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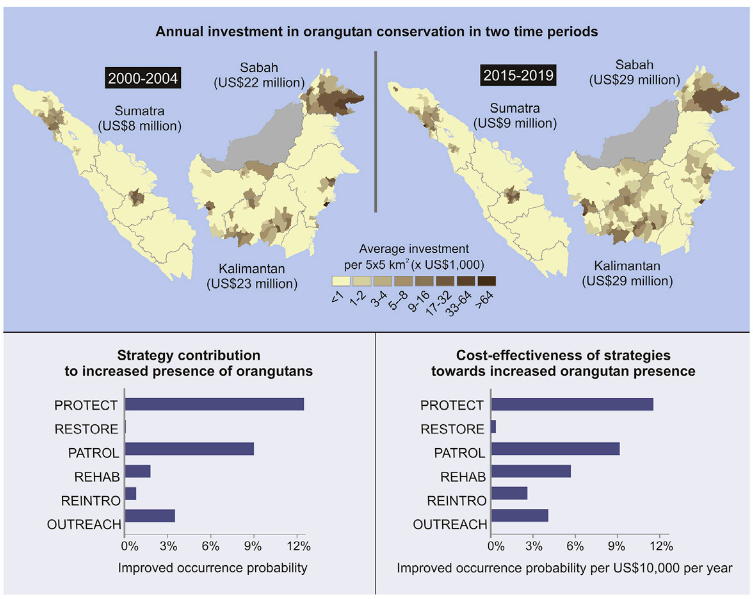
Effectiveness of 20 years of conservation investments in protecting orangutans

Graphical abstract



Highlights

- Efficient investment requires knowing what to best spend where, when, and on what
- Our analyses of 20 years of orangutan conservation funding inform optimal spending
- Conservation strategies differ in cost effectiveness of the number of orangutans saved
- Cost effectiveness varies geographically due to threats and costs of land and labor

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In brief

Orangutan conservation continues to face challenges in halting the species' decline. Santika et al. evaluate the cost effectiveness of 20 years of orangutan conservation investments in a spatiotemporal context. Differences in the number of orangutans saved per dollar spent on different conservation strategies can help inform more efficient resource allocation.

Santika et al., 2022, Current Biology *32*, 1–10
April 25, 2022
https://doi.org/10.1016/j.cub.2022.02.051

Please cite this article in press as: Santika et al., Effectiveness of 20 years of conservation investments in protecting orangutans, Current Biology (2022), https://doi.org/10.1016/j.cub.2022.02.051

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Effectiveness of 20 years of conservation investments in protecting orangutans

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SUMMARY

Conservation strategies are rarely systematically evaluated, which reduces transparency, hinders the cost-effective deployment of resources, and hides what works best in different contexts. Using data on the iconic and critically endangered orangutan (*Pongo* spp.), we developed a novel spatiotemporal framework for evaluating conservation investments. We show that around USD 1 billion was invested between 2000 and 2019 into orangutan conservation by governments, nongovernmental organizations, companies, and communities. Broken down by allocation to different conservation strategies, we find that habitat protection, patrolling, and public outreach had the greatest return on investment for maintaining orangutan populations. Given the variability in threats, land-use opportunity costs, and baseline remunerations in different regions, there were differential benefits per dollar invested across conservation activities and regions. We show that although challenging from a data and analysis perspective, it is possible to fully understand the relationships between conservation investments and outcomes and the external factors that influence these outcomes. Such analyses can provide improved guidance toward a more effective biodiversity conservation. Insights into the spatiotemporal interplays between the costs and benefits driving effectiveness can inform decisions about the most suitable orangutan conservation strategies for halting population declines. Although our study focuses on the three extant orangutan species of Sumatra and Borneo, our findings have broad application for evidence-based conservation science and practice worldwide.

INTRODUCTION

The three orangutan species—*Pongo pygmaeus* in Indonesian and Malaysian Borneo and *P. abelii* and *P. tapanuliensis* in Sumatra, Indonesia—are in rapid decline,[1–4] and there is a global concern about the risk of their extinction in the wild.[5–7] The main drivers of orangutan decline are the loss and degradation of forest habitat, mostly for agricultural development,[1–4] and

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https://doi.org/10.1016/j.cub.2022.02.051

killing.[8,9] Over the past 50 years, a diversity of activities has been implemented to reduce and mitigate threats to orangutans.[10,11] Which activities lead to the best outcome, however, is subject to extensive debate.[12,13] Furthermore, the species are distributed across four regions (Sumatra and Kalimantan [Indonesia] and the Malaysian states of Sabah and Sarawak) (Figure 1) with differential exposure to threats, heterogeneous biophysical and socioeconomic characteristics, and diverse

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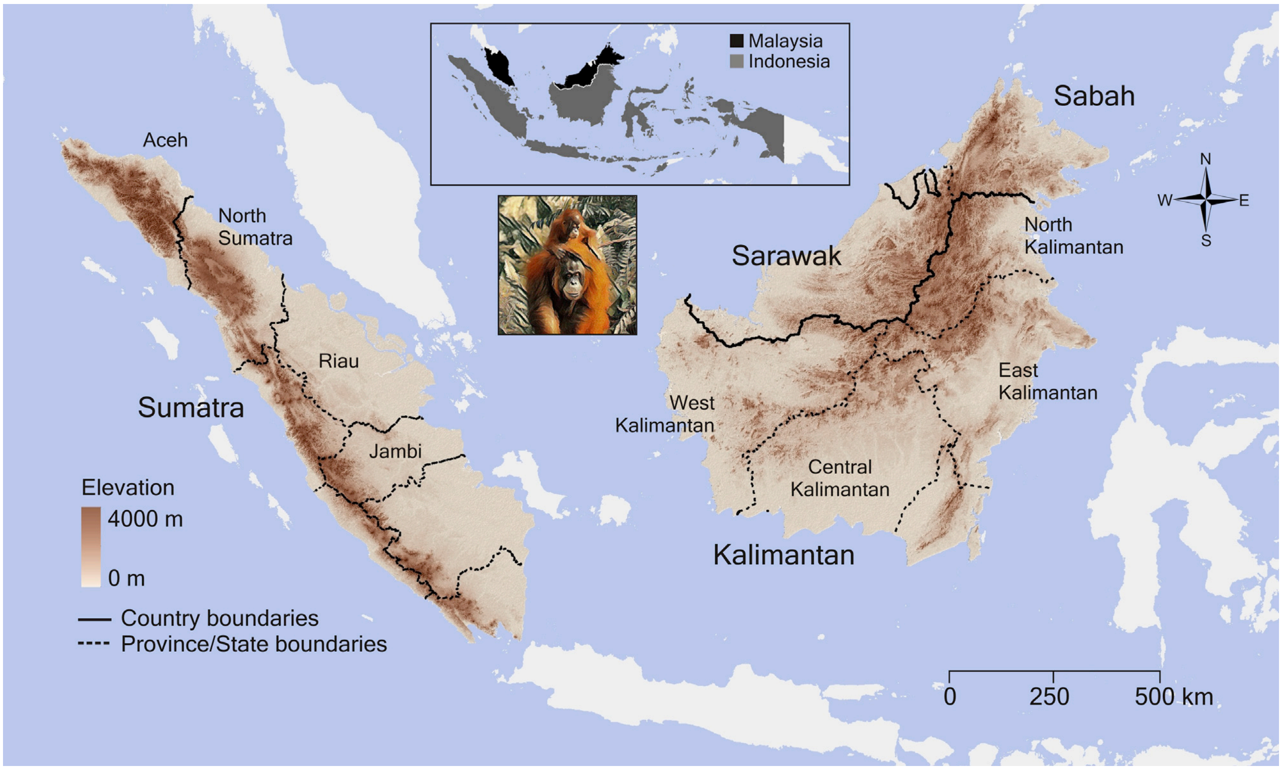

Figure 1. Islands covering the orangutan range
Sumatra, Indonesia (470,000 km^2), and Borneo (including Kalimantan, Indonesia, and Sabah and Sarawak, Malaysia) (740,000 km^2). Scale bar in bottom right indicates geographic scale. See also Figure S4.

government policies. As a result, the extent to which the activities and the concomitant funding are benefiting species persistence is unknown as are the key externalities that shape these benefits.[13]

We developed a comprehensive framework to assess the impact of conservation investments in wildlife conservation across spatial and temporal scales. We applied this framework to investments in orangutan conservation activities across Kalimantan, Sabah, and Sumatra between 2000 and 2019. We collected data on financial investments from private and public organizations involved in orangutan conservation in these regions. The benefit of a given conservation activity was estimated as the improvement in the predicted orangutan occurrence compared with the counterfactual of no activity. By comparing the spatiotemporally explicit investments with the estimated benefit, we evaluated the efficiency of two decades of investments in six activities aiming to reduce orangutan population declines: (1) habitat protection and management, (2) habitat restoration, (3) patrolling and law enforcement, (4) rescue and rehabilitation, (5) translocation and reintroduction, and (6) public outreach and capacity building. The orangutan conservation theory of change (ToC) pathways representing the chain of outcomes resulting from the conservation activities are shown in Figures S1 and S2. The estimated investment in research on orangutans and their habitats (excepting those exclusive to orangutan rehabilitation and translocation) was also quantified (Figure S3). Through application of our framework to orangutan conservation, we were able to answer the following: (1) Which conservation activities have been conducted, at what costs, and how were they distributed spatially? (2) What was the net benefit of each conservation activity? (3) Within the contemporary range of wild orangutan, which activities yielded the greatest return on investment, and how did this vary between regions?

RESULTS

Investment in conservation activities for orangutans

In the period between 2000 and 2019, the total nominal investment on orangutan-related conservation activities across Kalimantan, Sumatra, and Sabah was US$870 million. In real value, i.e., the nominal value adjusted for inflation (STAR Methods), this equates to US$1.16 billion. The annual average of the nominal investment in the period 2015–2019 was US$67 million, which was a nearly 3-fold increase compared with the annual average of US$26 million from 2000 to 2005 (Figure 2A). The real value of investment had increased 1.3 times (Figure 2A) and varied by region. Between 2000 and 2019, an average annual operating expenditure valued at $24–26 million had been allocated in both Kalimantan and Sabah, whereas in Sumatra, there was an average annual expenditure of $8 million (Figures 2B and 3). Considering regional differences in the available habitat, Sabah had the greatest per unit habitat investment overall, with an average annual operational expenditure of $676 per km^2 of orangutan habitat (Figure 2C). Comparatively, Sumatra invested $272 per km^2 annually,

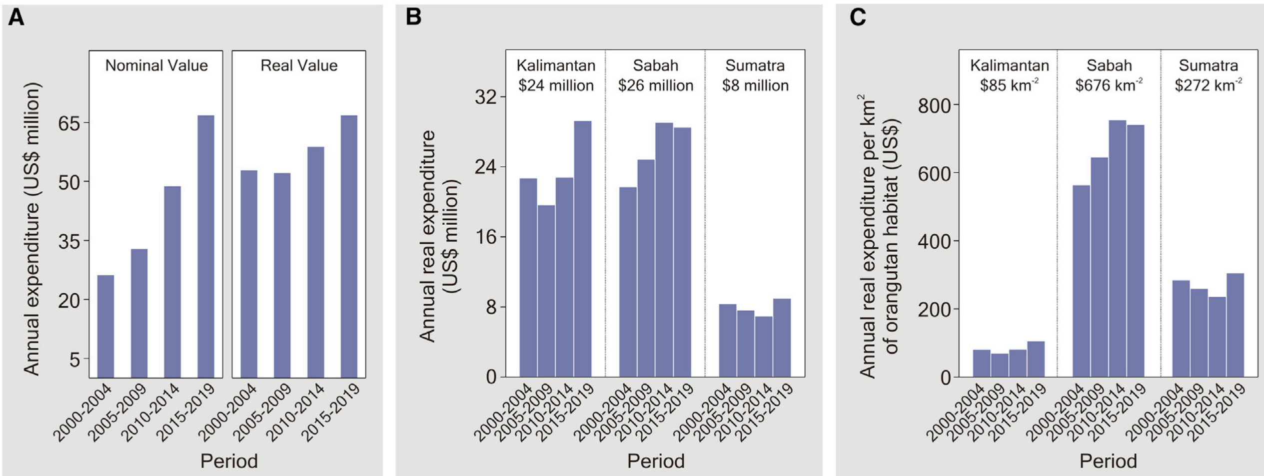

Figure 2. Changes in nominal and real investments into orangutan conservation over time and by region

Figure360▷ For a Figure360 author presentation of Figure 2, see the figure legend at https://doi.org/10.1016/j.cub.2022.02.051.

(A) Total investment (nominal and real value, in US$) spent annually on orangutan-related conservation activities across Kalimantan, Sabah, and Sumatra.

(B and C) The annual total real expenditure of conservation activities (B) and per km^2 of orangutan habitat (C), broken down by region. Conservation activities assessed include the six core activities in which the impacts on orangutan survival may be captured over a short time period (5 years): habitat protection, habitat restoration, patrolling and law enforcement, rescue and rehabilitation, translocation and reintroduction, and public outreach and capacity building, and research-related activities considered influencing conservation and land use management decision in the long term.

whereas Kalimantan only invested $85 per km^2 annually on average.

The allocation of investments to different conservation activities differed between regions (Figure 4A). In Kalimantan, the largest proportion of the total annual investment was assigned to habitat protection (31%), followed by rescue and rehabilitation (18%) and public outreach (16%). In Sabah, patrolling and law enforcement made up the largest proportion of the total annual expenditure (38%), followed by habitat protection (20%) and outreach programs (15%). In Sumatra, a substantial proportion of the total annual investment was allocated to habitat protection (47%), followed by patrolling (20%) and public outreach (14%).

In Kalimantan, orangutan translocation and reintroduction programs were the most expensive activity ($427 per km^2), whereas habitat protection was $252 per km^2 (Figure 4B). In Sabah, patrolling was the most expensive activity ($1,303 per km^2), double that of habitat protection. In Sumatra, habitat protection was the most expensive approach ($734 per km^2), double that of patrolling activities. Sabah had the greatest investment in research ($407 per km^2 per annum) compared with less than $150 per km^2 per annum in Kalimantan and Sumatra.

Benefits of conservation activities for orangutans

Between 2000–2004 and 2015–2019, the mean probability of orangutan occurrence across the wild orangutan contemporary range in Kalimantan, Sumatra, and Sabah declined by approximately 20%. Based on our analysis of the relationship between the species' probability of occurrence and density (Figure S4), this translates to an estimated decline from 17.4 to 13.8 (95% confidence interval [CI]: from 15.1–19.7 to 11.4–16.2) individuals per 5 × 5 km^2 grid cell on average between 2000 and 2019 for Kalimantan, from 13.9 to 11.4 (95% CI: from 10.6–17.2 to 7.6–15.2) individuals per grid cell for Sabah, and from 10.3 to 8.7 (95% CI: from 7.9–12.7 to 6.3–11.1) individuals per grid cell for Sumatra (Figure S4).

The benefit of a conservation activity was estimated by comparing the orangutan occurrence probability (given existing conservation actions) with the counterfactual in the absence of conservation activity. Across the three regions, habitat protection and patrolling were estimated to generate the greatest benefits in maintaining orangutan occurrence (Figure 5A). In Kalimantan, habitat protection and patrolling were associated with an average 13% and 3.6% improvements, respectively, in the species' occurrence probability per 5 × 5 km^2 grid cell every 5 years between 2000 and 2019 compared with the counterfactual of no investment in these activities (Figure 5B). In Sabah, habitat protection and patrolling were estimated to improve orangutan occurrence by 8.7% and 12%, respectively, whereas in Sumatra, they contributed to 16% and 12% improvements in occurrence, respectively (Figure 5B). Besides these two conservation activities, public outreach activities generated a large benefit for the orangutan populations in Sabah, providing 7.4% improvement in the occurrence probability compared with the counterfactual of no outreach programs (Figure 5B).

Return on investment of orangutan conservation activities

The return on investment for a given orangutan conservation activity was estimated as the improvement in the species' occurrence probability compared with the counterfactual in the absence of the activity divided by the investment cost for that activity. Across Kalimantan, Sabah, and Sumatra and within the orangutan's contemporary range, habitat protection was estimated to generate the highest return on investment overall, providing an average 12% improvement in orangutan probability of occurrence per 5 × 5 km^2 grid cell per annual investment of US$10,000 compared with the counterfactual (Figure 6A).

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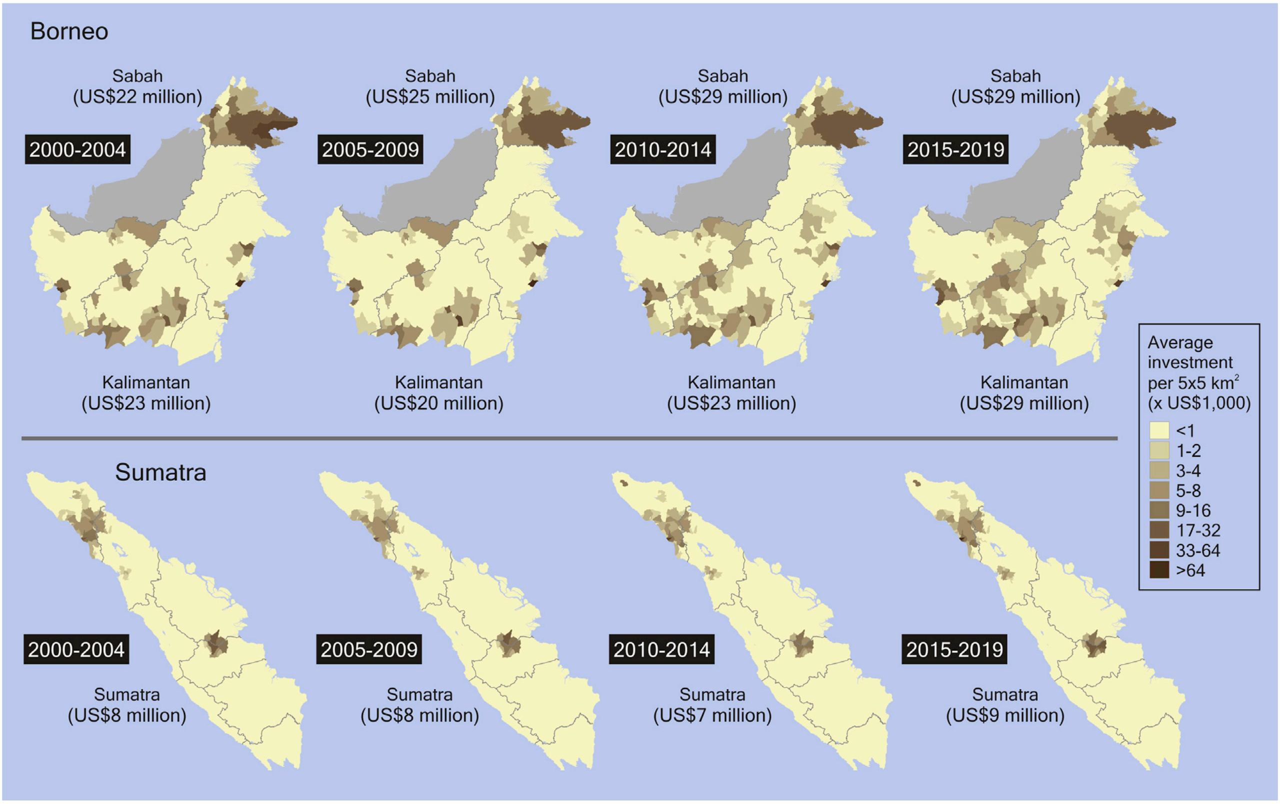

Figure 3. The change in the distribution of investment to orangutan conservation in Borneo and Sumatra aggregated to the subdistrict level
Values inside the parenthesis represent the annual total real expenditure for a given period and region. In the first period (2000–2004), investments in Borneo were focused in Sabah and spread across the orangutan range in west, central, and east Kalimantan. Investments in later periods gradually became clustered more around orangutan sanctuaries near the Gunung Palung, Tanjung Puting, Sebangau, and Kutai National Parks and the interior part of Borneo. In Sumatra, the main increase in investment was in the Jantho Nature Reserve at the northern part of the island and Batang Toru. See also Figure S5.

Patrolling activities had moderate benefit per dollar, providing a 9.2% improvement in the orangutan occurrence probability.

There were variations in the return on investment of conservation activities across the different regions (Figure 6B). In Kalimantan, habitat protection had the highest benefit per dollar (providing an average improvement of 21% in the orangutans' probability of occurrence per 5 × 5 km^2 grid cell per US$10,000 annual investment compared with the counterfactual), followed by patrolling (9.4%). This translates to an estimated density benefit of 7.4 orangutans per 25 km^2 for every annual expenditure of US$10,000 for habitat protection and a density benefit of 3.2 orangutans for patrolling activities. In Sabah, outreach programs had the highest benefit per dollar invested (average improvement of 6.1% in occurrence probability per 5 × 5 km^2 grid cell per US$10,000 annual investment compared with the counterfactual), followed by habitat protection (5.3%). This translates to a density benefit of 2.2 orangutans per 25 km^2 for every annual expenditure of US$10,000 for each activity of outreach and habitat protection. In Sumatra, patrolling had the highest benefit per dollar (average improvement of 16% in occurrence probability per 5 × 5 km^2 grid cell per US$10,000 annual investment relative to the counterfactual). This translates to a density benefit of 2.3 orangutans per 25 km^2 for every annual expenditure of US$10,000.

DISCUSSION

Implications for orangutan conservation policies in different regions

Kalimantan

In Kalimantan, habitat protection produced the best outcome in reducing the decline in the orangutan probability of occurrence (Figure 5B). Large-scale forest loss and the expansion of industrial agriculture, especially in unprotected lands (in non-state-forest zones and forest areas designated for land clearing and conversion to agroindustries) occurred at rapid rates, especially between 2005 and 2015.[14] These lowland areas typically co-occur with orangutan populations, and without forest protection, extensive areas of orangutan habitats and subsequently large populations of orangutans would have been lost. The average investment per km^2 for habitat protection in Kalimantan was generally lower than that in Sumatra and Sabah ($252 per km^2 versus $734 and $664 per km^2 for Sumatra and Sabah, respectively) (Figure 4B), reflecting Kalimantan's earlier stage of development compared with the other two regions.[15] Consequently, habitat protection by government, companies, or rural communities was considered to provide an excellent return on investment in reducing the decline in orangutan occurrence (Figure 6B).

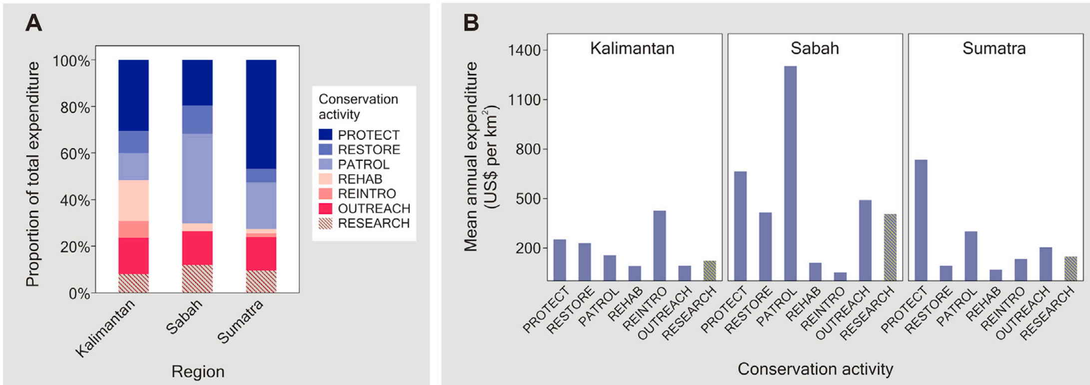

Figure 4. Expenditure allocation to different strategies

Proportion of total expenditure allocated to different conservation activities (A) and mean annual real expenditure for different activities (B) (US$ per km^2) broken down by region. The costs of conservation activities assessed include the six core activities considered affecting the orangutan survival in the short term (5 years): habitat acquisition and protection (PROTECT), habitat restoration (RESTORE), patrolling and law enforcement (PATROL), rescue and rehabilitation (REHAB), translocation and reintroduction (REINTRO), public outreach and capacity building (OUTREACH), and research-related activities considered influencing orangutan persistence in the long term (RESEARCH). See also Figure S5.

Annual spending on translocation and reintroduction in Kalimantan had increased 4-fold since 2000 (from $0.7 million in 2000 to $2.8 million in 2019) (Figure S5), and this reflects the growing application of this conservation tool in response to increasing land pressure. Rapid large-scale deforestation over the past 20 years has led to escalated negative interactions between humans and wild orangutans.[3,4,9] Rescue and translocation of orangutans to conservation areas or protected forests have provided readily implementable actions to remove animals from immediate danger arising from such negative interactions. Removing orangutans and translocating them to large forest blocks deemed more suitable for their survival may seem straightforward and is often presented as an efficient conservation tool, particularly when alternative conservation activities may require planning and extensive negotiation with multisectoral and multilevel stakeholders.[16] However, the relative success of this conservation approach is still not known and might be relatively low, and there is a potential negative impact of these exercises on the viability of metapopulations.[16] Furthermore, translocation and reintroduction can be costly and are associated with high mortality rates.[17] In Kalimantan, translocations were the most expensive conservation activities in terms of operational cost per km^2, and the cost greatly exceeds those in other regions ($427 per km^2 versus $41 and $121 per km^2 for Sabah and Sumatra) (Figure 4B).

The number of orangutans residing outside of protected areas is substantial in Kalimantan.[3,4] Hence, continuing land clearing in this region is anticipated to lead to frequent negative interactions between orangutans and people, and potentially higher prevalence of orangutan removal. An ongoing and increasing focus on translocation and reintroduction programs in Kalimantan could potentially undermine the allocation of funding to other activities with substantially higher and lasting benefits such as habitat protection, patrolling, and outreach programs. There is a need to seek solutions that would enable orangutans and people to coexist, such as better land use planning through creation of buffer zones separating orangutan habitats and rural settlements and improved partnership between conservation actors and rural communities in building relationships of reciprocity, acknowledgment, and care.[18]

The expenditure cost per square kilometer for habitat protection in Kalimantan was generally lower than that in other regions (Figure 4B), suggesting that it is relatively inexpensive to effectively reduce orangutan decline rates through this action. Habitat protection is therefore a worthy investment to pursue to allow orangutans to remain in their native habitats in this region. Further, given that the current conservation expenditure per square kilometer of orangutan habitat in Kalimantan is substantially lower than that in other regions (Figure 2C), increasing the amount of investment for habitat protection here could potentially reduce the orangutan decline rates significantly.

The costs associated with patrolling activities in Kalimantan were $155 per km^2 and significantly lower than that in other regions ($1,303 and $302 per km^2 for Sabah and Sumatra, respectively), whereas outreach programs were $93 per km^2 and also lower than that in other regions ($491 and $204 per km^2 for Sabah and Sumatra) (Figure 4B). This is likely because human population density, remuneration rates, and market influence in Kalimantan are generally lower compared with other regions.[15] Larger investments can therefore potentially be allocated to these activities to monitor, prevent negative human-wildlife interactions, and assist rural communities living within close proximity to forests inhabited by orangutans.[13] Local communities are also likely to benefit from maintaining forest cover, as forests can support and sustain the flow of ecosystem services and provide benefits to broader community well-being (e.g., by preventing soil erosion and floods and regulating air quality).[19–21]

Sabah

In Sabah, patrolling produced the best outcome in reducing the decline in orangutan occurrence probability, followed by habitat protection (Figure 5B). During the study period, the Sabah government increased the size of protected areas from 12% to nearly 30% of the state land area,[22,23] and by 2020, more than 70% of orangutans in Sabah were found inside protected areas.[16,22] This is quite different from the situation in Indonesia, where most terrestrial protected areas were established before 2005 (currently covering 23% of the total land area for Kalimantan and Sumatra) and the expansion of forest protection since 2005 was mainly

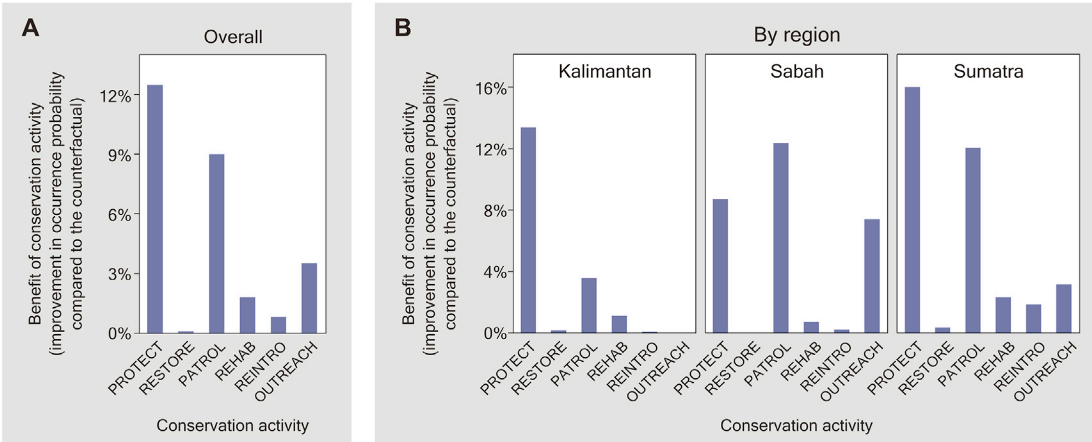

Figure 5. The benefit of six orangutan conservation activities within the wild orangutan contemporary range

Estimated by comparing the orangutan probability of occurrence (given existing conservation actions) with the counterfactual in the absence of conservation activity, (A) averaged across the three regions and (B) individually by region. Conservation activities evaluated include the six core activities: habitat protection (PROTECT), habitat restoration (RESTORE), patrolling and law enforcement (PATROL), rescue and rehabilitation (REHAB), translocation and reintroduction (REINTRO), and public outreach and capacity building (OUTREACH). Research-related activities (RESEARCH) was excluded from the benefit analysis as it is considered to primarily influence conservation actions and land use management decisions in the long term. See also Figure S4.

through the establishment of community-based land tenure and acquisition of private land by conservation non-government organizations (NGOs). Consequently, a high level of investment specifically from the Sabah government has been allocated to resource-intensive patrolling activities for these protected areas, but lower investment had been allocated to habitat protection since all these new areas were gazetted by the government without incurring any high significant direct cost or land purchase for their creation. Significantly higher baseline remuneration rates in Malaysia compared with Indonesia[24,25] have also likely contributed to the high cost associated with patrolling activities.

Public outreach programs, community engagement, and capacity building also provided benefits to protecting orangutan populations in Sabah (Figure 5B), and these programs were mainly carried out by various state agencies and their NGO partners. Despite higher operational cost per square kilometer for public outreach in Sabah than in Kalimantan and Sumatra (\$491 per km^2 versus \$93 and \$204 per km^2 for Kalimantan and Sumatra) (Figure 4B), the activity provided the best return on investment in terms of orangutan occurrence benefits (Figure 6B). Unlike in Kalimantan and Sumatra, there has been a limited change in land cover in Sabah over the past 20 years as deforestation had mostly occurred before 2000.[14] Consequently, only a low number of orangutan individuals were displaced and required rehabilitation or translocation between 2000 and 2019, and this explains why the expenditures for rehabilitation and reintroduction programs were small (Figure 4).

Sumatra

In Sumatra, habitat protection produced the best outcome in reducing the decline in the orangutan's probability of occurrence, followed by patrolling activities (Figure 5B). However, the cost of habitat protection was expensive compared with the cost of other activities in the region and compared with habitat protection in other orangutan regions in Indonesia (\$735 versus \$252 per km^2 for Kalimantan) (Figure 4B). This is likely attributed to the higher opportunity cost of land for conversion to agriculture and the cost associated with establishing and managing land in this relatively developed region.[15] During the study period, several land acquisitions and their protection occurred across the orangutan range in Sumatra (e.g., within the Leuser Ecosystem). Such initiatives, consequently, incurred significant direct costs on land purchase and management establishment. Despite providing the highest benefit on orangutan occurrence (Figure 5B), due to the high land-related cost (Figure 4B), the protection strategy was considered less efficient in terms of monetary value (Figure 6B). On the other hand, the costs of patrolling were moderate (\$302 per km^2), which is higher than that in Kalimantan (\$155 per km^2) but substantially lower than that in Sabah (\$1,303 per km^2) (Figure 4B). This could be partly due to the lower baseline remuneration rates in Indonesia compared with Malaysia despite baseline prices of goods in both countries being relatively similar.[24,25] Due to the moderate costs for patrolling, this activity provided the best return on investment in terms of orangutan occurrence benefit in Sumatra (Figure 6B).

Rescue and rehabilitation activities provided only a small benefit for maintaining the probability of occurrence of orangutans in their range (i.e., they provide limited deterrence to poaching and trafficking), and this is similar to the presence of reintroduction sites and outreach activities in the island (Figure 5B). Similar to the situation in Sabah, the investment in rehabilitation activities in Sumatra was minor (Figure 4); hence, the return on investment for probability of occurrence has limited applicability.

Caveats and limitations

There are four key limitations in our analysis. The first pertains to the accuracy of our investment dataset. Although we attempted to comprehensively collect information on all investment, it is likely that we missed a few. Additionally, in some instances, detailed information on the amount of investment for different activities for a particular organization was not available. To overcome this issue, we estimated activity expenditure amounts based on the activities described in the organization's reports or website and the costs of

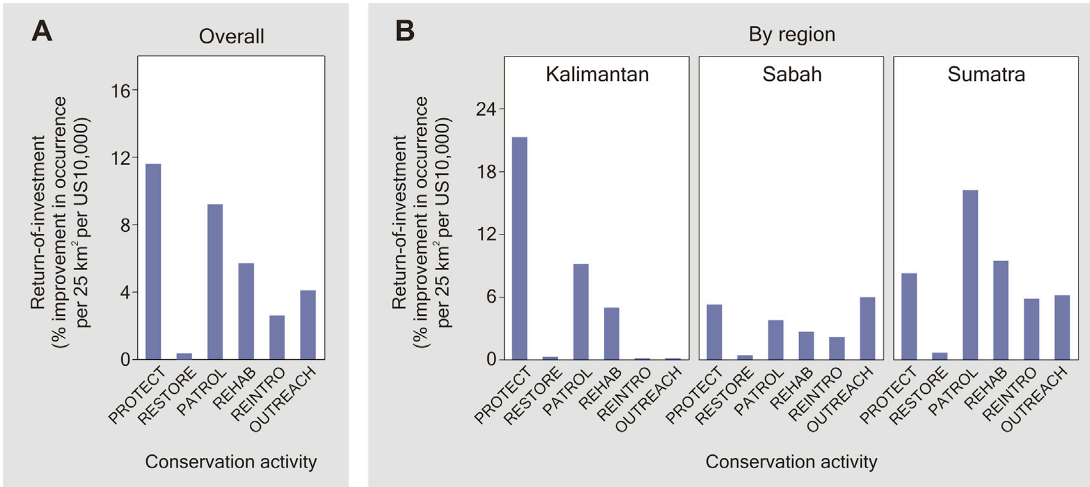

Figure 6. Return on investment of six orangutan-related conservation activities

Defined as the percentage improvement in orangutan probability of occurrence per 5 × 5 km^2 per US$10,000 investment.

Overall across the three regions (A) and broken down by region (B). Conservation activities assessed include the six core activities: habitat protection (PROTECT), habitat restoration (RESTORE), patrolling and law enforcement (PATROL), rescue and rehabilitation (REHAB), translocation and reintroduction (REINTRO), and awareness raising, capacity building, and policy (OUTREACH). Research-related activities (RESEARCH) was excluded from the return on investment analysis as it is considered as primarily influencing conservation actions and land use management decisions in the long term.

those activities undertaken by similar-sized organizations operating in the same region for which we had specific data. The second limitation is associated with the modeling approach and the implications on the estimation of conservation benefits. We assumed that the effect of a conservation activity on the orangutan presence can be adequately captured in the model mainly through variable distance to the location of that conservation program as a proxy (STAR Methods). As such, in a grid cell where multiple activities are operating simultaneously with different levels of importance (e.g., patrolling is carried out with higher efforts than public outreach programs), the model assumes equal importance of all actions. As research programs usually co-occur simultaneously with other conservation activities, the impact of research is difficult to estimate accurately through our modeling approach. This was the reason why we excluded research from the cost-benefit analysis. The third limitation relates to the methodology for constructing the counterfactual scenarios. We applied the most sensible, relevant, and practical approach for defining the counterfactuals. In reality, these counterfactual scenarios are much more complicated and influenced by multiple biophysical and socioeconomic factors.[26] The fourth limitation pertains to province-level differences in threats and government policies in Indonesia. Our cost-benefit analyses were aggregated to provide general and broad island-based inference to inform national policies. Province-level analysis would likely generate more nuanced outcomes from the modeling output to guide local policy at the subisland level. We have tried to adequately address these limitations wherever possible and are convinced that despite these caveats, the results of the analysis appropriately reflect the situation on the ground.

Conclusions and recommendations

Judicious planning for conservation under a constrained budget requires an understanding of the dynamics of conservation investments and activities and how they relate to species trends across their spatial range. Such an analysis is however rarely conducted, as it requires comprehensive spatiotemporally explicit data on the species, the natural environment and threats, conservation activities, investments in these activities, and an estimation of the counterfactual situation without the investment. Using orangutans as a case study, our analysis estimated that habitat protection, patrolling, and public outreach provided large benefits in slowing down the decline in orangutan numbers. However, given variability in threats and development circumstances and stages in different regions where orangutans occur, the most cost-effective conservation activity was different across regions. Our findings highlight the importance of accounting for regional differences in land pressure and socioeconomic elements to guide the focus of investment in different areas and contexts to achieve the desired conservation goals.

We recommend the application of our findings in planning for future funding and policy strategies for orangutan conservation to ensure optimal use of limited resources and application of the analytical framework to the conservation of other wildlife. It would be highly beneficial for orangutans and other species if data on their distribution and densities and detailed information on conservation programs, (i.e., where are they conducted and when, what kind of activities are specifically involved, and how frequently these activities are conducted) could be transparently and centrally coordinated, made publicly available, and regularly updated by participating organizations working in species conservation. Such transparency on spending could help facilitate open discussions about improving the existing strategies.

STAR★METHODS

Detailed methods are provided in the online version of this paper and include the following:

SUPPLEMENTAL INFORMATION

Supplemental information can be found online at https://doi.org/10.1016/j.cub.2022.02.051.

ACKNOWLEDGMENTS

We thank the United States Fish and Wildlife Service, Orangutan Foundation of UK, Natural Sciences and Engineering Research Council of Canada (NSERC), Nacey Maggioncalda Foundation, Leakey Foundation, University of Wisconsin – Oshkosh, Disney Conservation Fund, Direktorat Perguruan Tinggi Republik Indonesia, the Sabah Biodiversity Council for research approval (ref: JKM/MBS.1000-2/2 JLD.6 (79)), the Department of Aviation Malaysia (ref: UMS/IBTP7.2/800), Yayasan Sabah Sdn. Bhd, Charles Garcia and Ronnie Bibi, the Sabah Forestry Department, UNDP-GEF for funding, Darwin Initiative for the Survival of Species (grant no. 09/016, DEFRA, UK), Nacey Maggioncalda Foundation, and University of Wisconsin – Oshkosh.

AUTHOR CONTRIBUTIONS

Conceptualization, E. Meijaard, T.S., J.S., M.V., M.A., S.A.W., and K.A.W.; methodology, T.S., E. Meijaard, J.S., M.V., M.A., S.A.W., K.A.W., H.P., and D.J.I.S.; software, T.S. and M.V.; formal analysis, T.S., E. Meijaard, J.S., M.V., M.A., and S.A.W.; investigation, E. Meijaard, T.S., J.S., M.V., M.A., S.A.W., E. Massingham, D.J.I.S., A.M.A., T.S.A., G.L.B., E.J.B., D.F.R.P.B., R.A.D., A.E., G.F., B.G., M.H., T.P.I., R.L.J., T.K., C.D.K., A.L., D.L., M.M., A.J.M., J.G.A.M., L.M., A.M., S.M., C.M., N.N., D.P.-F., D.P., R.R., G.M.R., A.R., J.S., E.S., M.S., D.S., S.S., M.J.S., I.S., A.T., R.Z., and A.Y.; data curation, E. Meijaard, T.S., J.S., M.V., M.A., and S.A.W.; writing – original draft, E. Meijaard, T.S., J.S., M.V., M.A., S.A.W., and K.A.W.; supervision, J.S., M.A., and E. Meijaard; project administration, J.S., funding acquisition, J.S., M.A., E. Meijaard, S.A.W., and K.A.W.

DECLARATION OF INTERESTS

The authors declare no competing interests.

Received: November 5, 2021
Revised: January 3, 2022
Accepted: February 16, 2022
Published: March 10, 2022

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STAR★METHODS

KEY RESOURCES TABLE

REAGENT or RESOURCE	SOURCE	IDENTIFIER
Deposited data		
Orangutan conservation investment data	This paper, Tables S1 and S2	http://apesportal.eva.mpg.de/
Orangutan nest surveys 2015-2019	This paper	http://apesportal.eva.mpg.de/
Orangutan or nest encounters and reconnaissance surveys 2015-2019	This paper	http://apesportal.eva.mpg.de/
Sightings of orangutans reported by village residents through interviews 2015-2019	This paper	http://apesportal.eva.mpg.de/
Orangutan survey data from 2000 to 2015	Wich et al.,[1] Voigt et al.,[3] and Santika et al.[4]	http://apesportal.eva.mpg.de/
Elevation (m a.s.l) *ELEV*	SRTM 90m Digital Elevation Database v4.1[6,27]	https://cgiarcsi.community/data/srtm-90m-digital-elevation-database-v4-1/
Rainfall during the dry season (mm) *SDRY*	WorldClim2[28]	https://www.worldclim.org/data/bioclim.html; BIO17
Rainfall during the wet season (mm) *SWET*	WorldClim2[28]	https://www.worldclim.org/data/bioclim.html; BIO16
Distance to nearest city (km) *CITY*	Provincial map from the Geospatial Information Agency Indonesia[29] and GeoNames Gazetteer[30]	http://www.geonames.org/; https://tanahair.indonesia.go.id/portal-web
Percentage of peatland area *PEAT*	Peat hydrological area map[31]	http://pkgppkl.menlhk.go.id/v0/en/kesatuan-hidrologis-gambut-nasional-skala-1250-000/
Percent forest cover *FOREST*	Global Forest Change dataset,[32] Indonesia's primary and secondary forest map,[33] and Intact Forest Landscapes data[34]	https://earthenginepartners.appspot.com/science-2013-global-forest/download_v1.7.html; https://glad.umd.edu/dataset/primary-forest-cover-loss-indonesia-2000-2012
Percentage of degraded peatland *DEGPT*	Peat hydrological area map,[31] Global Forest Change dataset,[32] Indonesia's primary and secondary forest map,[33] and Intact Forest Landscapes data[34]	https://earthenginepartners.appspot.com/science-2013-global-forest/download_v1.7.html; https://glad.umd.edu/dataset/primary-forest-cover-loss-indonesia-2000-2012; http://pkgppkl.menlhk.go.id/v0/en/kesatuan-hidrologis-gambut-nasional-skala-1250-000/
Distance to oil palm plantations (km) *OPDST*	Oil palm plantation distribution map[15,35–37]	https://nusantara-atlas.org/
Survey effort *SURV*	Orangutan survey datasets across Indonesia and Malaysia[1,4,16,38,39]	See row 5, this table
Distance to research centres/activities (km) *RSCHR*	This paper	See Table S1
Distance to protected areas (km) *PRTCA*	Forest Zone Maps,[4,40] Community Forestry areas,[41] and this paper	http://webgis.dephut.go.id:8080/kemenhut/index.php/id/peta/petapiaps and Table S1
Distance to patrolling activities (km) *PTROL*	This paper	See Table S1
Distance to rehabilitation centres (km) *RHCTR*	This paper	See Table S1
Distance to reintroduction sites (km) *RINTR*	This paper	See Table S1
Distance to public outreach programs (km) *COMRC*	This paper	See Table S1

(*Continued on next page*)

Please cite this article in press as: Santika et al., Effectiveness of 20 years of conservation investments in protecting orangutans, Current Biology (2022), https://doi.org/10.1016/j.cub.2022.02.051

Continued

REAGENT or RESOURCE	SOURCE	IDENTIFIER
Experimental models: Organisms/strains		
Bornean orangutan (*Pongo pygmaeus*)	N/A	N/A
Sumatran orangutan (*Pongo abelii*)	N/A	N/A
Tapanuli orangutan (*Pongo tapanuliensis*)	N/A	N/A
Software and algorithms		
R software	N/A	https://www.r-project.org/
R code	N/A	https://doi.org/10.5281/zenodo.6080322
Arc-GIS	N/A	https://www.arcgis.com/index.html
Other		
Computation of inflation adjusted investment	This paper	See method details
Computation of counterfactuals	This paper	See method details
Computation of cost effectiveness	This paper	See method details

RESOURCE AVAILABILITY

Lead contact

Further information and requests for resources should be directed to and will be fulfilled by the lead contact, Truly Santika (t.santika@greenwich.ac.uk).

Materials availability

This study did not generate new unique reagents.

Data and code availability

- The raw investment data and orangutan survey data reported in this study cannot be deposited in a public repository because of confidentiality issues. To request access, ask the lead contact for contact information for the entities listed in Tables S1 and S2. In addition, processed datasets derived from these data have been deposited at the APES database (http://apesportal.eva.mpg.de/) and will be publicly available as of the date of publication. Accession numbers or DOIs are listed in the key resources table.
- This paper analyzes existing, publicly available data. The accession numbers for the datasets are listed in the key resources table.
- All non-confidential data reported in this paper will be shared by the lead contact upon request.
- All original code is available in this paper's supplemental information.
- Any additional information required to reanalyze the data reported in this paper is available from the lead contact upon request.

EXPERIMENTAL MODEL AND SUBJECT DETAILS

We collected data on orangutan conservation investments across Borneo and Sumatra for the period 2000–2019, based on the most recent yearly budget allocations available, comprising a total of 259 investments. We identified initial lists of organizations that were carrying out orangutan conservation activities. An organization was considered to be conducting orangutan conservation activities if it met two criteria:

1) the goals or conservation activity descriptions specifically mentioned orangutans, or in the case of habitat conservation activities orangutans were specifically mentioned in relation to the affected habitat; and
2) the orangutan-related conservation activities were conducted on the ground in the orangutan range regions (Borneo and Sumatra) regardless of where the organization was headquartered.

For every investment, we recorded the entity or organization managing the conservation activity, the sector of the entity (e.g., government agency, non-government organization (NGO), and rescue centres), the location where the activity had taken place, the allocation of funds spent on each category of conservation activities during the latest available financial year (see below), the years between 2000 and 2019 when the activities were undertaken, and the investment amount.

Other data used are detailed in the key resources table.

METHOD DETAILS

Our study framework consists of four steps of analyses: (1) collating data on conservation investments; (2) modelling the change in the distribution of the species under study; (3) estimating the benefit of conservation activities on that species through changes in the species occurrence; and (4) estimating the return-on-investment.

Our study area covers the orangutan range in the island of Sumatra, Indonesia (470,000 km^2) and Borneo (including Kalimantan, Indonesia and Sabah, Malaysia) (740,000 km^2) (Figure 1). We excluded the Malaysian state of Sarawak, as we have insufficient data on orangutan surveys and conservation investment in this region. The orangutan range in Sarawak is small compared to the overall orangutan range and leaving out Sarawak should not affect our overall findings. For the spatial unit of analysis, we used a grid-cell with a resolution of 5×5 km^2. This resolution corresponds to the average home range of adult male orangutans, which overlaps with the home range of several females.[42] As the temporal unit of analysis, we used four time periods: 2000-2004, 2005-2009, 2010-2014, and 2015-2019.

Collecting data on conservation investments

We collected investment data through direct communications with identified organizations, and via desktop research and review of publicly available data on each organization's expenditure reports (i.e., grant and project databases, corporate sustainability reports, annual reports, budgets and financial reports, tax filings of donors and implementing organizations and charity commission reports, and organization websites) (see Tables S1 and S2 for the source of information on investment and the list of organizations or entities). To avoid double counting investments from both donors and implementers, we only used data on investments made by organizations implementing orangutan conservation activities on the ground in orangutan habitat.

Where an organization's investment amounts by activity were not specified (i.e., data were only available on the overall amounts), we looked for data from any project grants related to orangutan conservation the organization received where amounts spent on specific activities were detailed. Where no detailed data were available for a given organization, we estimated activity expenditures amounts based on the activities described in the organization's reports or website, and the costs of those activities undertaken by similar-sized organizations operating in the same region for which we did have specific data. We tested these estimations for accuracy by requesting selected organizations to check our figures for their budgets. For government-funded habitat protection activities, we also included community-based forest management, especially the *Hutan Desa* (Village Forest) scheme in Indonesia. We only included *Hutan Desa* areas where the boundaries overlap with the orangutan range. We used an estimated cost of US$50 per ha for establishing *Hutan Desa*.[43] For oil palm concessions certified under the Roundtable on Sustainable Palm Oil and timber concessions certified under the Forest Stewardship Council where no sustainability investment was specified, we estimated that US$10 per ha (RSPO) or US$1 per ha (FSC) was spent on High Conservation Value areas. These averages were based on data from several companies for which we had more detailed information on investment per unit area. The expenditure data we collected from various organization reports and databases were mostly in US$ (US Dollar). The amounts of spending in a given year originally provided in national currencies (Indonesian Rupiah and Malaysian Ringgit) were converted to US$ using the currency conversion rate applicable to that year.

We categorized organizations into six sectors: (1) government, including agencies, national parks, and government-funded community-based forest management; (2) bilateral or multilateral bodies; (3) non-governmental organizations (NGOs); (4) rescue centres, including sanctuaries for care of orphaned or seized wildlife, (5) commercial corporations including industrial agriculture, timber and pulp, logging, and mining; and (6) research centres and universities. For commercial corporations, oil palm plantation companies certified by the Roundtable for Sustainable Palm Oil (RSPO) that spent funds to maintain High Conservation Value lands which were known to have orangutans (based on the overlap with the species' ranges) were included even if the company reports did not specifically mention orangutan conservation. We did the same for timber plantations and logging companies certified by the Forestry Stewardship Council (FSC). This is because both RSPO and FSC require the conservation values (including orangutans) in the concession to be maintained, and independent audits are carried out to verify this.[44,38] We assumed that uncertified plantations, logging, or mining concessions did not invest in orangutan conservation unless our review of orangutan investment information identified them specifically as doing so. For research, funding for local studies of orangutans by researchers (local and foreign) was counted if: (1) the research was part of the work of an in-situ research centre focused on orangutans or including orangutan studies, and the studies met our criteria for relevance to orangutan conservation; or (2) the research project came up in search results for orangutan conservation investments and met both our criteria. Investments in orangutan habitat range by government agencies with direct management authority for orangutans or any orangutan habitat areas were included regardless of orangutan mentions.

For missing annual data on investment, we estimated the amount of spending by fitting an Ordinary Least Square (OLS) regression model to the available data covering different years. For an entity with limited investment data, we estimated the overall investment envelope based on the trends captured for similar-sized organizations. For NGOs and rescue centres, we identified a consistent pattern of a 2-3% increase in annual expenditure for orangutan conservation between 2000 and 2019 across Indonesia and Malaysia. Similarly, we identified a 4-5% increase in government's annual expenditure for orangutan conservation over the same period in Malaysia and wildlife conservation activities in general for Indonesia. For that reason, we applied 2.5% and 4.5% annual increases for missing NGO data and missing government data, respectively.

Allocating investment data to activities

Expenditure data by individual activities were not consistently available from all orangutan conservation entities, hence we grouped similar activity types into the six broad categories described below. For each investment unit, we first recorded the entity, entity sector, the location where the entity was operating, and funds spent during the latest available financial year on six categories of conservation activities based on the Conservation Measures Partnership Action Classifications.[39] Six categories of activities related to orangutan conservation were identified across the three regions. The classification of activities were informed by the Conservation Measures Partnership[39] and include: (1) habitat protection and acquisition (PROTECT); (2) habitat restoration (RESTORE); (3) patrolling and law enforcement (PATROL); (4) rescue and rehabilitation (REHAB); (5) translocation and reintroduction (REINTRO); and (6) public outreach and awareness raising, capacity building and policy (OUTREACH) (Figures S1 and S2). Besides these six core activities, we also estimated investment in research activities that may influence conservation and land use management decisions (RESEARCH) (Figure S3). Details about the activity categories are as follows:

1) Habitat protection and acquisition (PROTECT), includes management and maintenance of the land, such as firefighting, invasive plant or animal control, fencing or other infrastructure related to protection, avoided deforestation payments or costs, habitat purchase, community land reserves or forestry including payment to communities to establish protection;
2) Habitat restoration (RESTORE), includes replanting, growing nursery stock, maintenance of restored forest by watering, and other activities needed to establish and maintain restored habitat;
3) Patrolling and law enforcement (PATROL), includes rangers and wardens and their associated expenses, infrastructure like guard posts and patrol equipment, and investigation, prosecution, and incarceration costs;
4) Rescue and rehabilitation (REHAB), includes activities related to intake, captive care and rehabilitation of orangutans;
5) Orangutan reintroduction and translocation (REINTRO), includes orangutan releases, post-release monitoring and research to identify release sites or release outcomes. Orangutan releases include: (a) the release of rehabilitated ex-captive orangutans to reinforce existing wild populations; (b) reintroduction of populations within historic range but outside the current distribution; and (c) wild-to-wild translocationof orangutans captured because they were considered an immediate or potential threat to humans and human activities, or where the orangutans are themselves threatened by humans and human activities; and
6) Public outreach, awareness raising, capacity building and policy (OUTREACH), includes community outreach, training and capacity building for environmentally friendly livelihoods and human-orangutan conflict mitigation, policy development or advocacy on orangutan conservation related issues.

An additional expenditure category of administrative and overhead costs (costs for operation of the entity rather than the implementation of activities) was excluded from our model. Although the cost of operating the organizations, businesses and agencies is vital to the ability to deliver the orangutan conservation activities, and represents millions more dollars spent annually, these expenditures did not meet our criteria for conservation activities implemented within orangutan range.

Orangutan conservation Theory of Change (ToC) pathways

The Theory of Change (ToC) pathways for each orangutan conservation activity (Figures S1–S3) represent the chain of outcomes resulting from the conservation activities within the short term (five years after the activity is initiated) and long term (more than five years after initiation) that can lead to reduced threats and positive impacts on species population trends. We considered the short term, five-year time interval in the ToC to conform to the data analysis and modelling approach we used. Under this ToC framework, it is assumed that PROTECT actions establish land regulation, management and enforcement to prevent habitat degradation and poaching. RESTORE actions facilitate forest regrowth, either through active restoration (e.g., reforestation and hydrological rehabilitation) or passive restoration (natural regeneration). The presence of PATROL activities helps reduce wildlife and forest crimes, and law enforcement actions can further establish this deterrence. REHAB includes the transfer of animals seized by authorities, a preliminary step in a legal process that, when it culminates in sanctions, can deter crime. Additionally, REHAB actions provide opportunities for releasable animals to become part of a successful release program. REINTRO actions facilitate orangutans released into natural habitats where they can improve the viability of existing wild populations or establish new viable populations. REINTRO actions can also pose real disease, genetic and behavioural risks to wild orangutan populations, and thus have the potential to have both positive and negative impacts on the species. OUTREACH actions assist communities in mitigating human-orangutan conflicts and supporting behavioural changes to facilitate coexistence between orang-utan and people and support conservation of orangutans and their habitats.

Unlike these six core conservation activities whereby the benefits on orangutan survival are likely to be realized over the short term (within five years period), RESEARCH activities may take longer time to benefit orangutans. Most research consists of several stages of activities (e.g., field survey and data collection, data analysis, and consultation with different stakeholders) that may take several years to produce findings to inform or provide recommendations for conservation actions and policies. These policy recommendations subsequently may take several more years to be implemented and therefore begin to benefit the species. Nonetheless, research sites whereby researcher presence is maintained over the long term are recognized to have a deterrent effect on poaching and forest crimes.[45]

Please cite this article in press as: Santika et al., Effectiveness of 20 years of conservation investments in protecting orangutans, Current Biology (2022), https://doi.org/10.1016/j.cub.2022.02.051

Orangutan survey data

We used an existing database of orangutan survey data from 2000 to 2015[1–4,16,46,47] and new survey data from 2015 to 2019, from both Borneo and Sumatra. These data consisted of: (a) orangutan nest encounters obtained from transects surveys, both on the ground and from aerial surveys (occupied aircraft and drones); (b) orangutan or nest encounters obtained from reconnaissance or opportunistic surveys; and (c) sightings of orangutans reported by village residents through interviews. To reduce potential false detection of orangutans in the interview data, we selected only villages where more than 30% of respondents reported orangutan sightings as an indicator of orangutan presence. For each time period, any 5×5 km^2 grid-cell with orangutan sightings or nest encounters was assigned "presence", whereas grid-cells with one survey or more without any sightings of orangutans or nests was assigned "absence". Absence records in a grid-cell for a given time period can therefore represent real absence (the species never occurred in that grid-cell) or loss (the species used to be present in that grid-cell, but not anymore). Grid-cells without any survey were excluded in the model building.

QUANTIFICATION AND STATISTICAL ANALYSIS

Inflation-adjusted value of investment

The investment data represent the nominal value of investment. To obtain the real value of investment to facilitate intra-country comparison and discern the actual purchasing power of organizations in implementing activities on the ground across different regions, we adjusted the nominal value with inflation rates.[48] Inflation rates have changed dramatically in Indonesia and Malaysia between 2000 and 2019 (https://data.worldbank.org/indicator/NY.GDP.DEFL.KD.ZG). The consumer price indices (CPI) in both countries are similar and therefore were not employed in the adjustment. The real value of investment in time period 2000-2004 (t=1), 2005-2009 (t=2), and 2010-2014 (t=3) can be expressed in reference to the present period 2015-2019 (t=4), i.e.

$$\widehat{C}_t = C_t \times (r_1+1)^{5\times b1} \times (r_2+1)^{5\times b2} \times (r_3+1)^{5\times b3}$$

$$\text{with}(b1,b2,b3)=(1,1,1)\text{if } t=1,$$
$$(b1,b2,b3)=(0,1,1)\text{if } t=2,\text{ or}$$
$$(b1,b2,b3)=(0,0,1)\text{if } t=3.$$

where $\widehat{C}_t$ is the real value of investment at time period t relative to the present period; C_t is the nominal value of investment at time period t; and r_1, r_2 and r_3 is the average inflation rates for time period t=1, t=2, and t=3, respectively.

We aggregated the yearly investment data into four time periods to conform to the baseline time interval used in the orangutan occurrence change analysis: 2000-2004, 2005-2009, 2010-2014, and 2015-2019. We also calculated the estimated investment in each 5×5 km^2 grid-cell for each of the six activities plus investments into orangutan-related research.

Modeling the change in species distributions

We used the Generalized Boosted Regression Modelling (GBM) approach[27] to fit the orangutan presence-absence data for each of the four time periods for each orangutan region (i.e. Kalimantan, Sabah, and Sumatra) using 15 environmental predictors (Table S3). These regional divisions were chosen to account for the broad threat and socioeconomic patterns and government policies at the national and island levels. The environmental predictors included static variables over the timeframe of interest, such as elevation, long-term mean monthly rainfall during the dry and wet months, distance to nearest city, and percentage of peatland, and dynamic variables (with changing spatial configurations over the different time periods t), including forest cover ($FORST_t$), percentage of degraded peatland (<30% forest cover) ($DEGPT_t$), distance to nearest industrial oil palm plantation, and distance to conservation activities that are considered to be delivering benefits to orangutans. These conservation activities included forest protection through the establishment of protected areas (including national parks, nature reserves, watershed protection forest, and community-based forest management) ($PRTCA_t$), patrolling activities ($PTROL_t$), rehabilitation centres ($RHCTR_t$), orangutan translocation and reintroduction sites ($RINTR_t$), and orangutan-related public outreach and awareness raising ($COMRC_t$). To control for spatiotemporal effects of survey protocols on orangutan presence reports, we included survey effort (i.e., the number of surveys on orangutans conducted in each grid-cell) and distance to orangutan research centres or activities as predictor variables. All predictor variables were weakly correlated.

For each regional-based GBM model, we estimated the model parameters (Figure S6) and the change in the probability of occurrence of orangutans through the four time periods in each region. The baseline probabilities of occurrence differed between regions. To standardize the change in occurrence across the different regions, and to provide a practical representation of the population change through time to inform policy, we translated the probability of occurrence data to density estimates. This was done by assessing the correlation between the predicted orangutan probability of occurrence (generated from the GBM) and the density rates calculated directly from the orangutan transect dataset over grid-cells where transect surveys were conducted (Figure S4).

Estimating the benefit of conservation activities and the return-on-investment

The counterfactual scenario, reflecting the absence of conservation activity between 2000 and 2019, was calculated by estimating how each activity modifies the predictor variables in the GBM models. The association between the outcome potentially generated from each activity and the predictor variables was informed by the orangutan conservation Theory of Change (ToC) pathways (supplemental

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information; Figures S1 and S2). The habitat protection strategy (PROTECT) is assumed to affect forest loss and ecosystem protection more broadly.[19] Our analysis suggested that areas assigned to protected areas were able to halve deforestation rates (compared to the rates within 50 km of the protected area boundaries) in Borneo and reduce deforestation rates by a quarter in Sumatra (Figure S7A), and this is likely because pressure to convert forest to other land uses was stronger in Sumatra than in Borneo overall.[15,28] Hence, the counterfactual scenario in the absence of PROTECT assumes that: (a) the counterfactual forest loss rates inside protected areas were roughly 2 or 4 times the actual rates for Borneo and Sumatra respectively (i.e. $FORST_{1,counterfactual} = FORST_0 - (r \times FLOSS_1)$, and $FORST_{t,counterfactual} = FORST_{t-1,counterfactual} - (r \times FLOSS_t)$ for $t>1$, where $r=2$ for Borneo and $r=4$ for Sumatra), (b) the counterfactual percentage of degraded peatland (<30% forest cover) inside protected areas ($DEGPT_{t,counterfactual}$) is higher than the actual ($DEGPT_t$); and (c) the counterfactual distance to forest protection was the actual distance multiplied by 100 (i.e. $PRTCA_{t,counterfactual} = PRTCA_t \times 100$), thus forest protection having negligible effect.

The habitat restoration strategy (RESTORE) is assumed to affect forest gain. Our analysis suggested that areas assigned to habitat restoration in Borneo and Sumatra were able to increase forest cover at twice the rate outside habitat restoration areas (Figure S7B). Hence, the counterfactual scenario in the absence of RESTORE assumes that the counterfactual forest gain inside restoration areas was half the actual forest gain (i.e. $FORST_{1,counterfactual} = FORST_0 + (0.5 \times FGAIN_1)$, and $FORST_{t,counterfactual} = FORST_{t-1,counterfactual} + (0.5 \times FGAIN_t)$ for $t>1$).

For conservation activities such as patrolling and law enforcement (PATROL), rescue and rehabilitation (REHAB), translocation and reintroduction (REINTRO), and outreach and advocacy (OUTREACH), the counterfactual scenario in the absence of the activity assumes that the counterfactual distance to the activity was the actual distance multiplied by 100 (i.e. $PTROL_{t,counterfactual} = PTROL_t \times 100$ for PATROL, $RHCTR_{t,counterfactual} = RHCTR_t \times 100$ for REHAB, $RINTR_{t,counterfactual} = RINTR_t \times 100$ for REINTRO, and $COMRC_{t,counterfactual} = COMRC_t \times 100$ for OUTREACH). Our analysis suggested that deforestation rates in areas with PATROL, REINTRO, or OUTREACH activities were similar to the rates in areas without such activities. Therefore, we assumed that the counterfactual forest cover is the same as the actual.

The benefit of each conservation activity in each 5×5 km^2 grid-cell was estimated as the percent improvement in the orangutan probability of occurrence compared to the counterfactual scenario. Specifically for the translocation and reintroduction strategy (REINTRO), we further multiplied the benefit by 50%. This is considering that post-release mortality rates of individual released orangutans can range widely between 20% and 80%,[17,29,30] thus the median value of 50% was chosen. In calculating the benefit, we focussed only on activities that had occurred within the contemporary ranges of wild orangutans, therefore excluded reintroduction sites outside the orangutan range such as the Jantho Nature Reserve and Bukit Tigapuluh National Park in Sumatra.

Return-on-investment from orangutan conservation activity in each 5×5 km^2 grid-cell was estimated as the benefit of conservation activity in improving orangutan probability of occurrence compared to the counterfactual scenario divided by the cost of activity in that grid-cell. The conservation activities with the largest return-on-investment will deliver the largest improvements in orangutan occurrence per dollar.

R code

All original code has been deposited at https://doi.org/10.5281/zenodo.6080322 and is publicly available as of the date of publication. DOIs are listed in the key resources table.