Connectivity for the conservation of Borneo's biodiversity

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ABSTRACT

Ecological connectivity is fundamental to biodiversity conservation and climate adaptation, facilitating species movement, genetic exchange, and ecological function across landscapes. In Borneo, connectivity is increasingly threatened by deforestation, agricultural expansion, infrastructure development, and urbanization, leading to habitat fragmentation and isolation. This chapter examines the status of connectivity in Borneo, highlighting key threats, existing conservation initiatives, and strategies to enhance connectivity across the island's diverse landscapes. Major impediments include widespread habitat loss from oil palm plantations, infrastructure projects such as the Pan-Borneo Highway, and the relocation of Indonesia's capital to East Kalimantan. These developments reduce habitat permeability, disrupt wildlife corridors, and limit species' ability to track climate-driven shifts in suitable habitat. Conservation efforts, including the Heart of Borneo Initiative and regional connectivity projects in Sabah and Sarawak, have sought to mitigate these impacts by expanding protected area networks, restoring habitat corridors, and integrating connectivity into land-use planning. However, challenges remain, including governance complexities, enforcement gaps, and financial constraints. This chapter outlines pathways for strengthening connectivity through large-scale land-use planning, Indigenous and community-led conservation, restoration and reforestation, and improved monitoring of connectivity effectiveness. A case study from Sabah demonstrates the potential for data-driven conservation planning to optimize protected area expansion while enhancing

connectivity for climate resilience and species persistence. Ultimately, ensuring ecological connectivity in Borneo will require coordinated action across Brunei Darussalem, Malaysia, Indonesia, and alongside sustained investment in conservation science, policy, and enforcement.

KEYWORDS

connectivity, habitat corridors, deforestation, climate resilience, biodiversity conservation, land-use planning, ecological restoration, protected areas, species movement

THE ECOLOGY OF CONNECTIVITY

Ecological connectivity, defined as the movement of organisms and the flow of natural processes across landscapes and seascapes, is a fundamental component of biodiversity conservation and climate adaptation (Brodie et al. 2025). As such, connectivity is incorporated into conservation planning around the world, albeit at a variety of scales ranging from wildlife overpasses across roads (Corlatti et al. 2009) to habitat corridors linking protected areas (Brodie et al. 2016a, Struebig et al. 2024) to trans-national treaties promoting movement across regional and continental scales (Novianto 2012). Connectivity forms a critical part of the Kunming–Montreal Global Biodiversity Framework's (UN-CBD 2022) "30 × 30" initiative, which aims to designate 30% of the Earth's surface as *well-connected* protected areas by 2030.

Connectivity is important to the persistence of many species and populations (Brodie et al. 2025). While some taxa are adapted to living in isolated populations (Tilman 1988), many plants and animals require movements across the landscape to find food, space, mates, or other critical resources. Corridors can enhance dispersal, leading to increased fitness, greater population abundance, and higher species diversity (Gilbert-Norton et al. 2010, Resasco 2019). Conversely, loss of connectivity in fragmented habitats contributes to higher extinction risks across a range of ecosystems and taxa (Johnson et al. 2018, Magris et al. 2018, Valenzuela-Aguayo et al. 2020, Cecino and Treml 2021). Connectivity becomes even more important in our rapidly changing climate. As abiotic conditions change, many species need to shift their ranges to track suitable climate niches

(McElwain 2018, Carrera et al. 2022), making the maintenance or restoration of landscape-scale connectivity a critical tool for enhancing ecological climate resilience.

Beyond its role in population dynamics, connectivity is integral to the maintenance of ecosystem processes, including ecosystem services that benefit humans (Brodie et al. 2025). Corridors help sustain species that contribute to ecosystem stability, such as trees that regulate water quality and store carbon (Ziter et al. 2013, Grass et al. 2019), as well as maintain key ecological interactions, such as pollination and pest control that affect agricultural productivity (Mitchell et al. 2013, Lamy et al. 2016).

Despite its fundamental role in ecology and conservation, connectivity should not be viewed as an end-point conservation goal in and of itself, but rather as a mechanism for ensuring biodiversity persistence. Consequently, efforts to quantify connectivity for assessment and monitoring should focus on its contribution to species survival and ecosystem function. While the spatial target of the 30 × 30 initiative—protecting 30% of land and sea—can be measured directly, the criterion of being "well-connected" has been more difficult to define. Determining whether protected areas or landscapes meet this standard requires a clear operational framework. Here, we adopt the definition proposed by Brodie et al. (2025: 4), which states that "A landscape, seascape, or protected area network is well-connected if organismal movement is sufficient to maintain the long-term persistence of focal taxa, sustain ecological functions, or support the provision of ecosystem services, relative to counterfactuals with equivalent habitat availability but no barriers to movement." This definition emphasizes that connectivity should be evaluated in relation to its ecological outcomes rather than simply the presence of corridors or linkages.

THE STATUS OF CONNECTIVITY IN BORNEO

Terrestrial connectivity status

The expansion of agriculture, particularly oil palm plantations, has driven extensive habitat loss and fragmentation in Borneo, severely impacting biodiversity and ecosystem connectivity. Habitat conversion has led to significant declines in forest-dependent species, with population connectivity decreasing as landscapes become increasingly fragmented. For instance, projections indicate that between 2000 and 2020, the proportion of the landscape connected by dispersal for Sunda clouded leopards declined by nearly 58%, with their largest continuous habitat patches shrinking by over 60% and population size dropping by an estimated 62.5% (Macdonald et al. 2018). The impacts of fragmentation extend beyond individual species, as loss of contiguous forest disrupts ecological processes, genetic exchange, and species interactions. Connectivity models suggest that clouded leopard movement is facilitated by intact forest canopies and impeded in open areas and plantations (Hearn et al. 2018). Ongoing expansion of plantations continues to isolate populations, reducing the ability of species to move between habitat patches, increasing their vulnerability to climate change, and ultimately threatening long-term species persistence (Proctor et al. 2011).

Infrastructure development, particularly roads, pipelines, and rail lines, poses another major threat to connectivity in Borneo. The Pan-Borneo Highway, along with other large-scale infrastructure projects, is fragmenting forested landscapes, reducing habitat connectivity for species with large home ranges, and disrupting migration corridors (Sloan et al. 2019). There is also a proposal for a Trans-Borneo Railway (Yiau 2025); this could help transform Borneo into a nexus for regional trade (Lee et al. 2024), though would certainly fragment more forests (Goh 2020). In Sabah, planned road developments are projected to separate two major clusters of protected areas that together account for one-quarter of the region's total protected area, undermining the ecological integrity of conservation efforts within the Heart of Borneo (Sloan et al. 2019). In Kalimantan, planned and ongoing road and rail developments are expected to sharply reduce connectivity, with overall landscape permeability declining from 89% to 55% if these projects proceed (Alamgir et al. 2019). Infrastructure expansion also facilitates other forms of habitat degradation such as illegal logging, land colonization, and mining in previously intact forests (Alamgir et al. 2019). While some mitigation measures have been proposed, such as highway underpasses and corridor restoration projects, their implementation remains uncertain due to financial and logistical constraints, highlighting the need for stronger planning and legal protections to prevent irreversible fragmentation (Sloan et al. 2019).

Urban expansion is further exacerbating habitat fragmentation in Borneo, particularly with the rapid development of large-scale infrastructure projects such as the relocation of Indonesia's capital to East Kalimantan. This transition is expected to introduce extensive road networks and settlements, intensifying deforestation and disrupting remaining forest corridors (Kaszta et al. 2020). Core habitats for species such as the Sunda clouded leopard are already highly fragmented, with only 34% of Borneo's land area providing connected habitat, and much of this remains unprotected (Kaszta et al. 2020). The Pan-Borneo Highway alone is expected to contribute to 28% of the total predicted connectivity loss, with substantial impacts extending even into protected areas (Kaszta et al. 2020). The Pan-Borneo Highway will spur more roads to be constructed further inland, resulting in connectivity loss for large tracts of forests (Dayak Daily 2025). The relocation of Indonesia's capital has been identified as the single largest infrastructure-driven threat to habitat connectivity, accounting for 66% of projected connectivity loss across the island (Spencer et al. 2023). Although direct development impacts will primarily occur within a 30 km radius, secondary effects such as urban sprawl, local community displacement, road expansion, and increased resource extraction could extend up to 200 km, threatening lowland forests and critical habitats for wildlife (Spencer et al. 2023).

Aquatic connectivity status

Infrastructure development and urban expansion not only impact connectivity in forests and other terrestrial habitats, but also in less-highlighted aquatic environments such as rivers and wetlands. Water flow is a key factor for biodiversity in rivers (O'Keeffe and Quesne 2009), supporting the life cycles of aquatic organisms such as catadromous fishes, the transport of sediments and nutrients that build the physical habitats of streams and deltas, and providing flushes to replenish floodplains. Water flow connects upstream and downstream portions of rivers (longitudinal linkage) and connects rivers to wetlands and floodplains (lateral linkage). Infrastructure such as dams, dykes, and roads built across rivers create barriers to water flow and disrupt the biological and fluvial processes that the rivers support, creating fragmented systems that change habitats and their ability to support life. The ability of freshwater ecosystems to sustain biodiversity and deliver many ecosystem services is governed by the degree to which their natural flow regime and connectivity are maintained (Thieme et al. 2023).

There is an increasing trend of dam development in Borneo. Rivers where dams have been built or are in progress include the Kayan river cascade (Kayan hydropower dam and Mentarang Induk hydropower dam) (Koswaraputra 2024), the Murum, Balui, and

Baleh rivers in the Rajang basin of Sarawak, and the Sabah Ulu Padas hydropower dam (SEC 2023). The Kayan river cascade aims to provide energy for Indonesia's new capital, Nusantara. Sarawak has also announced that it is exploring the feasibility of dams on the Gaat, Tutoh, and Belaga rivers (Then 2024). Information on how dams have fragmented river stretches and impeded the movement of fishes and other aquatic life is scarce, constituting an important gap in knowledge. Assessment of the degree of fragmentation and the degree of water flow regulation from dams in Borneo is also lacking or is available only at course scales that are insufficient to guide local management. Some relevant information is available from the WWF Water Risk Filter (WWF 2025b), which provides spatial assessments of river fragmentation in several river basins in Brunei, Kalimantan, Sabah, and Sarawak; rivers in Sarawak's Rajang Basin have a higher degree of risk, likely from the multiple large hydropower dams that are developed within this single basin.

Barriers to movements in river have a particularly strong impact on migratory species. Long distance migratory freshwater fish species are not common in Borneo. Currently known are the catadromous eels (*Anguilla marmorata*), which have been found in Brunei's Temburong River (Zan et al. 2020) and Sabah's Papar River (Wong et al. 2017). Catadromous species migrate between inland waters and coastal habitats, spawning offshore (Wong et al. 2017). There are no dam developments within these rivers, with the Paper dam currently being put on-hold by the Sabah government (Miwil 2025). Several species have short-distance migration, for example mahseers (Cyprininae; locally known as 'Semah' and 'Empurau') that travel from the main stem river to smaller tributaries. Studies are currently ongoing to assess the impact of dams, particularly in the Baleh River, on these movements. Apart from the more direct impact of dams via impeding fish movements, such infrastructure also exerts a broader spectrum of ecological change in terms of altering water flow, hydrological regimes, fluvial sediment processes, and the life cycles of aquatic taxa that are evolved to particular flow regimes in natural, free-flowing rivers.

Borneo has extensive river networks throughout the island and opportunities remain to ensure that free-flowing rivers are protected where they are of high conservation value. This requires a concerted effort, engaging diverse stakeholders, to do land use planning at landscape and riverscape scales. Rivers and wetlands are connected to the terrestrial habitats in their catchment; as such, watersheds provide a useful management unit that incorporates both aquatic and terrestrial biodiversity. Riparian forests benefits river and wetland ecosystems by filtering sediments to reduce pollution and providing food for aquatic organisms while also providing habitat and corridors for terrestrial wildlife. By using hydrological units such as river basins, watersheds, or catchments as the basis for land use planning, it becomes possible to integrate hydrological considerations for freshwater ecosystem health alongside efforts to conserve forest habitats and maintain landscape connectivity. Adopting approaches such as integrated river basin or integrated watershed managements is one possible way forward.

Policy and governance challenges

Institutional and governance challenges present significant obstacles to maintaining ecological connectivity in Borneo (Brodie et al. 2016b). Unlike Peninsular Malaysia, where federally mandated National Physical Plans guide spatial planning, land-use decisions in Sabah and Sarawak fall under state jurisdiction, leading to a more fragmented governance structure (Taib and Siong 2008). While the Heart of Borneo Initiative provides a broad framework for cross-border connectivity planning, implementing connectivity measures at smaller spatial scales often requires state-led approaches that account for diverse land tenures and stakeholders (WWF 2007). For example, the establishment of a central Sabah corridor was facilitated by state control over the land through the Sabah Foundation, allowing for re-designation of land-use activities rather than complex multi-stakeholder negotiations. By contrast, the Sabah EcoLinc corridor, situated on community-owned land, required extensive consultations to align conservation goals with local interests (Vaz and Agama 2013). In West Kalimantan, recent governance reforms have begun to integrate connectivity directly into spatial planning policy. Several connectivity areas have been recognized as Provincial Strategic Areas including the Kubu Estuary Area, the Pawan-Sekadau-Pinoh Watershed, and the Embau Multispecies Corridor near Betung Kerihun–Danau Sentarum National Park. These areas are designated for biodiversity conservation and ecosystem services protection, including corridors for species like orangutans (*Pongo pygmaeus*) and gibbons (*Hylobates* spp.), as well as riparian habitats critical for flood regulation and water security.

Ensuring long-term political commitment to connectivity initiatives remains a major challenge, as conservation priorities often compete with economic development interests (Brodie et al. 2016b). Without sustained political support, designated connectivity areas risk becoming "paper corridors" subject to illegal encroachment, deforestation, and hunting (Jain et al. 2014). In Malaysia, protected areas and connectivity plans have been weakened in the past through de-gazettement or land-use changes driven by development pressures (Heng 2012, Hedges et al. 2013, Bernard et al. 2014). Even where legal protections exist, enforcement gaps further undermine corridor effectiveness, largely due to lack of funding as developmental budgets are often prioritized. Insufficient enforcement capacity, weak legal deterrents for offenders, and poor coordination between federal and state agencies have been identified as key barriers to effective conservation in Malaysia (Nagulendran et al. 2014). Narrow corridors in particular can become vulnerable to poaching and illegal activities, potentially turning them into ecological traps rather than functional linkages (Clements et al. 2010, Brodie et al. 2015b). Addressing these governance challenges requires strengthening cross-jurisdictional collaboration, ensuring consistent enforcement, and integrating connectivity planning into broader land-use policies to balance conservation and development needs.

CONNECTIVITY FOR CLIMATE CHANGE RESILIENCE

Maintaining and restoring connectivity is one of the most effective tools for promoting population and community resilience to climate change (Brodie et al. 2025). Overall, the vulnerability of tropical forests to near-term climate change is difficult to predict, and many taxa likely retain their ancestral tolerance of conditions much warmer than those of today (McElwain 2018, Saupe et al. 2019). Other taxa may be intolerant of warming or drying and have to shift their ranges to track suitable conditions (Chen et al. 2011). Indeed, throughout Earth’s history, many species have responded to climate fluctuations by undergoing such geographic range shifts (McElwain 2018, Carrera et al. 2022). But such movements are often severely constrained today, as habitat fragmentation and human-induced landscape modifications have severed connections and impeded movements (Brennan et al. 2022, Brodie and Watson 2023). Indeed, the current global protected area network is insufficient to support the range shifts required for most species to adapt to ongoing climate change

(Parks et al. 2023), necessitating substantial societal investment in the protection and restoration of connectivity even outside of the global protected estate (Liu et al. 2020, Nelson et al. 2024). In areas where connectivity is severely limited and immediate ecological restoration is not feasible, conservation translocations, such as assisted colonization, may serve as an alternative means of enhancing functional connectivity (Gaywood et al. 2022). While contentious, assisted colonization aligns with the reality of 'natural' climate-induced range shifts whereby species are increasingly inhabiting novel locations, as their ancestors did throughout every previous episode of climate change (Brodie et al. 2021).

In Borneo, as in many regions, connectivity for climate resilience can be accomplished by protecting or restoring corridors along elevational gradients. Rising temperatures could force lowland species to shift to higher-elevation area (Chen et al. 2011). But many protected areas, particularly those at lower elevations, are increasingly isolated within agricultural landscapes such that the myriad species with limited dispersal could be unable to reach higher elevation refugia (Scriven et al. 2015). Thus, strengthening connectivity between PAs through forest corridors along elevational gradients is essential to ensuring species persistence and ecosystem stability under climate change (Box 1) (Scriven et al. 2015, Mohd-Azlan et al. 2023). Similarly, protecting corridors of free-flowing rivers along elevational gradients and connections between river reaches in their tributary system is essential for climate resilience of riverine aquatic species. Because fishes and aquatic macroinvertebrates are ectothermic, all of their life stages are strongly influenced by ambient temperature. Unimpeded movements through the river network are therefore necessary for them to track their thermal niches (Pletterbauer et al. 2018).

Maintaining and restoring riparian corridors could promote climate resilience in riverine and riverside ecosystems for buffering against climate-induced hydrological changes. When such corridors are sufficiently wide, they can continue to provide connectivity and refuge for terrestrial species even during extreme flooding events, by ensuring that parts of the habitat remain above water. Floodplain restoration can shade rivers, mitigating extreme temperatures that threaten aquatic organisms (Fogel et al. 2022, Graziano et al. 2022) and supporting riverine connectivity. Intact riparian forests can mitigate flood severity by absorbing excess water, reducing erosion, and stabilizing riverbanks (Davis et al. 1996). Additionally, riparian vegetation regulates water flow, filtering sediments and pollutants while maintaining water quality for downstream ecosystems and human communities (Singh et al. 2021). As climate change increases the frequency and intensity of extreme weather events, protecting and reconnecting riparian corridors will be essential for maintaining ecological resilience.

EXISTING CONNECTIVITY INITIATIVES

Several wildlife corridors exist or are being developed in different parts of Borneo (Box 1). In the fragmented landscape of the Kinabatangan River in Sabah, for example, conservation efforts aim to establish wildlife corridors by restoring degraded forest. Groups including Regrow Borneo, Koperasi Pelancongan Batu Puteh Kinabatangan, and the Danau Girang Field Centre, are reforesting sections of the river corridor to improve habitat connectivity and replant trees across large areas of degraded habitat; the long-term goal is to restore up to 2,600 ha (Cowan 2023). The Kinabatangan floodplain, once continuous forest, has been largely converted to oil palm plantations since the 1980s, isolating wildlife populations. Protected areas and riparian buffers provide movement corridors for wildlife species (Alfred et al. 2012), but habitat degradation continues due to encroachment and erosion. Restoration efforts focus on strengthening these corridors, enabling species movement while reducing human-wildlife conflict (Cowan 2023).

Production landscapes such as those dominated by agriculture and logging can play a role in maintaining connectivity for plants and animals in Borneo. For example, the Kubaan-Puak corridor in Sarawak comprises production forests meant for logging while being home to forest-dependent Indigenous people and a wide array of globally significant wildlife species (WWF 2025a). The Malaysian High Conservation Value Forest Toolkit was first field-tested here, leading to recognition of the area as an important corridor that links the forests of Brunei to Kalimantan, through Sarawak, providing important transboundary connectivity. While large-scale habitat conversion to develop oil palm plantations has significantly fragmented natural ecosystems, conservation set-asides within the estates can provide refugia for some species and can enhance connectivity among remaining forest patches. Estate mangers can also take a proactive approach to creating wildlife corridors within their plantations, using enrichment planting with native species (particularly wild fruit trees) to facilitate the safe movement of animals through the plantation, thereby also reducing human-wildlife conflict. One example is the wildlife corridor that connects Ulu Kalumpang and Mount Louisa Forest Reserves (Baltazar 2019).

National regulations and voluntary certification schemes, such as the Roundtable on Sustainable Palm Oil (RSPO), mandate the preservation of High Conservation Value Areas (HCVAs), riparian buffers, and steep-slope forests to maintain ecological functions and habitat connectivity (Bicknell et al. 2023). However, the implementation of these set-asides varies widely, often lacking a scientific basis in their design, and many are too small or degraded to offer substantial connectivity benefits (Scriven et al. 2019, Bicknell et al. 2023). Current HCVAs contribute minimally to landscape connectivity, improving connectivity by only ~3%, though their potential impact could rise to 16% if fully reforested, particularly benefiting species with limited dispersal abilities (Scriven et al. 2019). In West Kalimantan, private sector engagement has also been critical. For example, PT Suka Jaya Makmur, part of the Alas Kusuma Group in Ketapang District, has voluntarily designated 50,000 ha of their High Conservation Value area as an orangutan corridor. This reflects a decade of capacity-building and collaboration with World Wildlife Fund Indonesia, including training on orangutan food and nesting trees and support for achieving Forestry Stewardship Council certification. Such commitments demonstrate the growing alignment between commercial forestry and biodiversity goals.

Riparian buffer zones are another important mechanism for maintaining connectivity in highly altered landscapes. Many industrial oil palm estates enforce regulations requiring forested buffers along riverbanks, with widths varying based on river size and ecological importance (Bicknell et al. 2023). These buffers help sustain hydrological processes and facilitate species movement through agricultural landscapes, though their effectiveness depends on their extent and integrity. In selectively logged forests, many wildlife species persist with minimal negative effects, but certain species remain sensitive to disturbance, making the retention of intact forest patches within logging concessions an important strategy for connectivity (Brodie et al. 2015c, Scriven et al. 2019, Maiwald et al. 2021). Despite their benefits, set-asides often suffer from reduced tree seedling density compared to primary forests, potentially limiting future forest regeneration and long-term connectivity (Fleiss et al. 2020) given that many Borneo wildlife species require forest cover. Strengthening conservation measures within production landscapes—through targeted reforestation, improved HCVA management, and enforcement of riparian buffer regulations—could be part of the larger toolkit for enhancing connectivity and improving the resilience of biodiversity in Borneo's rapidly changing land-use mosaic.

The Heart of Borneo Initiative: a tri-national connectivity vision

The Heart of Borneo (HoB) Initiative is a transboundary conservation effort launched in 2007 by the governments of Brunei Darussalam, Indonesia, and Malaysia (Novianto 2012), aiming to preserve approximately 220,000 km^2 of interconnected rainforest areas across Borneo (Figure 1). In Sarawak, the initial Heart of Borneo (HoB) initiative covered approximately 21,000 km^2. In 2018, it was expanded to about 27,000 km^2, creating a continuous landscape along the State's borders with Kalimantan, Sabah, and Brunei. This expanded area encompasses existing protected areas such as Gunung Apeng National Park, Bungo Range National Park, Gunung Pueh National Park, Kubah National Park, Gunung Gading National Park, Samunsam Wildlife Sanctuary, Matang Wildlife Centre, Kuching Wetland National Park, Bako National Park, Sampadi National Park, Santubong National Park, and Tanjung Datu National Park.

Based on its large spatial scale and the incredible biodiversity that it could protect, the HoB initiative represents one of the most significant transboundary efforts to connect and conserve forests anywhere the world. The HoB is not only a globally important biodiversity hotspot but also plays a critical role in supporting the lives and livelihoods of at least 23 million people, including Indigenous Dayak communities who depend on the forest for food, water, medicine, and cultural identity (Arip et al. 2024).

Although not all HoB areas are legally protected in the respective countries, this Initiative has achieved notable successes in promoting protected areas and sustainable land use, communicating the importance of connectivity to the public and policy-makers, and engaging local stakeholders since its inception. In Indonesia, for example, the HoB area has been designated as a national strategic area, with governance structures and strategic plans guiding conservation and sustainable development activities (HOB Indonesia). However, the regulatory process is still ongoing, with efforts currently focused on finalizing a presidential regulation to govern the spatial planning of the Jantung Kalimantan national strategic area. Additionally, the initiative has fostered cooperation among the three nations, leading to the development of a Strategic Plan of Actions comprising five main programs and 21 proposed actions aimed at conserving the HoB. Conservation measures within the initiative have helped protect critical landscapes that provide habitat for key species such as Bornean orangutans (*Pongo pygmaeus*), pygmy elephants (*Elephas maximus borneensis*), and hornbills (Bucerotidae). These forests are essential not only for biodiversity but also for regional water security, as many of Borneo's main rivers originate within the HoB, supplying much of the island's freshwater needs.

Despite these accomplishments, the HoB Initiative faces several challenges that threaten its long-term effectiveness. Funding constraints have been a persistent issue, limiting the capacity to implement and sustain conservation programs across the vast HoB region. Inadequate enforcement of environmental regulations has also allowed illegal activities, such as logging and wildlife poaching, to persist, undermining conservation efforts. Industrial developments such as coal mining, oil palm plantations, hydroelectric projects, and commercial logging concessions pose significant threats to the biodiversity and ecosystems of the region, leading to habitat loss, forest fragmentation, and disruption of ecosystem services (Arip et al. 2024). The increasing rate of lowland deforestation is particularly concerning, as these forests provide critical habitat for endangered species. Reports indicate that the extent of Borneo's lowland rainforest has declined sharply due to illegal logging and forest fires, and while some reforestation efforts are underway, restoration is challenging in many areas (Octama 2012).

One of the most pressing concerns is the ongoing political and economic shifts in Borneo, which add layers of complexity to conservation efforts. The relocation of Indonesia's capital to East Kalimantan is likely to substantially accelerate infrastructure development, potentially increasing deforestation and habitat fragmentation (Octama 2012). The relocation of the capital is motivated by the need to reshape the country's economic framework (Syaban & Appiah-Opoku, 2023) and will likely have major economic impacts on neighboring states in Malaysia (Ismail et al. 2024). At the same time, the political and economic shifts in Borneo present an opportunity to implement sustainability measures and incorporate green economy principles into urban planning and industrial expansion. Political differences between the Malaysian federal government and the states of Sabah and Sarawak have also influenced conservation efforts, as resource management decisions often occur at the state level rather than through centralized national policies (Arip et al. 2024). Meanwhile, Brunei's economic diversification strategies introduce another dimension of potential land-use changes that could impact the HoB's ecological integrity. Encouragingly, the Indonesian government has recently taken steps to revitalize its commitment to the Heart of Borneo. After several years of inactivity since 2017, the 2024–2043 RTRWP for West Kalimantan includes a formal commitment to reactivate the HoB platform. In December 2024, the national planning agency initiated efforts to align the RTRWPs of all five Kalimantan provinces to ensure that the Heart of Borneo is integrated into Indonesia's broader spatial planning framework.

Securing long-term political commitment remains a critical challenge for the HoB Initiative. While the initial agreement among the three countries demonstrated a strong commitment to conservation, shifting political priorities have sometimes hindered progress (Arip et al. 2024). High turnover of government personnel and varying levels of engagement at local and national levels have affected the continuity and effectiveness of conservation programs (Konrad 2022). Ensuring that conservation remains a high priority across all three nations will require stronger cross-border collaboration, increased financial investment, and the integration of conservation goals into broader socio-economic development plans.

Looking ahead, the HoB Initiative must adapt to emerging challenges and opportunities to achieve its conservation goals. Strengthening partnerships between governments, the private sector, local communities, and international organizations will be crucial for maintaining connectivity within the HoB landscape. Additionally, fostering greater involvement of Indigenous communities and local stakeholders in policy-making can lead to more effective and equitable conservation outcomes. The successes of the Heart of Borneo Initiative in promoting protected areas, advocating for sustainable land use, and engaging with local communities are commendable. However, addressing funding constraints, enforcement challenges, development pressures, and securing long-term political commitment are essential to ensure the initiative's continued success and the preservation of Borneo's rich biodiversity for future generations.

A statewide connectivity plan for Sarawak

Wildlife corridors are essential for long-term conservation, allowing animals to move between protected areas to find food, mates, and escape environmental changes such as habitat degradation and climate shifts. Most national parks in Sarawak are too small to sustain viable populations of large mammals, making connectivity critical for preventing inbreeding and extinction. Without corridors, populations become isolated, threatening Sarawak's globally significant biodiversity.

Research using camera trap data and metapopulation models has identified the most important areas in Sarawak where wildlife corridors are needed—those areas that contribute or, through restoration, could contribute the most to preventing extinctions of threatened wildlife species (Brodie et al. 2016a). This was used to generate a report on Sarawak Wildlife Corridors presented to the state government in 2015. Findings highlighted key dispersal routes, including the Kayan Mentarang–Betung Kerihun corridor, which is crucial for wildlife persistence. The Hose Mountains also emerged as a biodiversity hotspot, with mammal diversity comparable to the richest forests in Borneo. Protecting these corridors is a priority to maintain ecological connectivity across Sarawak and neighboring regions.

These analyses ranked the most important potential connectivity areas based on how well each could support wildlife movement and long-term species persistence (Figure 2). The most critical corridors included those linking Lanjak Entimau, Betung Kerihun, and Kayan Mentarang, which form a vital transboundary connection between key protected areas in Malaysia and Indonesia. The Hose Mountains provide another key linkage to Kayan Mentarang (Figure 3), helping to connect wildlife populations across the border. Additional priority areas include the corridor linking Pulong Tau, Ulu Temburong, and Kayan Mentarang, which enhances connectivity across Sarawak, Brunei, and Indonesia, and the Usun Apau–Kayan Mentarang corridor, which provides a necessary dispersal route for upland species. Many of these areas have been selectively logged, but research indicates that if forests are allowed to recover, they can continue to function as critical wildlife corridors.

To maintain landscape connectivity and prevent species loss, it is essential to secure and expand key protected areas. Finalizing and gazetting the Hose Mountains and Batu Laga National Parks is a crucial step, as these areas harbor exceptional mammal diversity and provide essential habitat for a wide range of species. In the Kayan Mentarang–Betung Kerihun corridor, the establishment of a new protected area that incorporates both ridgelines and river courses would provide comprehensive connectivity for multiple species. Another major conservation priority is the establishment of legally protected corridors in northern Sarawak, linking Gunung Mulu, Ulu Temburong, Pulong Tau, and Kayan Mentarang National Parks. World Wildlife Fund (WWF) initiatives have already begun to develop connectivity through the Kubaan Puak Forest Management Unit, and expanding this effort would help ensure that these parks remain ecologically linked. Similarly, protecting the Usun Apau–Kayan Mentarang corridor, particularly along ridgelines that serve as primary movement routes for many terrestrial species, would further strengthen connectivity across the region.

Protecting these corridors aligns with Sarawak's commitments to national and international conservation agreements, including the Malaysian National Policy on Biological Diversity 2022-2030 (Target 10), the Convention on Biological Diversity Target 11, the Heart of Borneo Initiative, and the Sarawak government's goal of designating one million hectares of Totally Protected Areas. Wildlife corridors are a cornerstone of long-term conservation in Sarawak. Implementing these proposed actions will significantly reduce extinction risks, support climate resilience, and reinforce Malaysia's leadership in biodiversity conservation.

PATHWAYS FORWARD: STRATEGIES FOR STRENGTHENING CONNECTIVITY

Large-scale land-use planning. Integrating connectivity into national and regional land-use planning frameworks is essential to ensure that conservation and development goals are aligned both within particular jurisdictions (e.g., states, provinces) and across Borneo's three nations: Malaysia (Sabah and Sarawak), Indonesia (the five Kalimantan provinces), and Brunei Darussalam. Without such integration, conservation agencies may seek to establish habitat corridors in areas targeted for infrastructure or agricultural expansion, leading to conflicting land-use priorities. A coordinated approach that incorporates connectivity into national land-use plans, sustainable certification schemes, and regional development strategies can help mitigate such conflicts (Brodie et al. 2016b). Connectivity planning should be informed by the best-available science to determine optimal locations for wildlife corridors, restoration areas, and infrastructure mitigation measures such as overpasses or underpasses. In some cases, the feasibility of connectivity measures depends as much on land tenure as on ecological suitability. For example, Sabah's EcoLinc corridor had to navigate community-controlled lands, leading to constraints on corridor width, while in central Sabah, connectivity measures were more easily implemented because the lands were managed by the Forestry Department and the Sabah Foundation. A recent milestone for Borneo's connectivity planning was the revision of West Kalimantan's Provincial Spatial Plan (RTRWP) for 2024–2043. The revised RTRWP now incorporates ecosystem-based planning and formally designates over 1.5 million hectares for biodiversity conservation and ecological function. This includes several wildlife movement corridors, such as a 484,000 ha orangutan and gibbon corridor and a 98,000 ha Irrawaddy dolphin migration zone. These designations now guide not only provincial-level planning but also district-level RTRWK processes.

Publicly available land tenure data, when incorporated into connectivity models, can enhance the feasibility of corridors by identifying areas where implementation is more politically and socially viable (Vaz and Agama 2013). This approach should be expanded across Borneo to create a more cohesive, transboundary conservation strategy. Additionally, incorporating large-scale land-use planning and connectivity into an integrated river basin or watershed management approach could offer added benefits, helping to manage not just forests and land but also the movement of water through rivers and streams—ultimately supporting both water security and aquatic biodiversity conservation.

Indigenous and community-led conservation. Indigenous and local governance structures play a critical role in connectivity conservation across Borneo, particularly in community-managed forests that act as stepping-stone corridors between protected areas. However, large-scale ecological processes such as species movements often extend beyond the boundaries of individual communities, requiring coordination at provincial, national, and transboundary levels. Effective connectivity strategies must account for different land tenure systems and socio-economic conditions, employing a mix of protected areas, riparian reserves, and sustainable land-use practices (Brodie et al. 2016b). Communities often consider the socio-economic and cultural impacts of roads and can propose alternative construction locations if their homes or lands were to be impacted. In Telupid, for example, inputs from communities and conservation NGOs about avoiding protected areas and elephant habitat pressured the Sabah government to consider an alternative road alignment (Abram et al. 2022).

In Kalimantan, many important habitat linkages pass through production landscapes, making it essential to engage local communities in conservation planning through incentives such as sustainable ecotourism and agroforestry programs. In Malaysia, some connectivity initiatives have relied on top-down government designations, while others, such as the Sabah EcoLinc project, have been driven by local communities who manage the land without formal legal designations. The long-term success of different approaches remains uncertain, highlighting the need for research on how top-down and bottom-up strategies affect corridor functionality over time. Non-governmental organizations (NGOs) have played a key role in bridging these governance approaches, facilitating partnerships between communities, scientists, and policymakers to develop viable connectivity solutions (Vaz and Agama 2013, MNRE/UNDP 2014).

Restoration and reforestation. Many key connectivity areas across Borneo, particularly in the lowlands, have been degraded by logging, plantation agriculture, and infrastructure expansion (Scriven et al. 2015). Expanding and improving habitat corridors through active restoration efforts is essential to maintaining ecological connectivity, particularly for species that depend on lowland forests. Without connectivity to upland forests, species in isolated lowland reserves face higher extinction risks as climate change alters habitat suitability. Reforestation efforts, especially in riparian zones and fragmented corridors, can facilitate species movements while providing additional benefits such as carbon sequestration and watershed protection. In Indonesia, initiatives such as the restoration of peatlands in Central Kalimantan have demonstrated the potential for large-scale ecological recovery, but more targeted efforts are needed to connect key conservation landscapes. Ensuring that restoration projects are designed with connectivity in mind—rather than simply increasing forest cover—will enhance their long-term ecological impact and support regional biodiversity conservation goals (MNRE/UNDP 2014).

Monitoring and research needs. Connectivity assessments in Borneo have largely focused on terrestrial mammals, particularly flagship species such as clouded leopards, elephants, and orangutans. However, connectivity planning must expand to include a broader range of taxa, including invertebrates and plants (Box 1), which play essential roles in ecosystem function. To improve connectivity planning, future research should integrate data on species movements, habitat requirements, and the effectiveness of corridors. Currently, many connectivity models rely on expert opinion, which, while valuable, should be complemented with empirical studies to validate corridor effectiveness. A key challenge is the lack of ecological data for many species. While large-bodied carnivores are often used as proxies for connectivity, research should assess whether their habitat needs align with those of other species (Brodie et al. 2015a). Additionally, priority taxa could be selected based on their ecological functions, such as large frugivores that aid in forest regeneration or pollinators critical for maintaining plant communities. Long-term monitoring of gene flow and metapopulation dynamics can also provide valuable insights into the effectiveness of connectivity initiatives (Box 2) (Beier et al. 2008, MNRE/UNDP 2014, Brodie et al. 2016a).

Financing connectivity. Ensuring sustainable financing for connectivity initiatives across Borneo is a major challenge, as conservation efforts must compete with economic pressures from agriculture, logging, and infrastructure development. State governments in Malaysia and provincial authorities in Indonesia rely heavily on revenue from land and resource extraction, making it difficult to secure long-term funding for conservation corridors (Brodie et al. 2016b). The Central Forest Spine initiative in Peninsular Malaysia, for example, has an estimated cost of over US $1 billion, highlighting the scale of investment needed for connectivity projects (MNRE/UNDP 2014). Potential funding mechanisms include conservation fees such as departure taxes for tourists, hotel bed taxes, or conservation license plates, all of which have been successfully used elsewhere to generate revenue for biodiversity protection (Brodie et al. 2016b). Payments for ecosystem services, such as carbon credits through REDD+ programs, could also provide financial support for habitat corridors while contributing to climate mitigation efforts. For example, the protection of the Kuamut Forest Reserve in Sabah was funded through carbon trading, effectively expanding a key connectivity corridor. Certification schemes such as the Forest Stewardship Council and the Roundtable on Sustainable Palm Oil (RSPO) could further support connectivity by requiring landscape-scale conservation planning in their sustainability criteria. A jurisdictional approach to RSPO certification in Sabah could serve as a model for integrating connectivity considerations into land-use policy across Borneo. The ecological fiscal transfer (EFT), introduced by the Malaysian government in 2019 and with increasing annual allocations since then, is a good step towards supporting the efforts of state governments to conserve forests and wildlife. However, the EFT should adopt a targeted approach to achieve conservation goals within each state. While area size is an important consideration, other critical factors — including connectivity, species richness, levels of endemism, and existing threats — must also be taken into account.

Public awareness and political capital. Raising awareness among policymakers, local communities, and industry stakeholders is essential for securing long-term support for connectivity initiatives. Public engagement efforts can help prevent conflicts between conservation and development objectives by fostering cross-sectoral collaboration. For example, infrastructure planning should be aligned with conservation goals to prevent roads and other developments from fragmenting critical habitat corridors (Brodie et al. 2016b). In some cases, resistance to connectivity initiatives stems from past conservation policies that excluded local communities from decision-making processes. In response, projects such as the Sabah EcoLinc have adopted more participatory approaches, allowing communities to manage corridor lands without formal legal designations. Building public support for connectivity can also be achieved through partnerships with influential cultural figures, such as the Borneo Futures initiative, which pairs conservation scientists with well-known local musicians to raise awareness about habitat connectivity. Economic assessments that highlight the long-term benefits of connectivity—such as ecotourism revenue, carbon sequestration, and ecosystem services—can also help strengthen political and financial commitments to conservation across Borneo (MNRE/UNDP 2014, Nagulendran et al. 2014).

[TEXT BOX 1] CASE STUDY: PROTECTED AREAS AND CONNECTIVITY IN SABAH

The Sabah government committed to increasing the coverage of Totally Protected Areas (TPAs) from 24.5% to 30% of the state's land area, requiring the designation of approximately 335,000 ha of additional protected forest. Central to this initiative was the goal of enhancing landscape connectivity to ensure long-term biodiversity persistence and climate resilience. The Sabah Forestry Department, in collaboration with scientific institutions and conservation organizations, adopted a data-driven approach to prioritize forest protection. This initiative integrated data on species distributions (vertebrates, butterflies, and timber trees), ecosystem services, and habitat connectivity to create a strategic conservation plan that optimized the multiple conservation objectives (Williams et al. 2020).

The project relied on advanced remote sensing techniques to assess forest carbon stocks, canopy biodiversity, and ecosystem functions across Sabah. These maps, combined with decades of field-based ecological research from the Southeast Asia Rainforest Research Partnership, the Universiti Malaysia Sabah, and other partners, generated a comprehensive understanding of biodiversity patterns, habitat connectivity, and forest dynamics. The planning framework explicitly incorporated connectivity by focusing on protecting dispersal corridors among protected areas, linking habitats across elevational gradients to facilitate species range shifts, and ensuring that protected areas were not isolated within fragmented landscapes. By integrating connectivity into conservation planning, the initiative increased the protection of habitat corridors and elevational linkages by 13% and 21%, respectively, with minimal reductions in the representation of other conservation priorities such as species distributions and carbon storage.

The results of this prioritization effort identified key regions for expanded protection, including the southwestern part of Sabah, which is rich in vertebrate and butterfly diversity and provides important corridor connections to Sarawak and Kalimantan; the Deramakot region, which supports a high diversity of plants and vertebrates and plays a crucial role in elevational connectivity; and areas east of the

Crocker Range, which encompass diverse forest types and contain high aboveground carbon stocks. By using systematic conservation planning tools, the project was able to recommend a spatially efficient protected area network that optimizes connectivity while minimizing trade-offs with other conservation objectives.

This science-based approach to protected area expansion offers a model for connectivity-focused conservation planning in Borneo and beyond. Rather than relying on ad hoc land acquisitions or protected area designation based solely on political concerns, the Sabah government's strategy ensures that new protected areas are designated where they are predicted to have the greatest impact on ecological resilience. The integration of connectivity into conservation decision-making enhances the long-term viability of species populations by facilitating movement between habitat patches, reducing isolation, and increasing resilience to environmental changes. Furthermore, the initiative aligns with global conservation targets, such as the Kunming-Montreal Global Biodiversity Framework, which emphasizes well-connected protected area networks. As land-use pressures continue to mount, data-driven conservation strategies that explicitly prioritize connectivity will be essential for maintaining biodiversity, ecosystem services, and climate resilience in Sabah and across Borneo.

[TEXT BOX 2] QUANTIFYING CONNECTIVITY FOR ASSESSMENT AND MONITORING

To effectively measure progress toward the 30 × 30 target for well-connected protected areas, connectivity must be quantified in a meaningful way. While various indices exist, there is no universal criterion for defining a "well-connected" landscape or network. We follow a recent synthesis providing an operational definition adaptable to different ecosystems, species, or ecological processes: "A landscape, seascape, or protected area network is well-connected if organismal movement is sufficient to maintain the long-term persistence of focal taxa, sustain ecological functions, or support the provision of ecosystem services, relative to counterfactuals with equivalent habitat availability but no barriers to movement" (Brodie et al. 2025: 4). This definition allows for assessing connectivity changes using real-world reference sites or simulation models. Connectivity status may shift due to human-driven pressures that alter movement patterns and ecological dynamics. Different species respond uniquely to these changes based on their sensitivity to habitat fragmentation and their reliance on connectivity for survival, reproduction, or dispersal. Reliable indicators are essential for tracking connectivity changes over time and across regions. Existing indicators primarily focus on structural rather than functional connectivity (i.e., where there is habitat rather than where there is actual organismal movement) and rarely incorporate direct measures of species persistence. To improve connectivity assessments, indicators should integrate functional connectivity with persistence metrics such as metapopulation capacity, which quantifies a landscape's ability to sustain populations. A multi-step framework could enhance this approach. First, structural connectivity is mapped using remote sensing (Saura and Torné 2009, Hesselbarth et al. 2019). Next, movement data—or proxies such as body size, which often scales with dispersal (Tucker et al. 2018)—are used to predict connectivity. Landscape conditions that influence connectivity, including barriers and habitat degradation, are then incorporated (main text, Figure 3). Finally, models can assess how connectivity affects species persistence (Strimas-Mackey and Brodie 2018) and ecological function (Brodie et al. 2018). These connectivity assessments allow for comparative ranking of potential corridors, enabling policymakers to prioritize areas that contribute most to regional connectivity and long-term biodiversity persistence (see 'A statewide connectivity plan for Sarawak' in the main text).

Sophisticated modeling approaches, enhanced computational capacity, and large-scale movement datasets are improving connectivity assessments. Emerging global biodiversity monitoring systems, including remote-sensing networks and movement-tracking databases like Movebank (Kays et al. 2022), are expanding our ability to quantify connectivity. However, significant data gaps remain, particularly in tropical regions and for many taxonomic groups (Bastille-Rousseau et al. 2018). To address these gaps, researchers can leverage alternative methods such as camera traps, acoustic sensors, and environmental DNA to infer movement patterns. Advances in computational power and interdisciplinary collaboration between ecologists, conservationists, and data scientists are also improving our ability to model connectivity at global scales (Sloan et al. 2024).

Connectivity is dynamic, and conservation planning should align with the relevant timescales for species persistence and ecological processes. Some interventions, such as wildlife corridors or road underpasses, can be implemented quickly, whereas others, like reforestation, require decades to restore connectivity (Zeller et al. 2020). Aligning conservation actions with species' ecological timescales is essential for ensuring long-term persistence. While knowledge gaps remain, continued research, improved data-sharing, and interdisciplinary collaboration will enhance our ability to conserve connectivity and safeguard biodiversity across Borneo.

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FIGURE 1. Map of potential movement for forest-dependent organisms among existing protected areas (shown in black) (from UNEP-WCMC and IUCN 2025) in Borneo, simulated using circuit theoretic algorithms (McRae et al. 2009). Landscape resistance is the inverse of forest cover, as measured from spaceborne lidar (Burns et al. 2025); the potential movement depicted is log_{10}-transformed (cf. Deith and Brodie 2020) and unitless.

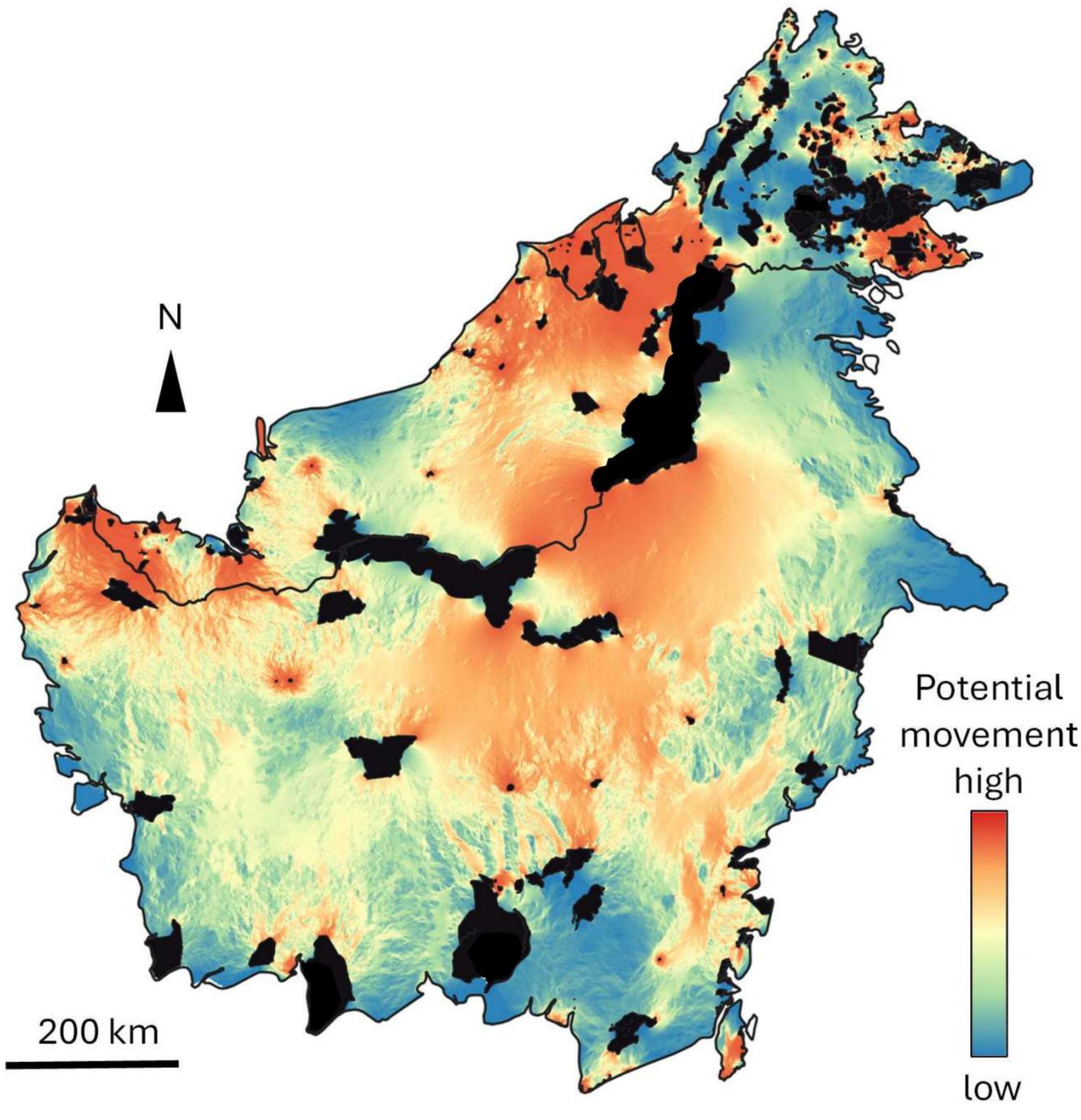
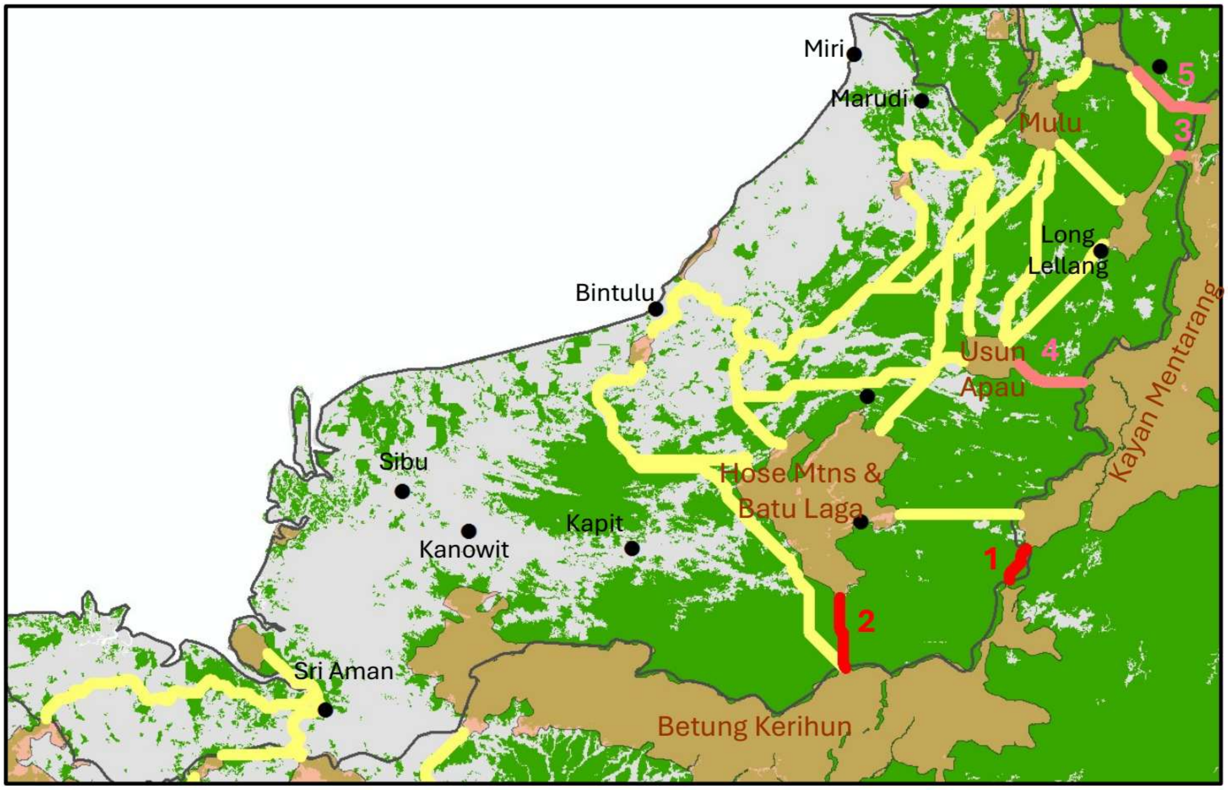


FIGURE 2. Possible habitat corridors between protected areas (brown) in Sarawak and adjoining areas ranked from most important (red) to important (pink) to less important (yellow) (Brodie et al. 2016a). Green background shows the extent of forested area. Note that importance values in the histogram (bottom panel) are on a log scale, so that corridor 1 is ~700 times more important than corridor 3 in terms of supporting the long-term persistence of multiple mammal populations. Inset shows a male Sunda clouded leopard (*Neofelis diardi*) photographed in the Hose Mountains, Sarawak (photo credit: J. Brodie).


Miri
Marudi
Mulu
5
3
Long
Lellang
Bintulu
Usun
Apau
4
Kayan Mentarang
Sibu
Kanowit
Kapit
Hose Mtns &
Batu Laga
1
2
Sri Aman
Betung Kerihun

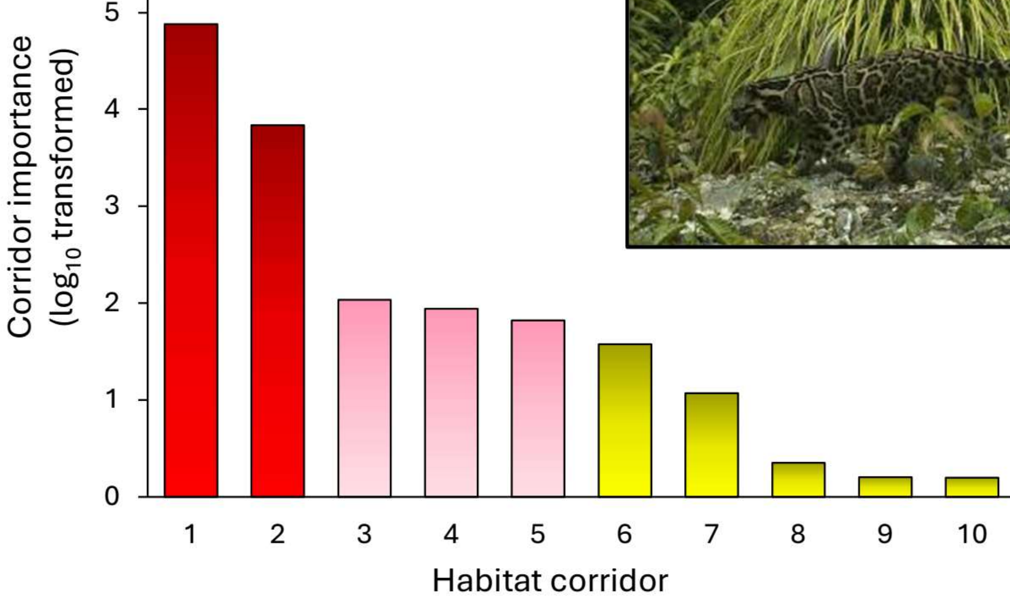

Corridor importance
($\log_{10}$ transformed)
0
1
2
3
4
5
6
1
2
3
4
5
6
7
8
9
10
Habitat corridor

FIGURE 3. Predicted dispersal routes for wildlife moving between the Hose Mountains, Usun Apau National Park, and Kayan Mentarang National Park, based on circuit theory algorithms (Brodie et al. 2016a). Red areas are those that many animals will travel through, blue are areas that few animals will use.