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

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Title page

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(<https://docs.google.com/spreadsheets/d/1ltnPMOip-ffk-vLsXNNOW3jmj3CGPm9Qk1WrkaM4E1o/edit#gid=1238906101>) and Carlos M. Duarte^{4,5}

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Competing interests: Authors declare no competing interests.

Data and materials availability: The data supporting the findings of this study are available in the Supplementary Materials (Appendix 3-5, Table 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>.

1 **Title:** Global COVID-19 lockdown highlights humans as both threats and custodians of
2 the environment

3

4 **Abstract**

5

6 The global lockdown to mitigate COVID-19 pandemic health risks has altered human
7 interactions with nature. Here, we report immediate impacts of changes in human
8 activities on wildlife and environmental threats during the early lockdown months of
9 2020, based on 877 qualitative reports and 332 quantitative assessments from 89
10 different studies. Hundreds of reports of unusual species observations from around the
11 world suggest that animals quickly responded to the reductions in human presence.
12 However, negative effects of lockdown on conservation also emerged, as confinement
13 resulted in some park officials being unable to perform conservation, restoration and
14 enforcement tasks, resulting in local increases in illegal activities such as hunting.
15 Overall, there is a complex mixture of positive and negative effects of the pandemic
16 lockdown on nature, all of which have the potential to lead to cascading responses
17 which in turn impact wildlife and nature conservation. While the net effect of the
18 lockdown will need to be assessed over years as data becomes available and persistent
19 effects emerge, immediate responses were detected across the world. Thus initial
20 qualitative and quantitative data arising from this serendipitous global quasi-
21 experimental perturbation highlights the dual role that humans play in threatening and
22 protecting species and ecosystems. Pathways to favorably tilt this delicate balance
23 include reducing impacts and increasing conservation effectiveness.

24

25 **Keywords**

26

27 Pandemic, biodiversity, restoration, global monitoring

28

29 **1.0 Introduction**

30

31 Human-driven alterations of atmospheric conditions, elemental cycles and biodiversity
32 suggest that the Earth has entered a new epoch, the Anthropocene (Crutzen, 2002;
33 Steffen et al., 2007). Negative impacts associated with human activities include a much
34 warmer Earth state, marked expansion of urbanization, and accelerating species
35 extinctions (Schipper et al., 2008). The perspective that the main role of humans is a
36 source of threats on species and ecosystems leads to the prediction that the global
37 human lockdown to mitigate COVID-19 health risks may alleviate human impacts, with
38 resulting positive environmental responses (Derryberry et al., 2020; Rutz et al., 2020).
39 Indeed, early reports indicate that restrictions led to immediate decreases in air, land
40 and water travel, with similar declines in industry, commercial exploitation of natural
41 resources and manufacturing, and lower levels of PM₁₀, NO₂, CO₂, SO₂ and noise
42 pollution (Bao and Zhang, 2020; March et al., 2021; Millefiori et al., 2021; Otmani et al.,
43 2020; Santamaria et al., 2020; Thomson et al., 2020; Terry et al., 2021 [this issue];
44 Ulloa et al., 2021 [this issue]).

45

46 Yet a more comprehensive consideration of the links between human activities and
47 species and ecosystems also acknowledges the role of humans as custodians of
48 nature, who engage in conservation research, biodiversity monitoring, restoration of
49 damaged habitats, and enforcement activities associated with wildlife protection (Bates
50 et al., 2020; Corlett et al., 2020; Evans et al., 2020; Manenti et al., 2020; Rondeau et al.,
51 2020; Zambrano-Monserrate et al., 2020; Kishimoto et al., 2021 [this issue]; Miller-
52 Rushing et al., 2021 [this issue]; Vale et al., 2021 [this issue]; Sumasgutner et al., 2021
53 [this issue]). Indeed, the global COVID-19 human confinement has disrupted
54 conservation enforcement, research activities and policy processes to improve the
55 global environment and biodiversity (Corlett et al., 2020; Evans et al., 2020; Zambrano-
56 Monserrate et al., 2020; Quesada-Rodriguez et al., 2021 [this issue]). The lockdown has
57 also created economic insecurity in rural areas, which may pose biodiversity threats as
58 humans seek to support themselves through unregulated and illegal hunting and fishing,
59 and conservation spending is reduced. In particular, declines in ecotourism in and
60 around national parks and other protected areas lowered local revenue, park staffing,
61 and funding to enforce hunting restrictions and invasive species management programs
62 (Spenceley et al., 2021; Waithaka et al., 2021). In many areas, restoration projects have
63 been postponed or even cancelled (Bates et al., 2020; Corlett et al., 2020; Manenti et
64 al., 2020).

65

66 Here, we consider the global COVID-19 lockdown to be a unique, quasi-experimental
67 opportunity to test the role of human activities in both harming and benefiting nature
68 (Bates et al., 2020). If the negative roles of humans on species and ecosystems

69 predominate, we would expect overwhelmingly positive reports of responses of nature
70 to human lockdown. We integrate 30 diverse observations from before and during the
71 peak lockdown period to examine how shifts in human behavior impact wildlife,
72 biodiversity threats, and conservation. We first analyze the mobility of humans on land
73 and waterways, and in the air, to quantify the change in human activities. Second, we
74 compile qualitative reports from social media, news articles, scientists, and published
75 manuscripts, describing seemingly lockdown-related responses of nature,
76 encompassing 406 media reports and 471 observations from 67 countries. Third, we
77 map the direction and magnitude of responses from wildlife, the environment and
78 environmental programs, using data collected before and during lockdown provided by
79 scientists, representing replicated observations across large geographic areas. We
80 collated data from 84 research teams that maintained or accessed existing monitoring
81 programs during the lockdown period, reporting 326 responses analyzed using a
82 standardized analytical framework. We accounted for factors including autocorrelation
83 and observation bias using mixed effects statistical models, and selected the most
84 robust available baselines for each study to report lockdown-specific effect sizes (see
85 methods). We empirically describe the type, magnitude, and direction of responses for
86 those linked with confidence to the lockdown, and offer integrated outcomes supported
87 by examples drawn from our results. Finally, we use these results to provide
88 recommendations to increase the effectiveness of conservation strategies.

89

90 **2.0 Materials and Methods**

91

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

97

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

112

113 **2.1 Human Mobility Data**

114

115 Data on government responses to COVID-19 across countries and time were retrieved
116 from the Oxford COVID-19 Government Response Tracker (Hale et al., 2021), which
117 also reports where the restrictions on internal movement apply to the whole or part of
118 the country. The global population under confinement of internal movement was
119 calculated by adding up the population of countries where the restriction is general, and
120 20% of the population of countries where the restriction is targeted, as an estimate of
121 the fraction of the population affected. Population data by country corresponding to year
122 2020 have been obtained from the Population Division of the Department of Economic
123 and Social Affairs of the United Nations (United Nations, 2018). Note that the data about
124 restrictions contain missing information for some countries and dates. Therefore, the
125 calculated number of human confinement does not take into account the population of
126 countries with missing information and may thus underestimate the actual number of
127 humans under restriction.

128

129 Changes in human mobility data were recorded by a number of agencies globally, and
130 combined, describe how the lockdown affected movements on land, at sea and in the
131 air. Data on the restriction of individuals in residential areas and to parks were derived
132 from Google Community Mobility Reports (<https://www.google.com/covid19/mobility/>).
133 Data on driving were obtained from the Apple Maps Mobility Trends Report
134 (<https://www.apple.com/covid19/mobility>). Marine traffic and air traffic data were derived
135 from exactEarth Ltd. (<http://www.exactearth.com/>), and OpenSky Network
136 (<https://openskynetwork.org/>) respectively. Google Community Mobility Report data are
137 based on anonymized data on how long users stay in different types of localities and

138 are available aggregated to regional scales (usually country). Each regional mobility
139 report reflects a percentage change over time compared to a 5-week baseline (Jan. 3 to
140 Feb. 6, 2020). Similarly, Apple Maps Mobility Trends Reports are based on Apple maps
141 user data and aggregated by region to reflect the percent change in time Apple maps
142 users spent driving relative to a baseline (Jan. 12, 2020). The percent change in the
143 responses of human mobility through time allows identification of extreme inflections
144 related to human behavior. For Google and Apple data, we extracted the overall mobility
145 trends for each country until May 1st, which was selected from a sensitivity test and
146 before relaxation of confinement measures were introduced in most countries. We
147 further excluded within-country variations in mobility, and removed all countries with
148 extensive data gaps and countries that did not show a response to lockdown.

149

150 The first step to quantifying the effect due to the lockdown on community mobility
151 (residential and parks) and driving data identified the date of greatest change in each
152 time-series (data and script files are here: [https://github.com/rjcommand/PAN-](https://github.com/rjcommand/PAN-Environment)
153 Environment). Because each country had differing lockdown dates and multiple types of
154 lockdown, we identified critical transition dates which best explained the change in
155 mobility for each country. To do so, we used Generalized Additive Models (GAM (Wood,
156 2011)) on daily mobility levels in each country, using the Oxford Covid-19 Government
157 Response Tracker database of country-level containment policies (C1-C7) to define a
158 variable for the before and after lockdown periods, running up to 15 models per country
159 depending on the number of different kinds of lockdown measures imposed. From these
160 models, we selected the lockdown date that explained the greatest amount of change.

161 We manually identified the confinement dates in cases where the models did not
162 converge or when multiple unexplained inflection points were detected (N = 10
163 countries). Percent change was calculated as the mean percentages after
164 implementation of the confinement measure selected from the models.

165

166 For marine traffic mobility, satellite AIS (S-AIS) data for April 2019 and 2020 were
167 obtained from exactEarth Ltd. (<http://www.exactearth.com/>), a space-based data service
168 provider which operates a constellation of 65 satellites to provide global AIS coverage at
169 a high-frequency rate (< 5 min average update rate). The latest upgrade in the
170 constellation entered into production in February 2019 and S-AIS coverage was
171 equivalent for both periods (exactEarth Ltd., pers comm.). Values represented the
172 monthly number of unique vessels within grid cells of 0.25 x 0.25 degrees. We
173 calculated the vessel density as the number of vessels per unit area, considering the
174 difference of cell size across the latitudinal gradient (March et al., 2021). Grid cells from
175 the Caspian Sea and with <10% ocean area were removed from the analysis, based on
176 the GADM Database of Global Administrative Areas (version 3.6, <https://gadm.org/>).
177 Further quality control procedures were provided in more detail in a complementary
178 publication. We calculated the percentage change in marine traffic density between
179 April 2019 and April 2020 per country and Exclusive Economic Zones (EEZ, Figs. S6 &
180 S7) using a Generalized Linear Model (GLM (R Core Team, 2020; Pinheiro et al.,
181 2021)).

182

183 For air traffic mobility, data were downloaded from the OpenSky network
184 (<https://openskynetwork.org>). OpenSky uses open-source, community-based receivers
185 to receive air traffic data from around the world and makes these data available in an
186 online repository. The online database consists of latitude and longitude of departure
187 and landing for all flights detected where receivers are available. Data are limited in
188 some areas, including Africa and parts of Asia. We downloaded daily data for 129
189 countries where data were available in April 2019 (1,302,282 flights) and the same
190 period in April 2020 (316,609 flights, when most countries included in the analysis had
191 imposed international travel restrictions) to compare the total volume of traffic departing
192 from, or arriving to, all countries where data were available for both years. We
193 aggregated these flights by country, then ran a GLM on the daily number of 5 flights in
194 each country, accounting for the day of the week and comparing 2020 (countries in
195 lockdown) to 2019. We used this model to calculate a t-statistic for the lockdown effect
196 in each country, and then calculated a percentage change in flight volume based on
197 numbers of flights per country in April 2019 versus the lockdown period in April 2020.

198

199 **2.2 Qualitative Observations**

200

201 Observational evidence of the impact of the first four months of the COVID-19 lockdown
202 on society, the environment and biodiversity was collected and collated through: (1)
203 internet searches with the keywords nature, conservation, environment and COVID-19;
204 (2) calls on social media for personal observations and for volunteers to contribute from
205 our networks; (3) Web of Science general search for papers (terms: nature,

206 conservation, environment, COVID-19) released released between May to August 2020
207 that also used qualitative evidence to investigate the lockdown effect, and (4) through
208 volunteer contributions from our global PAN-Environment working group of over 100
209 scientists. Each qualitative observation (N = 877 observations) was assigned a
210 geographic location (latitude and longitude) and classified by observation type
211 (described in Appendix 1, Table A1), including a description and details on the species
212 impacted (where relevant). Reports that listed several impacts (e.g., independent
213 observations, species, or locations) were entered as multiple lines. Following entry to
214 our dataset, each observation was assigned an effect score from 0-10 (as described in
215 Appendix 1, Table A2) to distinguish between observations with ephemeral effects with
216 unknown impacts from those that will have widespread or persistent outcomes with
217 strong effects in positive or negative directions. Qualitative data were recorded for all
218 continents, except Antarctica, representing 67 countries. Non country-specific
219 observations were also included, representing 20% of all anecdotes. The majority of
220 countries were represented by less than five observations (51 countries), while South
221 Africa submitted approximately one third of the total observations (total = 297). This high
222 representation in South Africa was a known bias due to the use of African birding
223 forums to collect citizen science data which were organized to communicate and
224 engage widely as lockdown measures were implemented. Similarly, other known biases
225 included high relative representation of charismatic species and those that were easily
226 observed during lockdown by humans (e.g., giant pandas and garden birds). Most
227 reports were gathered from English sources, however, over 100 observations were
228 translated from Italian, and another 50 and 10 were from Spanish and Afrikaans,

229 respectively. We interpreted our results in this context by focusing on the inferences that
230 can be made in spite of these biases, and in combination with the empirical data. See
231 Appendix 3 (Table S3) for the full dataset.

232

233

234 **2.3 Empirical Data**

235

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

247

248 With this overall approach, we were able to provide insights on the immediate changes
249 likely due to the lockdown (69 studies used a historical reference period including the
250 lockdown months in previous years; studies compared the strict lockdown period to the
251 same months in pre-lockdown years, described in detail for each study in Appendix 4,

252 Table A4). In other cases, the reference was an area representing a reference state
253 (i.e., remote areas or large, well-governed protected areas did not undergo a difference
254 in human activities due to lockdown measures). If observations were unavailable prior to
255 the start of the pandemic lockdown or for reference year(s), comparisons were made (if
256 sensible) during and after the lockdown, i.e., the reference was the post-confinement
257 period (8 studies). For instance, litter accumulation at two locations was measured from
258 the strict lockdown in April 2020, and over two months as restrictions eased. Spatial
259 comparisons between areas impacted by the lockdown with unaffected sites were also
260 included to detect lockdown related effects. These unaffected sites were considered as
261 reference areas after evaluation by the relevant research teams who contributed the
262 data (2 studies). The rationale for each study design and selection of the baseline
263 period is reported in Table A4 and A5 (Appendix 4 and 5), and was reviewed by the
264 core analysis team to ensure the baseline period comprised a suitable reference for the
265 given response of interest. Total percent changes were calculated as the difference
266 between the response coefficient (attributed to the lockdown) relative to the reference
267 coefficient. For instance, if we observed a 400% increase in a response during the
268 lockdown, this translates to an effect which was 4 times greater. We used Generalized
269 Linear, Additive Mixed (GAMM (Wood, 2004)) or Linear Mixed-Effects (LME (Pineiro et
270 al., 2021)) models, as best suited for each data type. Suitability was based on the
271 distribution of the response data, fit of the statistical data and the covariates that needed
272 to be accounted for to estimate the appropriate coefficients. In brief, for each dataset,
273 we quantified percentage change from expected or typical values, as well as an effect
274 size in the form of a t-statistic standardized by sample size (Bradley et al., 2019).

275 Datasets and results summary tables for each analysis of human mobility and empirical
276 datasets are deposited in a GitHub repository, filed under each contributing author's
277 name: <https://github.com/rjcommand/PAN-Environment>. The independent data
278 availability statement for each study is reported in Table A5 (Appendix 5).

279

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

290

291 **3.0 Results**

292

293 **3.1 Human mobility on land, in the air and on water**

294

295 The global peak of lockdown occurred on April 5th, 2020, at which time 4.4 billion people
296 were impacted (Fig. 1), representing 57% of the world's population. In the weeks before
297 and after this lockdown peak, residents of most countries spent much more time at

298 home (Fig. 2). Country specific critical transition dates (which occurred primarily in late
299 March leading up to the April peak) were used to assess the total change in mobility
300 until May 1st. During this period, driving decreased by 41%, there was a 20% overall
301 reduction in park visits, particularly in Central and South American countries, although
302 Nordic countries were an exception (Figs. S1 & S2). The April 2020 period also saw
303 major disruptions in community, food transport, and supply chains, with a 9% decrease
304 in marine traffic globally and a 75% total reduction in air traffic (both relative to April
305 2019, Figs. A3-A5). Thus, the COVID-19 lockdown has led to a significant global
306 reduction in human mobility, notably travel, causing an “anthropause” (Rutz et al.,
307 2020).

308

309 **3.2 Effects on wildlife around the world**

310

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

320 reductions in mortality, apparently in response to altered levels of human activity (Fig.
321 4).

322

323 Our quantitative assessments suggest a mixed role of human confinement in positively
324 and negatively influencing wildlife (Fig. 5). Some species changed their behavior (e.g.,
325 daily activity patterns) and relocated to entirely new areas, including seeking new food
326 sources and roaming to unusual areas. This included air space, such as when critically
327 endangered Griffon vultures in Israel flew further afield in 2020, apparently due to
328 reduced military training during the lockdown (Appendix 4, Table A4, StudyID 55). Some
329 animals also moved to human settlements from rural locations (e.g., golden jackals:
330 Appendix 4, Table A4, StudyID 28), while other species showed very little changes (Fig.
331 5 showing distribution of wildlife responses as effect sizes which center on zero).

332

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

341

342 **3.3 Changes in biodiversity threats**

343

344 The pandemic lockdown generally highlighted the enormous and wide-ranging impacts
345 that humans have on the environment and wildlife. For instance, in a remote forest area
346 in Spain, a 45% reduction in NO₂ and SO₂ lead to reduced atmospheric deposition of
347 NO₃⁻ and SO₄²⁻, and limited the input of N and S to soil ecosystems (Appendix 4, Table
348 A4, StudyID 84). Ocean fishing was also reduced by 12% based on our analysis of
349 68,555 vessels representing 145 national flags and 14 gear types (including drifting
350 longlines and nets, purse seines and trawlers, Appendix 4, Table A4, StudyID 5).
351 Animal deaths from vehicle strikes on roads and vessel strikes in the water during peak
352 lockdown were dramatically lower than baseline periods in two data sets (e.g., 19%
353 reduction: South Korea, 42% reduction: USA, Appendix 4, Table A4, StudyIDs 7 & 27).
354 There was also a marked reduction in ocean noise, which can negatively impact a wide
355 range of marine organisms, as reported from several locations. For example, lockdown-
356 related reductions in ferry traffic, seaplane activity, and recreational boating activity near
357 the transport hub of Nanaimo Harbour, Canada, combined to reduce the sound
358 pressure levels by 86% (Appendix 4, Table A4, StudyID 23). In urban parks in Boston,
359 noise from road traffic dropped by as much as 50% as traffic volumes decreased
360 (Appendix 4, Table A4, StudyID 52; Terry et al., 2021 [this issue]). On roadways, parks
361 and beaches around the world, direct pollution from humans was also reduced during
362 the lockdown. For example, surveys of 15 beaches in Colombia and Cuba found
363 negligible evidence of noise, human waste, and litter during the strict lockdown period,
364 in contrast to pervasive human impact before the lockdown (Appendix 3, Table A3,
365 Lines 742-748).

366

367 While some biodiversity threats were alleviated, as discussed above, responses were
368 highly variable. For example, marine traffic increased slightly in some regions (Appendix
369 4 and 5, Fig. A4 and A5) including shifts of fishing fleets to near-shore coastlines. In
370 some regions, fishing activities intensified rather than declined (e.g., some recreational
371 fisheries and commercial fisheries) (Fig. 5). Other impacts escalated, including massive
372 increases in plastic waste due to discarded personal protective equipment to prevent
373 COVID-19 transmission, and abnormally large crowds of visitors to parks for recreation
374 in countries where outdoor activities were permitted (e.g., a 47% visitation increase in
375 the Swiss National Park, Appendix 4, Table A4, StudyID 57). In many parks, hikers
376 were observed expanding trails, destroying or changing local habitats, and even
377 trampling endangered orchid species (Appendix 3, Table A3).

378

379 The lockdown also interrupted conservation enforcement activities with dire
380 consequences including increased illegal activities, such as hunting, deforestation, and
381 the dumping of waste (Figs. 4 and 5). For instance, pangolins, which are amongst the
382 world's most trafficked mammals (for food and traditional medicine), seem to have come
383 under even greater pressure; trade seizures increased in India by >500% (i.e., a 5-fold
384 increase) during the lockdown period (Appendix 4, Table A4, StudyID 62). Indeed, a
385 spike in exploitation of many animal species for food and trade was reported from
386 around the world (e.g., China, Kenya, India, Peru, South Africa, Sri Lanka, UK), often for
387 national parks and protected areas. For example, in the protected Bugoma Forest
388 reserve in Uganda (Appendix 4, Table A4, StudyID 19), increased use of animal snares

389 during the pandemic was detected, which can injure and kill non-target animals,
390 including endangered species such as chimpanzees. Likewise, during the lockdown, the
391 conch fishery in the Bahamas shifted to smaller illegal-sized juvenile animals from a
392 nursery area (Appendix 4, Table A4, StudyID 47).

393

394 **3.4 Responses of social systems which support biological conservation**

395

396 We found that management and conservation systems were initially weakened and
397 even ceased in many areas of the world (the median effect size was negative in both
398 the qualitative and quantitative data sets: Figs. 4b and 5b). In one region of the
399 Amazon, Brazil, the deforested area relative to historical years increased by 168% (i.e.,
400 a 1.68-fold change) during the lockdown, and a similar response was seen for the
401 eruption of fire hotspots in Colombia, both attributed to a lack of enforcement (Appendix
402 4, Table A4, StudyID 35). Environmental monitoring and community-based programs to
403 restore habitats or remove waste from beaches have also been severely restricted.
404 Anecdotes highlight that pest management programs have not been able to recruit
405 community volunteers to trap rats and mobilize personnel to combat locust outbreaks. In
406 one dramatic example, failure to remove non-native mice from remote seabird islands is
407 expected to lead to the loss of two million seabird chicks in 2020 (Appendix 3, Table A3,
408 Line 265).

409

410 The number of observers contributing to community science efforts has also
411 immediately declined for many programs (e.g., eBird Colombia, eButterfly, Nature's

412 Notebook and the LEO Network; Crimmins et al., 2021 [this issue]), although growth
413 was also noted in some US programs in particular cities and regions (eBird and
414 iNaturalist, Appendix 4, Table A4; Crimmins et al., 2021 [this issue]; Hochachka et al.,
415 2021 [this issue]). A lack of reporting can be a major conservation concern, such as
416 when the number of whale observers declined by 50% along the Pacific Northwest
417 during the lockdown, leading to a reduced ability of ships to avoid striking whales
418 (Appendix 3, Table A3, Line 272).

419

420 **4.0 Discussion**

421

422 The COVID-19 lockdown provided an unprecedented, serendipitous opportunity to
423 examine the multi-faceted links between human activity and the environment, providing
424 invaluable insights that can inform conservation strategies and policy making.

425 Specifically, this lockdown has created a period during which global human activity,
426 especially travel, was drastically reduced, enabling quasi-experimental investigation of
427 effects across a large number of ‘replicates’ (Bates et al., 2020).

428

429 Overall, we found that both positive and negative responses of human activity on
430 species and ecosystems are prevalent – results that are inconsistent with the prevailing
431 view of humans as primarily harming biodiversity. Indeed, while the qualitative
432 observations presented here provide evidence of interpretation bias, viewing unusual
433 behaviours in wildlife as positive (Fig. 4), our quantitative assessments were balanced
434 between negative and positive responses (Fig. 5). Even if our dataset does not

435 represent a random sampling design, the reports collated are a comprehensive
436 inventory of information across the globe. Emerging from this initial dataset is support
437 for both negative and positive responses of wildlife to human activity and the systems in
438 place to monitor and protect nature. Thus, the lockdown provides a striking illustration of
439 the positive role humans can play as custodians of biodiversity. While negative impacts
440 were expected, the potential for humans to positively influence biological conservation
441 through scientific research, environmental monitoring, opportunistic citizen reporting,
442 conservation management, restoration and enforcement activities was strong in our
443 datasets. Combined, these activities jointly deliver conservation benefits.

444

445 Another major take-home from this synthesis effort is that humans and their activities
446 have measurable impacts on food availability for animals from both land and marine
447 habitats, including that of top predators and scavengers. The role of human-sourced
448 food is an important driver of wildlife occurrence and condition. For instance, in
449 Singapore, feral pigeons shifted their diets from human foods to more natural food
450 sources and their numbers declined (Appendix 4, Table A4, StudyID 75, Soh et al.,
451 2021 [this issue]). At a university campus in South Africa, red-winged starlings lost body
452 mass, presumably because their typical foraging grounds were bare of waste food
453 (Appendix 4, Table A4, StudyID 58). Scavenging crows also spread to coastal beaches
454 in Australia when human food was no longer available (Gilby et al., 2021 [this issue]).
455 Many species that are routinely fed during wildlife tours (e.g., sharks (Gallagher and
456 Huveneers, 2018)) have not had access to this supplementary food due to drastically
457 reduced tourism. This appeared to drive a change in the abundance and types of

458 species that were detected at sites in the Bahamas during the lockdown period
459 (Appendix 4, Table A4, StudyID 67). In addition to food, animal use of nutritional
460 supplements was also influenced by human activities. For instance, in response to
461 reduced traffic on highways in the Canadian Rockies, mountain goats spent more time
462 at mineral licks, interpreted as a wildlife benefit (Appendix 4, Table A4, StudyID 37).

463

464 Another major take-home from this synthesis effort is that many wildlife and ecosystem
465 responses were unexpected. A classic example is from the Baltic Sea, where due to the
466 lockdown, only researchers and a park warden were present on a seabird island during
467 2020. The number of people on the island was thus reduced by 92%, by contrast to
468 normal years where summer visitors enjoy the island. The reduction in human presence
469 corresponded with the unexpected arrival of 33 white-tailed eagles where no more than
470 three had been observed in each year for several decades (white-tailed eagle: Fig. 3).

471 By regularly flying near a murre colony, the eagles flushed incubating birds at
472 disturbance rates 700% greater (7-fold increase) than historical rates, resulting in
473 abandoned ledges where the birds lay their eggs, and subsequent increased egg
474 predation by gulls and crows (Appendix 4, Table A4, StudyID 31; Hentati-Sundberg et
475 al., 2021 [this issue]). The absence of humans in this case seems to have negatively
476 impacted a species of conservation concern, through changing the distribution of a
477 species which evoked a predator avoidance response.

478

479 Hunting also increased across many countries, including in parks, to supplement
480 incomes. A classic example is the increase in pangolin hunting which was likely due to a

481 combination of reduced protection from forest departments, increased sales of hunting
482 permits, and greater illegal hunting. This is surprising considering the possible role of
483 pangolins as intermediary hosts of SARS-COV-2, and calls to halt the consumption of
484 wildlife to avoid future zoonoses (Zhang et al., 2020). Furthermore, it is clear that
485 resilient socio-ecological systems are fundamental to supporting nature conservation.

486

487 We further find that impacts of the lockdown on human hunting activity have created not
488 only direct but cascading ecological impacts. For instance, in North America the large
489 greater snow goose population is considered a pest due to grazing on crops. Goose
490 numbers are controlled during their migration to the High Arctic by allowing spring
491 hunting. Yet, hunting pressure decreased by up to 54% in 2020 in comparison with
492 2019, and geese benefitted from undisturbed foraging, resulting in rapid weight gain to
493 fuel their northward migration (Appendix 4, Table A4, StudyID 25; LeTourneux et al.,
494 2021 [this issue]). Indeed, hunters from Mittimatalik (Nunavut) reported that those birds
495 arriving in the Arctic this year were unusually large and healthy. This year's cohort of
496 geese, which graze the fragile arctic tundra and degrade the habitat for other species,
497 will potentially drive future population growth and environmental impacts (Snow Goose,
498 Fig. 3).

499

500 The magnitudes of some effects were also more dramatic than anticipated, such as in
501 cases where the lockdown coincided with reproductive activity. For example, in
502 Colombia, a hotspot of bird diversity, species richness in residential urban areas in Cali
503 increased on average by 37% when human activity was lowest during the lockdown,

504 which coincided with the beginning of the breeding season. Similarly, various species of
505 sea turtles benefited from nesting on undisturbed beaches during the lockdown period.
506 In Florida, for instance, lockdown-related beach closures in a conservation area were
507 linked to a surprising 39% increase in nesting success in loggerhead turtles, attributed
508 to a lack of disturbances from fishers and tourists with flashlights, and lack of
509 obstructions such as sandcastles (Appendix 4, Table A4, StudyID 74).

510

511 **4.1 Management implications**

512

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

527 rather than reducing traffic volume, reducing traffic speed would lead to less noise
528 pollution and protect both wildlife and human safety.

529

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

549

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

570

571 It is unclear if any of the changes in animal distribution, abundance, behavior and
572 sources of food will persist once the lockdown restrictions cease. Many of the

573 responses observed may be transient. For example, animals roaming in areas typically
574 supporting intense human activity may retreat back to smaller ranges once human
575 activity resumes full-scale. However, negative impacts resulting from the interruption of
576 conservation efforts may be long-lasting and reverse years and decades of such efforts.
577 It is likely that long-term impacts of hunting will be apparent into the future in the
578 abundance of this species (Appendix 4, Table A4, StudyID 47), and in most other cases
579 where illegal activities have injured or removed animals. On the positive side, strong
580 recruitment success of endangered species in areas where disturbance declined may
581 have long-lasting positive effects, particularly where the beneficiary species, such as
582 sea turtles, have long life spans. Long-term studies should track the cohorts of the 2020
583 wildlife generation over years and decades to integrate the positive and negative
584 conservation impacts of the human lockdown.

585

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

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807 **Figure Legends**

808

809 **Fig. 1.** Total humans under COVID-19 mobility restrictions. Time series of the number
810 of humans under lockdown across the global population under the 2020 COVID-19
811 mitigation policies. This assumes that in countries with targeted restrictions, a fraction of
812 20% of the population was under lockdown. Assuming different fractions, similar time
813 patterns but different magnitudes of populations under lockdown are obtained. For
814 example, assuming fractions of 20% and 30%, April 5th was the day with the maximum
815 population under lockdown equal to 57% and 61% of the global population, respectively.
816 Assuming fractions of 5% and 10%, April 26th was the day with the maximum
817 population under lockdown equal to 53% and 54% of the population, respectively.

818

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

821

822 **Fig. 3.** Reports of 275 species that occupied an unusual area (distribution change), or
823 shifted in number (abundance change) were attributed to a reduction in human
824 activities. Changes in species distributions were observed around the world as
825 qualitative observations (Appendix 3, Table A3, albeit with biases in effort such as
826 greater coverage in the Northern Hemisphere and South Africa), and based on
827 empirical data of time series surveys and bio logging data using statistical modeling to
828 quantify change. Only changes that were attributed to the lockdown with high

829 confidence are included here (Appendix 4, Table A4). Bubble size represents data
830 density (the largest bubble represents 41-60 observations and the smallest is 1-20).
831

832 **Fig. 4.** Qualitative negative and positive effects observed which were relative to the
833 response observed (Appendix 4, Table A4). Negative effects indicate a dampening in
834 the responses which were grouped into categories representing “Human Mobility &
835 Activities”, Biodiversity Threats”, “Wildlife Responses” and “Social Systems &
836 Structures”, while positive effects indicate an increase. The effect score is based on the
837 criteria outlined in Appendix 1, Table A2, and considered the duration, spatial extent
838 and total impact of the effect on the response. A negative or positive effect direction is
839 relative to each category is based on the observed effect, rather than an interpreted
840 impact. For instance, a negative effect on noise is a decrease in noise (which may have
841 had positive wildlife impacts). a) Distribution of effects showing the direction and
842 magnitude. The dotted line is the intercept, and the colored line indicates the median
843 effect score. b) The mean effect score for categories falling within effects on human
844 activities (blue), biodiversity threats (orange), biodiversity (green) and social systems
845 (purple). Bars are the mean across reports pooled for positive and negative effects on
846 the y-axis category, and white numbers are the number of observations upon which the
847 mean is based.

848

849 **Fig. 5.** Responses during the lockdown based on our empirical data (Appendix 5, Table
850 A5) where positive and negative effects represent the observed direction of change for
851 the different response categories. 71 studies which attributed the observed effect to the

852 lockdown with high confidence are included (i.e., a qualitative confidence score of 3 or
853 greater out of a maximum of 5). Frequency histograms (panels a-d) show bars
854 representing data density and a curve representing a smoothed distribution of effect
855 sizes and direction. The dotted line is zero, and the solid colored line is the median.
856 Only responses that were attributed to the lockdown with high confidence are included.
857 a) Human activities and mobility (blue) includes measured responses in human
858 activities and mobility, such as related to commuting and recreational activities
859 (categories are described in Appendix 1, Table A1). b) Biodiversity threats (orange)
860 include categories that harm wildlife and natural systems, such as hunting, fishing,
861 mining, vehicle strikes, wildlife trade, environmental pollution, and deforestation. c)
862 Wildlife responses (green) incorporate observations of animals and plants related to
863 performance (e.g., reproduction, health, foraging) and habitat use (abundance and
864 distribution) and community change (species richness). d) Social systems (purple)
865 include environmental monitoring, restoration, conservation, and enforcement. The
866 chord diagrams highlighted the observed positive and negative effects which were
867 attributed to different lockdown-related drivers as identified by each study (black), and
868 linked to what was measured by each study where responses grouped into the four
869 categories: human activities and mobility, biodiversity threats, wildlife responses, and
870 social systems and structures. One chord represents one measured response.

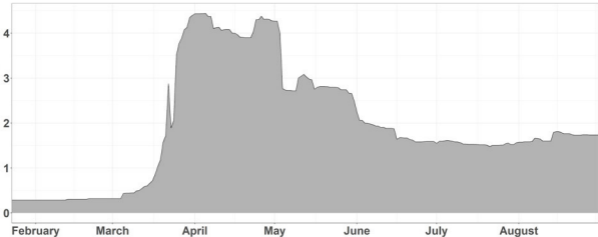
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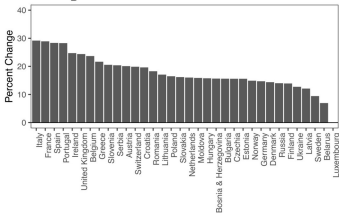
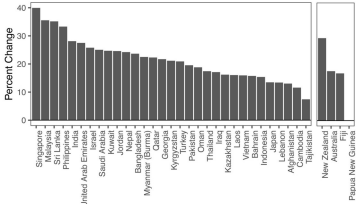
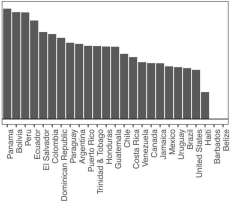
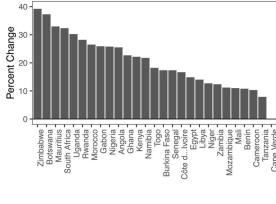
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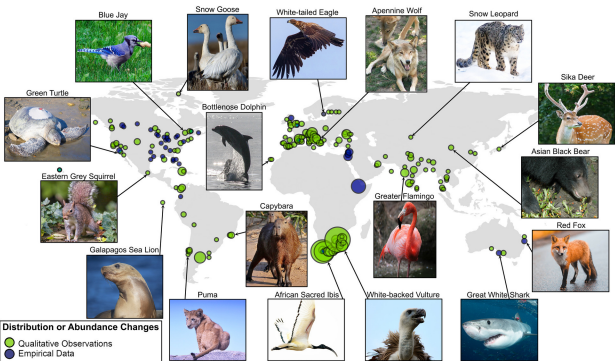
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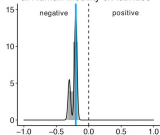
Billions of Humans Under Mobility Restrictions



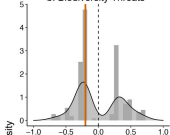




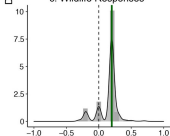
a. Human Mobility & Activities



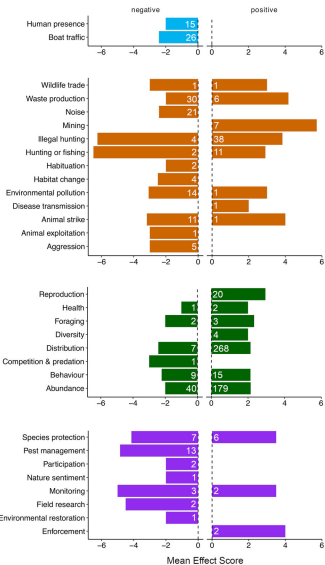
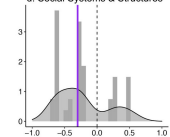
b. Biodiversity Threats



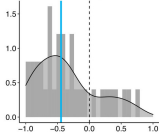
c. Wildlife Responses



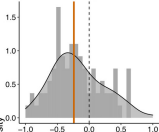
d. Social Systems & Structures



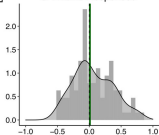
a. Human Mobility & Activities



b. Biodiversity Threats



c. Wildlife Responses



d. Social Systems & Structures

