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

Amanda E. Bates^{a,*}, Richard B. Primack^b, Brandy S. Biggar^a, Tomas J. Bird^c, Mary E. Clinton^a, Rylan J. Command^d, Cerren Richards^a, Marc Shellard^e, Nathan R. Geraldini^e, Valeria Vergara^f, Orlando Acevedo-Charry^g, Zuania Colón-Piñero^h, David Ocampo^g, Natalia Ocampo-Peñuelaⁱ

* Corresponding author.

E-mail addresses: bates.amanda@gmail.com (A.E. Bates), primack@bu.edu (R.B. Primack), bsbiggar@mun.ca (B.S. Biggar), tomasbird@gmail.com (T.J. Bird), meclinton@mun.ca (M.E. Clinton), rjcommand@mun.ca (R.J. Command), cerrenrichards@gmail.com (C. Richards), marc.shellard@gmail.com (M. Shellard), nathan.geraldini@kaust.edu.sa (N.R. Geraldini), Valeria.Vergara@ocean.org (V. Vergara), oaacevedoc@unal.edu.co (O. Acevedo-Charry), zcolonp@gmail.com (Z. Colón-Piñero), algorab2@gmail.com (D. Ocampo), ocamponata@gmail.com (N. Ocampo-Peñuela), sanchez.linam@gmail.com (L.M. Sánchez-Clavijo), mihaicristian.adamescu@g.unibuc.ro (C.M. Adamescu), sorin.cheval@meteoromania.ro (S. Cheval), tudor.racoviceanu@unibuc.ro (T. Racoviceanu), md.adams@utoronto.ca (M.D. Adams), egide.kalisa@utoronto.ca (E. Kalisa), vincent.kuure@utoronto.ca (V.Z. Kuire), vikram.aditya@atree.org (V. Aditya), pia.anderwald@nationalpark.ch (P. Anderwald), samuel.wiesmann@nationalpark.ch (S. Wiesmann), sonja.wipf@nationalpark.ch (S. Wipf), gb64@st-andrews.ac.uk (G. Badihi), mh295@st-andrews.ac.uk (M.G. Henderson), Hanspeter.Loetscher@anu.gr.ch (H. Loetscher), katja.baerenfaller@siaf.uzh.ch (K. Baerenfaller), ibenedetti@biologia.unipi.it (L. Benedetti-Cecchi), fabio.bulleri@unipi.it (F. Bulleri), iacopo.bertocci@unipi.it (I. Bertocci), emaggi@biologia.unipi.it (E. Maggi), luca.rindi@biologia.unipi.it (L. Rindi), chiara.ravaglioli@biologia.unipi.it (C. Ravaglioli), kristina.boerder@dal.ca (K. Boerder), jbonnel@whoi.edu (J. Bonnel), mathias.somme@orange.fr (D. Mathias), philippe.archambault@bio.ulaval.ca (P. Archambault), laurent.chauvaud@univ-brest.fr (L. Chauvaud), cbraun@whoi.edu (C.D. Braun), sthorold@whoi.edu (S.R. Thorold), Jacob.Brownscombe@dfo-mpo.gc.ca (J.W. Brownscombe), Jon.Midwood@dfo-mpo.gc.ca (J.D. Midwood), Christine.Boston@dfo-mpo.gc.ca (C.M. Boston), jillbrooks85@gmail.com (J.L. Brooks), StevenCooke@cunet.carleton.ca (S.J. Cooke), victor.china@gmail.com (V. China), uri.roll@gmail.com (U. Roll), jbelmaker@tauex.tau.ac.il (J. Belmaker), zvuloni@npa.org.il (A. Zvuloni), marta.coll.work@gmail.com (M. Coll), mortega@ent.cat (M. Ortega), Brendan.connors@dfo-mpo.gc.ca (B. Connors), lisa.lacko@dfo-mpo.gc.ca (L. Lacko), djay782@aucklanduni.ac.nz (D.R.M. Jayathilake), mark.j.costello@nord.no (M.J. Costello), theresa@usanpn.org (T.M. Crimmins), lorianne.barnett@gmail.com (L. Barnett), ellen@usanpn.org (E.G. Denny), katgerst@email.arizona.edu (K.L. Gerst), rmarsh85@gmail.com (R.L. Marsh), erin@usanpn.org (E.E. Posthumus), reilly@usanpn.org (R. Rodriguez), alyssa@usanpn.org (A. Rosemartin), sara.n.schaffer@gmail.com (S.N. Schaffer), jeff@usanpn.org (J.R. Switzer), gnublet@gmail.com (K. Wong), susan.cunningham@uct.ac.za (S.J. Cunningham), petra.sumasgutner@univie.ac.at (P. Sumasgutner), arjun.amar@uct.ac.za (A. Amar), robert.thomson@uct.ac.za (R.L. Thomson), stfmiq001@myuct.ac.za (M. Stofberg), sally.hofmeyr@gmail.com (S. Hofmeyr), jessleena.suri@gmail.com (J. Suri), rstuarts@utas.edu.au (R.D. Stuart-Smith), paul@carijoa.com (P.B. Day), G.Edgar@utas.edu.au (G.J. Edgar), antonia.cooper@utas.edu.au (A.T. Cooper), fdeleo@uvic.ca (F.C. De Leo), garmergrant75@gmail.com (G. Garner), paulson.desbrisay@canada.ca (P.G. Des Brisay), michael.schrimpf@umanitoba.ca (M.B. Schrimpf), nicola.koper@umanitoba.ca (N. Koper), diamond2@uw.edu (M.S. Diamond), rdwyer2@usc.edu.au (R.G. Dwyer), cameron.baker@uqconnect.edu.au (C.J. Baker), c.franklin@uq.edu.au (C.E. Franklin), ronf@post.bgu.ac.il (R. Efrat), bergerod@bgu.ac.il (O. Berger-Tal), ohad@npa.org.il (O. Hatzofe), victor@ifisc.uib-csic.es (V.M. Eguíluz), jorgeprodriguez@gmail.com (J.P. Rodríguez), juanf@ifisc.uib-csic.es (J. Fernández-Gracia), delusto@unav.es (D. Elustondo), vicentalatayud65@gmail.com (V. Calatayud), Philina.English@dfo-mpo.gc.ca (P.A. English), sarcher@lumcon.edu (S.K. Archer), Sarah.Dudas@dfo-mpo.gc.ca (S.E. Dudas), Dana.Haggarty@dfo-mpo.gc.ca (D.R. Haggarty), austin@beneaththewaves.org (A.J. Gallagher), Brendan@beneaththewaves.org (B.D. Shea), ollieshipley7@gmail.com (O.N. Shipley), bgilby@usc.edu.au (B.L. Gilby), jab086@student.usc.edu.au (J. Ballantyne), aolds@usc.edu.au (A.D. Olds), chender1@usc.edu.au (C.J. Henderson), tschlach@usc.edu.au (T.A. Schlacher), whalliday@wcs.org (W.D. Halliday), nickawbrown@gmail.com (N.A.W. Brown), kenzie.woods@gmail.com (M.B. Woods), sigal@mcmaster.ca (S. Balshine), juanes@uvic.ca (F. Juanes), mitchell.rider@rsmas.miami.edu (M.J. Rider), p.albano@rsmas.miami.edu (P.S. Albano), nhammerschlag@rsmas.miami.edu (N. Hammerschlag), g.hays@deakin.edu.au (G.C. Hays), n.esteban@swansea.ac.uk (N. Esteban), yhyhpan@gmail.com (Y. Pan), gjhe@ust.hk (G. He), takanao.tanaka@hotmail.co.jp (T. Tanaka), bgilby@usc.edu.au (M.J.S. Hensel), bgilby@usc.edu.au (R.J. Orth), cpatrick@vims.edu (C.J. Patrick), jonas.sundberg@slu.se (J. Hentati-Sundberg), Olof.olsson@su.se (O. Olsson), margot@hakai.org (M.L. Hessing-Lewis), nickhiggs@ceibahamas.org (N.D. Higgs), mark.hindell@utas.edu.au (M.A. Hindell), clive.mcmahon@utas.edu.au (C.R. McMahon), robert.harcourt@mq.edu.au (R. Harcourt), christophe.guinet@cebc.cnrs.fr (C. Guinet), SHirsch@marinelife.org (S.E. Hirsch), JPerrault@marinelife.org (J.R. Perrault), shoover@marinelife.org (S.R. Hoover), jreilly@marinelife.org (J.D. Reilly), chl42@st-andrews.ac.uk (C. Hobaiter), thibaud.gruber@gmail.com (T. Gruber), charlie.huveneers@flinders.edu.au (C. Huveneers), v.udyawer@aims.gov.au (V. Udyawer), tom.clarke@flinders.edu.au (T.M. Clarke), laura.kroesen@gmail.com (L.P. Kroesen), david_hik@sfu.ca (D.S. Hik), seth.cherry@canada.ca (S.G. Cherry), justin.belluz@hakai.org (J.A. Del Bel Belluz), jennifer.jackson@hakai.org (J.M. Jackson), Shengjie.Lai@soton.ac.uk (S. Lai), ctamb@ualberta.ca (C.T. Lamb), gregory.leclair@maine.edu (G.D. LeClair), jparmelee@une.edu (J.R. Parmelee), mchatfield@centerforwildlifestudies.org (M.W.H. Chatfield), cfrederick@centerforwildlifestudies.org (C.A. Frederick), lsd@ewha.ac.kr (S. Lee), jolie731@naver.com (H. Park), janechoi2633@gmail.com (J. Choi), frederic.letourneux@gmail.com (F. LeTourneux), thierrygrandmont19@hotmail.com (T. Grandmont), frederic.ddb@gmail.com (F.D. de-Broin), joel_bety@uqar.ca (J. Bêty), gilles.gauthier@bio.ulaval.ca (G. Gauthier), pierre.legagneux@bio.ulaval.ca (P. Legagneux)

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Lina M. Sánchez-Clavijoⁱ, Cristian M. Adamescu^j, Sorin Cheval^k, Tudor Racoviceanu^j, Matthew D. Adams^l, Egide Kalisa^l, Vincent Z. Kuuire^l, Vikram Aditya^m, Pia Anderwaldⁿ, Samuel Wiesmannⁿ, Sonja Wipfⁿ, Gal Badihi^o, Matthew G. Henderson^o, Hanspeter Loetscher^p, Katja Baerenfaller^q, Lisandro Benedetti-Cecchi^r, Fabio Bulleri^r, Iacopo Bertocci^r, Elena Maggi^r, Luca Rindi^r, Chiara Ravaglioli^r, Kristina Boerder^s, Julien Bonnel^t, Delphine Mathias^u, Philippe Archambault^v, Laurent Chauvaud^w, Camrin D. Braun^x, Simon R. Thorrold^x, Jacob W. Brownscombe^y, Jonathan D. Midwood^y, Christine M. Boston^y, Jill L. Brooks^z, Steven J. Cooke^z, Victor China^{aa}, Uri Roll^{aa}, Jonathan Belmaker^{ab,fr}, Assaf Zvuloni^{ac}, Marta Coll^{ad}, Miquel Ortega^{ae}, Brendan Connors^{af}, Lisa Lacko^{af}, Dinusha R.M. Jayathilake^{ag}, Mark J. Costello^{ah}, Theresa M. Crimmins^{ai}, LoriAnne Barnett^{ai}, Ellen G. Denny^{ai}, Katharine L. Gerst^{ai}, R.L. Marsh^{ai}, Erin E. Posthumus^{ai}, Reilly Rodriguez^{ai}, Alyssa Rosemartin^{ai}, Sara N. Schaffer^{ai}, Jeff R. Switzer^{ai}, Kevin Wong^{ai}, Susan J. Cunningham^{aj}, Petra Sumasgutner^{ak}, Arjun Amar^{aj}, Robert L. Thomson^{aj}, Miqkayla Stofberg^{aj}, Sally Hofmeyr^{aj}, Jessleena Suri^{aj}, Rick D. Stuart-Smith^{al}, Paul B. Day^{am}, Graham J. Edgar^{al}, Antonia T. Cooper^{al}, Fabio Cabrera De Leo^{an,ao}, Grant Garner^{ao}, Paulson G. Des Brisay^{ap}, Michael B. Schimpf^{aq}, Nicola Koper^{aq}, Michael S. Diamond^{ar}, Ross G. Dwyer^{as}, Cameron J. Baker^{at}, Craig E. Franklin^{at}, Ron Efrat^{aa}, Oded Berger-Tal^{aa}, Ohad Hatzofe^{au},

jslewi10@asu.edu (J.S. Lewis), jdhaight@asu.edu (J. Haight), zhuliu@tsinghua.edu.cn (Z. Liu), Jarod.Lyon@delwp.vic.gov.au (J.P. Lyon), rob.hale@delwp.vic.gov.au (R. Hale), dallas.dsilva@vfa.vic.gov.au (D. D'Silva), ian.macgregor@helsinki.fi (I. MacGregor-Fors), enriquearbelaez@gmail.com (E. Arbeláez-Cortés), felipe.estela@javerianacali.edu.co (F.A. Estela), csanchezsarria23@gmail.com (C.E. Sánchez-Sarria), michelle.garciaarroyo@helsinki.fi (M. García-Arroyo), giannkas1@gmail.com (G.K. Aguirre-Sambon), ibanf17@gmail.com (J.C. Franco Morales), shahar.malamud@gmail.com (S. Malamud), talgav@gmail.com (T. Gavriel), hezibuba@mail.tau.ac.il (Y. Buba), shira.salin@gmail.com (S. Salinger), mai.lazarus@gmail.com (M. Lazarus), ruthy@npa.org.il (R. Yahel), yigael.ba@npa.org.il (Y.B. Ari), eyalm@npa.org.il (E. Miller), rotems@npa.org.il (R. Sade), guyl@npa.org.il (G. Lavian), zivbirman@npa.org.il (Z. Birman), manorg@npa.org.il (M. Gury), harelb@npa.org.il (H. Baz), iliab@npa.org.il (I. Baskin), alonp@npa.org.il (A. Penn), amidd@npa.org.il (A. Dolev), ogenli@npa.org.il (O. Licht), tabik@npa.org.il (T. Karkom), davidson1969@gmail.com (S. Davidzon), edom2222@gmail.com (A. Berkovitch), ofery@npa.org.il (O. Yaakov), raoulmanenti@gmail.com (R. Manenti), emilianomorieri85@gmail.com (E. Mori), francesco.ficetola@unimi.it (G.F. Ficetola), enrico.arti@gmail.com (E. Lunghi), D.March@exeter.ac.uk (D. March), b.j.godley@exeter.ac.uk (B.J. Godley), cecilia.martin@kaust.edu.sa (C. Martin), smihaly@uvic.ca (S.F. Mihaly), DBarclay@dal.ca (D.R. Barclay), Dugald@dal.ca (D.J.M. Thomson), rdewey@uvic.ca (R. Dewey), jbedard@uvic.ca (J. Bedard), aroha.miller@ocean.org (A. Miller), Amber.Dearden@ocean.org (A. Dearden), chapmanjen@outlook.com (J. Chapman), Lauren.dares@ocean.org (L. Dares), laura.kroesen@gmail.com (L. Borden), Donna.Gibbs@ocean.org (D. Gibbs), Schultz.jessica.a@gmail.com (J. Schultz), sergeenk@ualberta.ca (N. Sergeenko), Fiona.Francis@dfp-mpo.gc.ca (F. Francis), Amanda.Weltman@ocean.org (A. Weltman), nicolas.moity@fcdarwin.org.ec (N. Moity), jorge.ramirez@fcdarwin.org.ec (J. Ramírez-González), gmuientes@iim.csic.es (G. Mucientes), alex@iim.csic.es (A. Alonso-Fernández), itai.namir@gmail.com (I. Namir), avi-b@sci.haifa.ac.il (A. Bar-Massada), ron.chen@hamaarag.org.il (R. Chen), yedvab@gmail.com (S. Yedvab), Thomas.Kekey@gmail.com (T.A. Okey), steffen.oppel@gmail.com (S. Oppel), volen.arkumarev@bspb.org (V. Arkumarev), Samuel.Bakari@birdlife.org (S. Bakari), vladimir.dobrev@bspb.org (V. Dobrev), vsaravia@ornithologiki.gr (V. Saravia-Mullin), tasosbounas@gmail.com (A. Bounas), dobromir.dobrev@bspb.org (D. Dobrev), e.kret@wwf.gr (E. Kret), solmersi@gmail.com (S. Mengistu), cloep@saharaconservation.org (C. Pourchier), alazar.ruffo@gmail.com (A. Ruffo), milliontesfaye510@gmail.com (M. Tesfaye), wondafrash.mj61@gmail.com (M. Wondafrash), stoyan.nikolov@bspb.org (S.C. Nikolov), c.palmer1@lse.ac.uk (C. Palmer), lsileci@lse.ac.uk (L. Sileci), patrickthomasrex@gmail.com (P.T. Rex), chris.lowe@csulb.edu (C.G. Lowe), cesc@icm.csic.es (F. Peters), mattpine@uvic.ca (M.K. Pine), c.radford@aukland.ac.nz (C.A. Radford), lwl634@auklanduni.ac.nz (L. Wilson), l.mcwhinnie@hw.ac.uk (L. McWhinnie), alessia.scuderi1@gmail.com (A. Scuderi), a.jeffs@aukland.ac.nz (A.G. Jeffs), klprudic@arizona.edu (K.L. Prudic), maxim.larriee@montreal.ca (M. Larriée), kmcfarland@vtecostudies.org (K.P. McFarland), rsolis@sfu.ca (R. Solis), rah@oregonstate.edu (R.A. Hutchinson), nuno.queiroz@gmail.com (N. Queiroz), mafurtado2006@hotmail.com (M.A. Furtado), dws@mba.ac.uk (D.W. Sims), ejsouthall@yahoo.co.uk (E. Southall), claudio.quesada@gmail.com (C.A. Quesada-Rodríguez), jessidoro@zco@gmail.com (J.P. Diaz-Orozco), kuuleir@hawaii.edu (K.S. Rodgers), sarahjls@hawaii.edu (S.J.L. Severino), agramham8@hawaii.edu (A.T. Graham), mstefano@hawaii.edu (M.P. Stefanak), emadin@hawaii.edu (E.M.P. Madin), pryan31@gmail.com (P.G. Ryan), macleankyle1@gmail.com (K. Maclean), el.weideman@gmail.com (E.A. Weideman), c.s@utah.edu (Ç.H. Şekercioglu), kyle.kittelberger@utah.edu (K.D. Kittelberger), kusak@vef.hr (J. Kusak), Jeffrey.seminoff@noaa.gov (J.A. Seminoff), meh078@ucsd.edu (M.E. Hanna), taka.shimada@des.qld.gov.au (T. Shimada), M.Meekan@aims.gov.au (M.G. Meekan), kyle.smith@sanparks.org (M.K.S. Smith), m.mokhatla@mail.com (M.M. Mokhatla), Malcolm_SOH@nparks.gov.sg (M.C.K. Soh), e0727538@u.nus.edu (R.Y.T. Pang), Brey1_NG@nparks.gov.sg (B.X.K. Ng), Benjamin_LEE@nparks.gov.sg (B.P.Y.-H. Lee), Adrian_LOO@nparks.gov.sg (A.H.B. Loo), KENNETH_ER@nparks.gov.sg (K.B.H. Er), gabrielbarros@gmail.com (G.B.G. Souza), stallings@usf.edu (C.D. Stallings), joseph.curtis@ucsb.edu (J.S. Curtis), meaghanfaletti@aol.com (M.E. Faletti), jpeake1@usf.edu (J.A. Peake), mschram@usf.edu (M.J. Schram), Kara.Wall@MyFWC.com (K.R. Wall), ctery@bu.edu (C. Terry), mrothendler@gmail.com (M. Rothendler), lz106@wellesley.edu (L. Zipf), julloa@humboldt.org.co (J.S. Ulloa), anhernandez@humboldt.org.co (A. Hernández-Palma), bgomezv@humboldt.org.co (B. Gómez-Valencia), ccrúz@humboldt.org.co (C. Cruz-Rodríguez), yherrera@humboldt.org.co (Y. Herrera-Varón), mroa@humboldt.org.co (M. Roa), drodriguez@humboldt.org.co (S. Rodríguez-Buriticá), jochoa@humboldt.org.co (J.M. Ochoa-Quintero), reutvardi@gmail.com (R. Vardi), victor.vazquez@cocosphere.es (V. Vázquez), crequ@bgc-jena.mpg.de (C. Requena-Mesa), miyako.warrington@umanitoba.ca (M.H. Warrington), michelletaylor90@gmail.com (M.E. Taylor), lucy.woodall@zoo.ox.ac.uk (L.C. Woodall), paris@nektonmission.org (P.V. Stefanoudis), xiangliang.zhang@kaust.edu.sa (X. Zhang), Qiang.Yang@kaust.edu.sa (Q. Yang), Yuval.zuk15@gmail.com (Y. Zukerman), zehavas@npa.org.il (Z. Sigal), ayali@taux.tau.ac.il (A. Ayali), Eric.clua@univ-perp.fr (E.E.G. Clua), carzonpamela@gmail.com (P. Carzon), clemantine.seguigne@gmail.com (C. Seguine), andrea.corradini-2@unitn.it (A. Corradini), luca.pedrotti@stelviopark.it (L. Pedrotti), foleyc@hawaii.edu (C.M. Foley), catherinealexandra.gagnon@erebia.ca (C.A. Gagnon), cmilanes1@cuc.edu.co (C.B. Milanes), camilo.botero@u.u.edu.co (C.M. Botero), yunior.velazquez@uo.edu.co (Y.R. Velázquez), milchakova@gmail.com (N.A. Milchakova), smor@bas.ac.uk (S.A. Morley), environment.policy@tdc.uk.com (S.M. Martin), veronicananni7@gmail.com (V. Nanni), tanya.otero@ocean.org (T. Otero), julia.wakeling@ocean.org (J. Wakeling), sabarro@WWFCanada.org (S. Abarro), cyril.piou@cirad.fr (C. Piou), afliesobral@gmail.com (A.F.L. Sobral), eulogio.soto@uv.cl (E.H. Soto), emily.weigel@biosci.gatech.edu (E.G. Weigel), alejandro.bernal@mare-centre.pt (A. Bernal-Ibáñez), igestoso@mare-centre.pt (I. Gestoso), ecacabelos@mare-centre.pt (E. Cacabelos), francesca.cagnacci@fmach.it (F. Cagnacci), reny.devassy@kaust.edu.sa (R.P. Devassy), matthias.loretto@gmail.com (M.-C. Loretto), paumose@gmail.com (P. Moraga), christian.rutz@st-andrews.ac.uk (C. Rutz), duarteqcarlosm@gmail.com (C.M. Duarte).

VíctorM. Eguíluz^{av}, Jorge P. Rodríguez^{aw}, Juan Fernández-Gracia^{av}, David Elustondo^{ax},
 Vicent Calatayud^{ay}, Philina A. English^{az}, Stephanie K. Archer^{ba}, Sarah E. Dudas^{az},
 Dana R. Haggarty^{az}, Austin J. Gallagher^{bb}, Brendan D. Shea^{bb}, Oliver N. Shipley^{bb},
 Ben L. Gilby^{as}, Jasmine Ballantyne^{as}, Andrew D. Olds^{as}, Christopher J. Henderson^{as},
 Thomas A. Schlacher^{as}, William D. Halliday^{bc}, Nicholas A.W. Brown^{ao}, Mackenzie B. Woods^{ao},
 Sigal Balshine^{bd}, Francis Juanes^{ao}, Mitchell J. Rider^{be}, Patricia S. Albano^{be},
 Neil Hammerschlag^{be}, Graeme C. Hays^{bf}, Nicole Esteban^{bg}, Yuhang Pan^{bh}, Guojun He^{bi},
 Takanao Tanaka^{bh}, Marc J.S. Hensel^{bj}, Robert J. Orth^{bj}, Christopher J. Patrick^{bj},
 Jonas Hentati-Sundberg^{bk}, Olof Olsson^{bl}, Margot L. Hessing-Lewis^{bm}, Nicholas D. Higgs^{bn},
 Mark A. Hindell^{bo}, Clive R. McMahon^{bp}, Rob Harcourt^{bq}, Christophe Guinet^{br},
 Sarah E. Hirsch^{bs}, Justin R. Perrault^{bs}, Shelby R. Hoover^{bs}, Jennifer D. Reilly^{bs},
 Catherine Hobaiter^o, Thibaud Gruber^{bt}, Charlie Huvneers^{bu}, Vinay Udyawer^{bv},
 Thomas M. Clarke^{bu}, Laura P. Kroesen^{bw}, David S. Hik^{bw}, Seth G. Cherry^{bx},
 Justin A. Del Bel Belluz^{by}, Jennifer M. Jackson^{by}, Shengjie Lai^{bz}, Clayton T. Lamb^{ca},
 Gregory D. LeClair^{cb}, Jeffrey R. Parmelee^{cc}, Matthew W.H. Chatfield^{cd}, Cheryl A. Frederick^{cd},
 Sangdon Lee^{ce}, Hyomin Park^{ce}, Jaemin Choi^{ce}, Frédéric LeTourneau^{cf}, Thierry Grandmont^{cf},
 Frédéric Dulude de-Broin^{cf}, Joël Bêty^{cg}, Gilles Gauthier^{cf}, Pierre Legagneux^{cf,br},
 Jesse S. Lewis^{ch}, Jeffrey Haight^{ci}, Zhu Liu^{cj}, Jarod P. Lyon^{ck}, Robin Hale^{ck}, Dallas D'Silva^{cl},
 Ian MacGregor-Fors^{cm}, Enrique Arbeláez-Cortés^{cn}, Felipe A. Estela^{co},
 Camilo E. Sánchez-Sarria^{co}, Michelle García-Arroyo^{cm}, Giann K. Aguirre-Samboní^{co},
 Juan C. Franco Morales^{cp}, Shahar Malamud^{ab}, Tal Gavriel^{ab}, Yehezkel Buba^{ab},
 Shira Salingré^{ab}, Mai Lazarus^{ab}, Ruthy Yahel^{cq}, Yigael Ben Ari^{cq}, Eyal Miller^{cq}, Rotem Sade^{cq},
 Guy Lavian^{cq}, Ziv Birman^{cq}, Manor Gury^{cq}, Harel Baz^{cq}, Ilia Baskin^{cq}, Alon Penn^{cq},
 Amit Dolev^{cq}, Ogen Licht^{cq}, Tabi Karkom^{cq}, Sharon Davidzon^{cq}, Avi Berkovitch^{cq},
 Ofer Yaakov^{cq}, Raoul Manenti^{cr}, Emiliano Mori^{cs}, Gentile Francesco Ficetola^{cr},
 Enrico Lunghi^{ct}, David March^{cu}, Brendan J. Godley^{cu}, Cecilia Martin^e, Steven F. Mihalý^{cv},
 David R. Barclay^{cw}, Dugald J.M. Thomson^{cw}, Richard Dewey^{cv}, Jeannette Bedard^{cv},
 Aroha Miller^f, Amber Dearden^f, Jennifer Chapman^f, Lauren Dares^f, Laura Borden^f,
 Donna Gibbs^f, Jessica Schultz^f, Nikita Sergeenko^f, Fiona Francis^f, Amanda Weltman^f,
 Nicolas Moity^{cx}, Jorge Ramírez-González^{cx}, Gonzalo Mucientes^{cy},
 Alexandre Alonso-Fernández^{cy}, Itai Namir^{ab}, Avi Bar-Massada^{cz}, Ron Chen^{da},
 Shmulik Yedvab^{db}, Thomas A. Okey^{dc}, Steffen Ooppel^{dd}, Volen Arkumarev^{de}, Samuel Bakari^{df},
 Vladimir Dobrev^{de}, Victoria Saravia-Mullin^{dg}, Anastasios Bounas^{dg}, Dobromir Dobrev^{de},
 Elzbieta Kret^{dh}, Solomon Mengistu^{di}, Cloé Pourchier^{dj}, Alazar Ruffo^{dk}, Million Tesfaye^{dl},
 Mengistu Wondafrash^{di}, Stoyan C. Nikolov^{de}, Charles Palmer^{dm}, Lorenzo Sileci^{dm},
 Patrick T. Rex^{dn}, Christopher G. Lowe^{dn}, Francesc Peters^{do}, Matthew K. Pine^{dp},
 Craig A. Radford^{dq}, Louise Wilson^{dq}, Lauren McWhinnie^{dr}, Alessia Scuderi^{ds},
 Andrew G. Jeffs^{dq}, Kathleen L. Prudic^{dt}, Maxim Larrivée^{du}, Kent P. McFarland^{dv},
 Rodrigo Solis^{dw}, Rebecca A. Hutchinson^{dx}, Nuno Queiroz^{dy}, Miguel A. Furtado^{dy},
 David W. Sims^{dz}, Emily Southall^{dz}, Claudio A. Quesada-Rodríguez^{ea}, Jessica P. Diaz-Orozco^{ea},
 Ku'ulei S. Rodgers^{eb}, Sarah J.L. Severino^{eb}, Andrew T. Graham^{eb}, Matthew P. Stefanak^{eb},
 Elizabeth M.P. Madin^{eb}, Peter G. Ryan^{aj}, Kyle Maclean^{aj}, Eleanor A. Weideman^{aj},
 Çağan H. Şekercioğlu^{ec}, Kyle D. Kittelberger^{ec}, Josip Kusak^{ed}, Jeffrey A. Seminoff^{ee},
 Megan E. Hanna^{ef}, Takahiro Shimada^{eg}, Mark G. Meekan^{eh}, Martin K.S. Smith^{ei},
 Mohlamatsane M. Mokhatla^{ei}, Malcolm C.K. Soh^{ej}, Roanna Y.T. Pang^{ej}, Breyll X.K. Ng^{ej},
 Benjamin P.Y.-H. Lee^{ej}, Adrian H.B. Loo^{ej}, Kenneth B.H. Er^{ej}, Gabriel B.G. Souza^{ek},
 Christopher D. Stallings^{el}, Joseph S. Curtis^{el}, Meaghan E. Faletti^{el}, Jonathan A. Peake^{el},
 Michael J. Schram^{el}, Kara R. Wall^{el}, Carina Terry^b, Matt Rothendler^b, Lucy Zipf^b,
 Juan Sebastián Ulloaⁱ, Angélica Hernández-Palmaⁱ, Bibiana Gómez-Valenciaⁱ,
 Cristian Cruz-Rodríguezⁱ, Yenifer Herrera-Varónⁱ, Margarita Roaⁱ, Susana Rodríguez-Buriticáⁱ,
 Jose Manuel Ochoa-Quinteroⁱ, Reut Vardi^{em}, Víctor Vázquez^{en}, Christian Requena-Mesa^{eo},
 Miyako H. Warrington^{ep}, Michelle E. Taylor^{eq}, Lucy C. Woodall^{er}, Paris V. Stefanoudis^{er},
 Xiangliang Zhang^{es}, Qiang Yang^{es}, Yuval Zukerman^{aa}, Zehava Sigal^{au}, Amir Ayali^{et}, Eric E.

G. Clua^{eu}, Pamela Carzon^{eu}, Clementine Seguire^{eu}, Andrea Corradini^{ev}, Luca Pedrotti^{ew}, Catherine M. Foley^{eb}, Catherine Alexandra Gagnon^{cf}, Elijah Panipakoochoo^{ex}, Celene B. Milanes^{ey}, Camilo M. Botero^{ez}, Yuniór R. Velázquez^{fa}, Nataliya A. Milchakova^{fb}, Simon A. Morley^{fc}, Stephanie M. Martin^{fd}, Veronica Nanni^{fe}, Tanya Otero^{fg}, Julia Wakeling^{ff}, Sarah Abarro^{fg}, Cyril Piou^{fh}, Ana F.L. Sobral^{fi}, Eulogio H. Soto^{fj}, Emily G. Weigel^{fk}, Alejandro Bernal-Ibáñez^{fl}, Ignacio Gestoso^{fl}, Eva Cacabelos^{fl}, Francesca Cagnacci^{fm}, Reny P. Devassy^{fn}, Matthias-Claudio Loretto^{fo}, Paula Moraga^{fp}, Christian Rutz^{fq}, Carlos M. Duarte^e

^a Department of Ocean Sciences, Memorial University of Newfoundland, 0 Marine Lab Road, St. John's A1K 3E6, Canada

^b Biology Department, Boston University, 881 Commonwealth Avenue, Boston, MA 02215, United States

^c Northwest Atlantic Fisheries Centre, 80 E White Hills Rd, St. John's A1A 5J7, Canada

^d School of Ocean Technology, Fisheries and Marine Institute, Memorial University of Newfoundland, 155 Ridge Rd, St. John's, NL A1C 5R3, Canada

^e Red Sea Research Center and Computational Bioscience Research Center, King Abdullah University of Science and Technology, 23955 Thuwal, Saudi Arabia

^f Ocean Wise Conservation Association, 845 Avison Way, Vancouver V6B 3X8, Canada

^g Instituto de Investigación de Recursos Biológicos Alexander von Humboldt, Claustro de San Agustín, Villa de Leyva, Boyacá, Colombia

^h Department of Biology, University of Florida, Gainesville, FL 32611, USA

ⁱ Instituto de Investigación de Recursos Biológicos Alexander von Humboldt, Avenida Paseo Bolívar 16-20, Bogotá D.C., Colombia

^j Research Center for Systems Ecology and Sustainability, University of Bucharest, 050095 Bucharest, Romania

^k National Meteorological Administration, 013686 Bucharest, Romania

^l Department of Geography, Geomatics and Environment, University of Toronto, 3359 Mississauga Road, Mississauga, ON L5L 1C6, Canada

^m Ashoka Trust for Research in Ecology and the Environment, PO, Royal Enclave, Bengaluru, Karnataka 560064, India

ⁿ Swiss National Park, Chasè Planta-Wildenberg, Runatsch 124, 7530 Zerne, Switzerland

^o Origins of Mind, School of Psychology, University of St Andrews, St Marys Quad, St Andrews, Fife KY16 9JP, Scotland, United Kingdom

^p Office for Nature and Environment of the Grisons, Ringstrasse 10, 7001 Chur, Switzerland

^q Swiss Institute of Allergy and Asthma Research (SIAF), University of Zurich and Swiss Institute of Bioinformatics (SIB), 7265 Davos, Switzerland

^r Department of Biology, University of Pisa, Via Derna 1, I-56126 Pisa, Italy

^s Biology Department, Dalhousie University, 1355 Oxford Street, Halifax, NS B3H 4J1, Canada

^t Woods Hole Oceanographic Institution, Applied Ocean Physics and Engineering Department, Woods Hole, MA 02543, USA

^u Société d'Observation Multi-Modale de l'Environnement, 115 Rue Claude Chappe, 29280 Plouzané, France

^v ArcticNet, Département de Biologie, Université Océan, Université Laval, 2325 Rue de l'Université, Québec, QC G1V 0A6, Canada

^w Laboratoire des Sciences de l'Environnement Marin (LEMAR), UMR 6539 CNRS, UBO, IRD, Ifremer, Institut Universitaire Européen de la Mer (IUEM), LIA BeBEST, rue Dumont D'Urville, 29280 Plouzané, France

^x Biology Department, Woods Hole Oceanographic Institution, Woods Hole, MA 02543, USA

^y Great Lakes Laboratory for Fisheries and Aquatic Sciences, Fisheries and Oceans Canada, 867 Lakeshore Road, Burlington, Ontario L7S 1A1, Canada

^z Fish Ecology and Conservation Physiology Laboratory, Department of Biology, Carleton University, 1125 Colonel By Drive, Ottawa, ON K1S 5B6, Canada

^{aa} Mitrani Department of Desert Ecology, Jacob Blaustein Institutes for Desert Research, Ben-Gurion University of the Negev, Midreshet Ben-Gurion, Israel

^{ab} School of Zoology, Faculty of Life Sciences, Tel Aviv University, P.O. Box 39040, Tel Aviv 6997801, Israel

^{ac} Israel Nature and Parks Authority, Am V'Olamo 3, 95463 Jerusalem, Israel

^{ad} Institute of Marine Science (CSIC), Passeig Marítim de la Barceloneta 37-49 & Ecopath International Initiative (EII), Barcelona 08003, Spain

^{ae} Fundació ENT, Carrer Josep Llanza, 1-7, 2-3, Vilanova i la Geltrú, Barcelona, 08800 & Institut de Ciència i Tecnologia Ambiental, Universitat Autònoma de Barcelona, 08193 Bellaterra, Cerdanyola del Valles, Spain

^{af} Quantitative Assessment Methods Section, Stock Assessment and Research Division, Pacific Region, Fisheries and Oceans Canada, 401 Burrard St Suite 200, Vancouver, BC V6C 3L6, Canada

^{ag} School of Environment, University of Auckland, Auckland 1142, New Zealand

^{ah} Faculty of Biosciences and Aquaculture, Nord University, Bodo 1049, Norway

^{ai} USA National Phenology Network, School of Natural Resources and the Environment, University of Arizona, 1200 E. University Blvd, Tucson, AZ 85721, USA

^{aj} FitzPatrick Institute of African Ornithology, University of Cape Town, Rondebosch 7701, South Africa

^{ak} Core Facility Konrad Lorenz Research Center for Behaviour and Cognition, University of Vienna, Fischerau 11, A-4645 Grünau im Almtal, Austria

^{al} Institute for Marine and Antarctic Studies, University of Tasmania, Hobart, Tasmania 7001, Australia

^{am} Carjooa - Marine Environmental Consulting, 29 Sydenham Street, Rivervale, Perth, Western Australia 6103, Australia

^{an} Ocean Networks Canada, University of Victoria, Canada

^{ao} Department of Biology, University of Victoria, 3800 Finnerty Road, Victoria, BC V8P 5C2, Canada

^{ap} Environment and Climate Change Canada, 150-123 Main St, Winnipeg, MB R3C 4W2, Canada

^{aq} Natural Resources Institute, University of Manitoba, 66 Chancellors Cir, Winnipeg, MB R3T 2N2, Canada

^{ar} Department of Atmospheric Sciences, University of Washington, USA

^{as} School of Science and Engineering, University of the Sunshine Coast, Maroochydore DC, Queensland 4558, Australia

^{at} School of Biological Sciences, The University of Queensland, Brisbane, QLD 4072, Australia

^{au} Science Division, Israel Nature and Parks Authority, Am V'Olamo 3, 95463 Jerusalem, Israel

^{av} Instituto de Física Interdisciplinar y Sistemas Complejos IFISC (CSIC-UIB), E07122 Palma de Mallorca, Spain

^{aw} Instituto Mediterráneo de Estudios Avanzados IMEDEA (CSIC-UIB), 07190 Esporles, Spain

^{ax} Instituto de Biodiversidad y Medioambiente (BIOMA), Universidad de Navarra, Pamplona 31080, Spain

^{ay} Fundación CEAM, C/Charles R. Darwin 14, Parque Tecnológico, Paterna, Valencia 46980, Spain

^{az} Fisheries and Oceans Canada, Pacific Biological Station, 3190 Hammond Bay Rd, Nanaimo, BC V9T 6N7, Canada

^{ba} Louisiana Universities Marine Consortium, 8124 LA-56, Chauvin, LA 70344, United States

^{bb} Beneath the Waves, PO Box 126, Herndon, VA 20172, USA

^{bc} Wildlife Conservation Society Canada, P.O. Box 606, 202 B Ave, Kaslo, British Columbia V0G 1M0, Canada

^{bd} Department of Psychology, Neuroscience, and Behaviour, McMaster University, 1280 Main St W, Hamilton, ON L8S 4L8, Canada

^{be} Rosenstiel School of Marine & Atmospheric Science, University of Miami, 1320 S Dixie Hwy, Coral Gables, FL 33146, United States

^{bf} Deakin University, 75 Pigdons Road, Waurin Ponds, Geelong, VIC, Australia

^{bg} Department of Biosciences, Swansea University, Swansea SA2 8PP, Wales, UK

^{bh} Division of Social Science, Hong Kong University of Science and Technology, Clear Water Bay, Hong Kong

^{bi} Division of Environment and Sustainability, Hong Kong University of Science and Technology, Clear Water Bay, Hong Kong

^{bj} Virginia Institute of Marine Science, College of William and Mary, Sadler Center, 200 Stadium Dr, Williamsburg, VA 23185, United States

^{bk} Department of Aquatic Resources, Swedish University of Agricultural Sciences, Turistgatan 5, 453 30 Lysekil, Sweden

^{bl} Stockholm Resilience Centre, Stockholm University, SE-106 91 Stockholm, Sweden

- ^{bm} Hakai Institute, Pruth Harbour, Calvert Island, BC V0P 1H0, Canada
- ^{bn} Cape Eleuthera Institute, Cape Eleuthera Island School, PO Box EL-26029, Rock Sound, Eleuthera, The Bahamas
- ^{bo} Institute for Marine and Antarctic Studies, University of Tasmania, TAS 7005, Australia
- ^{bp} Sydney Institute of Marine Science, 19 Chowder Bay Rd, Mosman, NSW 2088, Australia
- ^{bq} Department of Biological Sciences, Macquarie University, Balaclava Rd, Macquarie Park, NSW 2109, Australia
- ^{br} Centre d'Études Biologiques de Chizé, Station d'Écologie de Chizé-La Rochelle Université, CNRS UMR7372, Villiers-en-Bois, France
- ^{bs} Loggerhead Marinelifelife Center, 14200 US-1, Juno Beach, FL 33408, United States
- ^{bt} Faculty of Psychology and Educational Sciences, Swiss Center for Affective Sciences, Chemin des Mines 9, 1202 Geneva, Switzerland
- ^{bu} College of Science and Engineering, Flinders University, Adelaide, SA 5042, Australia
- ^{bv} Arafura Timor Research Facility, Australian Institute of Marine Science, Darwin, NT 0810, Australia
- ^{bw} Department of Biological Sciences, Simon Fraser University, 8888 University Dr, Burnaby, BC V5A 1S6, Canada
- ^{bx} Parks Canada Agency, 5420 Highway 93, Radium Hot Springs, BC V0A 1M0, Canada
- ^{by} Hakai Institute, Victoria, BC V8W 1V8, Canada
- ^{bz} WorldPop, School of Geography and Environmental Science, University of Southampton, Hartley Library B12, University Rd, Highfield, Southampton SO17 1BJ, United Kingdom
- ^{ca} Department of Biology, University of British Columbia, 3333 University Way, Kelowna, BC V1V 1V7, Canada
- ^{cb} University of Maine, 168 College Ave, Orono, ME 04469, United States
- ^{cc} University of New England, Department of Biology, Biddeford, ME 04005, United States
- ^{cd} Center for Wildlife Studies, North Yarmouth, ME 04097, USA
- ^{ce} Ewha Womans University, 52 Ewhayeodae-gil, Daehyeon-dong, Seodaemun-gu, Seoul, South Korea
- ^{cf} Département de Biologie, Centre d'Études Nordiques, Université Laval, 2325 Rue de l'Université, Québec, QC G1V 0A6, Canada
- ^{cg} Département de Biologie, Centre d'Études Nordiques, Université du Québec à Rimouski, 300 Allée des Ursulines, QC G5L 3A1, Canada
- ^{ch} College of Integrative Sciences and Arts, Arizona State University, Mesa, AZ 85212, United States
- ^{ci} School of Life Science, Arizona State University, 1151 S. Forest Ave, Tempe, AZ 85281, Canada
- ^{cj} Department of Earth System Science, Tsinghua University, Beijing 100084, China
- ^{ck} Arthur Rylah Institute for Environmental Research, Department of Environment, Land, Water and Planning, Heidelberg, Victoria, Australia
- ^{cl} Victorian Fisheries Authority, Australia
- ^{cm} Ecosystems and Environment Research Programme, Faculty of Biological and Environmental Sciences, University of Helsinki, Niemenkatu 73, FI-15140 Lahti, Finland
- ^{cn} Grupo de Estudios en Biodiversidad, Escuela de Biología, Universidad Industrial de Santander, Ciudad Universitaria Carrera 27 Calle 9, Bucaramanga, Santander, Colombia
- ^{co} Departamento de Ciencias Naturales y Matemáticas, Pontificia Universidad Javeriana-Cali, Cl. 18 #118-250, Cali, Valle del Cauca, Colombia
- ^{cp} Facultad de Ciencias Básicas, Universidad Autónoma de Occidente, Calle 25, Vía Cali - Puerto Tejada 115-85 Km 2, Jamundí, Cali, Valle del Cauca, Colombia
- ^{cq} Israel Nature and Parks Authority, Am V'Olamo 3, Jerusalem 95463, Israel
- ^{cr} Dipartimento di Scienze e Politiche Ambientali, Università degli Studi di Milano, via Celoria 26, I-20133 Milano, Italy
- ^{cs} Consiglio Nazionale delle Ricerche, Istituto di Ricerca sugli Ecosistemi Terrestri, Via Madonna del Piano 10, 50019 Sesto Fiorentino, Italy
- ^{ct} Key Laboratory of the Zoological Systematics and Evolution, Institute of Zoology, Chinese Academy of Sciences, Beichen West Road 1, 100101 Beijing, China
- ^{cu} Centre for Ecology and Conservation, University of Exeter, Penryn Campus, Penryn TR10 9FE, UK
- ^{cv} Ocean Networks Canada, University of Victoria Queenswood Campus, 2474 Arbutus Road, Victoria, BC V8N 1V8, Canada
- ^{cw} Department of Oceanography, Dalhousie University, 1355 Oxford St., Halifax, Nova Scotia B4H 4R2, Canada
- ^{cx} Charles Darwin Research Station, Charles Darwin Foundation, Av. Charles Darwin, Santa Cruz, Galapagos, Ecuador
- ^{cy} Instituto de Investigaciones Marinas (IIM-CSIC), Eduardo Cabello 6, 36208 Vigo, Spain
- ^{cz} Department of Biology and Environment, University of Haifa at Oranim, 36006 Tivon, Israel
- ^{da} Hamaarag, The Steinhart Museum of Natural History, Tel Aviv University, P.O. Box 39040, Tel Aviv 6139001, Israel
- ^{db} The Mammal Center, Society for the Protection of Nature in Israel, Israel
- ^{dc} School of Environmental Studies, University of Victoria, PO Box 1700 STN CSC, Victoria, BC V8W 2Y2, Canada
- ^{dd} RSPB Centre for Conservation Science, Royal Society for the Protection of Birds, Cambridge, United Kingdom
- ^{de} Bulgarian Society for Protection of Birds, Sofia, Bulgaria
- ^{df} BirdLife International, Africa Partnership Secretariat, Nairobi, Kenya
- ^{dg} Hellenic Ornithological Society, Athens, Greece
- ^{dh} WWF Greece, Athens, Greece
- ^{di} Ethiopia Wildlife and Natural History Society, Addis Ababa, Ethiopia/Dilla University, Natural and Computational Sciences, Department of Biology, P.O. Box, 419, Dilla, Ethiopia
- ^{dj} Sahara Conservation Fund, Niamey, Niger
- ^{dk} Faculty of Natural Science, Department of Zoological Science, Addis Ababa University, Addis Ababa, Ethiopia
- ^{dl} Hawassa University, Shashemene, Ethiopia
- ^{dm} Department of Geography and Environment, London School of Economics and Political Science, UK
- ^{dn} Dept of Biological Sciences, California State University Long Beach, Long Beach, CA, USA
- ^{do} Institute of Marine Sciences (CSIC), Pg. Marítim de la Barceloneta 37-49, 08003 Barcelona, Catalunya, Spain
- ^{dp} Department of Biology, University of Victoria, Victoria, BC, Canada
- ^{dq} Institute of Marine Science, University of Auckland, New Zealand
- ^{dr} School of Energy, Geoscience, Infrastructure and Society, Heriot-Watt University, Edinburgh, Scotland, United Kingdom
- ^{ds} Marine and Environmental Science Faculty, University of Cádiz, Cádiz, Spain
- ^{dt} School of Natural Resources and the Environment, University of Arizona, Tucson, AZ, USA
- ^{du} Montreal Space for Life, Insectarium, Montreal, QC, Canada
- ^{dv} Vermont Center for Ecotudies, Norwich, VT, USA
- ^{dw} Resource and Environmental Management, Simon Fraser University, Burnaby, BC, Canada
- ^{dx} School of Electrical Engineering and Computer Science, Oregon State University, Corvallis, OR, USA
- ^{dy} Centro de Investigação em Biodiversidade e Recursos Genéticos/Research Network in Biodiversity and Evolutionary Biology, Campus Agrário de Vairão, Universidade do Porto, 4485-668 Vairão, Portugal
- ^{dz} Marine Biological Association of the United Kingdom, The Laboratory, Citadel Hill, Plymouth PL1 2PB, UK
- ^{ea} Pacuare Reserve, Ecology Project International, Limon, Costa Rica
- ^{eb} Hawai'i Institute of Marine Biology, University of Hawai'i at Mānoa, Kāne'ohe, HI 96744, USA
- ^{ec} School of Biological Sciences, University of Utah, 257 S 1400 E, Salt Lake City, UT 84112-0840, USA
- ^{ed} Department of Veterinary Biology, Veterinary Faculty, University of Zagreb, Zagreb, Croatia
- ^{ee} NOAA-National Marine Fisheries Service, 8901 La Jolla Shores Dr., La Jolla, CA 92037, USA
- ^{ef} Scripps Institution of Oceanography, 8622 Kennel Way, La Jolla, CA 92037, USA
- ^{eg} Red Sea Research Centre (RSRC), King Abdullah University of Science and Technology, Thuwal 23955-6900, Saudi Arabia
- ^{eh} Australian Institute of Marine Science, Indian Ocean Marine Research Centre (M096), University of Western Australia, 35 Stirling Highway, Crawley, Western Australia 6009, Australia
- ^{ei} Rondevlei Scientific Services, South African National Parks, Garden Route 6570, South Africa

- ^{ej} National Parks Board, 1 Cluny Rd, Singapore Botanic Gardens, Singapore 259569, Singapore
- ^{ek} Postgraduate Program in Ecology, Federal University of Rio de Janeiro, Av. Pedro Calmon, 550 Cidade Universitária da Universidade Federal do Rio de Janeiro, RJ 21941-901, Brazil
- ^{el} College of Marine Science, University of South Florida, St. Petersburg, FL 33701, USA
- ^{em} The Albert Katz International School for Desert Studies, Jacob Blaustein Institutes for Desert Research, Ben-Gurion University of the Negev, Midreshet Ben-Gurion, Israel
- ^{en} Department of Research and Development, Cocosphere Environmental Analysis, C/Cruz 39, 29120 Alhaurín el Grande, Málaga, Spain
- ^{eo} Department of Biogeochemical Integration, Max Planck Institute for Biogeochemistry, Hans-Knöll-Straße 10, 07745 Jena, Germany
- ^{ep} Natural Resources Institute, University of Manitoba, 317 Sinnott Bldg., 70 Dysart Rd., Winnipeg, MB R3T 2M6, Canada
- ^{eq} School of Ocean Sciences, Bangor University, Menai Bridge, Anglesey LL59 5AB, UK
- ^{er} Department of Zoology, University of Oxford, Zoology Research and Administration Building, 11a Mansfield Road, Oxford OX1 3SZ, United Kingdom
- ^{es} Computational Biosciences Research Center (CBRC), Computer, Electrical and Mathematical Sciences and Engineering (CEMSE) Division, King Abdullah University of Science and Technology, 23955 Thuwal, Saudi Arabia
- ^{et} School of Zoology, Tel Aviv University, Tel Aviv 6997802, Israel
- ^{eu} PSL Research University CRIOBE USR3278 EPHE-CNRS-UPVD BP1013, 98729 Papeetoi, French Polynesia
- ^{ev} Department of Civil, Environmental and Mechanical Engineering, University of Trento, via Calepina, 14, 38122 Trento, Italy
- ^{ew} Stelvio National Park, 23032 Bormio, SO, Italy
- ^{ex} Inuit Elder From the Community of Mittimatalik, Nunavut, Canada
- ^{ey} Civil and Environmental Department, Universidad de La Costa, Cl. 58 #55 - 66, Barranquilla, Atlántico, Colombia
- ^{ez} School of Law, Universidad Sergio Arboleda, Santa Marta, Colombia
- ^{fa} Multidisciplinary Studies Center of Coastal Zone, Universidad de Oriente, Avenida Patricio Lumumba S/N, Santiago de Cuba 90500, Cuba
- ^{fb} Institute of Biology of the Southern Seas, Russian Academician Science, Sevastopol 299011, Russia
- ^{fc} British Antarctic Survey, High Cross, Madingley Road, Cambridge, Cambridgeshire CB30ET, UK
- ^{fd} Government of Tristan da Cunha, Jamestown STHL 1ZZ, Saint Helena, Ascension and Tristan da Cunha
- ^{fe} Dipartimento di Scienze della Terra, dell'Ambiente e della Vita, Università degli Studi di Genova, Corso Europa 26, 16132 Genova, Italy
- ^{ff} Ocean Wise Conservation Association, 845 Avison Way, Vancouver, BC V6B 3X8, Canada
- ^{fg} WWF-Canada, 60 St Jacques St, Montreal, Quebec H2Y 1L5, Canada
- ^{fh} CIRAD, UMR CBGP, INRAE, IRD, Montpellier SupAgro, Univ. Montpellier, F-34398 Montpellier, France
- ^{fi} Okeanos Research Centre of the University of the Azores, Rua Prof. Dr. Frederico Machado, 9901-862 Horta, Azores, Portugal
- ^{fj} Centro de Observación Marino para Estudios de Riesgos del Ambiente Costero (COSTAR), Facultad de Ciencias del Mar y de Recursos Naturales, Universidad de Valparaíso, Viña del Mar, Chile
- ^{fk} School of Biological Sciences, Georgia Institute of Technology, Atlanta, GA 30332, USA
- ^{fl} MARE - Marine and Environmental Sciences Centre, Agência Regional para o Desenvolvimento da Investigação Tecnologia e Inovação, Funchal, Portugal
- ^{fm} Department of Biodiversity and Molecular Ecology, Research and Innovation Centre, Fondazione Edmund Mach, via Mach 1, 38010 San Michele all'Adige, Italy
- ^{fn} Red Sea Research Center, King Abdullah University of Science and Technology, 23955 Thuwal, Saudi Arabia
- ^{fo} Department of Migration, Max Planck Institute of Animal Behavior, Am Obstberg 1, 78315 Radolfzell, Germany
- ^{fp} Computer, Electrical and Mathematical Sciences and Engineering Division, King Abdullah University of Science and Technology, Thuwal 23955, Saudi Arabia
- ^{fq} Centre for Biological Diversity, School of Biology, University of St Andrews, Sir Harold Mitchell Building, St Andrews KY16 9TH, UK
- ^{fr} The Steinhardt Museum of Natural History, Tel Aviv University, P.O. Box 39040, Tel Aviv 6139001, Israel

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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 PM₁₀, NO₂, CO₂, SO₂, 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; Wai-thaka 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://opensky.net/work.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

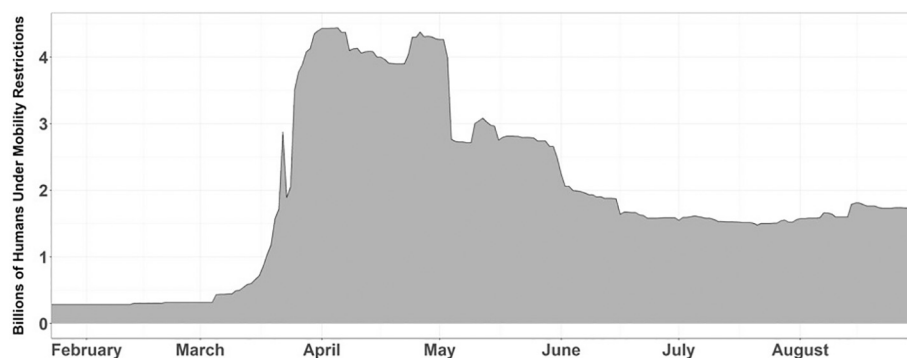


Fig. 1. Total humans under COVID-19 mobility restrictions. Time series of the number of humans under lockdown across the global population under the 2020 COVID-19 mitigation policies. This assumes that in countries with targeted restrictions, a fraction of 20% of the population was under lockdown. Assuming 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.

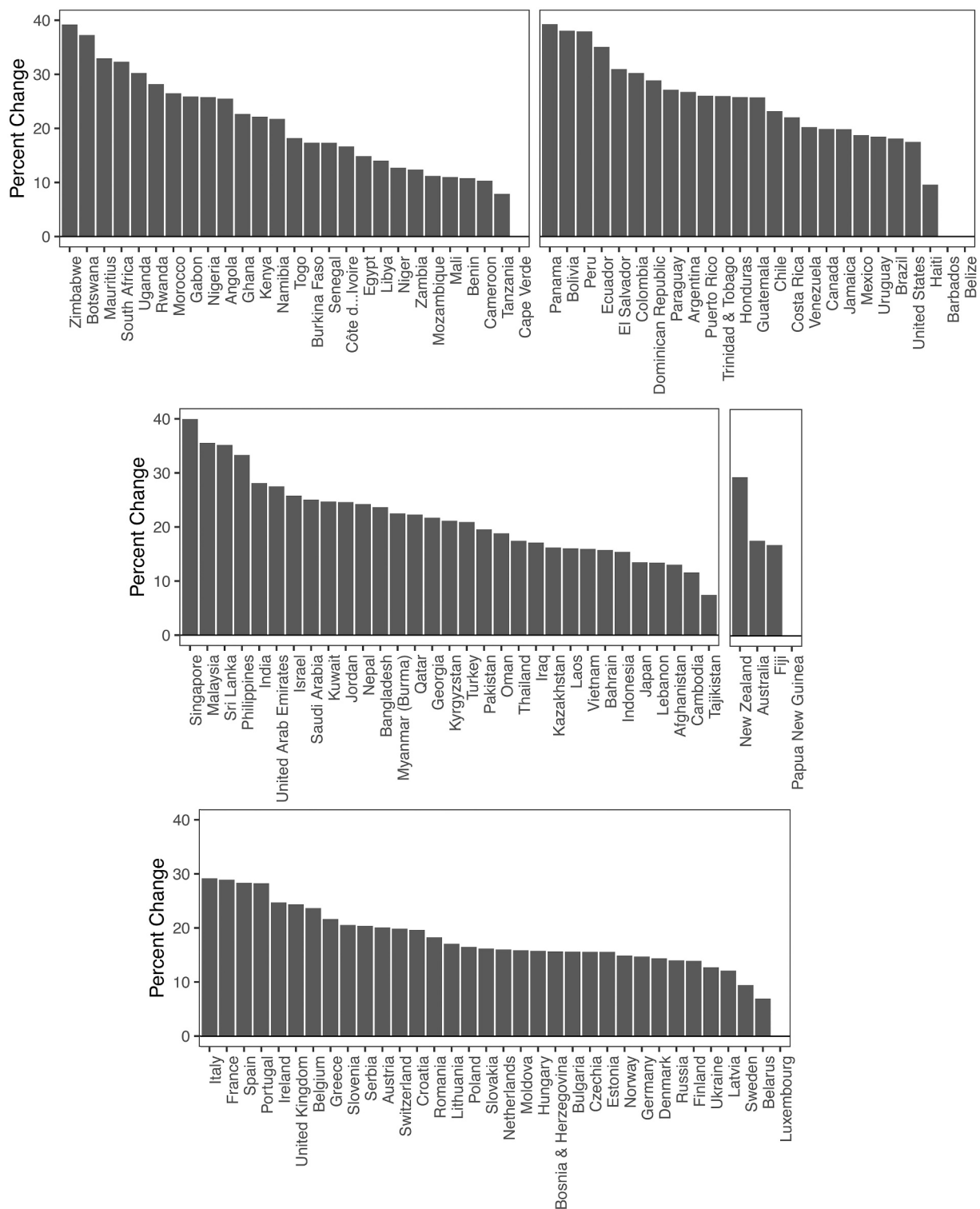


Fig. 2. Change in mobility. Percent change in time spent within home residences (residential) following implementation of confinement measures in each country.

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

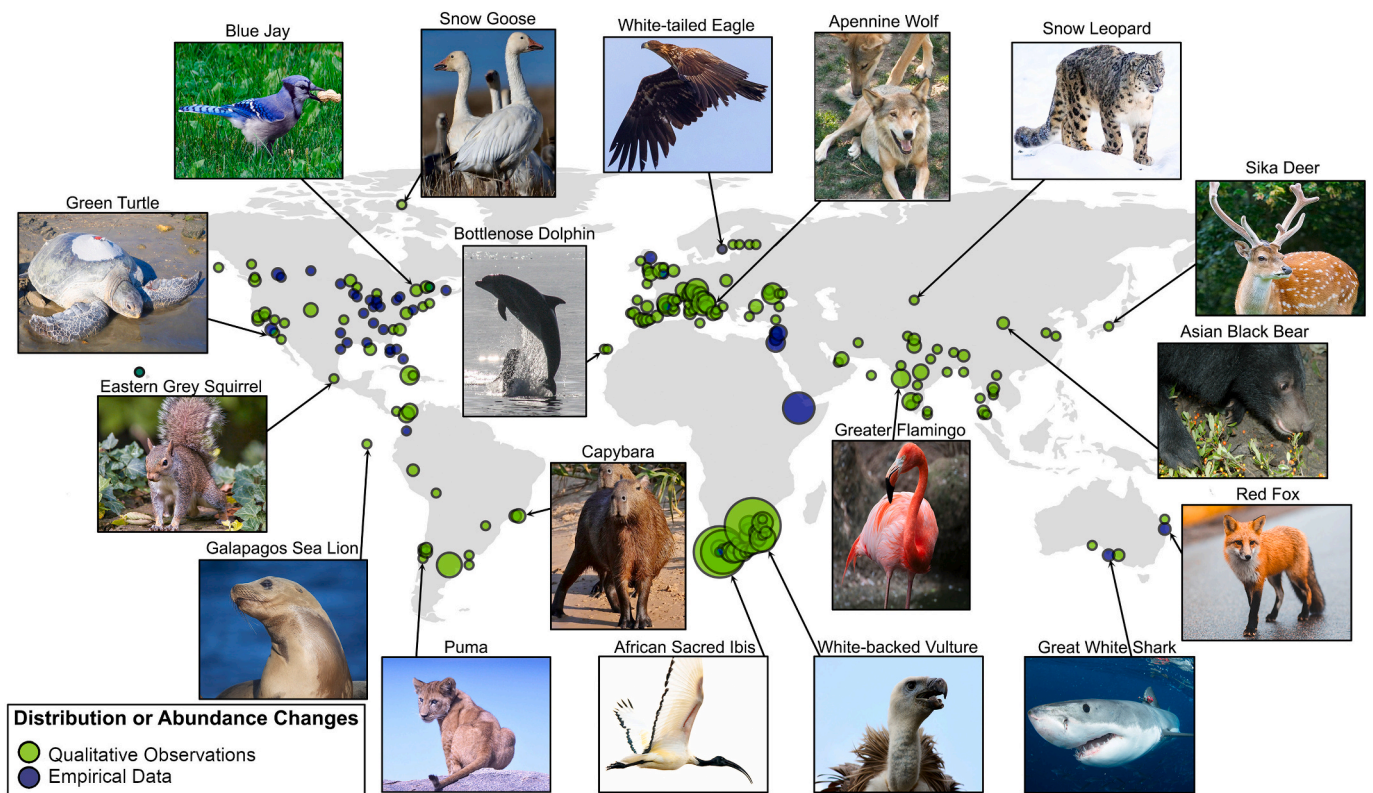


Fig. 3. Reports of 275 species that occupied an unusual area (distribution change), or shifted in number (abundance change) were attributed to a reduction in human activities. Changes in species distributions were observed around the world as qualitative observations (Appendix 3, Table A3, albeit with 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,

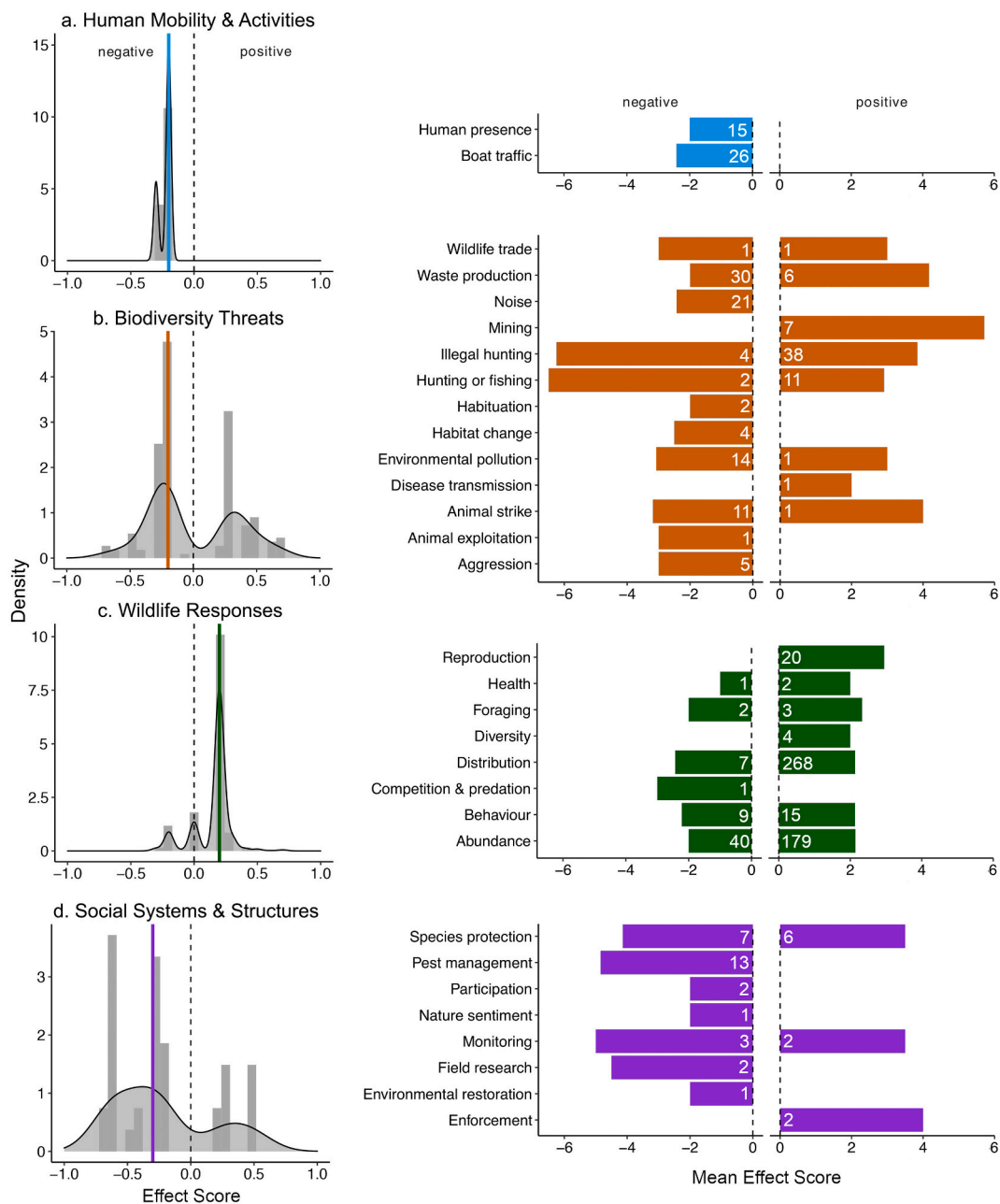


Fig. 4. Qualitative negative and positive effects observed which were relative to the response observed (Appendix 4, Table A4). Negative effects indicate a dampening in the responses which were grouped into categories representing “Human Mobility & Activities”, Biodiversity Threats”, “Wildlife Responses” 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

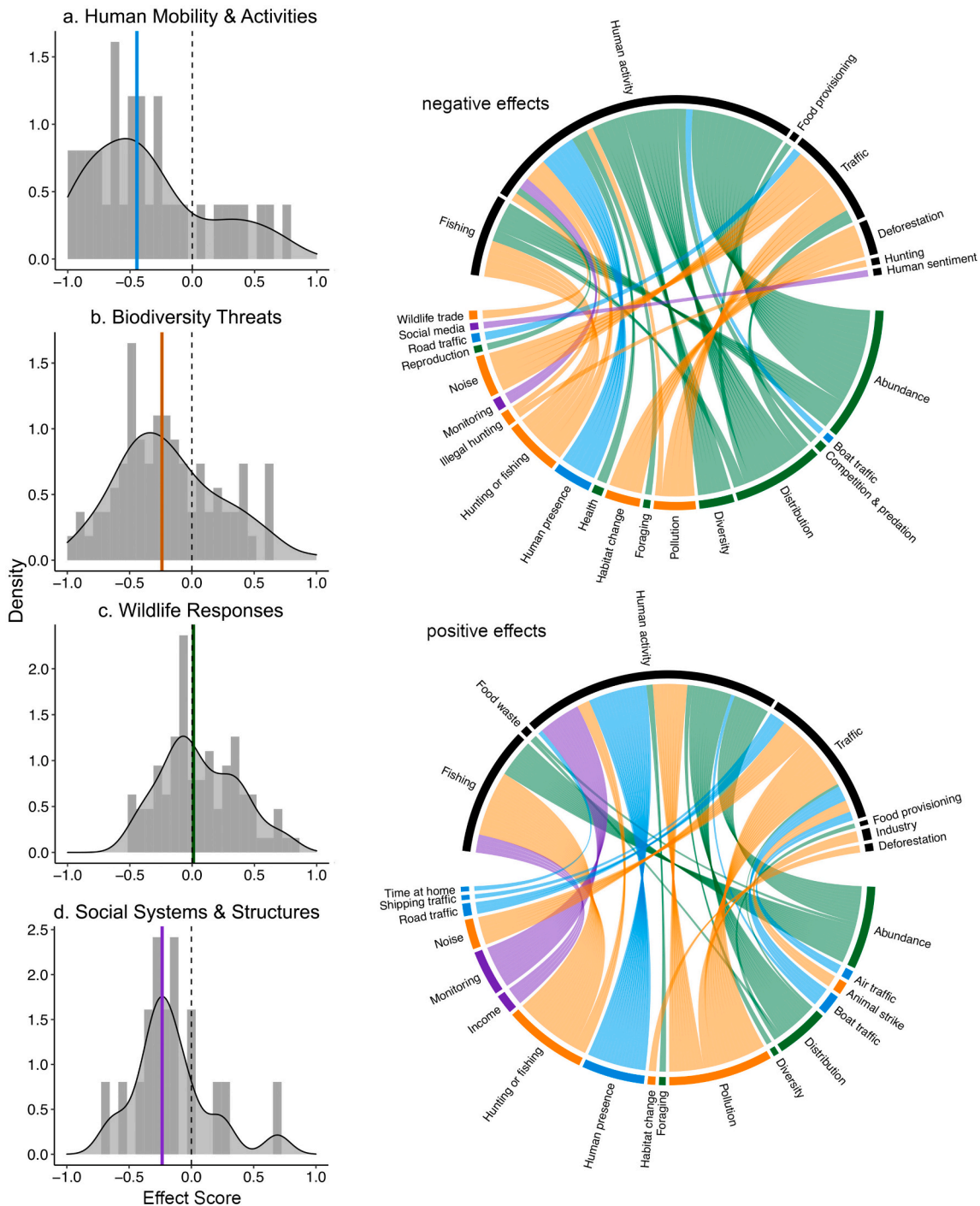


Fig. 5. Responses during the lockdown based on our empirical data (Appendix 5, Table A5) where positive and negative effects represent the observed direction of change for the different response categories. 71 studies that attributed the observed effect to the lockdown with high confidence are included (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 and structures (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 benefitted 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.

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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>.

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Appendices. Supplementary data

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