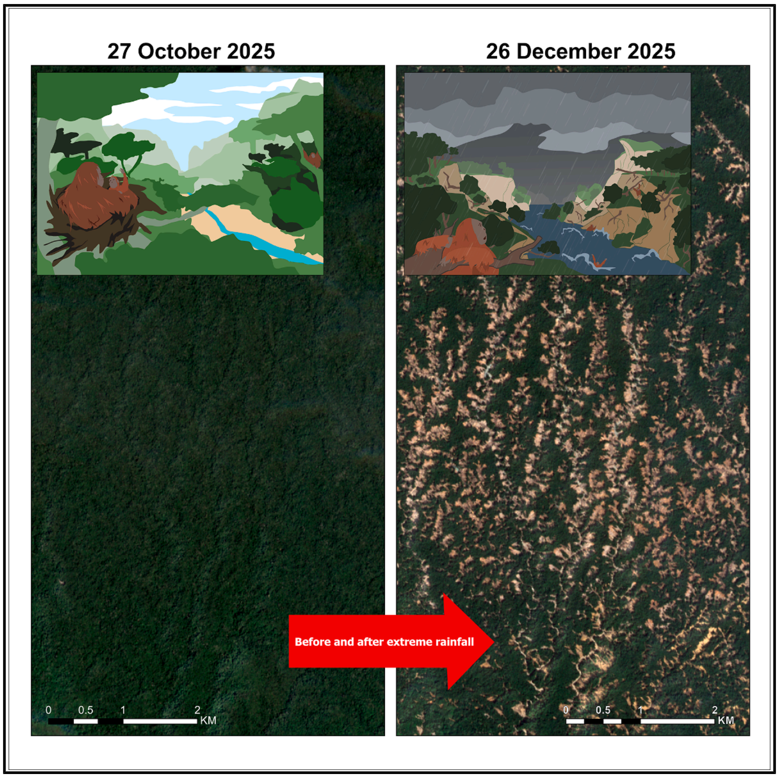
Report

Current Biology

# Extreme rainfall further endangers the world's rarest great ape

## Graphical abstract




## Highlights

- 2025 extreme rain caused 8,303 ha of landslides in the Tapanuli orangutan habitat
- Spatial data show ~11% of the West Block population likely perished
- Rapid debris flows left the arboreal primates no chance to escape
- Results show extreme weather is an immediate threat to great apes

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## In brief

Meijaard et al. report that the 2025 extreme rains triggered landslides, destroying 8,000+ hectares of Tapanuli orangutan habitat. The event killed ~11% of West Block orangutans. These findings prove that climate change-driven weather poses an immediate, catastrophic threat to the world's rarest great ape.

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Report

# Extreme rainfall further endangers the world's rarest great ape

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## SUMMARY

The critically endangered Tapanuli orangutan (*Pongo tapanuliensis*) was recognized as a species in 2017 and is the great ape species with the smallest wild population.[1] Fewer than 800 individuals remain in three isolated populations in Batang Toru (West, East, and South Block) in Sumatra, Indonesia, all affected by habitat fragmentation and degradation.[2–4] Studies indicate that sustained additional population losses exceeding 1% annually will result in extinction.[5] In November 2025, an extreme, multi-day rainfall event triggered widespread landslides in the West Block of the Batang Toru ecosystem—the orangutan's largest remaining habitat area. Satellite imagery revealed 8,303 ± 1,760 ha of landslide scars across the West Block, accounting for an 11.7% loss of forest cover. Spatial analysis suggests that 11% of the population (~58 individuals; range 18–120) resided within the landslide-affected areas. Landslide patterns indicate rapid and highly destructive events that left any orangutans caught in landslides with little chance of escape. The loss of these estimated 58 individuals represents a major shock to the viability of this Tapanuli orangutan population. Potential mortality caused by other effects, such as rainfall-induced canopy breakage and reduced food availability, has not been included and makes the estimate conservative. Given the species' slow reproduction and sensitivity to additional mortality, this single event constitutes a severe demographic shock with long-term implications for its viability. Our findings provide quantitative evidence that extreme rainfall events can directly threaten great ape survival, underscoring the urgent need for strengthened habitat protection and climate-responsive conservation planning.

## RESULTS

### Sentinel-2 and PlanetScope imagery to map landslides and flood scouring

The pre-event classification (Figure S1) shows that the study area was 99.3% forested, with 0.6% bare soil. The post-event classification estimated 8,303 ± 1,760 ha of newly denuded terrain (flood damage and landslide scars, henceforth referred to as "scars"), accounting for 11.7 ± 2.4% of the study area (Figure 1). Figure 2 illustrates the severity of the forest cover loss in a particularly intensely affected section of the West Block.

The post-event landcover classification achieved good accuracy (97.6% overall; Table S1). For the scar class, user's and producer's accuracies were 95.0% and 84.9%, while "forest" reached 98.0% and 99.3% (Table S1). The estimated scar area of 8,303 ± 1,760 ha is slightly above the mapped

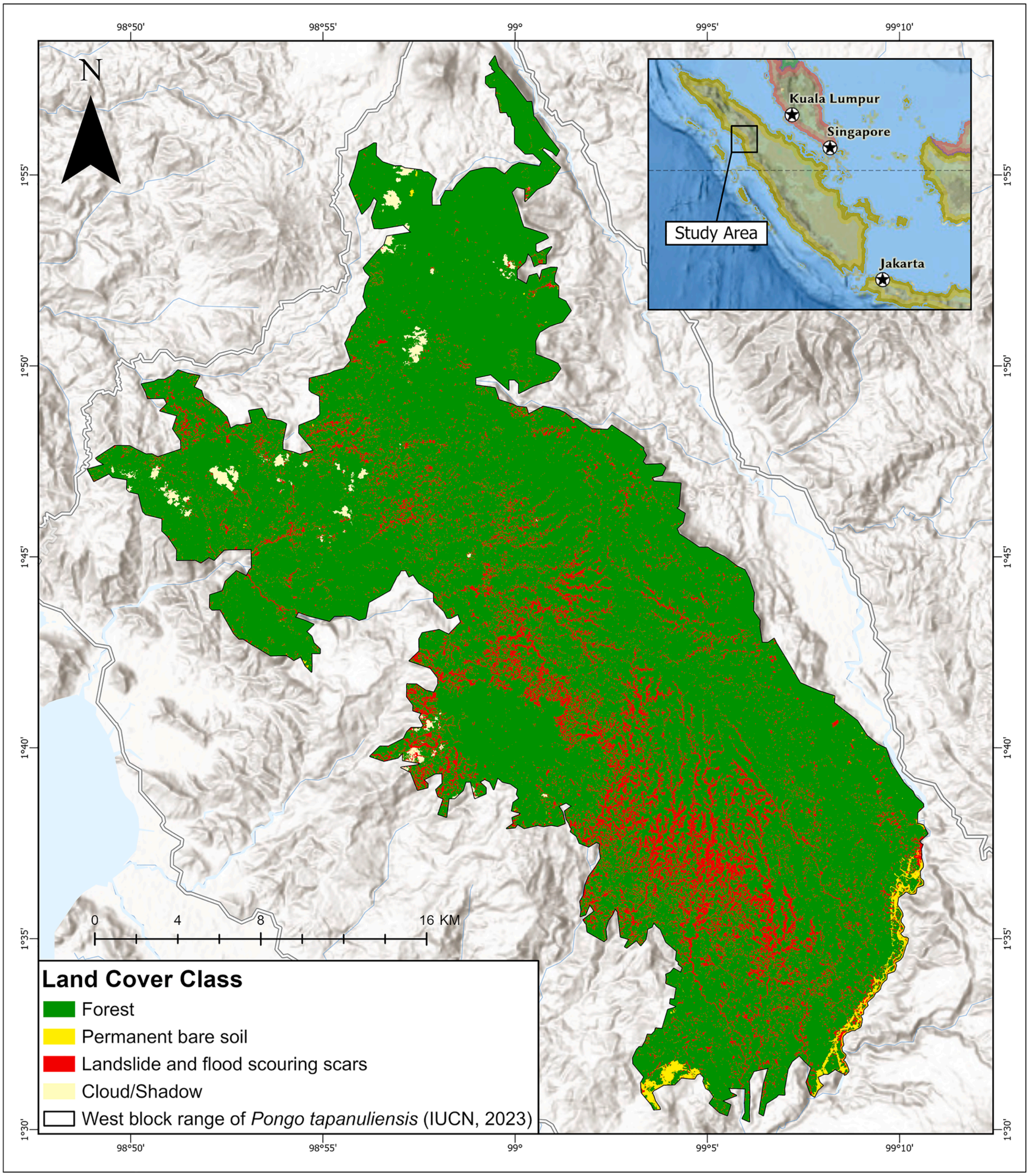


**Figure 1. Map of landslide scars**

The delineated area is the boundary of the West Block Tapanuli orangutan population.[6] Base map data derived from the Esri Topographic Map Service (source: Esri, TomTom, Garmin, FAO, NOAA, USGS, ©OpenStreetMap contributors, and the GIS User Community).
See also Figure S1.

area (7,419 ha) because the producer's accuracy (≈85%) is lower than the user's accuracy (95.0%). Consequently, the map slightly underestimates the true landslide area (see Table S1 for details and Document S1 for pre-event classification accuracy).

## Quantifying habitat loss and direct orangutan mortality

We identified 50,185 individual scars, with a mean area of 0.15 ha and a maximum area of 95.7 ha. Of these, 1,054 exceeded 1 ha, and 57 exceeded 10 ha. In at least some areas, landslide distribution appears to be drainage-controlled, following first- and

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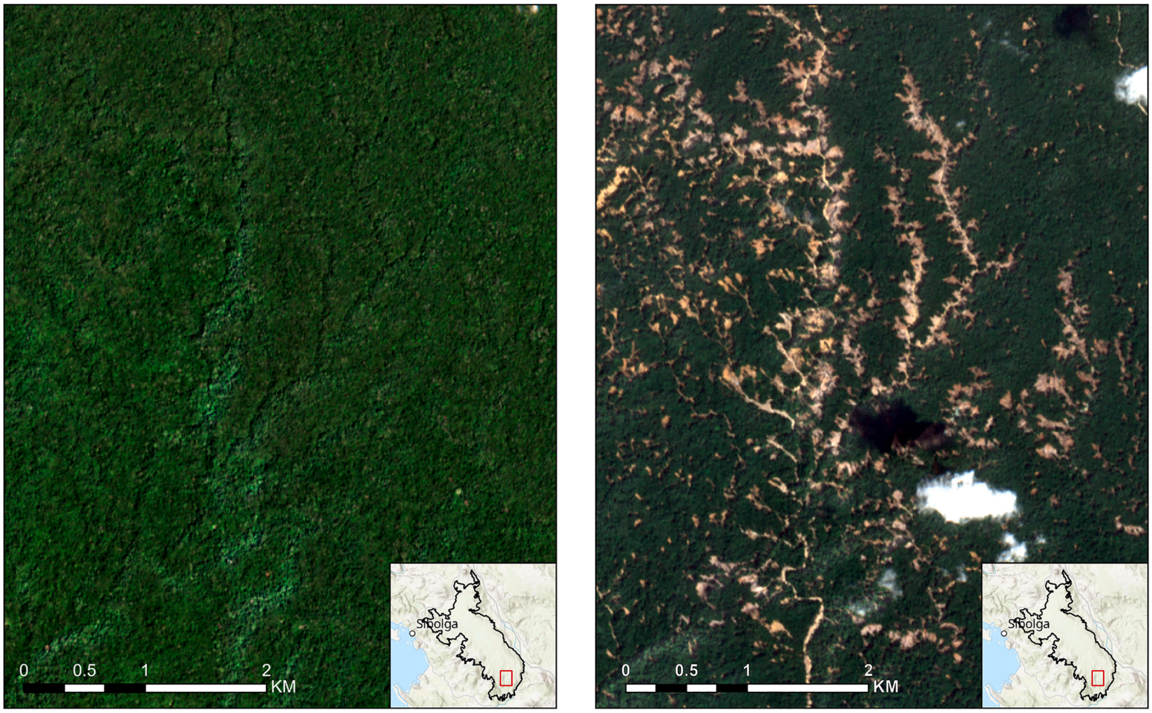


**Figure 2. Pre- and post-event imagery**

(A) Sentinel-2 image dated 27 October 2025 showing full forest cover.

(B) Sentinel-2 image of the same area dated 26 December 2025 showing the extent of scars (cream color), clouds, and remaining forest.

Image: Copernicus Sentinel data 2025; Base map data derived from the Esri Topographic Map Service (source: Esri, TomTom, Garmin, FAO, NOAA, USGS, ©OpenStreetMap contributors, and the GIS User Community).

second-order streams (Figure S2), though isolated landslides unrelated to fluvial networks were also observed. These landslides removed all above-ground biomass and soil; we therefore expect the scars to provide near-zero food resources for orangutans for at least 5–10 years until pioneer forest regrowth provides opportunities.[7] Landslides were disproportionately concentrated between 600 and 1,000 m asl. This zone accounts for 72.6% of the West Block's total area but contained 82.3% of the recorded landslide area. Conversely, elevations above 1,000 m asl were less affected, representing 11.3% of the West Block but only 1.9% of the landslide area. How these elevational differences in impact will affect future food supply remains unclear. The 2025 landslides far exceeded the landslides of previous decades. For example, a 2019 satellite image of the West Block showed ~1,000 small landslides with a total area of 42.57 ha, a maximum size of 1.36 ha, and a mean of 0.04 ha, thus some 200 times smaller compared with the 2025 event.

The overlay of the 1 $km^2$ orangutan density surface[3] with the scar areas resulted in an estimated 58 orangutans that were directly affected (range: 18–120, based on the pre-event population confidence interval [CI]). Whether these animals died, were injured, or only lost their home range habitat depends on the severity and speed of the landslides. Most of the landslides in the *PlanetScope* image appear to be shallow, translational slides, almost certainly occurring at the weathering boundary between mostly intact bedrock and weathered material. This is common in high-intensity rainfall events, causing a rapid increase in pore-water pressures at the permeability boundary.[8]

The landslides are nearly all directly connected to the channel system (i.e., there is little debris left on the hillside), which means they have generated channelized debris flows that would have been extremely destructive. All this evidence indicates that slope failure was rapid and destructive. Such violent failures typically occur without warning and thus offer little chance of escape.[9,10]

Orangutan mortality in these landslides would have resulted from tree falls, landslide burial, or drowning. Given the high density (>50,000) of sudden, steep-slope landslides causing canopy collapse and debris flow into drainage networks, and the limited opportunity for arboreal escape during rapid slope failure, we consider mortalities by burial, trauma, or subsequent drowning to be likely. Furthermore, because a single orangutan home range (~500–850 ha for females and ~2,500 ha for males[11]) would have been subjected to multiple, near-simultaneous slope failures during the multi-day deluge, the probability of an individual being caught in at least one debris flow is higher than in isolated landslide events. We therefore interpret the density-weighted overlap between scars and habitat as representing direct mortality rather than mere displacement. Nevertheless, only one orangutan death has been reported in the media,[12] which appeared to be an animal that had drowned, with the corpse showing signs of severe abrasion. This worst-case scenario of 100% mortality of orangutans caught in landslides indicates that ~11% (range 3–21%) of the West Block population (estimated at 581 in 2016) died during the 5-day event. Other orangutans may be indirectly affected, as discussed below.

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**Figure 3. An aerial view of the Batang Toru landscape**

This area near Sipansihaporas shows the deeply dissected nature of the terrain.
Photo credit: Gabriella Fredriksson.

Rainfall intensity and regional geomorphology determine the severity of landslide and flood hazards in tropical mountain regions. In steep, deeply weathered landscapes such as Batang Toru (Figure 3), high-intensity precipitation rapidly increases pore-water pressure, destabilizing slopes and triggering landslides, debris flows, and canopy structure failure.[16,17] Once rainfall surpasses a critical threshold, even intact old-growth forest cannot prevent slope collapse. Thus, the intensity of the late-November 2025 rainfall explains the scale of habitat destruction observed across the Tapanuli orangutan's core range.

### Biological meaning of losses

Great apes have slow life histories, and orangutans the slowest, with interbirth intervals of 6–9 years.[18,19] Combined with the small size and isolation of the three Tapanuli orangutan populations, this makes them highly vulnerable to stochastic habitat disturbances. Population models for Sumatran orangutans assumed catastrophic events occurring at a 2% annual probability (once every 50 years) and causing 20% mortality but did not incorporate post-event reproductive suppression among survivors.[5] Moreover, the November deluge likely exceeds the frequency and impact assumptions of those models, as such extreme rainfall events are becoming more probable, amplifying both direct mortality and longer-term reductions in reproductive output.

Reproductive suppression could occur if orangutans were forced to disperse to lower-quality habitats, for example, if landslides displaced them to higher-elevation habitats where food is scarcer or if displaced orangutans had to share remaining lower-elevation habitats with more individuals. The 8,303 ± 1,760 ha of forest that was lost eliminated key food sources, but how this affects overall food availability remains unclear. Because we assume that all orangutans caught in landslides died, this would leave the remaining habitats to a reduced population. In that case, there would be no increased competition but just a smaller population. Until field surveys are conducted, we cannot know this.

Another factor that may affect orangutan population viability is the long-term impact on food supply. In steep landslide areas

## DISCUSSION

### Extent and characteristics of the rainfall event

Between 23 and 28 November 2025, rainfall ranged from 103 mm in Padang Lawas Utara to 1,003 mm in West Sumatra (Badan Meteorologi, Klimatologi, dan Geofisika: Meteorology, Climatology, and Geophysical Agency [BMKG], local meteorological data). Within the affected West Block, 564 mm fell over the same period, including 2 days exceeding 150 mm (207 and 204 mm).[13] Daily rainfall >150 mm is exceptional and approaches a 100-year return level[14]; multi-day totals near 1,000 mm surpass historically observed extremes. Such extremes are becoming more probable under current climatic conditions, as heavy rainy-season precipitation has intensified across many mountainous regions[15] and extreme events are expected to increase in intensity and likelihood faster than the 7% expected from the Clausius-Clayperon relationship per degree of warming.[14]

where topsoil has disappeared, it will take time before pioneer species become established, providing food to orangutans. Extreme rainfall events can also impact tree growth and mortality in areas not directly impacted by landslides. For example, Dipterocarps and several other species in Malaysian lowland forest[20] showed reduced growth in relation to extreme rainfall in 48% of tree species, while survival decreased in 92% of the species during periods of high rainfall.[21] Orangutans do not normally feed on dipterocarp fruits, but the impact of excessive rain and waterlogged soils on tree growth and phenology likely applies to other tree families, and we expect that fruit and other orangutan food sources have been reduced in the West Block.

Finally, landslide-driven forest damage increases locomotor costs and reduces food availability for orangutans, which are specialized for energy-efficient arboreal travel in continuous canopy forests. Canopy gaps force repeated vertical climbing, among the most metabolically expensive forms of primate locomotion, while disturbance also lowers fruit tree density and increases distances between food patches.[22–26] Increased ground travel in structurally degraded forests further elevates energetic costs and risk.[27] Because orangutans operate near minimal daily energy budgets, even small increases in movement costs can reduce feeding time, impair reproduction, and raise mortality.[23] Consequently, the extensive structural damage documented here likely imposes substantial energetic stress on surviving Tapanuli orangutans, compounding direct mortality with longer-term demographic impacts.

There are currently too many unknowns to determine how the one-off mortality from landslides, changes in food availability, and locomotor costs will affect remaining orangutans in the West Block. Orangutans (*Pongo* sp.) are resilient and survive in a wide range of degraded and fragmented habitats.[28–30] Determining whether such resilience also applies to the Tapanuli orangutan, a refuge species (*sensu* Kerley et al.[31]) surviving in marginal habitat,[32] requires detailed field surveys. Among others, these need to quantify impact on orangutan food availability via tree damage and fruit/flower loss, orangutan nutritional stress levels, and reproductive rates, as well as densities and population trends.

## Climate change link

Cyclone Senyar was an anomalous event, as such storms rarely form in the Strait of Malacca due to its equatorial proximity. The storm formed when bursts of cool continental air swept over the warm waters of the Malacca Strait, creating a shallow but coherent low-level circulation that allowed the cyclone to develop.[33] While not intense in wind strength, the resulting rainfall was catastrophic. In a rapid attribution study, Kew et al.[34] evaluated the inferred contribution of human-induced climate change to the event, alongside the effects of the prevailing La Niña and the negative phase of the Indian Ocean dipole (IOD), both of which amplify heavy rainfall. For the Strait of Malacca, they estimated that the current La Niña and negative IOD conditions contributed about 5%–13% to the rainfall intensity. When estimating the role of climate change in the event,[35] they found that despite relatively large discrepancies between different observation-based datasets, human-induced climate change has likely increased both the intensity and likelihood of such deluges compared with a pre-industrial climate. For the Malacca Strait region, they estimated the increase in extreme rainfall associated with rising global mean temperatures at about 9%–50%.[34] This increasing intensity of such events suggests that the Tapanuli orangutan's remaining habitat is under greater threat than previously recognized.

Globally, including in Southeast Asia, the frequency and intensity of heavy precipitation have risen and are projected to increase further through the 21st century.[36–38] Projections of extreme rainfall in Indonesia[39] show large spatial and seasonal variations but overall suggest an increase in wet extremes during the wet season, with the most extreme events surpassing records from the studied historical period of 1987–2014. The study further finds that in northern Sumatra, the wet season (December to February) is expected to become wetter and the dry season (June to August) drier. Analyzing regional trends, Marzuki et al.[40] found rainfall increases in Central–Northern Sumatra are concentrated from November to February, coinciding with the peak monsoon season, driven by enhanced moisture transport from the Indian Ocean and South China Sea. We expect extreme rainfall events to have increasingly negative impacts on the survival of all three species of orangutan.

## Policy implications

The November 2025 rainfall event underscores the vulnerability of the Tapanuli orangutan, a species for which even marginal increases in mortality or declines in habitat quality can trigger population-level declines. Because the species' persistence hinges on near-zero mortality[41] and the maintenance of stable, high-quality forest, the scale of habitat destruction documented here indicates that current conservation safeguards are insufficient to ensure long-term viability.

The Government of Indonesia has temporarily halted major developments in the Batang Toru landscape, including mining, oil palm, and hydropower expansion.[42] This decision offers a rare opportunity to reassess ecological risks and reset development pathways given the species' extreme vulnerability and the parallel risks posed to human lives. Capitalizing on this momentum will require converting the temporary halt into a structured review process that integrates updated climate-risk assessments, landslide-susceptibility mapping, and habitat-carrying-capacity data to protect the species' habitat. Strengthening and potentially expanding protection of lowland and riparian forests will not only benefit orangutans but also provide flood mitigation and slope stabilization benefits for downstream communities. Furthermore, improving conflict-mitigation capacity is essential, as displaced orangutans may enter human-modified landscapes. Ultimately, a government-led task force could help stabilize the population during the recovery period.

Given that extreme rainfall events are becoming more frequent and that this is—at least in part—a consequence of climate change, the international community shares responsibility to support Indonesia's mitigation efforts. This includes mobilizing rapid biodiversity-recovery financing, providing technical expertise to improve hazard forecasting and ecological restoration planning, and ensuring that global climate-finance mechanisms recognize the losses experienced by the Tapanuli orangutan. International partners can bolster Indonesia's leadership by co-developing green development alternatives that reduce pressure on the Batang Toru ecosystem while providing economic benefits locally.

To operationalize these recommendations, we recommend an immediate moratorium on land-use activities that degrade remaining habitat, alongside the expansion of protected areas around the West Block and key corridors. We recommend urgent consideration of the designation of the Batang Toru ecosystem as a National Strategic Area (*Kawasan Strategis Nasional*), which would provide a stronger legal basis for long-term protection of the species. Civil society groups have underscored that the Batang Toru landscape functions not only as a critical habitat but also as a climate buffer and water source for millions of people and that a strategic national status would enhance coordination across ministries and strengthen oversight of land-use decisions that contribute to ecological degradation and hydrometeorological hazards.[43,44]

The crisis facing the Tapanuli orangutan illustrates the convergence of climate instability, biodiversity loss, and vulnerability, calling for a coordinated response matching the scale of the threat. While Indonesia's immediate actions have created political momentum for decisive conservation measures, sustained international support is essential. Through strengthened domestic protection, climate-responsive planning, and global financial and technical assistance, we can still prevent the first modern extinction of a great ape species—demonstrating a shared commitment to safeguarding irreplaceable biodiversity and the communities that share this landscape in a rapidly changing climate.

## RESOURCE AVAILABILITY

### Lead contact

Requests for further information and resources should be directed to and will be fulfilled by the lead contact, Erik Meijaard (emeijaard@borneofutures.org).

### Materials availability

This study did not generate any new, unique materials.

### Data and code availability

- The shapefile for the landslide scars has been deposited at Data: https://doi.org/10.5281/zenodo.18616925 and is publicly available as of the date of publication.
- This paper does not report original code.
- Any additional information required to reanalyze the data reported in this paper is available from the lead contact upon request.

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## AUTHOR CONTRIBUTIONS

Conceptualization, E.M., D.L.A.G., and S.W.; methods, M.W., S.N., R.D., N.U., and A.D.; writing—original draft preparation, E.M., R.D., P.H., D.S., A.D., H.K., and F.E.L.O.; writing—review and editing, D.S., J.S., E.A., and S.W.; visualization, M.W. and S.N.; supervision, E.M. All authors have read and agreed to the published version of the manuscript.

## DECLARATION OF INTERESTS

E.M. and R.D. are employees and shareholders of Borneo Futures.

## STAR★METHODS

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

- KEY RESOURCES TABLE
- EXPERIMENTAL MODEL AND STUDY PARTICIPANT DETAILS
  - Rationale and study area
- METHOD DETAILS
- QUANTIFICATION AND STATISTICAL ANALYSIS
  - Accuracy assessment

## SUPPLEMENTAL INFORMATION

Supplemental information can be found online at https://doi.org/10.1016/j.cub.2026.05.029.

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## REFERENCES

1. Nater, A., Mattle-Greminger, M.P., Nurcahyo, A., Nowak, M.G., de Manuel, M., Desai, T., Groves, C., Pybus, M., Sonay, T.B., Roos, C., et al. (2017). Morphometric, Behavioral, and Genomic Evidence for a New Orangutan Species. Curr. Biol. *27*, 3487–3498.e10. https://doi.org/10.1016/j.cub.2017.09.047.
2. Laurance, W.F., Wich, S.A., Onrizal, O., Fredriksson, G., Usher, G., Santika, T., Byler, D., Mittermeier, R., Kormos, R., Williamson, E.A., et al. (2020). Tapanuli orangutan endangered by Sumatran hydropower scheme. Nat. Ecol. Evol. *4*, 1438–1439. https://doi.org/10.1038/s41559-020-1263-x.
3. Wich, S.A., Singleton, I., Nowak, M.G., Utami Atmoko, S.S., Nisam, G., Arif, S.M., Putra, R.H., Ardi, R., Fredriksson, G., Usher, G., et al. (2016). Land-cover changes predict steep declines for the Sumatran orangutan (*Pongo abelii*). Sci. Adv. *2*, e1500789. https://doi.org/10.1126/sciadv.1500789.
4. Wich, S.A., Fredriksson, G., Usher, G., Kühl, H.S., and Nowak, M.G. (2019). The Tapanuli orangutan: Status, threats and steps for improved conservation. Cons. Sc. Pract. *1*, e33. https://doi.org/10.1111/csp2.33.
5. Marshall, A.J., Lacy, R., Ancrenaz, M., Byers, O., Husson, S.J., and Leighton, M. (2009). Orangutan population biology, life history, and conservation. Perspectives from population viability analysis models. In Orangutans: Geographic Variation in Behavioral Ecology and Conservation, S. Wich, S.U. Atmoko, T.M. Setia, and C.P. van Schaik, eds. (Oxford University Press), pp. 311–326.
6. Wich, S.A., Ni'Matullah, S., Sherman, J., and Meijaard, E. (2023). Spatial Data for *P. tapanuliensis* Red Listing (Borneo Futures). IUCN. *Pongo tapanuliensis*. The IUCN Red List of Threatened Species. https://doi.org/10.2305/IUCN.UK.2023.RLTS.T120588639A120588662.en. https://www.iucnredlist.org/species/120588639/120588662. e.T120588639A120588662.
7. Ardi, R. (2023). Ekologi Suksesi Habitat Orangutan Sumatera di Hutan Dataran Rendah dan Hutan Rawa Gambut. MSc Dissertation (Medan, Indonesia: Universitas Sumatera Utara.). https://repositori.usu.ac.id/handle/123456789/87752.
8. Cho, S.E. (2017). Prediction of shallow landslide by surficial stability analysis considering rainfall infiltration. Eng. Geol. *231*, 126–138. https://doi.org/10.1016/j.enggeo.2017.10.018.
9. Alonso, E.E. (2021). Triggering and motion of landslides. Géotechnique *71*, 3–59. https://doi.org/10.1680/jgeot.20.RL.001.
10. Froude, M.J., and Petley, D.N. (2018). Global fatal landslide occurrence from 2004 to 2016. Nat. Hazards Earth Syst. *18*, 2161–2181. https://doi.org/10.5194/nhess-18-2161-2018.

11. Singleton, I., and van Schaik, C.P. (2001). Orangutan Home Range Size and Its Determinants in a Sumatran Swamp Forest. Int. J. Primatol. *22*, 877–911. https://doi.org/10.1023/a:1012033919441.

12. Khadka, N.S. (2025). Fears grow that world's rarest apes were swept away in Sumatran floods. BBC News. BBC. https://www.bbc.com/news/articles/cj4q1l0ly7wo

13. Agincourt Resources (2025). Agincourt Resources' Response to the Garoga Flood: Fast, Fact-Based Action. https://agincourtresources.com/2025/12/02/agincourt-resources-response-to-the-garoga-flood-fast-fact-based-action. Agincourt Resources.

14. Gründemann, G.J., van de Giesen, N., Brunner, L., and van der Ent, R. (2022). Rarest rainfall events will see the greatest relative increase in magnitude under future climate change. Commun. Earth Environ. *3*, 235. https://doi.org/10.1038/s43247-022-00558-8.

15. Pepin, N.C., Arnone, E., Gobiet, A., Haslinger, K., Kotlarski, S., Notarnicola, C., Palazzi, E., Seibert, P., Serafin, S., Schöner, W., et al. (2022). Climate Changes and Their Elevational Patterns in the Mountains of the World. Rev. Geophys. *60*, RG000730. https://doi.org/10.1029/2020RG000730.

16. Hastuty, I.P., and Ahmad, F. (2024). Landslide Analysis Using Geographic Information System (GIS) in South Tapanuli Regency. held in Singapore. 2024, H. Hazarika, S.K. Haigh, B. Chaudhary, M. Murai, and S. Manandhar, eds. (Springer Nature), pp. 297–307.

17. Samosir, A.G.M.B., Sutisna, S., Prakoso, L.Y., and Wilopo, W. (2025). Analysis of Landslide Disaster Vulnerability in North Tapanuli Regency Using a Grid-Based Geographic Information System Approach. Multidisc, Res. *4*, 4485–4498. https://doi.org/10.55927/eajmr.v4i9.380.

18. Emery Thompson, M., and Sabbi, K. (2024). Evolutionary Demography of the Great Apes. Ch. 19. In Human Evolutionary Demography, O. Burger, R. Lee, and R. Sear, eds. (Open Book Publishers), pp. 423–474. https://doi.org/10.11647/OBP.0251.19.

19. Wich, S.A., Atmoko, S.U., Setia, T.M., and van Schaik, C. (2009). Orangutans. Geographic Variation in Behavioral Ecology and Conservation (Oxford University Press). https://doi.org/10.1093/acprof:oso/9780199213276.001.0001.

20. Margrove, J.A., Burslem, D.F.R.P., Ghazoul, J., Khoo, E., Kettle, C.J., and Maycock, C.R. (2015). Impacts of an Extreme Precipitation Event on Dipterocarp Mortality and Habitat Filtering in a Bornean Tropical Rain Forest. Biotropica *47*, 66–76. https://doi.org/10.1111/btp.12189.

21. O'Brien, M.J., Hector, A., Ong, R., and Philipson, C.D. (2024). Tree growth and survival are more sensitive to high rainfall than drought in an aseasonal forest in Malaysia. Commun. Earth Environ. *5*, 179. https://doi.org/10.1038/s43247-024-01335-5.

22. Knott, C.D. (1998). Changes in Orangutan Caloric Intake, Energy Balance, and Ketones in Response to Fluctuating Fruit Availability. Int. J. Primatol. *19*, 1061–1079. https://doi.org/10.1023/A:1020330404983.

23. Vogel, E.R., Knott, C.D., Crowley, B.E., Blakely, M.D., Larsen, M.D., and Dominy, N.J. (2011). Bornean orangutans on the brink of protein bankruptcy. Biol. Lett. *8*, 333–336. https://doi.org/10.1098/rsbl.2011.1040.

24. Halsey, L.G., Coward, S.R.L., and Thorpe, S.K.S. (2016). Bridging the gap: parkour athletes provide new insights into locomotion energetics of arboreal apes. Biol. Lett. *12*, 20160608. https://doi.org/10.1098/rsbl.2016.0608.

25. Thorpe, S.K., Crompton, R.H., and Alexander, R.M. (2007). Orangutans use compliant branches to lower the energetic cost of locomotion. Biol. Lett. *3*, 253–256. https://doi.org/10.1098/rsbl.2007.0049.

26. Widyastuti, K., Reuillon, R., Chapron, P., Abdussalam, W., Nasir, D., Harrison, M.E., Morrogh-Bernard, H., Imron, M.A., and Berger, U. (2022). Assessing the impact of forest structure disturbances on the arboreal movement and energetics of orangutans—An agent-based modeling approach. Front. Ecol. Evol. *10*, 983337. https://doi.org/10.3389/fevo.2022.983337.

27. Spehar, S.N., and Rayadin, Y. (2017). Habitat use of Bornean Orangutans (*Pongo pygmaeus morio*) in an Industrial Forestry Plantation in East Kalimantan, Indonesia. Int. J. Primatol. *38*, 358–384. https://doi.org/10.1007/s10764-017-9959-8.

28. Ancrenaz, M., Ambu, L., Sunjoto, I., Ahmad, E., Manokaran, K., Meijaard, E., and Lackman, I. (2010). Recent surveys in the forests of Ulu Segama Malua, Sabah, Malaysia, show that orang-utans (*P. p. morio*) can be maintained in slightly logged forests. PLoS One *5*, e11510. https://doi.org/10.1371/journal.pone.0011510.

29. Ancrenaz, M., Oram, F., Ambu, L., Lackman, I., Ahmad, E., Elahan, H., Kler, H., Abram, N.K., and Meijaard, E. (2015). Of pongo, palms, and perceptions – A multidisciplinary assessment of orangutans in an oil palm context. Oryx *49*, 465–472. https://doi.org/10.1017/S0030605313001270.

30. Meijaard, E., Albar, G., Nardiyono, Y., Rayadin, Y., Ancrenaz, M., and Spehar, S. (2010). Unexpected ecological resilience in Bornean Orangutans and implications for pulp and paper plantation management. PLoS One *5*, e12813. https://doi.org/10.1371/journal.pone.0012813.

31. Kerley, G.I.H., Kowalczyk, R., and Cromsigt, J.P.G.M. (2012). Conservation implications of the refugee species concept and the European bison: king of the forest or refugee in a marginal habitat? Ecography *35*, 519–529. https://doi.org/10.1111/j.1600-0587.2011.07146.x.

32. Meijaard, E., Ni'matullah, S., Dennis, R., Sherman, J., Onrizal, and Wich, S.A. (2021). The historical range and drivers of decline of the Tapanuli orangutan. PLoS One *16*, e0238087. https://doi.org/10.1371/journal.pone.0238087.

33. Qing, A., and Begum, S. (2025). Cyclone Senyar was rare for Southeast Asia – could a storm like it ever hit Singapore? The Straits Times via Asia News Network. Singapore Press Holdings (SPH). https://asianews.network/cyclone-senyar-was-rare-for-southeast-asia-could-a-storm-like-it-ever-hit-singapore/.

34. Kew, S., Zachariah, M., Barnes, C., Rajapakse, L., and Basconcillo, J. (2025). Increasing heavy rainfall and extreme flood heights in a warming climate threaten densely populated regions across Sri Lanka and the Malacca Strait. World Weath. Attr. Sci. Rep. *78*, 126259. https://doi.org/10.25560/126259.

35. van Oldenborgh, G.J., van der Wiel, K., Kew, S., Philip, S., Otto, F., Vautard, R., King, A., Lott, F., Arrighi, J., Singh, R., et al. (2021). Pathways and pitfalls in extreme event attribution. Ch. 166. Clim. Change *166*, 13. https://doi.org/10.1007/s10584-021-03071-7.

36. Alexander, L.V., and Arblaster, J.M. (2017). Historical and projected trends in temperature and precipitation extremes in Australia in observations and CMIP5. Weather Clim. Extremes *15*, 34–56. https://doi.org/10.1016/j.wace.2017.02.001.

37. Seneviratne, S.I. (2023). Weather and Climate Extreme Events in a Changing Climate. In Climate Change, V. Masson-Delmotte, P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, and M.I. Gomis, et al., eds. (Cambridge University Press), pp. 1513–1766. https://doi.org/10.1017/9781009157896.013.

38. Singh, V., and Qin, X. (2020). Study of rainfall variabilities in Southeast Asia using long-term gridded rainfall and its substantiation through global climate indices. J. Hydrol. *585*, 124320. https://doi.org/10.1016/j.jhydrol.2019.124320.

39. Kurniadi, A., Weller, E., Salmond, J., and Aldrian, E. (2024). Future projections of extreme rainfall events in Indonesia. Int. J. Clin. Med. *44*, 160–182. https://doi.org/10.1002/joc.8321.

40. Marzuki, M., Ramadhan, R., Yusnaini, H., Vonnisa, M., Muharsyah, R., Nugraha, Y., Sari, A.Y., and Erajalita, A. (2025). Long-Term Spatial–Temporal Variability, Trends and Extreme Rainfall Events Over Indonesia Based on 43 Years of CHIRPS Data. Int. J. Clin. Med. *45*, e70107. https://doi.org/10.1002/joc.70107.

41. Wich, S., and Meijaard, E. (2021). Saving the Tapanuli orangutan requires zero losses. Oryx *55*, 10–11. https://doi.org/10.1017/S0030605320001052.

42. Wirayani, P. (2025). Indonesia Halts Agincourt, PTPN III Operations After Floods. Bloomberg. Bloomberg L.P. https://www.bloomberg.com/news/articles/2025-12-06/indonesia-halts-agincourt-ptpn-iii-operations-after-floods.

43. Manaf, A. (2025). Green Justice Desak Pemerintah Tetapkan Ekosistem Batang Toru Jadi Kawasan Strategis Nasional. RMOLSumut. Rakyat Merdeka Online (RMOL). https://www.rmolsumut.id/green-justice-desak-pemerintah-tetapkan-ekosistem-batang-toru-jadi-kawasan-strategis-nasional.

44. Wicaksono, R.A. (2025). Ekosistem Batang Toru Diminta Jadi Kawasan Strategis Nasional. Betahita. Betahita.id. https://betahita.id/news/detail/11641/ekosistem-batang-toru-diminta-jadi-kawasan-strategis-nasional.html?v=1765508098.

45. ESRI. (2024). ArcGIS Pro (Environmental Systems Research Institute, Inc.). https://www.esri.com/en-us/arcgis/products/arcgis-pro/overview.

46. European Space Agency (ESA). (2024). Copernicus Sentinel Data. Sentinel-2 User Guide (European Space Agency). https://browser.dataspace.copernicus.eu/.

47. Planet Labs. PBC. (2024). PlanetScope Imagery Product Specifications. Planet Labs PBC. https://www.planet.com/products/planet-imagery/.

48. Kiribou, R., Tehoda, P., Chukwu, O., Bempah, G., Kühl, H.S., Ferreira, J., Sop, T., Carvalho, J., Mengel, M., Kulik, L., et al. (2024). Exposure of African ape sites to climate change impacts. PLoS Clim. *3*, e0000345. https://doi.org/10.1371/journal.pclm.0000345.

49. Garrido-Pérez, E.I., Dupuy, J.M., Durán-García, R., Ucan-May, M., Schnitzer, S.A., and Gerold, G. (2008). Effects of lianas and Hurricane Wilma on tree damage in the Yucatan Peninsula, Mexico. J. Trop. Ecol. *24*, 559–562. https://doi.org/10.1017/S0266467408005221.

50. Putz, F.E. (1984). The natural history of lianas on Barro Colorado Island, Panama. Ecology *65*, 1713–1724. https://doi.org/10.2307/1937767.

51. Negrón-Juárez, R.I., Chambers, J.Q., Guimaraes, G., Zeng, H., Raupp, C.F.M., Marra, D.M., Ribeiro, G.H.P.M., Saatchi, S.S., Nelson, B.W., and Higuchi, N. (2010). Widespread Amazon forest tree mortality from a single cross-basin squall line event. Geophys. Res. Lett. *37*, L16701. https://doi.org/10.1029/2010GL043733.

52. Olofsson, P., Foody, G.M., Herold, M., Stehman, S.V., Woodcock, C.E., and Wulder, M.A. (2014). Good practices for estimating area and assessing accuracy of land change. Remote Sens. Environ. *148*, 42–57. https://doi.org/10.1016/j.rse.2014.02.015.

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## STAR★METHODS

### KEY RESOURCES TABLE

| REAGENT or RESOURCE | SOURCE | IDENTIFIER |
|---|---|---|
| Basemaps and World Topographic Map Layer | ESRI[45] | https://www.esri.com/en-us/arcgis/products/arcgis-pro/overview |
| Sentinel-2 imagery | Copernicus Sentinel Data[46] | https://browser.dataspace.copernicus.eu/ |
| Planetscope imagery | Planet Labs PBC[47] | https://www.planet.com/products/planet-imagery/ |

### EXPERIMENTAL MODEL AND STUDY PARTICIPANT DETAILS

#### Rationale and study area

Despite a century of research, the impacts of extreme rainfall on great apes remain unquantified,[48] placing the present study in uncharted territory. Likewise, no studies have assessed the structural vulnerability of Batang Toru's forests to compound hazards like landslides and flooding, despite analyses identifying the broader landscape as susceptible.[16,17] Here, we provide quantitative evidence that a single extreme weather event may have severely impacted the Tapanuli orangutan. Unlike modelled catastrophes that assume no lasting reproductive impacts, this event's habitat destruction likely reduced population viability through two pathways: 1) direct mortality and (2) reduced food availability and increased energetic stress that lowers fecundity. We focus on the primary pathway by mapping pre-and post-event habitat in the Batang Toru West Block ("West Block" hereafter), the species' largest remaining stronghold. We quantify land-cover changes, and integrate predictive density surfaces[3] to estimate landslide-related mortality and potential population-level impacts. Given these findings and the potential impacts to the species' long-term survival, we provide recommendations to avert its extinction.

We focused our analysis on the West Block of Tapanuli orangutan habitat north of the Batang Toru River using the boundary of the resident ("Extant") population from the IUCN Red List account for *P. tapanuliensis*.[6] The study area covers 71,161 ha.

### METHOD DETAILS

We used four Sentinel-2 Level 2A images to determine land cover before and after the late November extreme weather event. These images were dated 27 October 2025 (pre-event image), 3 December 2025, 23 December 2025, and 26 December 2025. We cropped each image to the West Block of the Tapanuli orangutan range. The analysis was aided by two *PlanetScope* 3 m resolution multispectral images dated 3 and 23 December 2025, which covered 18% and 95% of the study area respectively. This high-resolution imagery was provided courtesy of Mighty Earth and Planet.

The initial analysis relied on a Sentinel-2 image acquired on 3 December 2025, but this scene had 36% cloud cover over the study area. For the present analysis, we used imagery with substantially lower cloud cover, primarily the Sentinel-2 scene from 23 December 2025 (6.94% cloud cover). Residual clouded areas in this image were supplemented with cloud-free pixels from Sentinel-2 scenes acquired on 3 and 26 December 2025 (the latter with 9.26% cloud cover) and, where available, from 3 m resolution *PlanetScope* imagery. Although the 23 December *PlanetScope* scene provided higher spatial resolution, it became available only after the Sentinel-2 classification had been completed. Given the high classification accuracy achieved with Sentinel-2, we did not re-run the classification using *PlanetScope* data alone; instead, *PlanetScope* imagery was used to support visual interpretation and accuracy assessment. The pre-event baseline was derived from a Sentinel-2 image acquired on 27 October 2025 (5.61% cloud cover), selected as the most suitable cloud-minimized scene prior to the rainfall event.

We applied a Support Vector Machine (SVM) classification model (ESRI ArcGIS Pro) to distinguish between three land-cover classes: forest, bare soil, and cloud or cloud shadow. We collected the training data by visually interpreting the Sentinel-2 images. Landslides are clearly visible in the 10 m true colour composites due to the strong spectral contrast with surrounding forest. We generated two land-cover maps using (1) the pre-event image and (2) the post-event image. For the post-event land cover, we then identified landslide and flood scouring scars as pixels that changed from the 'forest' class in the pre-event classification to the 'bare soil' class in the post-event classification. 'Bare soil' pixels classified as such in the pre- and post-event maps were labelled as 'pre-event bare soil'. Thus, the resulting post-event land cover has four classes: forest, scar (post-event bare soil), pre-event bare soil, and cloud or cloud shadow.

We used the 3-meter resolution *PlanetScope* imagery to look in more detail at whether we could identify any visual edge effects around flood and landslide scars (e.g., fallen trees, broken canopy), but no such damage was visible. It seems that most of the landslides occurred in patches of up to a few to a hundred hectares where probably initial tree falls pulled down trees, creating a downslope domino effect. Such effects have been demonstrated following hurricanes in Mexican rainforest[49] and Panama,[50] for example, while half a billion trees were estimated to have died following a single squall line across the Amazon.[51]

## QUANTIFICATION AND STATISTICAL ANALYSIS

### Accuracy assessment

We conducted an accuracy assessment on the pre- and post-event land-cover classification result (Table S1, Table S2). Adhering to the good practice framework of Olofsson et al.,[52] we applied a stratified random sampling design to assess map accuracy, using the ESRI ArcGIS Pro Generate Random Sample tool. To ensure statistical rigour, we moved beyond simple pixel counting, instead using an error-adjusted estimator. This approach provided unbiased area estimates for forest loss and landslide scars, complete with 95% confidence intervals to quantify the precision of our results.

For the post-event land-cover classification, 350 validation points were generated across the four target classes: clouds/shadows (n = 100), scars (n = 100), forest (n = 100), and pre-event bare soil (n = 50). We visually interpreted these sample points and assigned a reference (ground-truth) label based on multi-temporal Sentinel-2 imagery from 3, 23, and 26 December 2025, which was further supported by high-resolution (3 m) *PlanetScope* imagery acquired on 3 December 2025. To accurately interpret pre-event bare soil from landslide scars, we additionally visualized the pre-event Sentinel-2 imagery acquired on 27 October 2025. For the pre-event land-cover classification, a total of 300 validation points were generated across three target classes: clouds/haze (n = 100), forest (n = 100), and pre-event bare soil (n = 100). These sample points were visually interpreted and assigned reference (ground-truth) labels based on the pre-event Sentinel-2 imagery acquired on 27 October 2025.

The classification accuracy assessment for the baseline (pre-event) land-cover classification was high with an overall accuracy of 99.8% (Table S2). The forest class achieved a user's accuracy of 100% and a producer's accuracy of 99.8%, indicating nearly perfect alignment between the map and the reference data for this class. Other classes, including clouds/haze and pre-event bare soil, showed high reliability with user's accuracies of 97.0% and 96.0%, respectively. The adjusted extent of forest cover prior to the extreme weather event was 66,833.4 ± 135 ha. For areas of cloud (5.61%) on the pre-event image we visually checked imagery from August 2025 and confirmed that all cloud on the pre-event image was forest. This provided an accurate baseline to measure forest loss attributed to the landslides.

### *Assessing impact on orangutans*

To estimate the number of orangutans affected by the rainfall-event, we used 1x1 km grid-cell orangutan density data that had been generated through a predictive model using environmental and human-impact variables, that included elevation, habitat conditions (forest cover, forest type, aboveground carbon), human pressure (population density, distance to roads), and climate (annual rainfall, rainfall variability, mean annual temperature, temperature range).[3] While this represents the most comprehensive available dataset, we acknowledge potential changes in distribution since 2016 due to ongoing threats, e.g., habitat fragmentation.[2] To each scar polygon we assigned the density of the corresponding grid cell in which the scar was located. We estimated the total number of orangutans directly affected by multiplying the scar area with density. The estimate has uncertainty from both the scar-area estimate (±1,760 ha, see main text) and the density model estimate (95% CI: 180–1,201 individuals;[3,4]). Because the scar-area confidence interval is narrower (±21%) compared with the density-model uncertainty, we approximate the 95% CI on impacted orangutans by proportionally scaling the point estimate with the published total-population CI.