, and random effects) (available in Appendix 2). The core author team further consulted on the analysis of each dataset to ensure consistency across studies. The original authors reviewed and edited their data following transcription.

With this overall approach, we were able to provide insights on the immediate changes likely due to the lockdown (69 studies used a historical reference period including the lockdown months in previous years; studies compared the strict lockdown period to the same months in pre-lockdown years, described in detail for each study in Appendix 4, Table A4). In other cases, the reference was an area representing a reference state (i.e., remote areas or large, well-governed protected areas did not undergo a difference in human activities due to lockdown measures). If observations were unavailable prior to the start of the pandemic lockdown or for reference year(s), comparisons were made (if sensible) during and after the lockdown, i.e., the reference was the post-confinement period (8 studies). For instance, litter accumulation at two locations was measured from the strict lockdown in April 2020, and over two months as restrictions eased. Spatial comparisons between areas impacted by the lockdown with unaffected sites were also included to detect lockdown related effects. These unaffected sites were considered as reference areas after evaluation by the relevant research teams who contributed the data (2 studies). The rationale for each study design and selection of the baseline period is reported in Table A4 and A5 (Appendices 4 and 5), and was reviewed by the core analysis team to ensure the baseline period comprised a suitable reference for the given response of interest. Total percent changes were calculated as the difference between the response coefficient (attributed to the lockdown) relative to the reference coefficient. For instance, if we observed a 400% increase in a response during the lockdown, this translates to an effect which was 4 times greater. We used Generalized Linear, Additive Mixed (GAMM (Wood, 2004)) or Linear Mixed-Effects (LME (Pinheiro et al., 2021)) models, as best suited for each data type. Suitability was based on the distribution of the response data, fit of the statistical data, and the covariates that needed to be accounted for to estimate the appropriate coefficients. In brief, for each dataset, we quantified percentage change from expected or typical values, as well as an effect size in the form of a t-statistic standardized by sample size (Bradley et al., 2019). Datasets and results summary tables for each analysis of human mobility and empirical datasets are deposited in a GitHub repository, filed under each contributing author's name: https://github.com/rjcommand/PAN-Environment. The independent data availability statement for each study is reported in Table A5 (Appendix 5).

Different datasets were analyzed using statistical models with parameters dependent on the type, duration and complexity of each response and study design. Table S5 (Appendix 5) provides a summary of the information that was collected from the authors who contributed each study, a description of the methods and relevant references, analysis type, spatial scale, details on the temporal or spatial baselines and how they were accounted for or interpreted, reports of any confounding factors (included as covariates), model results summary table links to GitHub, interpretation, and confidence score that the observed effect was indeed due to the lockdown (with a rationale for this selection). The relevant information for interpretation across studies was subsequently transcribed to Table S4 (Appendix 4).

3. Results

3.1. Human mobility on land, in the air and on water

The global peak of lockdown occurred on April 5th, 2020, at which time 4.4 billion people were impacted (Fig. 1), representing 57% of the world's population. In the weeks before and after this lockdown peak, residents of most countries spent much more time at home (Fig. 2). Country-specific critical transition dates (which occurred primarily in late March leading up to the April peak) were used to assess the total change in mobility until May 1st. During this period, driving decreased by 41%, there was a 20% overall reduction in park visits, particularly in Central and South American countries, although Nordic countries were an exception (Figs. S1 & S2). The April 2020 period also saw major disruptions in community, food transport, and supply chains, with a 9% decrease in marine traffic globally and a 75% total reduction in air traffic (both relative to April 2019, Figs. A3-A5). Thus, the COVID-19 lockdown has led to a significant global reduction in human mobility, notably travel, causing an "anthropause" (Rutz et al., 2020).

3.2. Effects on wildlife around the world

As humans retreated, animals quickly moved to fill vacated spaces (Fig. 3) (Derryberry et al., 2020; Zellmer et al., 2020). In our dataset, approximately half of the qualitative observations and more than one third of all measured quantitative species responses that were linked with some confidence to the lockdown related to unusual animal sightings in urban areas (both land and waterways), and to species occurring in different abundances compared to pre-perturbation baseline estimates (Figs. 4 and 5). Many initial observations painted a rosy picture of wildlife "rebounding"; indeed, our qualitative observations of wildlife responses are predominantly positive, likely reflecting reporting biases (Fig. 4). Reports include changes in behavior, reproductive success, health, and reductions in mortality, apparently in response to altered levels of human activity (Fig. 4).

Our quantitative assessments suggest a mixed role of human confinement in positively and negatively influencing wildlife (Fig. 5). Some species changed their behavior (e.g., daily activity patterns) and relocated to entirely new areas, including seeking new food sources and roaming to unusual areas. This included air space, such as when critically endangered Griffon vultures in Israel flew further afield in 2020, apparently due to reduced military training during the lockdown (Appendix 4, Table A4, StudyID 55). Some animals also moved to human settlements from rural locations (e.g., golden jackals: Appendix 4, Table A4, StudyID 28), while other species showed very little changes (Fig. 5 showing distribution of wildlife responses as effect sizes which center on zero).

There was also qualitative evidence of increased human-wildlife conflicts (described in Appendix 3, Table A3 under the categories: Biodiversity threat, Human-wildlife interaction, Aggression). Four non-fatal shark attacks on humans occurred over a span of five weeks in French Polynesia, a number typically observed over a whole year, and an unusually high number of fatal shark attacks has been reported for Australia. On land, monkeys that normally live closely and peacefully with humans near a pilgrim center in Uttar Pradesh, in northern India, attacked residents – atypical behavior that may be related to starvation and corresponding aggression.

3.3. Changes in biodiversity threats

The pandemic lockdown generally highlighted the enormous and wide-ranging impacts that humans have on the environment and wildlife. For instance, in a remote forest area in Spain, a 45% reduction in NO_2 and SO_2 lead to reduced atmospheric deposition of NO_3^- and SO_4^{2-}, and limited the input of N and S to soil ecosystems (Appendix 4, Table A4, StudyID 84). Ocean fishing was also reduced by 12% based on our analysis of 68,555 vessels, representing 145 national flags and 14 gear types (including drifting longlines and nets, purse seines and trawlers, Appendix 4, Table A4, StudyID 5). Animal deaths from vehicle strikes on roads and vessel strikes in the water during peak lockdown were dramatically lower than baseline periods in two data sets (e.g., 19% reduction: South Korea, 42% reduction: USA, Appendix 4, Table A4, StudyIDs 7 & 27). There was also a marked reduction in ocean noise, which can negatively impact a wide range of marine organisms, as reported from several locations. For example, lockdown-related reductions in ferry traffic, seaplane activity, and recreational boating activity near the transport hub of Nanaimo Harbour, Canada, combined to reduce the sound pressure levels by 86% (Appendix 4, Table A4, StudyID 23). In urban parks in Boston, noise from road traffic dropped by as much as 50% in some areas as traffic volumes decreased (Appendix 4, Table A4, StudyID 52; Terry et al., 2021 [this issue]). On roadways, parks and beaches around the world, direct pollution from humans was also reduced during the lockdown. For example, surveys of 15 beaches in Colombia and Cuba found negligible evidence of noise, human waste, and litter during the strict lockdown period, in contrast to pervasive human impact before the lockdown (Appendix 3, Table A3, Lines 742–748).

While some biodiversity threats were alleviated, as discussed above, responses were highly variable. For example, marine traffic increased slightly in some regions (Appendices 4 and 5, Fig. A4 and A5) including shifts of fishing fleets to near-shore coastlines. In some regions, fishing

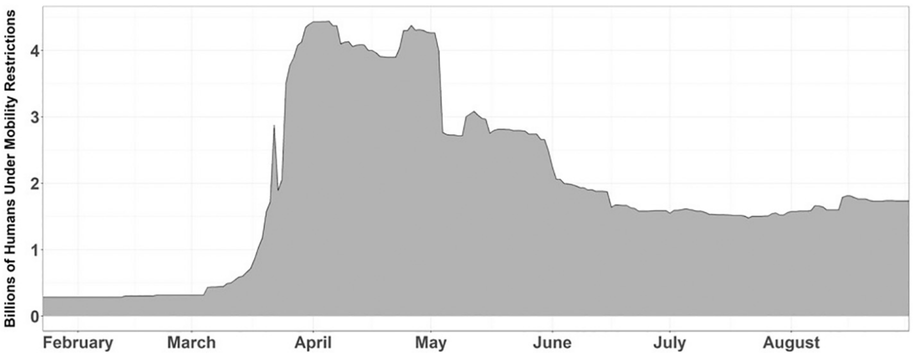

Fig. 1. Total humans under COVID-19 mobility restrictions. Time series of the number of humans under lockdown across the global population under the 2020 COVID-19 mitigation policies. This assumes that in countries with targeted restrictions, a fraction of 20% of the population was under lockdown. Assuming different fractions, similar time patterns but different magnitudes of populations under lockdown are obtained. For example, assuming fractions of 20% and 30%, April 5th was the day with the maximum population under lockdown equal to 57% and 61% of the global population, respectively. Assuming fractions of 5% and 10%, April 26th was the day with the maximum population under lockdown equal to 53% and 54% of the population, respectively.

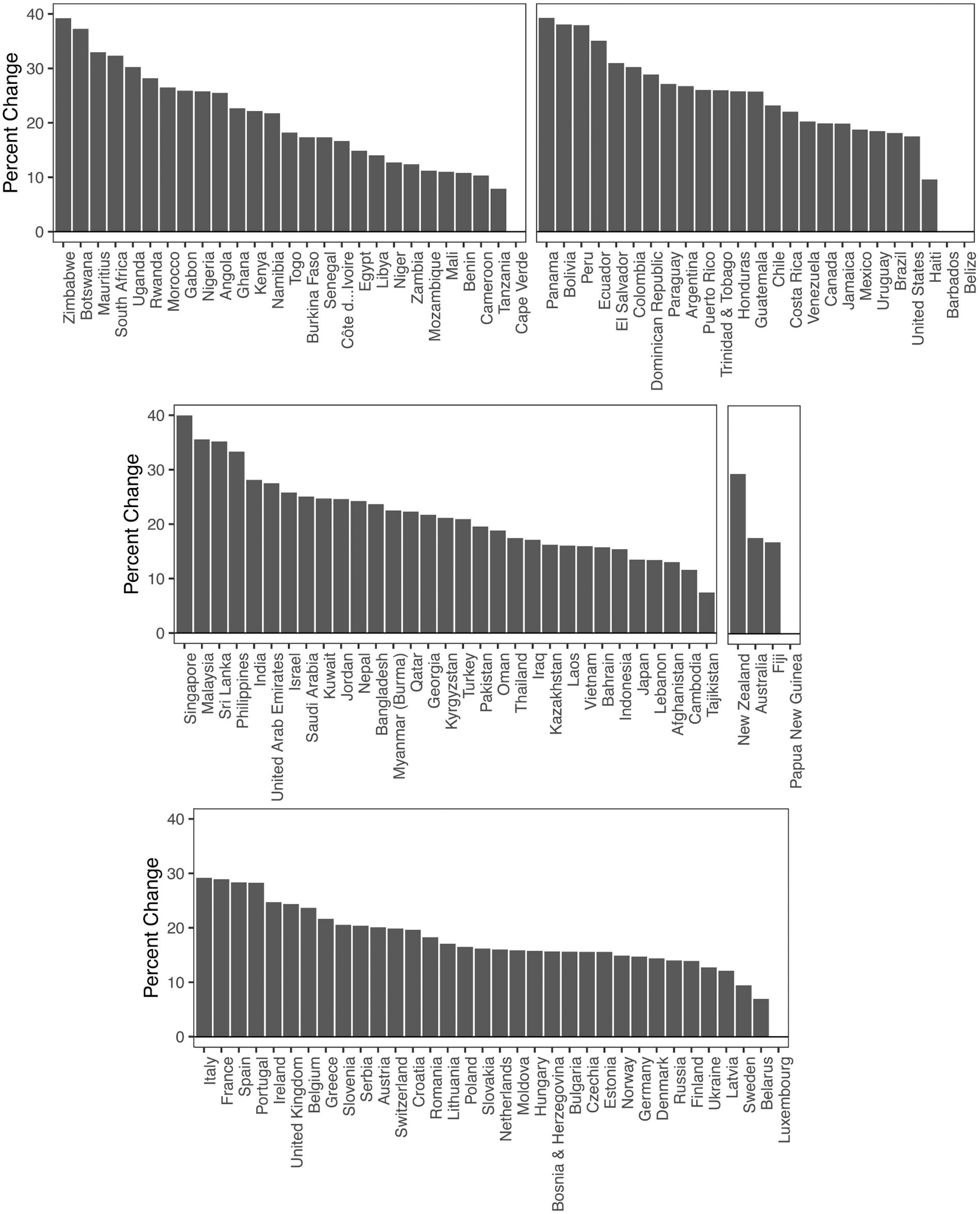

Fig. 2. Change in mobility. Percent change in time spent within home residences (residential) following implementation of confinement measures in each country.

activities intensified rather than declined (e.g., some recreational fisheries and commercial fisheries) (Fig. 5). Other impacts escalated, including massive increases in plastic waste due to discarded personal protective equipment to prevent COVID-19 transmission, and abnormally large crowds of visitors to parks for recreation in countries where outdoor activities were permitted (e.g., a 47% visitation increase in the Swiss National Park, Appendix 4, Table A4, StudyID 57). In many parks, hikers were observed expanding trails, destroying or changing local habitats, and even trampling endangered orchid species (Appendix 3, Table A3).

The lockdown also interrupted conservation enforcement activities with dire consequences including increased illegal activities, such as hunting, deforestation, and the dumping of waste (Figs. 4 and 5). For instance, pangolins, which are amongst the world's most trafficked mammals (for food and traditional medicine), seem to have come under even greater pressure; trade seizures increased in India by >500% (i.e., a 5-fold increase) during the lockdown period (Appendix 4, Table A4, StudyID 62). Indeed, a spike in exploitation of many animal species for

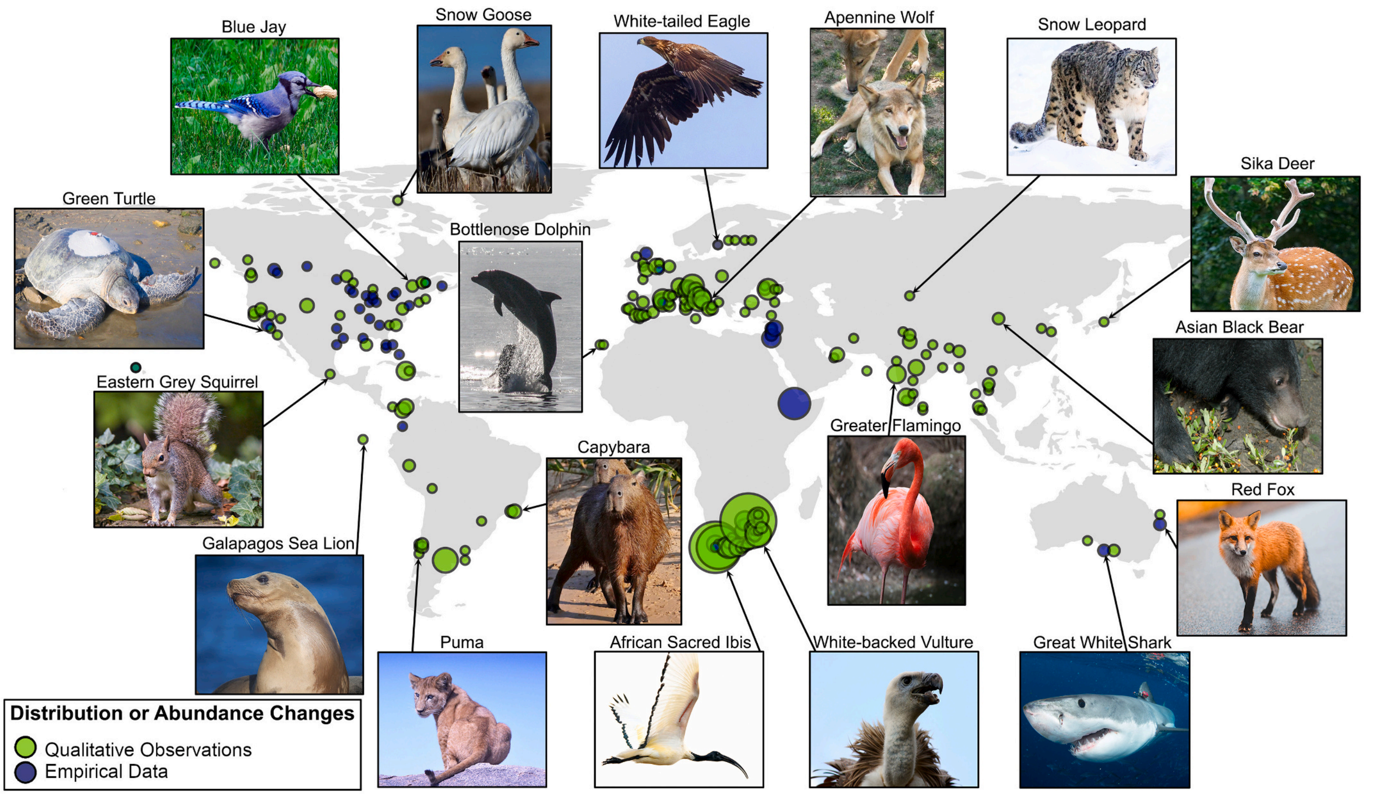

Fig. 3. Reports of 275 species that occupied an unusual area (distribution change), or shifted in number (abundance change) were attributed to a reduction in human activities. Changes in species distributions were observed around the world as qualitative observations (Appendix 3, Table A3, albeit with biases in effort such as greater coverage in the Northern Hemisphere and South Africa), and based on empirical data of time series surveys and bio-logging data using statistical modeling to quantify change. Only changes that were attributed to the lockdown with high confidence are included here (Appendix 4, Table A4). Bubble size represents data density (the largest bubble represents 41–60 observations and the smallest is 1–20).

food and trade was reported around the world (e.g., China, Kenya, India, Peru, South Africa, Sri Lanka, UK), often in national parks and protected areas. For example, in the protected Bugoma Forest reserve in Uganda (Appendix 4, Table A4, StudyID 19), increased use of animal snares during the pandemic was detected, which can injure and kill non-target animals, including endangered species such as chimpanzees. Likewise, during the lockdown, the conch fishery in the Bahamas shifted to smaller illegal-sized juvenile animals from a nursery area (Appendix 4, Table A4, StudyID 47).

3.4. Responses of social systems which support biological conservation

We found that management and conservation systems were initially weakened and even ceased in many areas of the world (the median effect size was negative in both the qualitative and quantitative data sets: Figs. 4b and 5b). In one region of the Amazon, Brazil, the deforested area relative to historical years increased by 168% (i.e., a 1.68-fold change) during the lockdown, and a similar response was seen for the eruption of fire hotspots in Colombia, both attributed to a lack of enforcement (Appendix 4, Table A4, StudyID 35). Environmental monitoring and community-based programs to restore habitats or remove waste from beaches have also been severely restricted. Anecdotes highlight that pest management programs have not been able to recruit community volunteers to trap rats and mobilize personnel to combat locust outbreaks. In one dramatic example, failure to remove non-native mice from remote seabird islands is expected to lead to the loss of two million seabird chicks in 2020 (Appendix 3, Table A3, Line 265).

The number of observers contributing to community science efforts has also immediately declined for many programs (e.g., eBird Colombia, eButterfly, Nature's Notebook and the LEO Network; Crimmins et al., 2021 [this issue]), although growth was also noted in some US programs in particular cities and regions (eBird and iNaturalist, Appendix 4, Table A4; Crimmins et al., 2021 [this issue]; Hochachka et al., 2021 [this issue]). A lack of reporting can be a major conservation concern, such as when the number of whale observers declined by 50% along the Pacific Northwest during the lockdown, leading to a reduced ability of ships to avoid striking whales (Appendix 3, Table A3, Line 272).

4. Discussion

The COVID-19 lockdown provided an unprecedented, serendipitous opportunity to examine the multi-faceted links between human activity and the environment, providing invaluable insights that can inform conservation strategies and policy making. Specifically, this lockdown has created a period during which global human activity, especially travel, was drastically reduced, enabling quasi-experimental investigation of effects across a large number of 'replicates' (Bates et al., 2020).

Overall, we found that both positive and negative responses of human activity on species and ecosystems are prevalent – results that are inconsistent with the prevailing view of humans as primarily harming biodiversity. Indeed, while the qualitative observations presented here provide evidence of interpretation bias, viewing unusual behaviours in wildlife as positive (Fig. 4), our quantitative assessments were balanced between negative and positive responses (Fig. 5). Even if our dataset does not represent a random sampling design, the reports collated are a comprehensive inventory of information across the globe. Emerging from this initial dataset is support for both negative and positive responses of wildlife to human activity and the systems in place to monitor and protect nature. Thus, the lockdown provides a striking illustration of the positive role humans can play as custodians of biodiversity. While negative impacts were expected, the potential for humans to positively influence biological conservation through scientific research,

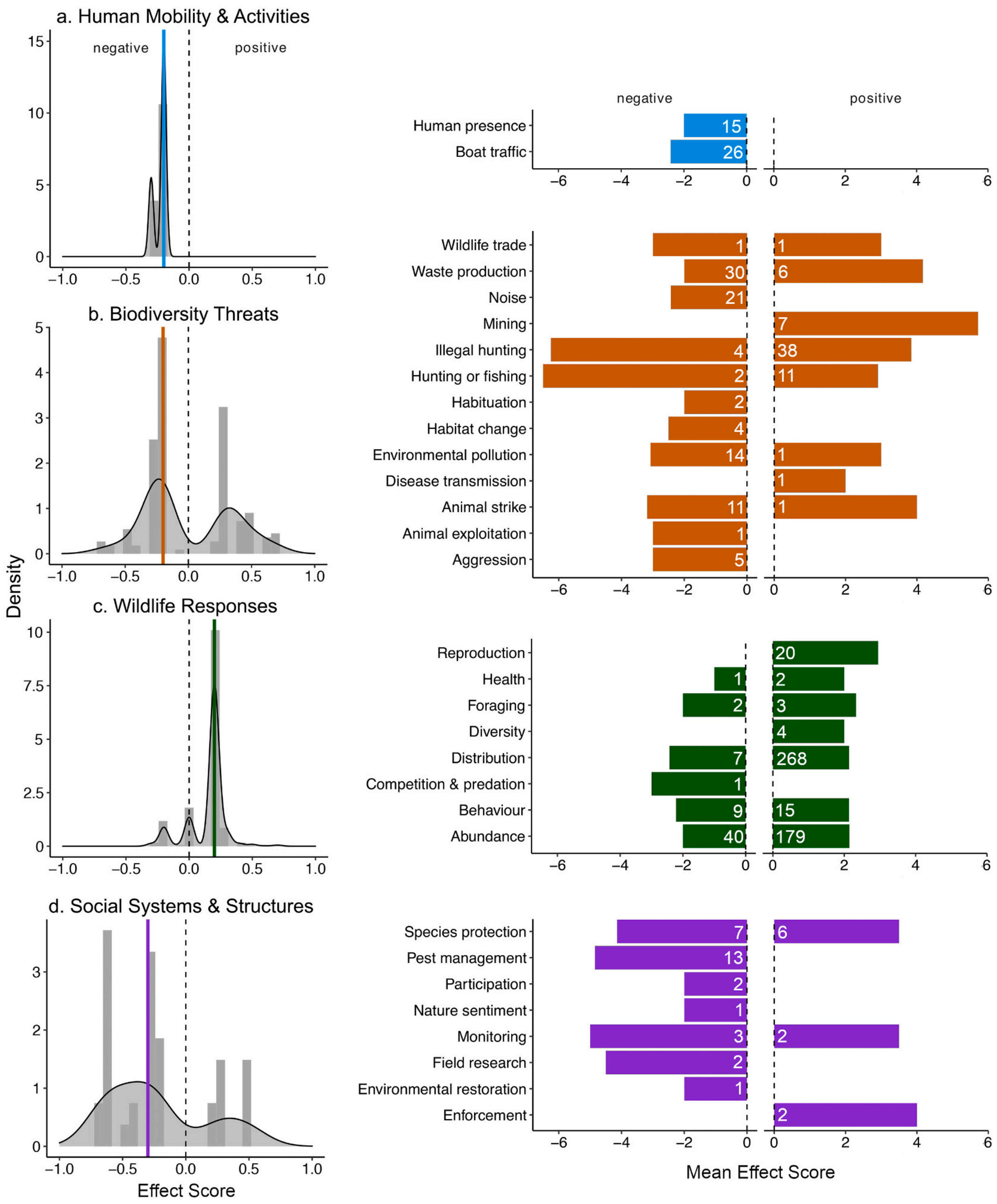

Fig. 4. Qualitative negative and positive effects observed which were relative to the response observed (Appendix 4, Table A4). Negative effects indicate a dampening in the responses which were grouped into categories representing "Human Mobility & Activities", Biodiversity Threats", "Wildlife Responses" and "Social Systems & Structures", while positive effects indicate an increase. The effect score is based on the criteria outlined in Appendix 1, Table A2, and considered the duration, spatial extent and total impact of the effect on the response. A negative or positive effect direction is relative to each category is based on the observed effect, rather than an interpreted impact. For instance, a negative effect on noise is a decrease in noise (which may have had positive wildlife impacts). a) Distribution of effects showing the direction and magnitude. The dotted line is the intercept, and the colored line indicates the median effect score. b) The mean effect score for categories falling within effects on human activities (blue), biodiversity threats (orange), biodiversity (green) and social systems (purple). Bars are the mean across reports pooled for positive and negative effects on the y-axis category, and white numbers are the number of observations upon which the mean is based. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

environmental monitoring, opportunistic citizen reporting, conservation management, restoration, and enforcement activities was strong in our datasets. Combined, these activities jointly deliver conservation benefits.

Another major take-home from this synthesis effort is that humans and their activities have measurable impacts on food availability for animals from both land and marine habitats, including that of top predators and scavengers. The role of human-sourced food is an important driver of wildlife occurrence and condition. For instance, in Singapore, feral pigeons shifted their diets from human foods to more natural food sources and their numbers declined (Appendix 4, Table A4, StudyID 75, Soh et al., 2021 [this issue]). At a university campus in South Africa, red-winged starlings lost body mass, presumably because their typical foraging grounds were bare of waste food (Appendix 4, Table A4, StudyID 58). Scavenging crows also spread to coastal beaches in Australia when human food was no longer available (Duarte et al., 2021 [this issue]). Many species that are routinely fed during wildlife tours (e.g., sharks (Gallagher and Huveneers, 2018)) have not had access

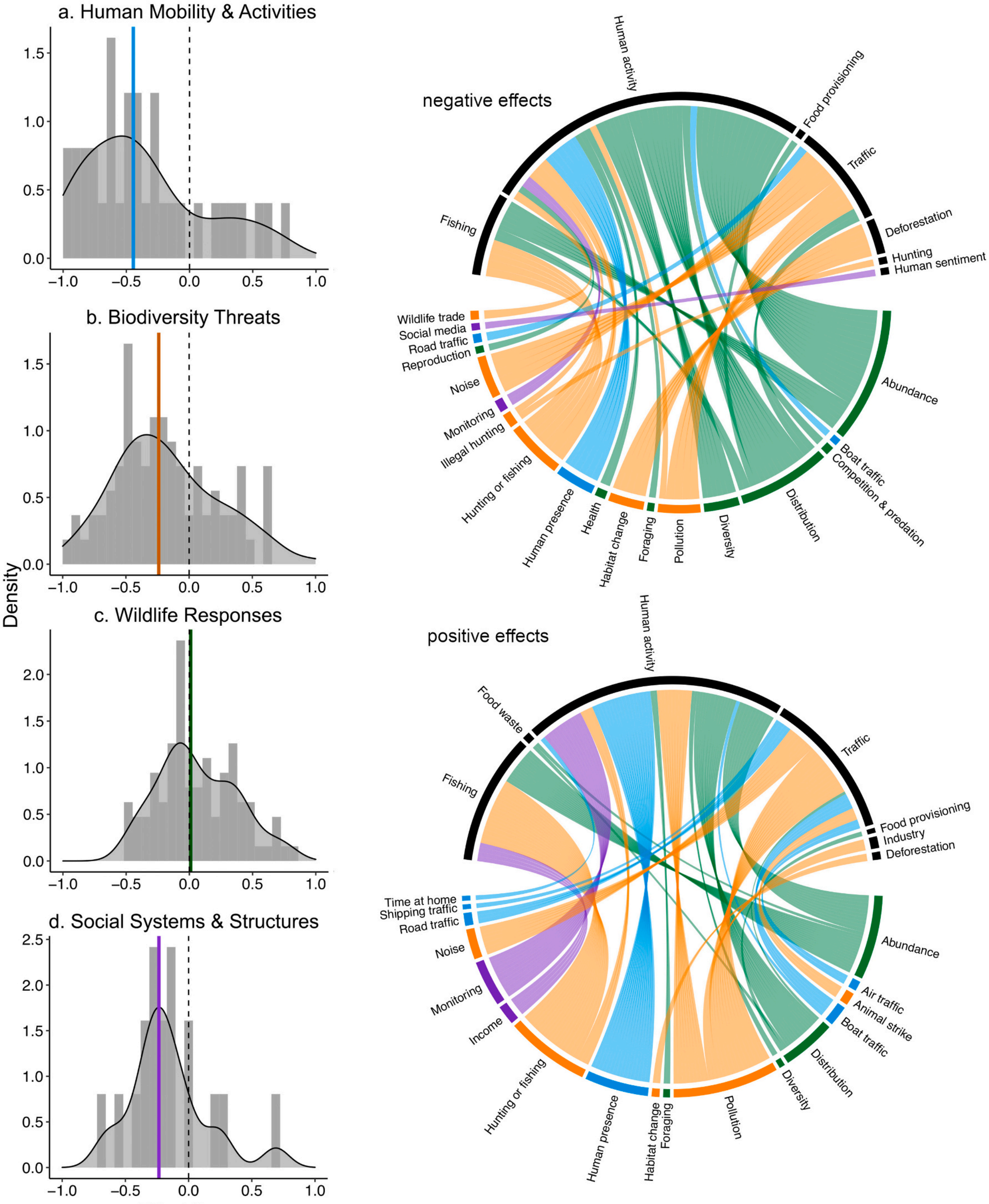

Fig. 5. Responses during the lockdown based on our empirical data (Appendix 5, Table A5) where positive and negative effects represent the observed direction of change for the different response categories. 71 studies that attributed the observed effect to the lockdown with high confidence are included (i.e., a qualitative confidence score of 3 or greater out of a maximum of 5). Frequency histograms (panels a-d) show bars representing data density and a curve representing a smoothed distribution of effect sizes and direction. The dotted line is zero, and the solid colored line is the median. Only responses that were attributed to the lockdown with high confidence are included. a) Human activities and mobility (blue) includes measured responses in human activities and mobility, such as related to commuting and recreational activities (categories are described in Appendix 1, Table A1). b) Biodiversity threats (orange) include categories that harm wildlife and natural systems, such as hunting, fishing, mining, vehicle strikes, wildlife trade, environmental pollution, and deforestation. c) Wildlife responses (green) incorporate observations of animals and plants related to performance (e.g., reproduction, health, foraging) and habitat use (abundance and distribution) and community change (species richness). d) Social systems (purple) include environmental monitoring, restoration, conservation, and enforcement. The chord diagrams highlighted the observed positive and negative effects which were attributed to different lockdown-related drivers as identified by each study (black), and linked to what was measured by each study where responses were grouped into the four categories: human activities and mobility, biodiversity threats, wildlife responses, and social systems and structures. One chord represents one measured response. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

to this supplementary food due to drastically reduced tourism. This appeared to drive a change in the abundance and types of species that were detected at sites in the Bahamas during the lockdown period (Appendix 4, Table A4, StudyID 67). In addition to food, animal use of nutritional supplements was also influenced by human activities. For instance, in response to reduced traffic on highways in the Canadian Rockies, mountain goats spent more time at mineral licks, interpreted as a wildlife benefit (Appendix 4, Table A4, StudyID 37).

Another major take-home from this synthesis effort is that many wildlife and ecosystem responses were unexpected. A classic example is from the Baltic Sea, where due to the lockdown, only researchers and a park warden were present on a seabird island during 2020. The number of people on the island was thus reduced by 92%, by contrast to normal years where summer visitors enjoy the island. The reduction in human presence corresponded with the unexpected arrival of 33 white-tailed eagles where no more than three had been observed in each year for several decades (white-tailed eagle: Fig. 3). By regularly flying near a murre colony, the eagles flushed incubating birds at disturbance rates 700% greater (7-fold increase) than historical rates, resulting in abandoned ledges where the birds lay their eggs, and subsequent increased egg predation by gulls and crows (Appendix 4, Table A4, StudyID 31; Hentati-Sundberg et al., 2021 [this issue]). The absence of humans in this case seems to have negatively impacted a species of conservation concern, through changing the distribution of a species which evoked a predator avoidance response.

Hunting also increased across many countries, including in parks, to supplement incomes. A classic example is the increase in pangolin hunting which was likely due to a combination of reduced protection from forest departments, increased sales of hunting permits, and greater illegal hunting. This is surprising considering the possible role of pangolins as intermediary hosts of SARS-COV-2, and calls to halt the consumption of wildlife to avoid future zoonoses (Zhang et al., 2020). Furthermore, it is clear that resilient socio-ecological systems are fundamental to supporting nature conservation.

We further find that impacts of the lockdown on human hunting activity have created not only direct but cascading ecological impacts. For instance, in North America the large greater snow goose population is considered a pest due to grazing on crops. Goose numbers are controlled during their migration to the High Arctic by allowing spring hunting. Yet, hunting pressure decreased by up to 54% in 2020 in comparison with 2019, and geese benefitted from undisturbed foraging, resulting in rapid weight gain to fuel their northward migration (Appendix 4, Table A4, StudyID 25; LeTourneux et al., 2021 [this issue]). Indeed, hunters from Mittimatalik (Nunavut) reported that those birds arriving in the Arctic in 2020 were unusually large and healthy. The cohort of geese from 2020, which graze the fragile arctic tundra and degrade the habitat for other species, will potentially drive future population growth and environmental impacts (Snow Goose, Fig. 3).

The magnitudes of some effects were also more dramatic than anticipated, such as in cases where the lockdown coincided with reproductive activity. For example, in Colombia, a hotspot of bird diversity, species richness in residential urban areas in Cali increased on average by 37% when human activity was lowest during the lockdown, which coincided with the beginning of the breeding season. Similarly, various species of sea turtles benefited from nesting on undisturbed beaches during the lockdown period. In Florida, for instance, lockdown-related beach closures in a conservation area were linked to a surprising 39% increase in nesting success in loggerhead turtles, attributed to a lack of disturbances from fishers and tourists with flashlights, and lack of obstructions such as sandcastles (Appendix 4, Table A4, StudyID 74).

4.1. Management implications

The global human lockdown experiment has revealed the strong potential for humans as custodians of the environment. The wealth of observations collated here provides compelling, near-experimental evidence for the role of humans as a source of threats to species ecosystems, illustrated by a range of increases in biodiversity threats with release from human disturbance during lockdown. Increases in biodiversity threats are consistent with the assumed role of human activity as a source of negative impacts on the environment. These observations help identify ways in which human disturbance may play stronger roles in impeding conservation efforts than previously recognized, even for well-studied species such as sea turtles. Our data also reveal contexts where one simple change in human activity could lead to multiple benefits. For instance, in one park near Boston, noise did not decrease as traffic volumes declined – surprisingly, noise levels increased, likely because cars were moving faster (Appendix 4, Table A4, StudyID 52). At the same time, greater traffic speed near parks can increase the probability of vehicle strikes (Nyhus, 2016), impacting both wildlife and humans. Thus, rather than reducing traffic volume, reducing traffic speed would lead to less noise pollution and protect both wildlife and human safety.

Considering how wildlife and humans have responded during the lockdown offers the potential to improve conservation strategies. In particular, restrictions and enforcement mechanisms to control human activities in conservation areas and parks seem critical to their effective functioning. Adaptive conservation management during reproductive seasons, such as during the nesting season of birds and sea turtles, may also have much stronger positive impacts than previously recognized. The pandemic also highlights the value of parks near urban centers that protect species and the environment, and offer opportunities for humans to conveniently enjoy nature without traveling long distances (Airoldi et al., 2021). The role of humans in supplying food for some animal species is also apparent, and suggests that this interaction can be managed to improve conservation outcomes, and avoid risks such as wildlife-human conflicts. Regulation of marine shipping traffic speed and volume can also have a major contribution to conservation, which would require, similar to the case of terrestrial systems, the identification and regulation of hotspots where strikes are frequent and noise levels are elevated; the analysis of detailed animal tracking data could further inform such interventions (Rutz et al., 2020). Our results also provide compelling evidence for the benefits of reducing noise levels, particularly at sea, and give additional impetus to policies that incentivize the development of noise reduction technologies (Duarte et al., 2021).

While many changes were linked to the lockdown, we failed to link effects to the lockdown in 18 different studies which represent a wide range of systems and contexts. Even so, what was interesting is that 15 of these studies focussed on wildlife responses. This includes where wildlife observations were in remote areas or under effective management and protection from human activities, or on species that are unresponsive to humans. For instance, we found that reduced wildlife tourism in 2020 at the Neptune Islands Group Marine Park, Australia, had no effects on white shark residency (Appendix 4, Table A4, StudyID 17; Huveneers et al., 2021 [this issue]). This is likely due to current regulations minimizing the impact of shark-diving tourism when it occurs, suggesting effectiveness of prior efforts to decrease animal harassment. Likewise, the distribution of hawksbill turtles (Chagos Archipelago, Indian Ocean), in an infrequently visited area that is effectively protected, was indistinguishable from previous years (Appendix 4, Table A4, StudyID 76). In remote northern Queensland, Australia, tagged estuarine crocodiles exhibited similar habitat use patterns despite restrictions on the number of people allowed into the area (Appendix 4, Table A4, StudyID 54). We also found strong changes that were attributed to other factors, such as the use of the Kerguelen toothfish fishing grounds (Australia) by seals in 2020 (Appendix 4, Table A4, StudyID 40). The seals' observed distribution changes during the lockdown period likely represent responses to other environmental factors, rather than changes in fishing effort.

It is unclear if any of the changes in animal distribution, abundance, behavior, and sources of food will persist once the lockdown restrictions cease. Many of the responses observed may be transient. For example, animals roaming in areas typically supporting intense human activity may retreat back to smaller ranges once human activity resumes full-scale. However, negative impacts resulting from the interruption of conservation efforts may be long-lasting and reverse years and decades of such efforts. For instance, it is likely that long-term impacts of overfishing of juveniles in nursery areas will be apparent into the future in the abundance of the queen conch from the Bahamas due to impacts on recruitment to the adult population (Appendix 4, Table A4, StudyID 47), and in most other cases where illegal activities have injured or removed animals. On the positive side, strong recruitment success of endangered species in areas where disturbance declined may have long-lasting positive effects, particularly where the beneficiary species, such as sea turtles, have long life spans. Long-term studies should track the cohorts of the 2020 wildlife generation over years and decades to integrate the positive and negative conservation impacts of the human lockdown.

Our finding of both positive and negative impacts of human confinement does not support the view that biodiversity and the environment will predominantly benefit from reduced human activity during lockdown – a perspective taken by some early media reports. Positive impacts of lockdown on wildlife and the environment stem largely from reduction of pressures that are typically an unintended consequence of human activity, such as ocean noise. In contrast, the negative impacts of the lockdown on biodiversity emerge from the disruption of the deliberate work of humans to conserve nature through research, restoration, conservation interventions, and enforcement. As plans to re-start the economic progress, we should strengthen the important role of people as custodians of biodiversity, with benefits in reducing the risks of future pandemics.

CRediT authorship contribution statement

A.E.B, R.B.P, and C.M.D. are co-leads of the working group PAN-Environment (PAN-E) and developed the manuscript concept, contributed data, analyses and interpretation. Authors divide into four groups ordered from first to last as follows: (1) core data analysis team who designed, collated, curated, analyzed data, and led the data visualization (10 authors from A.E.B to V.V.), (2) authors who provided empirical data, analyses, and result interpretations (304 authors: from O.A—C. to Z.S.), (3) authors who provided qualitative observations (23 authors: from A.A. to E.G.W.), and (4) authors who contributed to developing the article concept, interpretation of results, accessing data, or critical review (8 authors: from A.B. to C.R.). A.E.B. coordinated the team and led the development of the first draft in a shared working platform with expert input from many co-authors; C.M.D. is the senior author. Specific author contributions are further detailed in the Supplementary Information.

Declaration of competing interest

Authors declare no competing interests.

Acknowledgments

We especially thank volunteers and community scientists who reported sightings, photos, conducted beach clean-ups and participated as divers. Data, field and logistics support was also provided by G. Mowat, B. McLellan, L. Smit, L. Bird, E. Oldford, A.N. Guzman, J.A. Mortimor, J.-O. Laloë, M. Bigg, H.Valverde, M. Knight, L. Burke, J. Campbell, L. Curtis, S. Davies, O. Fontaine, C. Hansen, V. Hodes, S. Jeffery, J. Nephin, C. St Germain, C. Sanderson, S. Taylor, L. Gittens, S. Cove, T. Jones, C. James, S.K. Kinard, A. Solis, C. Holbert, A. Johnson, J.P. Richardson, J. Lefcheck, S. Marion, B.W. Lusk, B. Gonzales, K. Ariotti, T. Clasen, A. Field, K. Fraser, J. Grosso, G. LeFevre, H. Seaman, L. Wenk, J. Dennis, L. Meyer, M. Thiele, C. Roberts, J. Davey, C. Barry, M. Thibault, L. Parmelee, M. Davis, C. Charlebois, A. Lacorazza, A. Green, A. Carotenuto, C. Ferri, J. Faso, B. Cusick, M. Bangs, K. Wolf, J. Hanaeur-Milne, K. Gray, J. Marion, N. Dunham, C. Tiemann, S. Beck, D. Cieri, B. Toner, J. Collins, B. Coolbaugh, B. McClure, C. Lookabaugh, L. Merrill, A. Millier, B. Ver-Vaet, K. Stalling, N. Rux, K. Ramos, R. Joyce, A. Simpson, A. Flanders, M. McVicar, K. Brodewieck, A. Calhoun, J. Jansujwicz, D. Yorks, B. Keim, T. Wantman, M. Nemeth, S. Gabriel, A. Litterer, M. Mulligan, B. Moot, A. McFarland, M. Hosmer, P. Asherman, B. Gallagher, R. Currie, B. Guy, S. Grimaldi, A. LeClair, H.M. Park, J.I. Choi, T. Eguchi, S. Graham, J. Bredvik, B. Saunders, T. Coleman, J. Greenman, E. LaCasella, G. Lemons, R. Leroux, J. Milbury, L. Cox, N. Martinez-Takeshita, C. Turner-Tomaszewicz, T. Fahy, B. Schallmann, R. Nye, M.C. Cadieux, M. Séguin, A. Desmarais, C. Girard, C. Geoffroy, M. Belke-Brea, M.C. Martin, A. Suan, M. Scott, S. Yadev, M. McWilliam, Nelson Pacheco Soto, K. Mille, B. Maphanga, B. Jansen, E. Oliphant, B. Dewhirst, F. Hernández-Delgado, T. Jackson, J. Browder, L. Enright, E. Pearce, B. Hyla, J. Andersen, L. Peske, C. Bougain, M. Kassa, S. Zelleke, B. Abraham, N. Juhar, A. Seid, M. S. Omar, L. Arin, K. Smith, A. Sutton, B. Jones, E. Adekola, A. Bourne, S. Catto, N. Pindral, T. Risi, M. Truter, F. Kebede, J. Sanchez-Jasso, E. Budgell, R. Goswami, A. Mendis, D. Reddick, A. Turram, J. Kachelmann, N. Taube, J. Ribera Altimir, A. Manjabacas Soriano, C. Oldford, W. Hatch, M. Bird, R. Rueda-Guerrero, Emrah Çoban, Neslihan Güven, Kayahan Ağırkaya, Morteza Naderi, Çişel Kemahlı, Ercan Sıkdokur, Elif Çeltik and the volunteers of the KuzeyDoğa Society, Gustavo Jiménez-Uzcátegui, Jimmy Navas.

Field support and gathering of information were provided by the Vancouver Aquarium, Ecology Project International, Pacuare Reserve - Costa Rica, the Ein Avdat National Park, the Swiss National Park, Australia Zoo, WSL-SLFDavos, Medical Campus Davos, GRF, ARGO Davos, Heldstab AG Davos, Mr. Disch, DDO Davos, Dr. Födisch AG, W. Hatch, G. Jiménez-Uzcátegui, J. Navas, Arthur Rylah Institute, the Wildlife Management Division of the National Parks Board (Singapore), eBird Colombia (Global Big Day), the Red Ecoacústica Colombiana, the Reef Life Survey program, Integrated Marine Observing System (IMOS) and National Collaborative Research Infrastructure Strategy (NCRIS), Regional Government of the Azores, Institute of Biology of the Southern Seas, the Instituto de Investigación de Recursos Biológicos Alexander von Humboldt, and the Barcelona Coastal Ocean Observatory of the Institut de Ciències del Mar (CSIC).

Research was hosted with permission on the traditional territories of the Ktunaxa Nation and the Snuneymuxw First Nation, in the gardens of R.W. Byrne and J.A. Graves, and in Uganda by the National Forestry Authority and the Uganda Wildlife Authority. Beach access was granted from the California Marine Safety Divisions. Data from French Polynesia was collected under the special permit issued by the Ministry of Culture and Environment of French Polynesia ref.: N°011492/MCE/ENV from 16 Oct. 2019. Data collection from Costa Rica was conducted under the research permit R-SINAC-PNI-ACLAC-012-2020 from MINAE (Costa Rican Ministry of Energy and Environment). We thank Turkey's Department of Nature Conservation and National Parks and the Ministry of Agriculture and Forestry for granting our research permit (No. 72784983-488.04-114100). We thank the Galapagos National Park and the Charles Darwin Foundation for their institutional support. Data collection from Galapagos was conducted under research permit GNPD No. PC-41-20. This publication is contribution number 2398 of the Charles Darwin Foundation for the Galapagos Islands.

We also thank several organisations for providing data: the USA National Phenology Network's Nature's Notebook program, eButterfly, the Romanian Network for Monitoring Air Quality, the Instituto Nacional de Pesquisas Espaciais (INPE) from Brazil, Israel's National Biodiversity Monitoring Program run by HaMaarag, National Biodiversity Network, eBird, Global Biodiversity Information Facility, iNaturalist, The Mammal Society, Zoological Society of London, Port of London Authority, MarineTraffic, Korean Expressway Corporation, personnel in the British Indian Ocean Territory (BIOT), the Ministry for the Ecological Transition and the Demographic Challenge as NFC from the ICP-Forests programme in Spain, TECMENA, the Virginia Nature

Conservancy, and the Bugoma Primate Conservation Project, Mammal Center in the Society for the Protection of Nature in Israel, the Ethiopian Wildlife Conservation Authority, Coordinadora para o Estudo dos Mamíferos Mariños (CEMMA), Tiburones en Galicia, Ecoloxía Azul-Blue Ecology, Florida Fish and Wildlife Conservation Commission, C. Fischer, OCEARCH, Ocean Wise Conservation Association, and Israel Nature and Parks Authority (INPA). Collaboration between Australia's Integrated Marine Observing System (IMOS), the French Polar Institute, SNO-MEMO and CNES-TOSCA are also appreciated.

Further details and study-specific acknowledgements are provided in Appendix 5 (Table A5) as entered by the authors.

Data and materials availability

The data supporting the findings of this study are available in the Supplementary Materials (Appendices 3–5, Tables A3-A5). Raw datasets (where available) and results summary tables for each analysis of human mobility and empirical datasets are deposited in a github repository: https://github.com/rjcommand/PAN-Environment.

Funding

The Canada Research Chairs program provided funding for the core writing team. Field research funding was provided by A.G. Leventis Foundation; Agence Nationale de la Recherche, [grant number ANR-18-CE32-0010-01 (JCJC PEPPER)]; Agencia Estatal de Investigación; Agência Regional para o Desenvolvimento da Investigação Tecnologia e Inovação (ARDITI), [grant number M1420-09-5369-FSE-000002]; Alan Peterson; ArcticNet; Arkadaşlar; U.S. Army Corp of Engineers Northwestern Division; Artificial Reef Program; Australia's Integrated Marine Observing System (IMOS), National Collaborative; Research Infrastructure Strategy (NCRIS), University of Tasmania; Australian Institute of Marine Science; Australian Research Council, [grant number LP140100222]; Bai Xian Asia Institute; Batubay Özkan; BC Hydro Fish and Wildlife Compensation Program; Ben-Gurion University of the Negev; Bertarelli Foundation; Bertarelli Programme in Marine Science; Bilge Bahar; Bill and Melinda Gates Foundation; Biology Society of South Australia; Boston University; Burak Över; California State Assembly member Patrick O'Donnell; California State University Council on Ocean Affairs, Science & Technology; California State University Long Beach; Canada Foundation for Innovation (Major Science Initiative Fund and funding to Oceans Network Canada), [grant number MSI 30199 for ONC]; Cape Eleuthera Foundation; Centre National d'Etudes Spatiales; Centre National de la Recherche Scientifique; Charles Darwin Foundation, [grant number 2398]; Colombian Institute for the Development of Science and Technology (COLCIENCIAS), [grant number 811-2018]; Colombian Ministry of Environment and Sustainable Development, [grant number 0041 - 2020]; Columbia Basin Trust; Commission for Environmental Cooperation; Cornell Lab of Ornithology; Cultural Practices and Environmental Certification of Beaches, Universidad de la Costa, Colombia, [grant number INV.1106-01-002-15, 2020-21]; Department of Conservation New Zealand; Direction de l'Environnement de Polynésie Française; Disney Conservation Fund; DSI-NRF Centre of; Excellence at the FitzPatrick Institute of African Ornithology; Ecology Project International; Emin Özgür; Environment and Climate Change Canada; European Community: RTD programme - Species Support to Policies; European Commission Seventh Framework Programme; European Union; European Union's H2020 Marie Skłodowska-Curie Actions, [grant number 798091, 794938]; Faruk Eczacıbaşı; Faruk Yalçın Zoo; Field research funding was provided by King Abdullah University of Science and Technology; Fish and Wildlife Compensation Program; Fisheries and Oceans Canada; Florida Fish and Wildlife Conservation Commission, [grant numbers FWC-12164, FWC-14026, FWC-19050]; Fondo Europeo de Desarrollo Regional; Fonds Québécois de la Recherche Nature et Technologies; Foundation Segré; Fundação para a Ciência e a Tecnologia (FCT Portugal); Galapagos National Park Directorate Research, [grant number PC-41-20]; Gordon and Betty Moore Foundation, [grant number GBMF9881 and GBMF 8072]; Government of Tristan da Cunha; Habitat; Conservation Trust Foundation; Holsworth Wildlife Research Endowment; Institute of Biology of the Southern Seas, Sevastopol, Russia; Instituto de Investigación de Recursos Biológicos Alexander von Humboldt; Instituto Nacional de Pesquisas Espaciais (INPE), Brazil; Israeli Academy of Science's Adams Fellowship; King Family Trust; Labex, CORAIL, France; Liber Ero Fellowship; LIFE (European Union), [grant number LIFE16 NAT/BG/000874]; Mar'a de Maeztu Program for Units of Excellence in R&D; Ministry of Science and Innovation, FEDER, SPASIMM; Spain, [grant number FIS2016-80067-P (AEI/FEDER, UE)]; MOE-Korea, [grant number 2020002990006]; Mohamed bin Zayed Species Conservation Fund; Montreal Space for Life; National Aeronautics and Space Administration (NASA) Earth and Space Science Fellowship Program; National Geographic Society, [grant number NGS-82515R-20]; National Natural Science Foundation of China; National Oceanic and Atmospheric Administration; National Parks Board - Singapore; National Science and Technology Specific Project of China; National Science Foundation, [grant number DEB-1832016]; Natural Environment Research Council (NERC); Korea Research Foundation (KRF-2021R1A2C1011213), Korea Ministry of Environment (MOE-2021003360002, 2020002990006), Natural Sciences and Engineering Research Council of Canada (NSERC), Alliance COVID-19 grant program, [grant numbers ALLRP 550721 - 20, RGPIN-2014-06229 (year: 2014), RGPIN-2016-05772 (year: 2016)]; Neiser Foundation; Nekton Foundation; Network of Centre of Excellence of Canada: ArcticNet; North Family Foundation; Ocean Tracking Network; Ömer Külahçıoğlu; Oregon State University; Parks Canada Agency (Lake Louise, Yoho, and Kootenay Field Unit); Pew Charitable Trusts; Porsim Kanaf partnership; President's International Fellowship Initiative for postdoctoral researchers Chinese Academy of Sciences, [grant number 2019PB0143]; Red Sea Research Center; Regional Government of the Azores, [grant number M3.1a/F/025/2015]; Regione Toscana; Rotary Club of Rhinebeck; Save our Seas Foundation; Science & Technology (CSU COAST); Science City Davos, Naturforschende Gesellschaft Davos; Seha İşmen; Sentinelle Nord program from the Canada First Research Excellence Fund; Servizio Foreste e Fauna (Provincia Autonoma di Trento); Sigrid Rausing Trust; Simon Fraser University; Sitka Foundation; Sivil Toplum Geliştirme Merkezi Derneği; South African National Parks (SANParks); South Australian Department for Environment and Water; Southern California Tuna Club (SCTC); Spanish Ministry for the Ecological Transition and the Demographic Challenge; Spanish Ministry of Economy and Competitiveness; Spanish Ministry of Science and Innovation; State of California; Sternlicht Family Foundation; Suna Reyent; Sunshine Coast Regional Council; Tarea Vida, CEMZOC, Universidad de Oriente, Cuba, [grant number 10523, 2020]; Teck Coal; The Hamilton Waterfront Trust; The Ian Potter Foundation, Coastwest, Western Australian State NRM; The Red Sea Development Company; The Wanderlust Fund; The Whitley Fund; Trans-Anatolian Natural Gas Pipeline; Tula Foundation (Hakai Institute); University of Arizona; University of Pisa; US Fish and Wildlife Service; US Geological Survey South Central Climate Science Center; Valencian Regional Government; Vermont Center for Ecostudies; Victorian Fisheries Authority; VMRC Fishing License Fund; and Wildlife Warriors Worldwide.

Appendices. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.biocon.2021.109175.

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