Drivers and solutions to Southeast Asia's biodiversity crisis

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Abstract

Southeast Asia's terrestrial ecosystems harbour extraordinary levels of species diversity and endemism, shaped by a complex biogeographic history. These ecosystems, and the species that inhabit them, face mounting pressures from land-use change, deforestation and ancillary disturbance processes, infrastructure expansion, hunting and consumption, as well as climate change and invasive species. The pervasiveness and extent of these threats differ between nations. In this Review, we summarise current understanding of the drivers of species declines. Learning from past lessons and identifying evidence gaps that must be addressed to underpin future policy and practice decision-making, we provide actionable insights for overcoming the biodiversity crisis while accounting for the socio-economic realities of Southeast Asia's rapidly developing countries. A range of conservation interventions are required to protect biodiversity within human-modified landscapes and in intact forest areas. Emerging technologies now offer unprecedented tools for monitoring species populations and evaluating conservation effectiveness. Simultaneously, international sustainability commitments are more aligned than ever, with ambitious targets in place for climate mitigation, ecosystem restoration, and biodiversity protection. Effective conservation in Southeast Asia requires the adoption of innovative approaches to landscape conservation, proactive community-led forest management, strategies to reduce hunting and consumption, nature-based climate solutions and payments for ecosystem services.

[H1] Introduction

Tropical and subtropical terrestrial ecosystems are reservoirs of globally important biodiversity and ecosystem services, including climate regulation and the provision of resources and livelihoods, that are critical for human well-being and support millions of people[1]. Yet, these ecosystems face unprecedented challenges in the Anthropocene, as climate change intensifies the pressures of land-use change, infrastructure expansion and urbanisation, and resource overexploitation[1–3]. This confluence of threats has rendered many of the world's biodiverse forest ecosystems vulnerable to collapse[4].

These dynamics are most pronounced in Southeast Asia, the geopolitical region encompassing Brunei, Cambodia, Indonesia, Laos, Malaysia, Myanmar, the Philippines, Singapore, Thailand, Timor-Leste, and Vietnam (Fig. 1). This region harbours some of the planet's most species-diverse ecosystems[5–7], as its rich geological history — marked by episodic sea-level changes, continental shifts, and island isolation — has fostered extraordinary speciation and endemism observed nowhere else in the world[8,9]. Four of the world's biodiversity hotspots intersect Southeast Asia, reflecting multiple unique biogeographic zones: Indochina, Sunda, Wallacea, and the Philippines[8]. Nonetheless, the region has been at the epicentre of a biodiversity crisis, driven by political shifts, the rise of 'tiger cub economies', and rapidly expanding human populations (Fig. S1), which are currently estimated at 695 million in total and are projected to comprise 8% of the global total by 2050. Economic development has progressed rapidly, as average gross domestic product in the region has approximately tripled since the early 2000s and poverty now affects <5% of the population — a four-fold reduction over 40 years (Fig. S1). However, these economic gains have come at the expense of natural resources, fuelled by the expansion of agriculture (Fig. S2) and extractive industries (Fig. S3). Rising affluence and urbanisation have driven increased consumption; for example, although Southeast Asian nutrition is disproportionately characterised by high fish consumption compared with elsewhere in the world, meat is becoming a greater part of people's diet (Fig. S4). Despite the beginnings of a dietary shift, most agricultural production land is still devoted to commodity crops rather than meat production.

Extinction has been a defining process in Southeast Asia since the late Quaternary (~50,000 years ago), although its severity was lower than in the Nearctic or Australasia[10]. Prior to this period, large seed-dispersing megafauna, including elephants (Elephantidae), rhinos (Rhinocerotidae), and multiple orangutan species (*Pongo* spp.), were far more widespread than they are today[10,11]. The largely human-driven extirpations of these and other vertebrates profoundly altered the structure and functioning of Southeast Asia's forest ecosystems — a pattern that has accelerated during the Anthropocene[3].

Since 2004, the region's biodiversity loss has been recognised as distinct and severe[8,12–14]. The late Navjot Sodhi first coined the crisis, highlighting its gravity and warning of far-reaching ecological and societal consequences[8]. Subsequent research reinforced these concerns, prompting numerous calls to action[12–15]. However, updated projections indicate that effective mitigation efforts could not only prevent catastrophic ecological outcomes but actually result in net biodiversity gains by 2100[16] (Table S1). Given these evolving challenges and emerging opportunities, a reassessment of the region's conservation trajectory is both timely and essential. Accelerating climate change has compounded biodiversity loss, but also introduced new prospects for financing and advancing sustainable management[17]. Emerging technologies, such as robotics and remote sensing, now offer unprecedented tools for biodiversity monitoring to help ascertain the causes of species declines and evaluate conservation strategies[18]. Meanwhile, international sustainability commitments are more aligned than ever, as ambitious targets have been established for climate mitigation, ecosystem restoration, and biodiversity protection[17,19].

In this Review, we draw on contemporary research on the region's biodiversity crisis to update and refine understanding of its drivers, while emphasising the effectiveness of conservation efforts. We examine how historical land-use change and socio-economic pressures have shaped biodiversity loss and evaluate novel and innovative initiatives for reversing these trends. By integrating lessons from the past, and identifying evidence gaps that must be addressed to underpin future policy and practice, we provide actionable insights for solving the biodiversity crisis while navigating the socio-economic realities of Southeast Asia's rapidly developing nations.

[H1] Conservation challenges

Southeast Asia contains almost 15% of the world's tropical forests, and almost half of all tropical peatlands[20]. Together, these ecosystems support the highest density of carbon stocks globally[21,22](Table S1), 15% of the world's vertebrates and an estimated 7% of vascular plants [7,23]. The IUCN Red List indicates that the greatest threat to biodiversity across Southeast Asia is large-scale land-use change and associated ancillary processes such as logging and fire, which lead to the loss and degradation of species-rich forests (Table S2; Fig. 1, 2). Other established pressures include infrastructure expansion and urbanisation, and the hunting and consumption of species. These human-mediated pressures vary in prevalence and magnitude between countries (Fig. 2) and rarely operate in isolation (Fig. 3). Indeed, climate change, invasive species, and limits to human–wildlife coexistence pose emerging threats that are likely to interact with established drivers to attenuate (that is, antagonistic interactions) or amplify (synergistic interactions) species losses in the future[1,24–26] (Fig. 3). Conservation assessments of taxa underrepresented in the Red List are hindered by taxonomic and geographic knowledge gaps — so called Linnaean and Wallacea shortfalls[5,6]. Nevertheless, the hierarchies of threats for IUCN Red List taxa are likely to reflect patterns more broadly.

[H2] Land-use change, deforestation, and ancillary disturbance processes

Between 1992 and 2018, Southeast Asia lost 219,833 km^2 of forest[27] and experienced some of the highest deforestation rates in the world[28]. Peak deforestation shifted from Cambodia, Myanmar, Thailand, and Vietnam in the 1990s to Indonesia and Malaysia thereafter (Fig. S5): spatiotemporal analysis of forest-cover change data reveals that deforestation was concentrated in Cambodia, southern Myanmar, central Vietnam, Borneo (Sarawak and Kalimantan) and Sumatra prior to 2015, and that new deforestation hotspots are emerging in Laos, Sulawesi, West Papua, and West Java[27] (Fig. 1). Deforestation has slowed in Indonesia since 2017 [29], and signs exist that Thailand is transitioning to a net afforesting country[27]. Although Laos, Myanmar, the Philippines, Java, and Timor-Leste recorded a net gain in forest cover since the 1990s, these gains are balanced against substantial deforestation in biodiverse areas elsewhere[27] (Fig. 1).

Southeast Asia's moderately forested and logged-over lowland landscapes are particularly prone to deforestation (Box 1; Fig. 1). Moreover, a further >121,000 km^2 of carbon-rich peatlands were cleared between 2001 and 2022, together with ~3200 km^2 of mangroves[30,31]. Deforestation at both high elevation (169,964 km^2

between 2001 and 2018[32]) and low elevation[33] on the region's mountains poses new threats to habitat-restricted species, particularly endemics. Consequently, the ecological communities within deforested areas are characterised by a proliferation of broad-range generalist species at the expense of local specialists; a process called biotic homogenisation[34,35]. Deforestation also fragments habitat and reduces landscape connectivity, resulting in isolated species populations that are increasingly vulnerable to secondary pressures, such as edge effects, disturbance, and exploitation[36–38].

Deforestation and biodiversity loss in Southeast Asia is primarily driven by agriculture[27,28,39]. Over 1.35 million km^2 is now cultivated across the region after agricultural land more than doubled from the 1960s[40]. Although the environmental impacts of oil palm in Malaysia and Indonesia dominate the research agenda[41–43], this focus has overshadowed that of other 'forest-risk' commodity crops. For instance, Southeast Asia produces >90% of the world's natural rubber, which is associated with deforestation in Thailand, Indonesia and, increasingly, Cambodia and Vietnam[44]. Vietnam is now the world's second largest coffee producer[40] after accelerating production in the 1990s at the expense of central highland forests[45], and coconut cultivation in the Philippines and Indonesia has long affected coastal forests and island endemics[46,47]. The implications of rice cultivation for biodiversity are also frequently ignored[48], despite the region (primarily Thailand, Indonesia, Vietnam, Myanmar, and the Philippines) contributing 40% of global exports[49] and the need for new estates being promoted periodically in policy agendas as a method of enhancing food security. Growth in other agricultural markets is also implicated in deforestation (for example, durian in Malaysia, cashew and banana in Myanmar)[46,50,51].

Land-use dynamics are complex. Variation in production systems within and among countries should not be overlooked, as these systems impact biodiversity in different ways[52]. Unshaded monocultures (for example, sugarcane, oil palm), particularly annual crops (such as maize), result in drastically impoverished tropical biodiversity[53]. By contrast, perennials with longer rotation periods can support comparable species numbers to forest, especially when cultivated in shaded plantations or agroforests (such as cacao or coffee)[54]. Land-use pressures and solutions are thus often highly localised owing to inherent diversity in crop choice, rotation time and management. Accordingly, the level of threat that Southeast Asia's species face from land-use change is highly variable over space and time, reflecting the diversity of countries, cultures and sociopolitical systems across the region (Fig. 1).

Not all deforestation associated with agriculture is industrial-scale. Small-holder cultivation has a long history across Southeast Asia, contributing to both forest loss and gain[55,56]. Small-holder rice cultivation began on the mainland 4000 to 5000 years ago[57] and remains dominant[56]. Nonetheless, a shift in livelihoods away from small-scale agriculture and forest-use to commodity-driven markets is well underway. This transition can be rapid, taking only ~15 years in Indonesian Borneo[58], although the pace of change is highly variable. Outside the main oil palm producing areas of Borneo and Sumatra, Indonesia's central and eastern islands continue to produce small-holder cash crops (including coconut, cacao, coffee and cloves), often grown in agroforestry, which have comparatively better prospects for biodiversity than extensive monocultures[9]. In fact, small-holders are frequently invoked as both key drivers of biodiversity loss — owing to land conversion and swidden practices, high chemical use, and poor yields — as well as custodians of agrobiodiversity — through enhancing tree-cover, ecosystem functioning, and species populations[59,60].

Fire, used to clear and manage land, is now a pervasive threat to Southeast Asia's forests, and the effects of burning are exacerbated by disturbance, poor land management, and drought[28,61–63]. These effects are most severe in peatlands, where fires can spread belowground. Burning belowground carbon adds greatly to pollution and emissions, while prevention and mitigation measures are restricted by access[64–66]. The transboundary haze resulting from such fires is unique to the region, regularly bringing adverse outcomes for human health, agriculture, and biodiversity[64,65].

Fire is a powerful ecological filter, disrupting communities and ecosystem functioning[67,68]. Most research into the impacts of fire on tropical ecosystems is conducted in South and Central America[61], and relatively few studies focus on Southeast Asia. However, a 16-year long investigation in a Bornean peatswamp forest highlights the degree of damage fire can cause. Tree density, canopy cover, and invertebrate species diversity deteriorated by 92-95% in newly burned forest, as fires immediately compromise tree reproductive phenology and water quality nearby[69]. Commercially valuable fish populations collapsed within three months, while declines in threatened vertebrates took nine months to become apparent. Although the forest remained structurally compromised long after a burn event, signs of recovery were observed after 12 years.

[H2] Infrastructure expansion and urbanisation

Having recovered from the 1997 financial crisis, Southeast Asia experienced a development boom, characterised by rapid urbanisation and growth in energy and transport sectors (Fig. S3). The region hosts three of the world's 33 megacities (Bangkok, Manila and Jakarta, each comprising >10 million people), and Ho Chi Minh is expected to reach this status by 2030[70]. Mega-infrastructure projects include the relocation of Indonesia's capital from Java to Kalimantan in Borneo, >80 new hydropower dams along the Mekong[71], and the China-Indochina Peninsula Economic Corridor augmenting China's Belt and Road Initiative (BRI). The BRI, the largest infrastructure development in human history, will potentially bisect 21 protected areas in mainland Southeast Asia, including new and upgraded roads and highways in Cambodia, Laos, Vietnam, and Myanmar[72]. Road expansion exacerbates habitat fragmentation, disrupts species migration patterns, and further exposes biodiversity to people (for example, through hunting and conflict)[72], although many of these effects remain poorly documented[73]. Dam construction alters river flow and sediment movement, disrupting freshwater biodiversity and downstream wetlands, resulting in negative consequences for people[71,74–76]. The rapid urbanisation of Singapore resulted in major local extinctions, and a further 20% loss of species is predicted by 2100[77]; however, Singapore also provides prime examples of how green infrastructure can be implemented — such as innovative wildlife bridges, rooftop gardens, and other nature-based solutions[78].

Developing infrastructure requires immense natural resource exploitation and energy that, in turn, influences biodiversity. After China and India, Vietnam and Indonesia are the largest producers and consumers of Asia's cement, alongside sizeable markets in the Philippines, Thailand, and Malaysia[79]. Cement is often sourced from highly destructive quarrying of limestone karst habitats renowned for their exceptional endemism[80]. Coal mining, the largest source of energy-related carbon emissions globally, is also expanding extensively (Fig. S3), resulting in land clearance and contaminated water in Indonesian Borneo[81]. Surface mining is common for coal, gold, and other minerals, and can be highly destructive if poorly planned and regulated, particularly when artisanal, leading to deforestation, soil erosion, and displacement of people[82,83]. Although mining can generate income, the environmental and social impacts of more than half the world's mines remain undocumented, especially in Myanmar and Indonesia[84]. New markets are emerging for the metals that are essential to the global transition to net zero (such as cobalt and nickel in Indonesia and the Philippines; Fig. S3) and, although the contribution to global production is currently low, Southeast Asia (for example, Vietnam and Myanmar) holds sizeable reserves of rare earth metals[85]. Few large-scale mining impact evaluations are available. However, one example from Sulawesi (a global centre for nickel production) showed that nickel mining amplified deforestation and people's overall well-being deteriorated, despite improvements to their living standards in the short term[86].

[H2] Hunting and consumption of species

The hunting and capturing of species has received relatively little research attention[87,88], despite being an immediate threat to the survival of most of Southeast Asia's endangered vertebrates[89]. For instance, the Asian songbird crisis is the consequence of ~1000 species being traded, particularly in Indonesia[90]. Across the region, species are hunted for food, pest control, sport, traditional medicine, ornaments and/or decorations, and pets[91–93], but assessing the scale and magnitude of these activities is difficult owing to insufficient data[87] (Fig. S6). Historically, people hunted mainly for subsistence, but hunting is now a widespread source of income[92,94], and wildlife is traded across the region, particularly to fulfil large demand from China and increasingly Vietnam[93]. Overexploitation is driving species declines and extirpations leading to 'empty forest syndrome' (Box 2; Fig. S6). Snares, a key hunting method, are particularly damaging because they are largely indiscriminate (meaning they also capture non-target species) and are cheap and easy to use, meaning hundreds of snares can be set at any one time. Between 2010 and 2015, >200,000 snares were removed from five protected areas in Vietnam, Cambodia, and Laos alone[95]. Although data on the impact of hunting on species populations in the region are rare, one long-term study found snaring drove ungulate and primate declines in Cambodia[96].

Among local communities and indigenous peoples living in rural areas, such as in parts of Malaysia, Papua, Timor-Leste, and Vietnam, the meat of wild animals ('wildmeat') can be an important source of nutrition[94,97,98]. However, although the extent to which wildmeat underpins food security is uncertain, in many areas it is thought to be low due to wildlife depletion. Consumption of wildmeat can also be a crucial component of community identity and food culture[99,100], and contributes to well-being[101]. In areas of Indonesian Borneo[102] and Cambodia[103], wildmeat is consumed less than domestic meat and fish, and professional hunting groups external to local communities are largely responsible for the trade of high-value species. Wildmeat consumption is observed in urban areas of Thailand, Vietnam, Cambodia, Laos, and Indonesia[87,104–106], where it does not constitute a substantial proportion of dietary nutrients[92]. Although wildmeat can be considered a symbol of status and wealth[100,107], this is not always the case even within the same country (for example, Vietnam[108]).

A combination of species scarcity, rising consumer demand and improved market accessibility has resulted in wild animal products becoming increasingly high-value commodities, luring people into targeted commercial hunting. Increasing cross-border trade within Southeast Asian countries has enabled the supply of wildmeat from remote rural areas to places where demand is greatest (typically China and Vietnam)[109]. In Myanmar and Vietnam, the wildmeat trade is a source for the illegal trade in wild animal body parts nationally and internationally[92]. Southeast Asian diaspora also facilitate global trade in wild animal parts for traditional medicine. For instance, pangolin scales and bear bile are transported between Asia and South Africa to meet medicinal demand[110].

[H2] Emerging threats exacerbate species losses

Although the independent effects of different threats might be relatively well established[111–114], these drivers of biodiversity loss rarely occur in isolation. Land-use change compromises habitat quality[115,116], while enabling access for people. This combined influence increases interactions between people and wildlife, amplifying persecution, overexploitation and trade[117,118]. Trade routes and infrastructure development help invasive species spread and habitat modification disrupts the resilience of ecosystems, allowing invasives to establish[114]. Singapore exemplifies this situation: as a highly urbanised major trade hub, the island state has recorded at least 150 invasive species, costing an estimated US$1.72 billion to its economy since 1975[119]. Extrapolated over the Southeast Asia region, costs due to invasive species near US$17 billion.

Although infrequently cited as a major threat on the IUCN Red List for Southeast Asian species (Figs 2, 3), the narrow thermal niches of tropical taxa make them particularly vulnerable to the effects of climate change[120,121]. Evidence from microclimatic data suggests that the stability that led to this specialisation is breaking down, as mean annual temperatures beneath forest canopies in Southeast Asia are 0.37 °C warmer than in 1990[122]. Logging exacerbates thermal exposure, effectively reversing the protective function of the canopy on species residing in forest below[123]. At its most severe, seasonal and phenological shifts driven by climate change could force a transition of tropical dry forests to savanna in, for instance, the central mainland and the Lesser Sunda islands[124]. Drought conditions are already intensifying storm damage and forest fire risk across the region[66,125], and are expected to worsen in the future[25].

As coastal forests appear to be somewhat buffered from this process, the shift to novel climate conditions reported from other tropical regions is less prominent in Southeast Asia owing to its insular nature[122]. Inland, greater exposure to climate fluctuations and extremes is pushing species outside of their thermal optima, driving some to shift to higher elevations, notably New Guinea's birds[126] and Borneo's moths[127]. The potential for climate-driven mountaintop extinctions is understudied in the region[128], but is perhaps greatest in Indonesia and the Philippines where endemism is particularly high[8,9]. Deforestation at low and mid-elevations compounds the problem[33,129], exacerbating the simplification of ecological communities that is already underway[34]. Almost one-third of climate connectivity was lost across the tropics between 2000 and 2012, and degraded and fragmented areas were exposed to greater temperatures[130]. In turn, forest fragmentation and loss have influenced land surface warming, resulting in amplified temperatures experienced several kilometres away from deforestation events in Southeast Asia[131]. These processes also bring species into greater contact with novel competitors[128] and create more frontiers for conflict with people[132].

[H1] Conservation solutions

The diverse geopolitical landscape of Southeast Asia shapes both the magnitude and variety of threats to biodiversity. Solving the region's terrestrial biodiversity crisis therefore requires a combination of approaches tailored to the specific challenges faced within individual countries. Additionally, a range of conservation interventions are needed to protect biodiversity within human-modified landscapes as well as intact forest areas.

[H2] Protected area coverage and effectiveness

Protected areas (PA) are crucial in biodiversity conservation, acting as important refuges for threatened species. By 2020, Southeast Asia's PA network encompassed over 592,000 km^2 — equivalent to 13% of its land area and thus falling short of the ≥17% committed internationally at that time[133]. However, noteworthy disparities exist between countries. Cambodia protects almost 40% of its land for conservation, whereas Myanmar and Vietnam protect only 7% and 8%, respectively (Table S3). Laos undertook major policy reforms and formalised its PA system in 2023 to protect 19% of its land, whereas Timor-Leste's PA system began in 2016 and comprises 16%. Approximately 39% of the region's PAs are in Indonesia, which has the largest PA network by far. Yet, many PAs in the region were not designated for conservation, as they were established as game reserves or forestry controls during the colonial era. Some habitats remain underrepresented, although less so than in other Asian countries[133,134].

Despite facing some of the highest human pressures globally[135,136], Southeast Asia's PAs appear to be successful at reducing biodiversity loss. Collectively, these PAs have experienced three times less deforestation than unprotected forests[137] and, consequently, support higher bird and mammal diversity[138]. However, focusing on effectiveness at a regional scale masks the heterogenous, and often unintended, social-ecological outcomes within countries and among individual PAs[139]. Most of the avoided regional deforestation occurred in Malaysia and Cambodia (15% and 11%, respectively)[137]. The unintentional impacts of PAs often include leakage, in which disturbances are displaced to nearby unprotected land[140], and restrictions on local communities. For example, although PAs in Sumatra and Kalimantan have reduced deforestation (22% and 16%, respectively), trade-offs with well-being in neighbouring villages has often occurred[141]. Conversely, in Cambodia, communities bordering PAs had more secure forest access and better livelihoods than those further away[142], but relentless pressure on two parks led to their eventual degazettement for industrial agriculture[143].

Although expanding the conservation estate is vital to achieving global biodiversity goals[138,144], improving the effectiveness of existing PAs is equally important. Tools for evaluating PA management effectiveness are embedded in the Kunming–Montreal Global Biodiversity Framework (KM-GBF) (Box 3), but this process takes time. Only around one-quarter of PAs have been assessed globally[145]. Although >30% of PAs in Cambodia, Indonesia, and Singapore have been evaluated, <10% have been assessed in Malaysia, Myanmar, and the Philippines, and none in Laos or Timor-Leste[133]. PAs with management reporting are more likely to avoid deforestation, underscoring the need to scale up evaluations[137].

Adequate funding, staff capacity, and enforcement are vital for effective PAs, and those that fail are often characterised by corruption, land-use conflict, and contested land claims[146–148]. Government funding is inconsistent between and within countries[145], and is often supplemented by international finance. Thailand, for instance, employs more rangers per unit area than most Asian countries combined, whereas Myanmar employs among the fewest[149]. Although PA budgets in the Philippines are substantial, funding within Cambodia and Myanmar is highly unequal, and Timor-Leste's is uniformly inadequate[146]. Investment in PAs has increased substantially since the 1990s[149], and major improvements to patrolling, enforcement, and adaptive management have been made since the introduction of the Spatial Monitoring and Reporting Tool (SMART), which is now implemented in most countries. From 2007, hunting reduced and tiger density increased in Thailand's Western Forest Complex after the mainstreaming of SMART[146]. Nevertheless, following this success, calls have been made for a major scale-up in spending that would employ 7875 additional rangers at a cost of ~US$29 million in Southeast Asia's tiger range countries alone[150]. How authorities enforce laws and administer sanctions is also important, as perceptions of fairness and the avoidance of abuses of power are key factors influencing people's willingness to adhere to PA rules[151]. Tackling these factors will be crucial to the success of PAs, and could be more influential than merely focusing on more enforcement.

[H2] Landscape approaches to conservation

Focussing solely on PAs formally designated for biodiversity overlooks sizeable tracts of land that are protected for purposes other than conservation and can have considerable biodiversity value (Box 3). For instance, watershed protection covers 297,000 km^2 of forest in Indonesia (16% of the country), and large tracts of biodiversity-rich forest remain outside of formal PAs in Cambodia, Laos, and Myanmar. Landscape conservation approaches that incorporate such areas seek to maintain or enhance biodiversity and ecological connectivity across human-modified ecosystems while also meeting livelihood and development goals[152]. Nevertheless, governance in these alternative protected ecosystems is often weaker, and downgrading and degazetting are commonplace[146].

Collaboration between multiple stakeholders through financial incentives, certification schemes, and improved land tenure rights is central to promoting biodiversity in human-modified ecosystems. Southeast Asia's large and diverse private sector has an increasingly important role in these initiatives, particularly in forest restoration (Box 4). In Malaysia, for example, oil palm companies are financing forest restoration of a former logging concession (an area granted permission to harvest timber) to buffer threatened species from further habitat loss[153]. Indonesia's ecosystem restoration licences, which lease degraded logged-over forests for 60+ years, have also shown promise in achieving conservation and commercial objectives. For example, a major paper-pulp company has protected 1500 km^2 of Sumatran peatswamp forest since 2013 through such licenses, eliminating fires and enhancing carbon stocks[154]. By 2020, >6200 km^2 of licenses had been awarded to companies and non-governmental organisations across Indonesia, and many more are in development[155], although some sites continue to experience pressure from agriculture and infrastructure development[156]. Further research is needed into the long-term effectiveness of using such initiatives to finance conservation.

Landscape conservation approaches can be strengthened by agribusinesses and extractive industries pledging to eliminate deforestation from their supply chains. Indeed, >80% of Southeast Asia's oil palm refining capacity is under some form of zero deforestation commitment[157]. Pledges typically involve avoiding clearance of forests with high conservation or carbon value, not planting on peatland to minimise fire and soil-based emissions, and improving well-being outcomes for workers and local communities[158]. By 2015, oil palm sustainability commitments in Indonesia had reduced deforestation by 33%, but had limited success in addressing peatland clearance and fire[159]. However, early adopters of certification (approximately 2009 to 2015) tended to have the least remaining forest area, so little deforestation was avoided at that time. Social impacts of certification have been mixed: poverty has been alleviated in some villages but worsened in others, often as a result of trade-offs between environmental and social sustainability objectives[160,161].

The forest patches left behind in production landscapes have limited biodiversity value in isolation but, if managed collectively at a landscape-scale, can support the persistence and movement of threatened species populations[162–164]. Riparian habitats are particularly important as they are often protected during logging operations and, subsequently, in agriculture and provide refuge for many species[165,166]. Nonetheless, without adequate management these set-asides are prone to further degradation, encroachment and hunting, limiting their effectiveness as habitat and dispersal corridors[162,167]. Crucially, leveraging industry commitments to follow environmental policies and best practices and incentivising smallholders to follow best practices in their farmlands can lead to improved biodiversity outcomes without compromising agricultural productivity or yields[43,168]. Although voluntary certification schemes are prone to conceptual (for example, defining forests or avoiding leakage) and practical (such as ensuring transparency and integrating small-holders) challenges[169,170], those in the forestry and oil palm sectors have raised governmental standards and inspired sustainability initiatives in other agri-industries, including rubber and coconut. Decision support tools to help identify high conservation value land at a landscape-scale, ideally prior to development, continue to be needed[171].

[H2] Community-led forest management

Much of the intact forest of tropical countries is managed or used by indigenous people or local communities, who are likely to be critical for safeguarding biodiversity[172,173]. Participatory approaches to forest management, in which local communities are given rights and responsibilities over forest resources, are used prominently in Southeast Asia to address deforestation, rural poverty, and climate mitigation. Over 138,000 km^2 of forest is under formal community management, primarily in the Philippines, Indonesia, Vietnam, and Cambodia[174]. Indonesia, Laos, and Thailand formalised forest resource rights more recently (2014–2019), and initiatives in Myanmar and Malaysia continue to grow despite facing political and legal challenges[174,175]. Community forest management practices vary in different countries, as some schemes focus purely on protection whereas others permit ecotourism, agroforestry, and/or the extraction of forest products (including wildmeat) for local use[175,176]. To be successful, the schemes provide indigenous people or local communities with stable income through sustainable land-use practices that are compatible with conservation (Box 3), as well as access to funding for restoring degraded lands (Box 4)[176–178].

Giving indigenous people or local communities a stake in forest resources through community management can incentivise sustainable practices, which is effective in many cases. Cambodia allows local communities to manage forests within PAs[179], which has resulted in reduced deforestation and degradation[180]. Community-managed forests are also attributed with uplifting the protective function of PAs in Thailand[181], and improving canopy cover and landscape connectivity in the Philippines[178]. In Indonesia, where multiple schemes have been introduced, environmental benefits have commonly been reported[176,177], although not universally. A prominent community-managed forest initiative successfully avoided deforestation in Kalimantan and Sumatra between 2009 and 2014[182], although comparable outcomes have yet to be observed for this specific scheme or others nationwide[183].

The socio-economic benefits of community forestry have not been uniformly realised[177,184]. Effectiveness is highly dependent on local governance structures and leadership, community capabilities and capacity, and external support[176,178]. Weak enforcement of forest laws and ambiguous land tenure can aggravate deforestation in some community-managed forests, particularly in agricultural zones where external pressures are more intense than in extensively forested areas [182,185]. Without strong governance structures, wealthier households and community leaders disproportionately benefit, while poorer households remain disadvantaged, thus reinforcing existing inequities and injustices[175,186]. Long-term, inadequate financial and technical resources can lead to disillusionment. Empowering people through genuine participation in land-use decisions and locally-led initiatives is challenging, but critical to delivering positive biodiversity outcomes; for example, a community-led conservation scheme that co-produced management actions with local people, and designed and implemented a monitoring and evaluation framework, resulted in reduced hunting, logging, and forest clearance[187]. Nonetheless, aside from a limited number of case-studies, evaluation of the biodiversity credentials of community forest management remains limited[177,184].

[H2] Tackling unsustainable hunting

Disincentivising wildmeat consumption in urban areas must be the prominent focus in tackling hunting for non-subsistence purposes[87] because it plays a central role in overexploitation and trade dynamics. Law enforcement is crucial to close illegal wildlife markets and trade routes, and increased effectiveness is required from digital service platforms to reduce illegal products sold online[188]. Meat consumption in Southeast Asia remains below the global average but is increasing (Fig. S4), so ensuring this consumption is within ecologically sustainable levels and from non-wild stocks is key to food security. This approach is likely to benefit biodiversity longer-term by decreasing both the area of land needed for animal rearing and the demand for wildmeat. The EAT Planetary Health Diet, for instance, has been specifically designed to promote sustainable food systems[189].

Preventing illegal hunting and trafficking requires a multi-pronged approach. Near PAs, interventions include improving patrols, increasing penalties, and legislative reform to criminalise possession of snares[95,190]. Providing incentives for people to not hunt is yet to be adequately explored, but adoption of community-led models could increase the success of this approach[187]. For example, analogous investments into rural healthcare have led to declines in illegal logging within a national park in Indonesia[191]. Strengthening transnational and regional cross-border collaborations and agreements will also be necessary[192].

[H2] Funding biodiversity through climate mitigation

Despite investment, Southeast Asia's countries face substantial funding gaps for biodiversity conservation[146]. Climate change mitigation offers a promising additional source of funding, aligning the Paris Agreement with various international policy commitments, such as the KM-GBF and the United Nations Sustainable Development Goals. Owing to its vast carbon stocks and high deforestation risk, the region is especially well positioned to cost-effectively deliver on both climate and biodiversity objectives[21] (Table S1, S3). Such nature-based climate solutions include forest protection, ecosystem restoration, and sustainable land management. More than 1 million km^2 of forests across Southeast Asia could generate at least one biodiversity or ecosystem service co-benefit, alongside reducing emissions, and Thailand and Indonesia are especially important[193]. Optimising the spatial planning of nature-based climate solutions, so that the benefits for climate mitigation, people's livelihoods, and biodiversity are maximised, is crucial for long-term success. Wetland protection is particularly well-suited to Indonesia owing to its extensive tropical peatlands, where 49 tCO_2 ha^{-1} yr^{-1} could be saved in Sumatra and Kalimantan alone[17,193,194]. Forest restoration and agricultural improvement are ideal in Thailand and the Philippines, while forest protection and sustainable land management are typically the best strategies elsewhere[17].

Among the various payment for ecosystem service schemes that exist, the UN's Reducing Emissions from Deforestation and Forest Degradation (REDD+) initiative remains central to protecting forest via climate finance. Although early successes have been achieved (for example, Cambodia[195,196]), Southeast Asia's complex geopolitical landscape poses considerable challenges ahead. Indonesia is the region's largest country and carbon emitter (Fig. S5). Although deforestation has reduced across the country since 2017, regulatory tensions between national and regional government, along with deregulation efforts, disrupted its 2011 moratorium on forest clearance [197,198]. As with PAs and other area-based conservation measures, leakage can be problematic, and the biodiversity and livelihood co-benefits of emissions reductions can be costly and limit feasibility[21]. Discrepancies also persist between pledges and actual disbursements. For example, Norway pledged US$1 billion REDD+ to Indonesia in 2010, but had only released US$56 million 10-years later owing to delays in the measurement, reporting and verification of reduced emissions[199]. Carbon financing also faces credibility issues, such as inflated deforestation baselines used to measure progress[200]. One potential outcome is that local communities and governments that have managed to successfully protect their forests in the long-term might not be appropriately rewarded, despite these forests potentially having the greatest biodiversity value. Developing reliable counterfactuals to evaluate the performance of interventions and addressing the high costs of monitoring forests and biodiversity are sizeable issues that are being slowly overcome[195,201,202]. Strengthening inclusivity and benefit-sharing among indigenous people and local communities will be vital to securing further uptake of payments for ecosystem services schemes[203,204], particularly if these schemes are to incentivise biodiversity protection and alternatives to overexploitation[205].

[H2] Policy coordination and implementation

Although no single, straightforward solution exists for protecting forests and biodiversity[206], conservation activity in the region has greatly expanded since the crisis was first identified in the early 2000s[8]. Governments across Southeast Asia have increased conservation investment to meet obligations under the Convention on Biological Diversity and other multilateral sustainability agreements[207]. The ASEAN Centre for Biodiversity, established in 2005, provides regional coordination and policy guidance. The 2023 ASEAN Biodiversity Outlook report noted progress among countries towards the Aichi Biodiversity Targets, including raised awareness, mainstreaming biodiversity, incentivising sustainable practices, and revising National Biodiversity Strategies and Action Plans (NBSAPs)[207].

However, implementation of the KM-GBF (Box 3) —which replaced the Aichi Targets in 2022 — requires additional resources. Regional support for the KM-GBF is evident in the ASEAN Biodiversity Plan, its Green Initiative (which promotes large-scale tree planting), and a revised Biodiversity Dashboard for tracking national and regional progress. Most ASEAN countries are revising their NBSAPs, with varying degrees of completeness and ambition. Indonesia and Malaysia have updated their NBSAPs to cover all 23 targets, using drivers-based approaches linked to national development goals (Table S4). Cambodia has mapped preliminary national targets to the KM-GBF, but many lack specificity or are outdated. Elsewhere in the region, Thailand, Laos, Vietnam, and the Philippines are currently undertaking NBSAP revisions, although implementation is hindered by competing policy priorities and financing gaps. As of early 2025, Brunei and Myanmar were yet to submit updated plans or targets.

The inconsistent and often limited use of quantitative indicators is a persistent challenge — many are removed or changed between reporting cycles[208]. Improved metrics are needed for habitat loss, species overexploitation, climate impacts, and invasive species. Reporting of national and regional IUCN Red List data remains patchy and underdeveloped. Although participation of indigenous and local communities is increasing in some countries, it remains limited regionally. Weak inter-agency coordination (for example, between agriculture, environment and fisheries) hampers holistic understanding of biodiversity challenges and solutions within countries, and therefore implementation of the KM-GBF.

[H1] Summary and Future Research Perspectives

Southeast Asia's biodiversity crisis continues owing to the intersecting pressures described above. To help countries tackle the crisis, researchers should be contributing more to solutions and engaging directly in implementation science, rather than merely elucidating problems[209]. Biodiversity research needs to encompass a broader range of both established (for example, rubber and coconut) and emerging (for example, durian and cassava) forest-risk commodities and geographies, expanding beyond the intense focus on oil palm. Refocussing attention on crops where management options exist to minimise ecological damage (such as cacao, coconut, coffee) — especially in agroforestry — would be particularly beneficial. Moreover, this research will fill the gaps in global datasets (for example, PREDICTS, Living Planet Index; Fig. S6), thus helping to improve regional biodiversity monitoring and predictions.

The KM-GBF has spurred on the rapid development of biodiversity credits to financially support biodiversity protection and restoration. Although credits hold immense potential to attract investment for biodiversity in tropical countries, establishing and validating their scientific credibility will be key to avoiding issues around integrity and impact that plague carbon markets[19]. Unlike carbon, biodiversity is not fungible, meaning that research is needed to underpin a credit system that reflects the complexity and location-specific nature of biodiversity. Fundamental questions remain regarding how biodiversity gains can be reliably quantified, and what metrics should be used to track biodiversity change over time[210,211]. Practical and realistic economic frameworks are vital to ensuring sufficient demand and consistent sales of credits to help direct investment where it is needed most (that is, areas of high biodiversity threat, rather than easy biodiversity gain[210,211]). Furthermore, the revenue models adopted must channel the funding to indigenous peoples and local communities as the stewards of biodiverse lands[210,212]. Developing equitable and robust measurement and accounting approaches will be critical to establishing biodiversity credits as trusted, impactful tools for conservation finance.

Enhancing biodiversity monitoring requires integrating rapid, cost-effective tools alongside strengthened human and technological capacity. Taxonomic expertise is vital to understanding, cataloguing, and assessing biodiversity, yet remains undervalued in research[213,214]. Although advances in remote sensing, robotics and automated systems, and artificial intelligence will be transformative, reliance on technology alone is high-risk and could be exclusionary or harmful to indigenous people and local communities[18,215–217]. Instead, a hybrid approach that combines technology with local ecological knowledge[218] should be adopted to deliver robust data validation. To process the vast datasets technological tools generate, improved statistical methodologies and integrated models to facilitate accurate biodiversity surveys are required[219].

Synthesis methods, such as meta-analyses, synthetic controls, and impact evaluations using rigorous counterfactual designs, are key to generating the high-quality evidence needed to underpin policy and practice decision-making[220]. The social, as well as environmental, consequences of conservation solutions must be assessed within such frameworks to ensure potential socio-ecological trade-offs are fully understood[43,221]. Innovations could include assessing multiple drivers or management/policy interventions within the same analysis, evaluating outcomes at smaller jurisdictional scales to better inform activities[222], and using results to help target biodiversity surveys or interview-based case-studies. As the deadline for meeting the 2030 KM-GBF targets approaches, the need to evaluate effectiveness of potential other effective area-based conservation measures (OECMs) is paramount (Box 3).

Research ethics are fundamental, whether they relate to use of technology[216,217,223] or the inclusion of people within activities[87]. Work on Southeast Asia's biodiversity crisis is often dominated by high-income country researchers, whereas locally valuable studies in non-English languages face barriers to broader recognition[224]. Regional capacity continues to improve, but training opportunities are limited by funding, language, and location, making them highly competitive and sometimes ill-matched to competences needed for conservation (for example, planning, fundraising and project management)[225].

Meaningful collaboration with local scientists and communities should be paramount, and parachute science practices avoided, especially in the context of increased applications of artificial intelligence[226,227]. Researchers should cultivate self-awareness, expand literature searches into multiple languages, foster genuine partnerships, and promote meaningful knowledge exchange[228]. Women, indigenous communities, and other marginalised groups are vital stewards of biodiversity, but opportunities for these groups to contribute to research remain underdeveloped[229,230]. Publishers should enhance inclusivity standards, remove financial barriers, facilitate multilingual dissemination, and ensure equitable representation in peer review. Funders could also remove systemic obstacles by targeting investment in projects and training that strengthen research networks and amplify the roles of regional experts, so that practical, culturally-nuanced research receives due recognition[228].

Data sharing at all stages of the research process, from standardised data collection protocols and indicators (for example, for wildlife hunting, consumption, and trade) through to the findings of impact evaluations, is currently hindered by distrust of how data will be used and credited, and a lack of centralised open access information repositories[231,232]. Addressing these concerns would enable transparent learning from both research and intervention successes and failures. To date, insufficient knowledge sharing has led to mistakes being repeated and has slowed progress in tackling the terrestrial biodiversity crisis[146]. By following these recommendations, the research community will ensure that Southeast Asian nations are better positioned to solve their conservation challenges and realise the more optimistic projections for biodiversity in years to come.

References

1. Barlow, J. *et al.* The future of hyperdiverse tropical ecosystems. *Nature* **559**, 517–526 (2018).
2. Edwards, D. P. *et al.* Conservation of Tropical Forests in the Anthropocene. *Current Biology* **29**, R1008–R1020 (2019).
3. Malhi, Y., Gardner, T. A., Goldsmith, G. R., Silman, M. R. & Zelazowski, P. Tropical Forests in the Anthropocene. *Annu. Rev. Environ. Resour.* **39**, 125–159 (2014).
4. Doughty, C. E. *et al.* Tropical forests are approaching critical temperature thresholds. *Nature* **621**, 105–111 (2023).
5. Ondo, I. *et al.* Plant diversity darkspots for global collection priorities. *New Phytologist* **244**, 719–733 (2024).
6. Ong, X. R., Tan, B., Chang, C. H., Puniamoorthy, N. & Slade, E. M. Identifying the knowledge and capacity gaps in Southeast Asian insect conservation. *Ecology Letters* **28**, e70038 (2025).
7. Pillay, R. *et al.* Tropical forests are home to over half of the world's vertebrate species. *Frontiers in Ecol & Environ* **20**, 10–15 (2022).
8. Sodhi, N. S., Koh, L. P., Brook, B. W. & Ng, P. K. L. Southeast Asian biodiversity: an impending disaster. *Trends in Ecology & Evolution* **19**, 654–660 (2004).
9. Struebig, M. J. *et al.* Safeguarding imperiled biodiversity and evolutionary processes in the Wallacea center of endemism. *BioScience* **72**, 1118–1130 (2022).
10. Svenning, J.-C. *et al.* The late-Quaternary megafauna extinctions: Patterns, causes, ecological consequences and implications for ecosystem management in the Anthropocene. *Camb. prisms Extinction* **2**, e5 (2024).
11. McConkey, K. R., Aldy, F., Ong, L., Sutisna, D. J. & Campos-Arceiz, A. Lost mutualisms: Seed dispersal by Sumatran rhinos, the world's most threatened megafauna. *Biotropica* **54**, 346–357 (2022).
12. Hughes, A. C. Understanding the drivers of Southeast Asian biodiversity loss. *Ecosphere* **8**, e01624 (2017).

13. Wilcove, D. S., Giam, X., Edwards, D. P., Fisher, B. & Koh, L. P. Navjot's nightmare revisited: logging, agriculture, and biodiversity in Southeast Asia. *Trends in Ecology & Evolution* **28**, 531–540 (2013).
14. Yang, C. *et al.* Human Expansion-Induced Biodiversity Crisis over Asia from 2000 to 2020. *Research* **6**, 0226 (2023).
15. Coleman, J. L. *et al.* Top 100 research questions for biodiversity conservation in Southeast Asia. *Biological Conservation* **234**, 211–220 (2019).
16. Botterill-James, T., Yates, L. A., Buettel, J. C. & Brook, B. W. The future of Southeast Asia's biodiversity: A crisis with a hopeful alternative. *Biological Conservation* **296**, 110641 (2024).
17. Griscom, B. W. *et al.* National mitigation potential from natural climate solutions in the tropics. *Phil. Trans. R. Soc. B* **375**, 20190126 (2020).
18. Pringle, S. Identifying the opportunities and challenges for monitoring terrestrial biodiversity in the robotics age. *Nature Ecology and Evolution* (2025).
19. Swinfield, T., Shrikanth, S., Bull, J. W., Madhavapeddy, A. & Zu Ermgassen, S. O. S. E. Nature-based credit markets at a crossroads. *Nat Sustain* **7**, 1217–1220 (2024).
20. Vancutsem, C. *et al.* Long-term (1990–2019) monitoring of forest cover changes in the humid tropics. *Sci. Adv.* **7**, eabe1603 (2021).
21. Koh, L. P., Zeng, Y., Sarira, T. V. & Siman, K. Carbon prospecting in tropical forests for climate change mitigation. *Nat Commun* **12**, 1271 (2021).
22. Spawn, S. A., Sullivan, C. C., Lark, T. J. & Gibbs, H. K. Harmonized global maps of above and belowground biomass carbon density in the year 2010. *Sci Data* **7**, 112 (2020).
23. Raven, P. H. *et al.* The distribution of biodiversity richness in the tropics. *Sci. Adv.* **6**, eabc6228 (2020).
24. Brook, B., Sodhi, N. & Bradshaw, C. Synergies among extinction drivers under global change. *Trends in Ecology & Evolution* **23**, 453–460 (2008).
25. França, F. M. *et al.* Climatic and local stressor interactions threaten tropical forests and coral reefs. *Phil. Trans. R. Soc. B* **375**, 20190116 (2020).
26. Jaureguiberry, P. *et al.* The direct drivers of recent global anthropogenic biodiversity loss. *Sci. Adv.* **8**, eabm9982 (2022).
27. Jamaludin, J., De Alban, J. D. T., Carrasco, L. R. & Webb, E. L. Spatiotemporal analysis of deforestation patterns and drivers reveals emergent threats to tropical forest landscapes. *Environ. Res. Lett.* **17**, 054046 (2022).
28. Austin, K. G., González-Roglich, M., Schaffer-Smith, D., Schwantes, A. M. & Swenson, J. J. Trends in size of tropical deforestation events signal increasing dominance of industrial-scale drivers. *Environ. Res. Lett.* **12**, 054009 (2017).

29. Gaveau, D. L. A. *et al.* Slowing deforestation in Indonesia follows declining oil palm expansion and lower oil prices. *PLoS ONE* **17**, e0266178 (2022).
30. Gevaña, D. T., Camacho, L. D. & Pulhin, J. M. Conserving Mangroves for Their Blue Carbon: Insights and Prospects for Community-Based Mangrove Management in Southeast Asia. in *Threats to Mangrove Forests* (eds. Makowski, C. & Finkl, C. W.) vol. 25 579–588 (Springer International Publishing, Cham, 2018).
31. Sasmito, S. D. *et al.* Half of land use carbon emissions in Southeast Asia can be mitigated through peat swamp forest and mangrove conservation and restoration. *Nat Commun* **16**, 740 (2025).
32. He, X. *et al.* Accelerating global mountain forest loss threatens biodiversity hotspots. *One Earth* **6**, 303–315 (2023).
33. Chen, Y., Fuller, R. A., Lee, T. M. & Hua, F. Disproportionate low-elevation forest loss in over 65% of the world's mountains calls for targeted conservation. *One Earth* **7**, 1833–1845 (2024).
34. Mitchell, S. L. *et al.* Severity of deforestation mediates biotic homogenisation in an island archipelago. *Ecography* **2022**, e05990 (2022).
35. Newbold, T. *et al.* Widespread winners and narrow-ranged losers: Land use homogenizes biodiversity in local assemblages worldwide. *PLoS Biol* **16**, e2006841 (2018).
36. Grantham, H. S. *et al.* Anthropogenic modification of forests means only 40% of remaining forests have high ecosystem integrity. *Nat Commun* **11**, 5978 (2020).
37. Pfeifer, M. *et al.* Creation of forest edges has a global impact on forest vertebrates. *Nature* **551**, 187–191 (2017).
38. Mu, H. *et al.* A global record of annual terrestrial Human Footprint dataset from 2000 to 2018. *Sci Data* **9**, 176 (2022).
39. Curtis, P. G., Slay, C. M., Harris, N. L., Tyukavina, A. & Hansen, M. C. Classifying drivers of global forest loss. *Science* **361**, 1108–1111 (2018).
40. FAOSTAT. Food and Agriculture Organization of the United Nations: food and agricultural data. (2024).
41. Drescher, J. *et al.* Ecological and socio-economic functions across tropical land use systems after rainforest conversion. *Phil. Trans. R. Soc. B* **371**, 20150275 (2016).
42. Malhi, Y. *et al.* Logged tropical forests have amplified and diverse ecosystem energetics. *Nature* **612**, 707–713 (2022).
43. Zemp, D. C. *et al.* Tree islands enhance biodiversity and functioning in oil palm landscapes. *Nature* **618**, 316–321 (2023).
44. Wang, Y. *et al.* High-resolution maps show that rubber causes substantial deforestation. *Nature* **623**, 340–346 (2023).

45. Meyfroidt, P., Vu, T. P. & Hoang, V. A. Trajectories of deforestation, coffee expansion and displacement of shifting cultivation in the Central Highlands of Vietnam. *Global Environmental Change* **23**, 1187–1198 (2013).
46. Khoo, G. C. Durian matters. *Continuum* 1–7 (2024) doi:10.1080/10304312.2024.2421883.
47. Meijaard, E., Abrams, J. F., Juffe-Bignoli, D., Voigt, M. & Sheil, D. Coconut oil, conservation and the conscientious consumer. *Current Biology* **30**, R757–R758 (2020).
48. Propper, C. R. *et al.* Balancing food security, vertebrate biodiversity, and healthy rice agroecosystems in Southeast Asia. *Crop and Environment* **3**, 43–50 (2024).
49. Yuan, S. *et al.* Southeast Asia must narrow down the yield gap to continue to be a major rice bowl. *Nat Food* **3**, 217–226 (2022).
50. Wyckhuys, K. A. G. *et al.* Biological control of an agricultural pest protects tropical forests. *Commun Biol* **2**, 10 (2019).
51. Rege, A. & Lee, J. S. H. The socio-environmental impacts of tropical crop expansion on a global scale: A case study in cashew. *Biological Conservation* **280**, 109961 (2023).
52. Meijaard, E. *et al.* The environmental impacts of palm oil in context. *Nature Plants* **6**, 1418–1426 (2020).
53. Oakley, J. L. & Bicknell, J. E. The impacts of tropical agriculture on biodiversity: A meta-analysis. *Journal of Applied Ecology* **59**, 3072–3082 (2022).
54. Manson, S., Nekaris, K. A. I., Nijman, V. & Campera, M. Effect of shade on biodiversity within coffee farms: A meta-analysis. *Science of The Total Environment* **914**, 169882 (2024).
55. Kelley, L. C., Evans, S. G. & Potts, M. D. Richer histories for more relevant policies: 42 years of tree cover loss and gain in Southeast Sulawesi, Indonesia. *Global Change Biology* **23**, 830–839 (2017).
56. Rigg, J., Salamanca, A. & Thompson, E. C. The puzzle of East and Southeast Asia's persistent smallholder. *Journal of Rural Studies* **43**, 118–133 (2016).
57. Higham, C. F. *Early Mainland Southeast Asia: From First Humans to Angkor*. (River Books Press, Bangkok, 2014).
58. Santika, T. *et al.* Does oil palm agriculture help alleviate poverty? A multidimensional counterfactual assessment of oil palm development in Indonesia. *World Development* **120**, 105–117 (2019).
59. Li, P. & Nath, A. J. The history and revival of swidden agriculture research in the tropics. *CABI Agric Biosci* **5**, 84 (2024).
60. Schoneveld, G. C., Ekowati, D., Andrianto, A. & Van Der Haar, S. Modeling peat- and forestland conversion by oil palm smallholders in Indonesian Borneo. *Environ. Res. Lett.* **14**, 014006 (2019).
61. Bowman, D. M. J. S. *et al.* Vegetation fires in the Anthropocene. *Nat Rev Earth Environ* **1**, 500–515 (2020).

62. Van Wees, D. *et al.* The role of fire in global forest loss dynamics. *Global Change Biology* **27**, 2377–2391 (2021).
63. Voigt, M. *et al.* Deforestation projections imply range-wide population decline for critically endangered Bornean orangutan. *Perspectives in Ecology and Conservation* **20**, 240–248 (2022).
64. Kiely, L. *et al.* Assessing costs of Indonesian fires and the benefits of restoring peatland. *Nat Commun* **12**, 7044 (2021).
65. Santika, T. *et al.* Deterioration of respiratory health following changes to land cover and climate in Indonesia. *One Earth* **6**, 290–302 (2023).
66. Santika, T. *et al.* Interannual climate variation, land type and village livelihood effects on fires in Kalimantan, Indonesia. *Global Environmental Change* **64**, 102129 (2020).
67. He, T., Lamont, B. B. & Pausas, J. G. Fire as a key driver of Earth's biodiversity. *Biological Reviews* **94**, 1983–2010 (2019).
68. Pausas, J. G. & Keeley, J. E. Wildfires and global change. *Frontiers in Ecol & Environ* **19**, 387–395 (2021).
69. Harrison, M. E. *et al.* Impacts of fire and prospects for recovery in a tropical peat forest ecosystem. *Proc. Natl. Acad. Sci. U.S.A.* **121**, e2307216121 (2024).
70. Khor, N. *et al. World Cities Report 2022: Envisaging the Future of Cities*. 422 (2022).
71. Winemiller, K. O. *et al.* Balancing hydropower and biodiversity in the Amazon, Congo, and Mekong. *Science* **351**, 128–129 (2016).
72. Ng, L. S. *et al.* The scale of biodiversity impacts of the Belt and Road Initiative in Southeast Asia. *Biological Conservation* **248**, 108691 (2020).
73. Engert, J. E. *et al.* Ghost roads and the destruction of Asia-Pacific tropical forests. *Nature* **629**, 370–375 (2024).
74. Cho, M. S. & Qi, J. Characterization of the impacts of hydro-dams on wetland inundations in Southeast Asia. *Science of The Total Environment* **864**, 160941 (2023).
75. Orr, S., Pittock, J., Chapagain, A. & Dumaresq, D. Dams on the Mekong River: Lost fish protein and the implications for land and water resources. *Global Environmental Change* **22**, 925–932 (2012).
76. He, F. *et al.* Freshwater megafauna diversity: Patterns, status and threats. *Diversity and Distributions* **24**, 1395–1404 (2018).
77. Chisholm, R. A. *et al.* Two centuries of biodiversity discovery and loss in Singapore. *Proc. Natl. Acad. Sci. U.S.A.* **120**, e2309034120 (2023).
78. Tan, P. Y. & Abdul Hamid, A. R. B. Urban ecological research in Singapore and its relevance to the advancement of urban ecology and sustainability. *Landscape and Urban Planning* **125**, 271–289 (2014).

79. Ahmed, M. *et al.* An overview of Asian cement industry: Environmental impacts, research methodologies and mitigation measures. *Sustainable Production and Consumption* **28**, 1018–1039 (2021).
80. Clements, R., Sodhi, N. S., Schilthuizen, M. & Ng, P. K. L. Limestone Karsts of Southeast Asia: Imperiled Arks of Biodiversity. *BioScience* **56**, 733 (2006).
81. Werner, T. T. *et al.* Patterns of infringement, risk, and impact driven by coal mining permits in Indonesia. *Ambio* **53**, 242–256 (2024).
82. Dethier, E. N. *et al.* A global rise in alluvial mining increases sediment load in tropical rivers. *Nature* **620**, 787–793 (2023).
83. Timsina, S. *et al.* Tropical surface gold mining: A review of ecological impacts and restoration strategies. *Land Degrad Dev* **33**, 3661–3674 (2022).
84. Maus, V. & Werner, T. T. Impacts for half of the world's mining areas are undocumented. *Nature* **625**, 27–29 (2024).
85. IEA. *Global Critical Minerals Outlook 2024*. (International Energy Agency, www.iea.org, 2024).
86. Lo, M. *et al.* Implications of nickel mining on forest cover and local communities in Indonesia. *One Earth* (2024).
87. Ingram, D. J. *et al.* Wild meat is still on the menu: progress in wild meat research, policy, and practice from 2002 to 2020. *Annu. Rev. Environ. Resour.* **46**, 221–254 (2021).
88. Mazor, T. *et al.* Global mismatch of policy and research on drivers of biodiversity loss. *Nat Ecol Evol* **2**, 1071–1074 (2018).
89. Harrison, R. D. *et al.* Impacts of hunting on tropical forests in Southeast Asia. *Conservation Biology* **30**, 972–981 (2016).
90. Lees, A. C. & Yuda, P. The Asian songbird crisis. *Current Biology* **32**, R1063–R1064 (2022).
91. Lees, A. C. & Yuda, P. The Asian songbird crisis. *Current Biology* **32**, R1063–R1064 (2022).
92. McEvoy, J. F. *et al.* Two sides of the same coin – Wildmeat consumption and illegal wildlife trade at the crossroads of Asia. *Biological Conservation* **238**, 108197 (2019).
93. Lee, T. M., Sigouin, A., Pinedo-Vasquez, M. & Nasi, R. *The Harvest of Wildlife for Bushmeat and Traditional Medicine in East, South and Southeast Asia: Current Knowledge Base, Challenges, Opportunities and Areas for Future Research*. (Center for International Forestry Research (CIFOR), 2014). doi:10.17528/cifor/005135.
94. Pangau-Adam, M., Flassy, M., Trei, J., Waltert, M. & Soofi, M. The role of the introduced rusa deer *Cervus timorensis* for wildlife hunting in West Papua, Indonesia. *Ecol Sol and Evidence* **3**, e12118 (2022).
95. Gray, T. N. E. *et al.* The wildlife snaring crisis: an insidious and pervasive threat to biodiversity in Southeast Asia. *Biodivers Conserv* **27**, 1031–1037 (2018).

96. Nuttall, M. N. *et al.* Long-term monitoring of wildlife populations for protected area management in Southeast Asia. *Conservat Sci and Prac* **4**, e614 (2022).
97. Wong, J. T. *et al.* Factors influencing animal-source food consumption in Timor-Leste. *Food Sec.* **10**, 741–762 (2018).
98. Loke, V. P. W., Lim, T. & Campos-Arceiz, A. Hunting practices of the Jahai indigenous community in northern peninsular Malaysia. *Global Ecology and Conservation* **21**, e00815 (2020).
99. *Hunter-Gatherers in a Changing World*. (Springer International Publishing, Cham, 2017). doi:10.1007/978-3-319-42271-8.
100. Singh, S. Appetites and aspirations: Consuming wildlife in Laos. *Australian J of Anthropology* **21**, 315–331 (2010).
101. Wells, G. J. *et al.* Hundreds of millions of people in the tropics need both wild harvests and other forms of economic development for their well-being. *One Earth* **7**, 311–324 (2024).
102. Spencer, K. L. *et al.* Wild meat consumption in changing rural landscapes of Indonesian Borneo. *People and Nature* (In Review).
103. Coad, L., Lim, S. & Nuon, L. Wildlife and livelihoods in the Cardamom Mountains, Cambodia. *Front. Ecol. Evol.* **7**, 296 (2019).
104. Nguyen, M. & Jones, T. E. Predictors of support for biodiversity loss countermeasure and bushmeat consumption among Vietnamese urban residents. *Conservat Sci and Prac* **4**, e12822 (2022).
105. Pattiselanno, F., Lloyd, J. K. F., Sayer, J., Boedhihartono, A. K. & Arobaya, A. Y. S. Wild Meat Trade Chain on the Bird's Head Peninsula of West Papua Province, Indonesia. *Journal of Ethnobiology* **40**, 202–217 (2020).
106. Phoyduangsy, S. *et al.* The determinants of bushmeat consumption in urban areas in Laos. *Ann Environ Sci Toxicol* **6**, 063–068 (2022).
107. Sandalj, M., Treydte, A. C. & Ziegler, S. Is wild meat luxury? Quantifying wild meat demand and availability in Hue, Vietnam. *Biological Conservation* **194**, 105–112 (2016).
108. Olmedo, A., Veríssimo, D., Challender, D. W. S., Dao, H. T. T. & Milner-Gulland, E. J. Who eats wild meat? Profiling consumers in Ho Chi Minh City, Vietnam. *People and Nature* **3**, 700–710 (2021).
109. Jiao, Y., Yeophantong, P. & Lee, T. M. Strengthening International Legal Cooperation to Combat the Illegal Wildlife Trade Between Southeast Asia and China. *Front. Ecol. Evol.* **9**, 645427 (2021).
110. Nguyen, T. & Roberts, D. L. Exploring the Africa-Asia Trade Nexus for Endangered Wildlife Used in Traditional Asian Medicine: Interviews With Traders in South Africa and Vietnam. *Tropical Conservation Science* **13**, 194008292097925 (2020).
111. Benítez-López, A., Santini, L., Schipper, A. M., Busana, M. & Huijbregts, M. A. J. Intact but empty forests? Patterns of hunting-induced mammal defaunation in the tropics. *PLoS Biol* **17**, e3000247 (2019).

112. Newbold, T. *et al.* Global effects of land use on local terrestrial biodiversity. *Nature* **520**, 45–50 (2015).

113. Pigot, A. L., Merow, C., Wilson, A. & Trisos, C. H. Abrupt expansion of climate change risks for species globally. *Nat Ecol Evol* **7**, 1060–1071 (2023).

114. Roy, H. E. *et al.* Curbing the major and growing threats from invasive alien species is urgent and achievable. *Nat Ecol Evol* **8**, 1216–1223 (2024).

115. Ewers, R. M. *et al.* Logging cuts the functional importance of invertebrates in tropical rainforest. *Nat Commun* **6**, 6836 (2015).

116. Deere, N. J. *et al.* Maximizing the value of forest restoration for tropical mammals by detecting three-dimensional habitat associations. *Proceedings of the National Academy of Sciences* **117**, 26254–26262 (2020).

117. Struebig, M. J. *et al.* Addressing human-tiger conflict using socio-ecological information on tolerance and risk. *Nature communications* **9**, 3455 (2018).

118. Symes, W. S., Edwards, D. P., Miettinen, J., Rheindt, F. E. & Carrasco, L. R. Combined impacts of deforestation and wildlife trade on tropical biodiversity are severely underestimated. *Nat Commun* **9**, 4052 (2018).

119. Haubrock, P. J. *et al.* Biological invasions in Singapore and Southeast Asia: data gaps fail to mask potentially massive economic costs. *NB* **67**, 131–152 (2021).

120. Newbold, T., Oppenheimer, P., Etard, A. & Williams, J. J. Tropical and Mediterranean biodiversity is disproportionately sensitive to land-use and climate change. *Nat Ecol Evol* **4**, 1630–1638 (2020).

121. Perez, T. M., Stroud, J. T. & Feeley, K. J. Thermal trouble in the tropics. *Science* **351**, 1392–1393 (2016).

122. Trew, B. T. *et al.* Novel temperatures are already widespread beneath the world’s tropical forest canopies. *Nat. Clim. Chang.* **14**, 753–759 (2024).

123. Santos, E. G. *et al.* Structural changes caused by selective logging undermine the thermal buffering capacity of tropical forests. *Agricultural and Forest Meteorology* **348**, 109912 (2024).

124. Siyum, Z. G. Tropical dry forest dynamics in the context of climate change: syntheses of drivers, gaps, and management perspectives. *Ecol Process* **9**, 25 (2020).

125. Lohberger, S., Stängel, M., Atwood, E. C. & Siegert, F. Spatial evaluation of Indonesia’s 2015 fire-affected area and estimated carbon emissions using Sentinel-1. *Global Change Biology* **24**, 644–654 (2018).

126. Freeman, B. G., Scholer, M. N., Ruiz-Gutierrez, V. & Fitzpatrick, J. W. Climate change causes upslope shifts and mountaintop extirpations in a tropical bird community. *Proc. Natl. Acad. Sci. U.S.A.* **115**, 11982–11987 (2018).

127. Chen, I.-C., Hill, J. K., Ohlemüller, R., Roy, D. B. & Thomas, C. D. Rapid Range Shifts of Species Associated with High Levels of Climate Warming. *Science* **333**, 1024–1026 (2011).

128. Mata-Guel, E. O. *et al.* Impacts of anthropogenic climate change on tropical montane forests: an appraisal of the evidence. *Biological Reviews* **98**, 1200–1224 (2023).
129. Harris, J. B. C. *et al.* Rapid deforestation threatens mid-elevational endemic birds but climate change is most important at higher elevations. *Diversity and Distributions* **20**, 773–785 (2014).
130. Senior, R. A., Hill, J. K. & Edwards, D. P. Global loss of climate connectivity in tropical forests. *Nat. Clim. Chang.* **9**, 623–626 (2019).
131. Crompton, O., Corrêa, D., Duncan, J. & Thompson, S. Deforestation-induced surface warming is influenced by the fragmentation and spatial extent of forest loss in Maritime Southeast Asia. *Environ. Res. Lett.* **16**, 114018 (2021).
132. Abrahms, B. *et al.* Climate change as a global amplifier of human–wildlife conflict. *Nat. Clim. Chang.* **13**, 224–234 (2023).
133. Farhadinia, M. S. *et al.* Current trends suggest most Asian countries are unlikely to meet future biodiversity targets on protected areas. *Commun Biol* **5**, 1221 (2022).
134. Singh, M., Griaud, C. & Collins, C. M. An evaluation of the effectiveness of protected areas in Thailand. *Ecological Indicators* **125**, 107536 (2021).
135. Dwiyahreni, A. A. *et al.* Changes in the human footprint in and around Indonesia's terrestrial national parks between 2012 and 2017. *Sci Rep* **11**, 4510 (2021).
136. Geldmann, J., Manica, A., Burgess, N. D., Coad, L. & Balmford, A. A global-level assessment of the effectiveness of protected areas at resisting anthropogenic pressures. *Proc. Natl. Acad. Sci. U.S.A.* **116**, 23209–23215 (2019).
137. Graham, V. *et al.* Southeast Asian protected areas are effective in conserving forest cover and forest carbon stocks compared to unprotected areas. *Sci Rep* **11**, 23760 (2021).
138. Brodie, J. F. *et al.* Landscape-scale benefits of protected areas for tropical biodiversity. *Nature* **620**, 807–812 (2023).
139. Sreekar, R. *et al.* Conservation opportunities through improved management of recently established protected areas in Southeast Asia. *Current Biology* **34**, 3830-3835.e3 (2024).
140. Ford, S. A. *et al.* Deforestation leakage undermines conservation value of tropical and subtropical forest protected areas. *Global Ecol. Biogeogr.* **29**, 2014–2024 (2020).
141. Morgans, C. L. *et al.* Improving well-being and reducing deforestation in Indonesia's protected areas. *Conservation Letters.* **17**, e13010 (2024).
142. Clements, T., Suon, S., Wilkie, D. S. & Milner-Gulland, E. J. Impacts of protected areas on local livelihoods in Cambodia. *World Development* **64**, S125–S134 (2014).
143. Nuttall, M. *et al.* Protected area downgrading, downsizing, and degazettement in Cambodia: Enabling conditions and opportunities for intervention. *Conservat Sci and Prac* **5**, e12912 (2023).

144. Mallari, N. A. D., Collar, N. J., McGowan, P. J. K. & Marsden, S. J. Philippine protected areas are not meeting the biodiversity coverage and management effectiveness requirements of Aichi Target 11. *Ambio* **45**, 313–322 (2016).
145. Coad, L. *et al.* Widespread shortfalls in protected area resourcing undermine efforts to conserve biodiversity. *Frontiers in Ecol & Environ* **17**, 259–264 (2019).
146. Clements, T. *et al. Larger than Tigers: Inputs for a Strategic Approach to Biodiversity Conservation in Asia*. (European Commission: Directorate-General for International Cooperation and Development, 2018).
147. Graham, V. *et al.* Management resourcing and government transparency are key drivers of biodiversity outcomes in Southeast Asian protected areas. *Biological Conservation* **253**, 108875 (2021).
148. McKinnon, M. C. *et al.* What are the effects of nature conservation on human well-being? A systematic map of empirical evidence from developing countries. *Environ Evid* **5**, 8 (2016).
149. Farhadinia, M. S. *et al.* Economics of conservation law enforcement by rangers across Asia. *Conservation Letters.* **16**, e12943 (2023).
150. Gray, T. N. E., Belecky, M., Singh, R., Moreto, W. D. & Chapman, S. Insufficient numbers and poor working conditions for rangers protecting tigers. *Conservation Science and Practice* **6**, e13157 (2024).
151. Ibbett, H. *et al.* Improving compliance around protected areas through fair administration of rules. *Conservation Biology* e14332 (2024) doi:10.1111/cobi.14332.
152. Sayer, J. *et al.* Ten principles for a landscape approach to reconciling agriculture, conservation, and other competing land uses. *Proc. Natl. Acad. Sci. U.S.A.* **110**, 8349–8356 (2013).
153. Porras, I. & Paul, S. *Making the Market Work for Nature - How Biocredits Can Protect Biodiversity and Reduce Poverty*. (International Institute for Environment and Development, London, 2020).
154. Restorasi Ekosistem Riau. *Progress Report 2023*. 48 https://www.rekoforest.org/ (2023).
155. Harrison, R. D. *et al.* Restoration concessions: a second lease on life for beleaguered tropical forests? *Frontiers in Ecol & Environ* **18**, 567–575 (2020).
156. Engert, J. E., Ishida, F. Y. & Laurance, W. F. Rerouting a major Indonesian mining road to spare nature and reduce development costs. *Conservat Sci and Prac* **3**, e521 (2021).
157. ten Kate, A., Kuepper, B. & Piotrowski, M. *NDPE Policies Cover 83% of Palm Oil Refineries; Implementation at 78%*. 11 https://chainreactionresearch.com/report/ndpe-policies-cover-83-of-palm-oil-refineries-implementation-at-75/ (2020).
158. Proforest. *Understanding Commitments to No Deforestation, No Peat and No Exploitation (NDPE)*. https://www.proforest.net/fileadmin/uploads/proforest/Documents/Publications/infonote_04_introndpe.pdf (2020).
159. Carlson, K. M. *et al.* Effect of oil palm sustainability certification on deforestation and fire in Indonesia. *Proc. Natl. Acad. Sci. U.S.A.* **115**, 121–126 (2018).

160. Lee, J. S. H., Miteva, D. A., Carlson, K. M., Heilmayr, R. & Saif, O. Does oil palm certification create trade-offs between environment and development in Indonesia? *Environ. Res. Lett.* **15**, 124064 (2020).
161. Santika, T. *et al.* Impact of palm oil sustainability certification on village well-being and poverty in Indonesia. *Nature Sustainability* **4**, 109–119 (2021).
162. Deere, N. J. *et al.* Implications of zero-deforestation commitments: Forest quality and hunting pressure limit mammal persistence in fragmented tropical landscapes. *Conservation Letters* **13**, e12701 (2020).
163. Lucey, J. M. *et al.* Reframing the evidence base for policy-relevance to increase impact: a case study on forest fragmentation in the oil palm sector. *Journal of Applied Ecology* **54**, 731–736 (2017).
164. Ng, C. K.-C., Payne, J. & Oram, F. Small habitat matrix: How does it work? *Ambio* **50**, 601–614 (2021).
165. Deere, N. J. *et al.* Riparian buffers can help mitigate biodiversity declines in oil palm agriculture. *Frontiers in Ecology and the Environment* **20**, 459–466 (2022).
166. Luke, S. H. *et al.* Riparian buffers in tropical agriculture: Scientific support, effectiveness and directions for policy. *Journal of Applied Ecology* **56**, 85–92 (2019).
167. Scriven, S. A. *et al.* Testing the benefits of conservation set-asides for improved habitat connectivity in tropical agricultural landscapes. *Journal of Applied Ecology* **56**, 2274–2285 (2019).
168. Bicknell, J. E. *et al.* Enhancing the ecological value of oil palm agriculture through set-asides. *Nature Sustainability* 1–13 (2023).
169. Lambin, E. F. *et al.* The role of supply-chain initiatives in reducing deforestation. *Nature Clim Change* **8**, 109–116 (2018).
170. Lyons-White, J., Pollard, E. H. B., Catalano, A. S. & Knight, A. T. Rethinking zero deforestation beyond 2020 to more equitably and effectively conserve tropical forests. *One Earth* **3**, 714–726 (2020).
171. Sarkar, S. *et al.* Developing an objectives hierarchy for multicriteria decisions on land use options, with a case study of biodiversity conservation and forestry production from Papua, Indonesia. *Environment and Planning B: Urban Analytics and City Science* **44**, 464–485 (2017).
172. Sze, J. S. *et al.* Indigenous Peoples' Lands are critical for safeguarding vertebrate diversity across the tropics. *Global Change Biology* **30**, e16981 (2024).
173. Sze, J. S., Childs, D. Z., Carrasco, L. R. & Edwards, D. P. Indigenous lands in protected areas have high forest integrity across the tropics. *Current Biology* **32**, 4949-4956.e3 (2022).
174. RECOFTC. *Communities Are Improving Lives and Landscapes in Southeast Asia through Social Forestry*. https://www.recoftc.org/special-report/communities-improve-landscapes-southeast-asia (2020).
175. Wong, G. *et al.* Social forestry in Southeast Asia: Evolving interests, discourses and the many notions of equity. *Geoforum* **117**, 246–258 (2020).

176. Rakatama, A. & Pandit, R. Reviewing social forestry schemes in Indonesia: Opportunities and challenges. *Forest Policy and Economics* **111**, 102052 (2020).

177. Meijaard, E. *et al.* Toward improved impact evaluation of community forest management in Indonesia. *Conservation Science and Practice* **3**, e189 (2021).

178. Pulhin, J. M. *et al.* Contextualizing sustainable forest management and social justice in community-based forest management (CBFM) program in the Philippines. *Trees, Forests and People* **16**, 100589 (2024).

179. *Recognising Territories and Areas Conserved by Indigenous Peoples and Local Communities (ICCAs) Overlapped by Protected Areas*. (IUCN, International Union for Conservation of Nature, 2024). doi:10.2305/RSLY2962.

180. Ota, M. *et al.* Forest conservation effectiveness of community forests may decline in the future: Evidence from Cambodia. *PNAS Nexus* **2**, pgad320 (2023).

181. Agarwal, S., Sairorkham, B., Sakitram, P. & Lambin, E. F. Effectiveness of community forests for forest conservation in Nan province, Thailand. *Journal of Land Use Science* **17**, 307–323 (2022).

182. Santika, T. *et al.* Heterogeneous impacts of community forestry on forest conservation and poverty alleviation: Evidence from Indonesia. *People and Nature* **1**, 204–219 (2019).

183. Kraus, S., Liu, J., Koch, N. & Fuss, S. No aggregate deforestation reductions from rollout of community land titles in Indonesia yet. *Proc. Natl. Acad. Sci. U.S.A.* **118**, e2100741118 (2021).

184. Burivalova, Z., Hua, F., Koh, L. P., Garcia, C. & Putz, F. A Critical Comparison of Conventional, Certified, and Community Management of Tropical Forests for Timber in Terms of Environmental, Economic, and Social Variables. *CONSERVATION LETTERS* **10**, 4–14 (2017).

185. Santika, T. *et al.* Community forest management in Indonesia: Avoided deforestation in the context of anthropogenic and climate complexities. *Global Environmental Change* **46**, 60–71 (2017).

186. Andersson, K. P. *et al.* Wealth and the distribution of benefits from tropical forests: Implications for REDD+. *Land Use Policy* **72**, 510–522 (2018).

187. Novick, B. *et al.* Understanding the interactions between human well-being and environmental outcomes through a community-led integrated landscape initiative in Indonesia. *Environmental Development* **45**, 100791 (2023).

188. Morcatty, T. Q., Feddema, K., Nekaris, K. A. I. & Nijman, V. Online trade in wildlife and the lack of response to COVID-19. *Environmental Research* **193**, 110439 (2021).

189. Willett, W. *et al.* Food in the Anthropocene: the EAT–Lancet Commission on healthy diets from sustainable food systems. *The Lancet* **393**, 447–492 (2019).

190. Risdianto, D. *et al.* Examining the shifting patterns of poaching from a long-term law enforcement intervention in Sumatra. *Biological Conservation* **204**, 306–312 (2016).

191. Jones, I. J. *et al.* Improving rural health care reduces illegal logging and conserves carbon in a tropical forest. *Proc. Natl. Acad. Sci. U.S.A.* **117**, 28515–28524 (2020).

192. Wyatt, T. Transnational Collaborations. in *Wildlife Trafficking* 199–230 (Springer International Publishing, Cham, 2022). doi:10.1007/978-3-030-83753-2_7.

193. Sarira, T. V., Zeng, Y., Neugarten, R., Chaplin-Kramer, R. & Koh, L. P. Co-benefits of forest carbon projects in Southeast Asia. *Nat Sustain* **5**, 393–396 (2022).

194. Mishra, S. *et al.* Degradation of Southeast Asian tropical peatlands and integrated strategies for their better management and restoration. *Journal of Applied Ecology* **58**, 1370–1387 (2021).

195. Guizar-Coutiño, A., Jones, J. P. G., Balmford, A., Carmenta, R. & Coomes, D. A. A global evaluation of the effectiveness of voluntary REDD+ projects at reducing deforestation and degradation in the moist tropics. *Conservation Biology* **36**, e13970 (2022).

196. Pauly, M., Crosse, W. & Tosteson, J. High deforestation trajectories in Cambodia slowly transformed through economic land concession restrictions and strategic execution of REDD+ protected areas. *Sci Rep* **12**, 17102 (2022).

197. Ekawati, S., Subarudi, Budiningsih, K., Sari, G. K. & Muttaqin, M. Z. Policies affecting the implementation of REDD+ in Indonesia (cases in Papua, Riau and Central Kalimantan). *Forest Policy and Economics* **108**, 101939 (2019).

198. Gatto, A. & Sadik-Zada, E. R. REDD+ in Indonesia: An assessment of the international environmental program. *Environ Dev Sustain* (2024) doi:10.1007/s10668-024-05368-w.

199. Jong, H. N. *Indonesia to Receive $56m Payment from Norway for Reducing Deforestation.* https://news.mongabay.com/2020/05/indonesia-norway-redd-payment-deforestation-carbon-emission-climate-change/ (2020).

200. West, T. A. P. *et al.* Action needed to make carbon offsets from forest conservation work for climate change mitigation. *Science* **381**, 873–877 (2023).

201. Goetz, S. J. *et al.* Measurement and monitoring needs, capabilities and potential for addressing reduced emissions from deforestation and forest degradation under REDD+. *Environ. Res. Lett.* **10**, 123001 (2015).

202. Salzman, J., Bennett, G., Carroll, N., Goldstein, A. & Jenkins, M. The global status and trends of Payments for Ecosystem Services. *Nat Sustain* **1**, 136–144 (2018).

203. Aryal, K. *et al.* Carbon emission reduction initiatives: Lessons from the REDD+ process of the Asia and Pacific region. *Land Use Policy* **146**, 107321 (2024).

204. Wunder, S., Börner, J., Ezzine-de-Blas, D., Feder, S. & Pagiola, S. Payments for Environmental Services: Past Performance and Pending Potentials. *Annu. Rev. Resour. Econ.* **12**, 209–234 (2020).

205. Milson, C. E., Lim, J. Y., Ingram, D. J. & Edwards, D. P. The need for carbon finance schemes to tackle overexploitation of tropical forest wildlife. *Conservation Biology* e14406 (2024) doi:10.1111/cobi.14406.
206. Börner, J., Schulz, D., Wunder, S. & Pfaff, A. The Effectiveness of Forest Conservation Policies and Programs. *Annu. Rev. Resour. Econ.* **12**, 45–64 (2020).
207. ASEAN Centre for Biodiversity. *ASEAN Biodiversity Outlook 3*. (Philippines, 2023).
208. Han, X., Gill, M. J., Hamilton, H., Vergara, S. G. & Young, B. E. Progress on national biodiversity indicator reporting and prospects for filling indicator gaps in Southeast Asia. *Environmental and Sustainability Indicators* **5**, 100017 (2020).
209. Williams, D. R., Balmford, A. & Wilcove, D. S. The past and future role of conservation science in saving biodiversity. *CONSERVATION LETTERS* **13**, e12720 (2020).
210. Ducros, A. & Steele, P. *Biocredits to Finance Nature and People: Emerging Lessons*. (International Institute for Environment and Development, London, 2022).
211. Wunder, S. *et al.* Biodiversity credits: learning lessons from other approaches to incentivize conservation. Preprint at https://doi.org/10.31219/osf.io/qgwfc (2024).
212. Jones, J. P. G. *et al.* Net gain: seeking better outcomes for local people when mitigating biodiversity loss from development. *One Earth* **1**, 195–201 (2019).
213. Orr, M. C. C., Ascher, J. S., Bai, M., Chesters, D. & Zhu, C.-D. Three questions: How can taxonomists survive and thrive worldwide? *MT* **1**, (2020).
214. Sandall, E. L. *et al.* A globally integrated structure of taxonomy to support biodiversity science and conservation. *Trends in Ecology & Evolution* **38**, 1143–1153 (2023).
215. Guenat, S. *et al.* Meeting sustainable development goals via robotics and autonomous systems. *Nat Commun* **13**, 3559 (2022).
216. Tuia, D. *et al.* Perspectives in machine learning for wildlife conservation. *Nat Commun* **13**, 792 (2022).
217. Parris-Piper, N., Dressler, W. H., Satizábal, P. & Fletcher, R. Automating violence? The anti-politics of 'smart technology' in biodiversity conservation. *Biological Conservation* **278**, 109859 (2023).
218. Brittain, S. *et al.* Power to the people: Analysis of occupancy models informed by local knowledge. *Conservat Sci and Prac* **4**, e12753 (2022).
219. Ardiantiono *et al.* Improved cost-effectiveness of species monitoring programs through data integration. *Current Biology* **e3**, 391–397 (2025).
220. Burivalova, Z., Miteva, D., Salafsky, N., Butler, R. A. & Wilcove, D. S. Evidence types and trends in tropical forest conservation literature. *Trends in Ecology & Evolution* **34**, 669–679 (2019).
221. Grass, I. *et al.* Trade-offs between multifunctionality and profit in tropical smallholder landscapes. *Nat Commun* **11**, 1186 (2020).

222. Devenish, K. *et al.* No evidence of increased forest loss from a mining rush in Madagascar's eastern rainforests. *Commun Earth Environ* **5**, 489 (2024).
223. GPAI. *Biodiversity & Artificial Intelligence, Opportunities and Recommendations*. https://gpai.ai/projects/responsible-ai/environment/biodiversity-and-AI-opportunities-recommendations-for-action.pdf (2022).
224. Ocampo-Ariza, C. *et al.* Global South leadership towards inclusive tropical ecology and conservation. *Perspectives in Ecology and Conservation* **21**, 17–24 (2023).
225. Chao, N. *et al.* Strengthening capacity for species conservation in South-east Asia: a provisional assessment of needs and opportunities for the Asian Species Action Partnership. *Oryx* **56**, 760–763 (2022).
226. Asase, A., Mzumara-Gawa, T. I., Owino, J. O., Peterson, A. T. & Saupe, E. Replacing "parachute science" with "global science" in ecology and conservation biology. *Conservat Sci and Prac* **4**, e517 (2022).
227. Stefanoudis, P. V. *et al.* Turning the tide of parachute science. *Current Biology* **31**, R184–R185 (2021).
228. Valdez, J. *et al.* Strategies for advancing inclusive biodiversity research through equitable practices and collective responsibility. *Conservation Biology* e14325 (2024) doi:10.1111/cobi.14325.
229. James, R. *et al.* Conservation and natural resource management: where are all the women? *Oryx* **55**, 860–867 (2021).
230. Lima, H. S. D. M. & Cunha, H. F. A. The role of women and the obstacles to biodiversity conservation in developed and developing countries. *Environ Dev Sustain* (2024) doi:10.1007/s10668-024-05407-6.
231. Kreiken, B. E. & Arts, B. J. M. Disruptive data: How access and benefit-sharing discourses structured ideas and decisions during the Convention on Biological Diversity negotiations over digital sequence information from 2016 to 2022. *Global Environmental Change* **87**, 102892 (2024).
232. Von Wettberg, E. & Khoury, C. K. Biodiversity data: The importance of access and the challenges regarding benefit sharing. *Plants People Planet* **4**, 2–4 (2022).
233. Edwards, D. P., Tobias, J. A., Sheil, D., Meijaard, E. & Laurance, W. F. Maintaining ecosystem function and services in logged tropical forests. *Trends in Ecology & Evolution* **29**, 511–520 (2014).
234. Putz, F. E. *et al.* Sustaining conservation values in selectively logged tropical forests: the attained and the attainable. *Conservation Letters* **5**, 296–303 (2012).
235. Deere, N. J. *et al.* Maximizing the value of forest restoration for tropical mammals by detecting three-dimensional habitat associations. *Proceedings of the National Academy of Sciences* **117**, 26254–26262 (2020).
236. Marsh, C. J. *et al.* Logging alters tropical forest structure, while conversion to agriculture reduces biodiversity and functioning. Preprint at https://doi.org/10.1101/2022.12.15.520573 (2024).

237. Ewers, R. M. *et al.* Thresholds for adding degraded tropical forest to the conservation estate. *Nature* **631**, 808–813 (2024).
238. Gibson, L. *et al.* Primary forests are irreplaceable for sustaining tropical biodiversity. *Nature* **478**, 378–381 (2011).
239. Burivalova, Z., Şekercioğlu, Ç. H. & Koh, L. P. Thresholds of Logging Intensity to Maintain Tropical Forest Biodiversity. *Current Biology* **24**, 1893–1898 (2014).
240. Edwards, D. P. *et al.* Selective-logging and oil palm: multitaxon impacts, biodiversity indicators, and trade-offs for conservation planning. *Ecological Applications* **24**, 2029–2049 (2014).
241. Bicknell, J. E., Struebig, M. J., Edwards, D. P. & Davies, Z. G. Improved timber harvest techniques maintain biodiversity in tropical forests. *Current Biology* **24**, R1119–R1120 (2014).
242. Runting, R. K. *et al.* Larger gains from improved management over sparing–sharing for tropical forests. *Nature Sustainability* **2**, 53–61 (2019).
243. Miteva, D. A., Loucks, C. J. & Pattanayak, S. K. Social and environmental impacts of forest management certification in Indonesia. *PLoS ONE* **10**, e0129675 (2015).
244. Burivalova, Z. *et al.* What works in tropical forest conservation, and what does not: Effectiveness of four strategies in terms of environmental, social, and economic outcomes. *Conservat Sci and Prac* **1**, e28 (2019).
245. Dirzo, R. *et al.* Defaunation in the Anthropocene. *Science* **345**, 401–406 (2014).
246. Young, H. S., McCauley, D. J., Galetti, M. & Dirzo, R. Patterns, causes, and consequences of anthropocene defaunation. *Annu. Rev. Ecol. Evol. Syst.* **47**, 333–358 (2016).
247. Harrison, R. D. Emptying the Forest: Hunting and the Extirpation of Wildlife from Tropical Nature Reserves. *BioScience* **61**, 919–924 (2011).
248. Bogoni, J. A., Percequillo, A. R., Ferraz, K. M. P. M. B. & Peres, C. A. The empty forest three decades later: Lessons and prospects. *Biotropica* **55**, 13–18 (2023).
249. Gardner, C. J., Bicknell, J. E., Balwin-Cantello, W., Struebig, M. J. & Davies, Z. G. Quantifying the impacts of defaunation on natural forest regeneration in a global meta-analysis. *Nature Communications* (2019).
250. Sobral, M. *et al.* Mammal diversity influences the carbon cycle through trophic interactions in the Amazon. *Nat Ecol Evol* **1**, 1670–1676 (2017).
251. Brodie, J. F. *et al.* Defaunation impacts on the carbon balance of tropical forests. *Conservation Biology* e14414 (2024) doi:10.1111/cobi.14414.
252. Chanthorn, W. *et al.* Defaunation of large-bodied frugivores reduces carbon storage in a tropical forest of Southeast Asia. *Sci Rep* **9**, 10015 (2019).
253. Ferreiro-Arias, I. *et al.* Drivers and spatial patterns of avian defaunation in tropical forests. *Diversity and Distributions* e13855 (2024) doi:10.1111/ddi.13855.

254. Barlow, J. *et al.* Anthropogenic disturbance in tropical forests can double biodiversity loss from deforestation. *Nature* **535**, 144–147 (2016).
255. Betts, M. G. *et al.* Global forest loss disproportionately erodes biodiversity in intact landscapes. *Nature* **547**, 441–444 (2017).
256. Adams, William. M. *et al.* Biodiversity Conservation and the Eradication of Poverty. *Science* **306**, 1146–1149 (2004).
257. Roe, D. *et al.* Which components or attributes of biodiversity influence which dimensions of poverty? *Environ Evid* **3**, 3 (2014).
258. Tilker, A. *et al.* Habitat degradation and indiscriminate hunting differentially impact faunal communities in the Southeast Asian tropical biodiversity hotspot. *Commun Biol* **2**, 396 (2019).
259. Joppa, L. N. & Pfaff, A. High and Far: Biases in the Location of Protected Areas. *PLoS ONE* **4**, e8273 (2009).
260. Cook, C. N. Progress developing the concept of other effective area-based conservation measures. *Conservation Biology* **38**, e14106 (2024).
261. IUCN WCPA Task Force on OECMs. *Recognising and Reporting Other Effective Area-Based Conservation Measures*. (IUCN, International Union for Conservation of Nature, 2019). doi:10.2305/IUCN.CH.2019.PATRS.3.en.
262. CBD. *OP15: Kunming-Montreal Global Biodiversity Framework. CBD/COP/15/L25*. (2022).
263. Brennan, A. *et al.* Functional connectivity of the world's protected areas. *Science* **376**, 1101–1104 (2022).
264. Parks, L. & Tsioumani, E. Transforming biodiversity governance? Indigenous peoples' contributions to the Convention on Biological Diversity. *Biological Conservation* **280**, 109933 (2023).
265. Cook, C. N. Diverse approaches to protecting biodiversity: The different conservation measures discussed as possible other effective area-based conservation measures. *Conservation Letters.* **17**, e13027 (2024).
266. Gurney, G. G. *et al.* Biodiversity needs every tool in the box: use OECMs. *Nature* **595**, 646–649 (2021).
267. Arneth, A. *et al.* Making protected areas effective for biodiversity, climate and food. *Global Change Biology* **29**, 3883–3894 (2023).
268. Barnes, M. D., Glew, L., Wyborn, C. & Craigie, I. D. Prevent perverse outcomes from global protected area policy. *Nat Ecol Evol* **2**, 759–762 (2018).
269. Kuempel, C. D., Adams, V. M., Possingham, H. P. & Bode, M. Bigger or better: The relative benefits of protected area network expansion and enforcement for the conservation of an exploited species. *CONSERVATION LETTERS* **11**, e12433 (2018).

270. Dunne, D., Greenfield, P., Viglione, G. & Quiroz, Y. *Revealed: More than Half of Nations Fail to Protect 30% of Land and Sea in UN Nature Plans*. https://www.carbonbrief.org/revealed-more-than-half-of-nations-fail-to-protect-30-of-land-and-sea-in-un-nature-plans/ (2025).
271. Banin, L. F. *et al.* The road to recovery: a synthesis of outcomes from ecosystem restoration in tropical and sub-tropical Asian forests. *Phil. Trans. R. Soc. B* **378**, 20210090 (2023).
272. Busch, J. *et al.* Potential for low-cost carbon dioxide removal through tropical reforestation. *Nat. Clim. Chang.* **9**, 463–466 (2019).
273. Budiharta, S. *et al.* Restoring degraded tropical forests for carbon and biodiversity. *Environ. Res. Lett.* **9**, 114020 (2014).
274. Bodin, B. *et al.* A standard framework for assessing the costs and benefits of restoration: introducing The Economics of Ecosystem Restoration. *Restoration Ecology* **30**, e13515 (2022).
275. Budiharta, S. *et al.* Restoration to offset the impacts of developments at a landscape scale reveals opportunities, challenges and tough choices. *Global Environmental Change* **52**, 152–161 (2018).
276. Löfqvist, S. & Ghazoul, J. Private funding is essential to leverage forest and landscape restoration at global scales. *Nat Ecol Evol* **3**, 1612–1615 (2019).
277. Zu Ermgassen, S. O. S. E. & Löfqvist, S. Financing ecosystem restoration. *Current Biology* **34**, R412–R417 (2024).
278. Edwards, D. P. *et al.* Upscaling tropical restoration to deliver environmental benefits and socially equitable outcomes. *Current Biology* **31**, R1326–R1341 (2021).
279. Scheidel, A. & Work, C. Forest plantations and climate change discourses: New powers of 'green' grabbing in Cambodia. *Land Use Policy* **77**, 9–18 (2018).
280. Di Sacco, A. *et al.* Ten golden rules for reforestation to optimize carbon sequestration, biodiversity recovery and livelihood benefits. *Global Change Biology* **27**, 1328–1348 (2021).
281. Newing, H. *An Independent Review of the RSPO Remediation and Compensation Procedure (RaCP) 2015*. 58 https://rspo.org/resources/ (2020).
282. Erbaugh, J. T. *et al.* Global forest restoration and the importance of prioritizing local communities. *Nat Ecol Evol* **4**, 1472–1476 (2020).

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Author contribution statement

Researching data for article: J.S.H.L., N.J.D. T.S. and D.I.J.S; substantial contribution to discussion of content: all authors; writing: all authors; review and/or editing of manuscript before submission: all authors.

Competing interests

D.J.I. is a trustee of The Pangolin Project CIO (UK), a Field Science Co-Chair of the IUCN SSC Pangolin Specialist Group, and a member of the IUCN Sustainable Use and Livelihoods Specialist Group (SULi).

Related links

Global Platform for Sustainable Natural Rubber: https://sustainablenaturalrubber.org/
Roundtable on Sustainable Palm Oil: https://rspo.org/
Sustainable Coconut Partnership: https://www.coconutpartnership.org/
Kunming–Montreal Global Biodiversity Framework: https://www.cbd.int/gbf
Spatial Monitoring and Reporting Tool: https://smartconservationtools.org/
Wildmeat: www.wildmeat.org
Protected planet: https://www.protectedplanet.net/en
UN Decade on Ecosystem Restoration: https://www.decadeonrestoration.org
Bonn Challenge: https://www.bonnchallenge.org
New York Forest Declaration: https://forestdeclaration.org/
Paris Agreement: https://unfccc.int/process-and-meetings/the-paris-agreement
United Nations Sustainable Development Goals: https://sdgs.un.org/goals
Reducing Emissions from Deforestation and Forest Degradation, REDD+: https://redd.unfccc.int/
ASEAN Centre for Biodiversity: https://www.aseanbiodiversity.org/

Key points

1. Southeast Asia's terrestrial biodiversity crisis is driven by multiple interacting and often synergistic pressures — primarily land-use change, infrastructure development, and overexploitation — which vary in intensity across the region and demand coordinated, context-specific responses.
2. Effective protected areas require adequate funding, staffing, enforcement, and monitoring, while carefully managing unintended consequences such as displaced deforestation and negative impacts on local communities.
3. Maintaining biodiversity in human-modified ecosystems depends critically on financial incentives, certification schemes, and secure land tenure rights, and the forest patches that remain in the landscape need to be managed collectively to ensure species persistence and movement.
4. Community-led forest management can align conservation and local livelihoods when supported by strong governance, leadership, community capabilities and capacity, and sustained external investment in habitat restoration.
5. Reducing hunting for non-subsistence purposes requires a strong focus on curbing demand for wildmeat, particularly in urban areas, through enforcement to prevent illegal hunting, market closures, and disruption of physical and online trade routes.
6. Solving the crisis requires researchers to shift from diagnosing problems to delivering actionable and equitable solutions, increased focus on forest-risk commodities beyond oil palm, developing robust metrics to underpin biodiversity credits, and inclusive collaboration with Southeast Asian scientists, indigenous people and local communities.

Display items

Figures

Figure 1. **Geography of Southeast Asia's biodiversity crisis**. Bivariate map showing spatial overlap between forest condition and the extinction vulnerability of IUCN-evaluated vertebrates (881 amphibian, 1,451 reptile, 1,569 bird and 880 mammal species). Forest condition was derived from aboveground vegetation biomass maps reclassified using ecological thresholds of the aggregated response of 1,681 species to habitat degradation (Supplementary Methods). The thresholds were used to define three degradation classes: intact forest (71-100% biomass retained); degraded forests (32-70% biomass retained); and heavily-degraded forests (0-32% biomass retained). Red polygons indicate deforestation hotspots identified through 26 years of forest cover change assessments from global imagery (derived from ref.[27]). Photographic arrows denote the dominant drivers of deforestation across a selection of these disturbance frontiers. The map illustrates the sensitivity of biodiversity to forest degradation in Southeast Asia's lowland forests owing to the proliferation of commodity agriculture, plantation forestry and mining, but highlights substantial areas of intact forests and ecological communities in high-altitude, remote regions.

Figure 2. **Threats to biodiversity in Southeast Asian countries**. Country-specific appraisals showing the proportion of plant, fish, amphibian, reptile, bird and mammal species that are considered threatened according to the IUCN Red List (upper panels with blue bars), the prominent threats facing biodiversity, forest condition, and protected area (PA) coverage (lower panels with stacked bars). 'Threats' represents the percentage of key threats cited in the IUCN Red List database, aggregated across all 7,334 taxa assessed; 'Forest condition' is the percentage of overall forest cover considered intact (71-100% biomass retained), degraded (32-70% biomass retained), and heavily-degraded (0-32% biomass retained) (Supplementary Methods) as used in Fig. 1. 'PA coverage' denotes land protected as a percentage of total terrestrial surface area. White vertical bars indicate progress towards meeting the UN Convention on Biological Diversity Aichi Biodiversity Target 11 (17% of land protected by 2020; dashed white vertical line) and the Kunming–Montreal Global Biodiversity Framework Target 3 (30% of land protected by 2030; solid white vertical line) through protected areas. Countries within mainland Southeast Asia are presented on the top row, while insular countries are located on the bottom row. Considerable variation exists in threatened species, forest condition and progress towards the 30x30 protection target both within and between regions.

Figure 3. **Threat hierarchies, interactions and mitigation**. **a** | Dominance hierarchies for established and emerging threats to Southeast Asia's biodiversity, as listed on the IUCN Red List for vertebrates and plants. The ranges of 7,334 species are partially or fully contained within at least one Southeast Asian country, and

their conservation status is linked to threats in the Red Listing process. The area of the circle for each threat reflects the proportion of incidences the threat is cited across these species, noting that a species may be subjected to multiple threats across its range; larger circles therefore indicate that a greater number of species are impacted by the threat across the region. The lines linking pairs of threats reflect the co-occurrence of threats for species and the potential for these threats to interact: thicker lines represent more co-occurrences. Established threats comprise land-use change, logging, infrastructure development, exploitation and fire, and emerging threats include climate change and invasive species. Threats have been reclassified to aid presentation and match the main themes covered in the text (Table S2). **b** | Overview of conservation solutions prominent across Southeast Asia, along with the common barriers to implementation.

Boxes

Box 1 | **Tipping points in biodiversity responses to forest degradation**

Approximately 25% (>4 million km^2) of the world's tropical forests are designated for forestry[233]. Logging is widespread in Southeast Asia, targeting commercially valuable mature trees. This selective logging is particularly lucrative in the dipterocarp forests of insular Southeast Asia (primarily Indonesia, Malaysia, and Brunei), which support an unusually high diversity of timber tree species. Indeed, average timber yields of >100 m^3 ha^{-1} in Southeast Asia tend to be much greater than those achieved in other tropical regions, with second or even third harvests (albeit diminished) possible after a nominal rotation time[234]. Forests are therefore often cut several times before they become financially unviable, resulting in a gradual deterioration of forest biomass and structure[235,236].

A major analysis of 1,681 species responses to logging disturbance in Malaysia found the removal of aboveground biomass from forests during successive rounds of logging led to a turnover of specialists to generalists, terrestrial to arboreal, and large to small taxa[237]. Lightly logged forests (<29% vegetation biomass removed) retained high species and functional composition, while the most heavily degraded areas (>68% biomass removed (left photograph) had much lower biodiversity value. Counter to the impression provided by IUCN Red List assessments (Fig. 2; Table S2), populations of almost one-third of the species were enhanced after logging, leading to higher levels of overall biodiversity in logged forest and a 2.5-fold increase in total resource consumption by both mammals and birds[42] (middle and right photographs of a sun bear *Helarctos malayanus* and blue headed pitta *Hydrornis baudii*, respectively). Thus, not all biodiversity impacts from logging are equal, and a large area of Southeast Asia's logged forests hold considerable conservation value[238] while being highly prone to conversion (Fig. 1).

The capacity of logged forests to support biodiversity depends on the intensity and extent of disturbance[239], the number of felling cycles[240], and the extraction techniques used[241]. Efforts to minimise damage through reduced-impact logging techniques go a long way to lessen habitat degradation and promote biodiversity in production forests[241,242], as does limiting secondary disturbances from encroachment and road building (so called 'ghost roads'[73]). Such practices are central to voluntary forest management certification schemes, which have reduced deforestation, firewood dependence, malnutrition, and respiratory infections in parts of Indonesia[243]. Reduced-impact logging generally leads to better outcomes for forests, people, and biodiversity across the tropics, although understanding the potential interaction between logging disturbance and hunting in certified or non-certified forests remains a major research gap[244].

Box 2 | **Defaunation of tropical forests**

Defaunation is the decline and/or local extinction of animal species due to human activities from land-use change, habitat disturbance, and hunting (for example, wildmeat, fish and songbirds in the left, middle and right photographs, respectively). These extinctions and declines pose a growing threat to biodiversity and carbon-rich tropical forests globally[245,246] and can result in 'empty forest syndrome'[247]. The loss of large fauna, in particular, can disrupt critical ecological functions such as seed dispersal and carbon storage[248–250]. The long-term consequences of defaunation remain contentious. Declines in animal populations are shifting forest community composition towards smaller-fruited or wind-dispersed trees with lower wood density and reduced aboveground biomass, undermining ecosystem resilience and carbon storage potential[205,249,251]. For instance, nearly one-third of Thailand's forest biomass comprises trees reliant on large-bodied frugivores for seed dispersal. Simulating their removal via hunting revealed statistically significant tree community turnover and a 2.4–3.0% aboveground carbon reduction[252]. However, as most of the high-carbon trees of Asian forests are wind dispersed, defaunation impacts on carbon dynamics might be less severe in the region than for other parts of the tropics[251].

Despite the global significance of defaunation, research has predominantly focused on temperate zones and Latin America, leaving Southeast Asia comparatively underexplored[111,249,253]. Regional defaunation projections are based on very few empirical datasets[111,253] (Fig. S6). Addressing these gaps requires increasing the number of field-based studies to refine predictive models and identify defaunation drivers, and better open-access data-sharing to facilitate larger-scale or meta-analyses that should be designed to inform conservation strategies.

Defaunation is driven by both ecological and social factors, often in tandem, but few studies integrate these perspectives well. Researchers often emphasise habitat loss or degradation and their cascading effects on fauna, even in otherwise intact sites[254,255]. Rapid demographic and socioeconomic changes also shape human–wildlife interactions, but these have proven challenging to characterise at scale. Economic growth can reduce reliance on forests for subsistence and well-being[101,256,257], but wealthier, expanding populations tend to require more land and resources, amplifying pressures on biodiversity[1]. In Vietnam, Laos, and Malaysian Borneo, hunting pressures have driven higher functional extinction rates than habitat degradation[258]. Defaunation should therefore be treated as a socioecological problem, requiring an interdisciplinary approach that integrates land-use management, socio-economic dynamics and local livelihoods.

Box 3 | **Target 3 of the Kunming–Montreal Global Biodiversity Framework**

Protected areas (PAs) are the cornerstone of traditional global biodiversity conservation efforts, and now comprise ~16% of land globally. However, PAs have not been successful in halting biodiversity declines. To lessen their social and economic impacts, state-governed PAs have been disproportionately located where human population density and land costs are low[259]. This has limited their expansion and impacted marginalised people who live in such remote locations. Recognising these imbalances and the need for transformative action, the concept of 'other effective area-based conservation measures' (OECMs) has gained prominence since 2022[260,261]. OECMs comprise geographically defined areas other than PAs that achieve positive long-term outcomes for biodiversity and, where applicable, cultural, spiritual, socio-economic, and other locally relevant values, despite conservation not being their primary objective.

In 2022, the 195 government signatories to the Convention on Biological Diversity agreed to expand PA and OECM coverage across to the world to at least 30% by 2030 ('30x30')[262]. This pledge is part of Target 3 of the Kunming-Montreal Global Biodiversity Framework, which also states these sites should be effectively managed, equitably governed, ecologically representative, and well-connected. The premise is that OECMs can offer novel mechanisms to ensure that privately or community-governed areas important for biodiversity deliver conservation value and enhance ecological connectivity[263]. The obligation to equitable conservation means that OECMs are likely to provide recognition to, and empower, indigenous people and local communities who are stewards of large areas of land[264].

Many of the emerging conservation initiatives in Southeast Asia (see 'Conservation solutions'), including ecosystem restoration licences (left photograph), conservation set-asides (middle photograph) and community forest areas (right photograph), have the potential to be formally designated OECMs[265]. Importantly, official recognition of OECMs needs to have the free and informed consent of the people governing and stewarding each area, some of whom might be concerned about associated potential land-use restrictions[266]. Care must be taken during implementation to ensure no adverse impacts on food security occur[267], lessons are learnt from past mistakes with PAs[268], and that conservation funds are not too thinly distributed that management effectiveness is undermined[269].

However, just a few countries have formally incorporated OECMs into their National Biodiversity Strategies and Action Plans (NBSAPs). Indeed, only Thailand and Laos, out of six Southeast Asia countries assessed, have pledged in their NBSAPs to deliver 30x30 within their national borders (Table S3). This regional picture is indicative of a wider global pattern, in which 51% of nations have either committed to protect a lower percentage of land cover or failed to make any specific commitment[270].

Box 4 | **Restoring Southeast Asia's degraded landscape**

Restoration is high on the global sustainability agenda thanks to the UN Decade on Ecosystem Restoration and the Paris Agreement. Additionally, the Bonn Challenge and New York Forest Declaration aim to restore 3.5 million km^2 of degraded forest by 2030. Great potential exists to upscale restoration in Southeast Asia, although action lags behind other regions owing to several unique socioecological challenges[271,272].

Southeast Asian forests are often dominated by dipterocarp trees, which have limited dispersal ability and are highly prized for timber (Box 1), making natural regeneration difficult[271,273]. The most common restoration intervention is therefore planting nursery-grown saplings (left photograph), supplemented by other treatments such as weeding, cutting climbers, and thinning. The availability of seeds (middle photograph) for regeneration or saplings for active planting is also restricted by infrequent mast fruiting events and limits to the supply of seeds[271]. Upper estimates for merely starting restoration in the tropics and subtropics range from US$3,880-25,830 per hectare, depending on whether natural or active regeneration is used[274]. Peatland restoration brings additional challenges and costly interventions as hydrological processes need to be reinstated and fire eliminated[194,273]. The cost of restoring peatlands to offset oil palm impacts in Kalimantan could exceed US$3 billion alone[275]. Private finance, comprising mechanisms that learn from past failures, is clearly needed to address the scale of the challenge[276,277].

To deliver on restoration commitments, environmental challenges and trade-offs between objectives and competing land-uses need to be resolved[278]. Restoration activities are diverse, spanning forest recovery, regeneration of abandoned farmland, and plantation development. Restoration also has different meanings for different people. For instance, local communities might prioritise income from fruiting trees or non-timber forest products, returning some ecosystem functions over full ecosystem recovery. Early efforts to mitigate climate change through plantation forestry in Cambodia were associated with land grabs and forest clearance, contradicting their stated goals[279]. However, when implemented in appropriate locations with suitable approaches and investments, restoration can bring ecosystem and livelihood benefits[280]. Despite these challenges, multi-sectorial efforts are ongoing to make restoration work for people and environment, and include activities central to country commitments for climate-change mitigation. Initiatives such as the Roundtable on Sustainable Palm Oil provide remediation mechanisms for restoring high conservation value areas within agricultural land, some of which is channelled to social forestry[281]. Almost 295 million people live on land suitable for tropical forest restoration, many of whom are in Southeast Asia[282]. Empowering these local communities to restore, manage, monitor (bottom right photograph) and derive livelihood benefits from forests can align global goals for climate mitigation, conservation, environmental justice, and sustainable development.

ToC blurb

The terrestrial ecosystems of Southeast Asia are both globally important reservoirs of biodiversity, and a provider of resources and livelihoods for millions of people across the region. This Review summarises the threats to biodiversity in Southeast Asia, and the conservation solutions required to ensure successful outcomes for biodiversity and people.