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Drivers and solutions to Southeast Asia's biodiversity crisis

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20

21 **Abstract**

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

37

38 **[H1] Introduction**

39 Tropical and subtropical terrestrial ecosystems are reservoirs of globally important biodiversity and ecosystem
40 services, including climate regulation and the provision of resources and livelihoods, that are critical for human
41 well-being and support millions of people¹. Yet, these ecosystems face unprecedented challenges in the
42 Anthropocene, as climate change intensifies the pressures of land-use change, infrastructure expansion and
43 urbanisation, and resource overexploitation¹⁻³. This confluence of threats has rendered many of the world’s
44 biodiverse forest ecosystems vulnerable to collapse⁴.

45 These dynamics are most pronounced in Southeast Asia, the geopolitical region encompassing Brunei,
46 Cambodia, Indonesia, Laos, Malaysia, Myanmar, the Philippines, Singapore, Thailand, Timor-Leste, and
47 Vietnam (Fig. 1). This region harbours some of the planet’s most species-diverse ecosystems⁵⁻⁷, as its rich
48 geological history — marked by episodic sea-level changes, continental shifts, and island isolation — has
49 fostered extraordinary speciation and endemism observed nowhere else in the world^{8,9}. Four of the world’s
50 biodiversity hotspots intersect Southeast Asia, reflecting multiple unique biogeographic zones: Indochina,
51 Sunda, Wallacea, and the Philippines⁸. Nonetheless, the region has been at the epicentre of a biodiversity crisis,

52 driven by political shifts, the rise of ‘tiger cub economies’, and rapidly expanding human populations (Fig.
53 S1), which are currently estimated at 695 million in total and are projected to comprise 8% of the global total
54 by 2050. Economic development has progressed rapidly, as average gross domestic product in the region has
55 approximately tripled since the early 2000s and poverty now affects <5% of the population — a four-fold
56 reduction over 40 years (Fig. S1). However, these economic gains have come at the expense of natural
57 resources, fuelled by the expansion of agriculture (Fig. S2) and extractive industries (Fig. S3). Rising affluence
58 and urbanisation have driven increased consumption; for example, although Southeast Asian nutrition is
59 disproportionately characterised by high fish consumption compared with elsewhere in the world, meat is
60 becoming a greater part of people’s diet (Fig. S4). Despite the beginnings of a dietary shift, most agricultural
61 production land is still devoted to commodity crops rather than meat production.

62 Extinction has been a defining process in Southeast Asia since the late Quaternary (~50,000 years ago),
63 although its severity was lower than in the Nearctic or Australasia¹⁰. Prior to this period, large seed-dispersing
64 megafauna, including elephants (Elephantidae), rhinos (Rhinocerotidae), and multiple orangutan species
65 (*Pongo* spp.), were far more widespread than they are today^{10,11}. The largely human-driven extirpations of these
66 and other vertebrates profoundly altered the structure and functioning of Southeast Asia’s forest ecosystems —
67 a pattern that has accelerated during the Anthropocene³.

68 Since 2004, the region’s biodiversity loss has been recognised as distinct and severe^{8,12–14}. The late Navjot
69 Sodhi first coined the crisis, highlighting its gravity and warning of far-reaching ecological and societal
70 consequences⁸. Subsequent research reinforced these concerns, prompting numerous calls to action^{12–15}.
71 However, updated projections indicate that effective mitigation efforts could not only prevent catastrophic
72 ecological outcomes but actually result in net biodiversity gains by 2100¹⁶ (Table S1). Given these evolving
73 challenges and emerging opportunities, a reassessment of the region’s conservation trajectory is both timely
74 and essential. Accelerating climate change has compounded biodiversity loss, but also introduced new
75 prospects for financing and advancing sustainable management¹⁷. Emerging technologies, such as robotics and
76 remote sensing, now offer unprecedented tools for biodiversity monitoring to help ascertain the causes of
77 species declines and evaluate conservation strategies¹⁸. Meanwhile, international sustainability commitments
78 are more aligned than ever, as ambitious targets have been established for climate mitigation, ecosystem
79 restoration, and biodiversity protection^{17,19}.

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

85 the biodiversity crisis while navigating the socio-economic realities of Southeast Asia’s rapidly developing
86 nations.

87

88 **[H1] Conservation challenges**

89 Southeast Asia contains almost 15% of the world’s tropical forests, and almost half of all tropical peatlands²⁰.
90 Together, these ecosystems support the highest density of carbon stocks globally^{21,22}(Table S1), 15% of the
91 world’s vertebrates and an estimated 7% of vascular plants^{7,23}. The IUCN Red List indicates that the greatest
92 threat to biodiversity across Southeast Asia is large-scale land-use change and associated ancillary processes
93 such as logging and fire, which lead to the loss and degradation of species-rich forests (Table S2; Fig. 1, 2).
94 Other established pressures include infrastructure expansion and urbanisation, and the hunting and
95 consumption of species. These human-mediated pressures vary in prevalence and magnitude between countries
96 (Fig. 2) and rarely operate in isolation (Fig. 3). Indeed, climate change, invasive species, and limits to human–
97 wildlife coexistence pose emerging threats that are likely to interact with established drivers to attenuate (that
98 is, antagonistic interactions) or amplify (synergistic interactions) species losses in the future^{1,24–26} (Fig. 3).
99 Conservation assessments of taxa underrepresented in the Red List are hindered by taxonomic and geographic
100 knowledge gaps — so called Linnaean and Wallacea shortfalls^{5,6}. Nevertheless, the hierarchies of threats for
101 IUCN Red List taxa are likely to reflect patterns more broadly.

102

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

104 Between 1992 and 2018, Southeast Asia lost 219,833 km² of forest²⁷ and experienced some of the highest
105 deforestation rates in the world²⁸. Peak deforestation shifted from Cambodia, Myanmar, Thailand, and Vietnam
106 in the 1990s to Indonesia and Malaysia thereafter (Fig. S5): spatiotemporal analysis of forest-cover change data
107 reveals that deforestation was concentrated in Cambodia, southern Myanmar, central Vietnam, Borneo
108 (Sarawak and Kalimantan) and Sumatra prior to 2015, and that new deforestation hotspots are emerging in
109 Laos, Sulawesi, West Papua, and West Java²⁷ (Fig. 1). Deforestation has slowed in Indonesia since 2017²⁹,
110 and signs exist that Thailand is transitioning to a net afforesting country²⁷. Although Laos, Myanmar, the
111 Philippines, Java, and Timor-Leste recorded a net gain in forest cover since the 1990s, these gains are balanced
112 against substantial deforestation in biodiverse areas elsewhere²⁷ (Fig. 1).

113 Southeast Asia’s moderately forested and logged-over lowland landscapes are particularly prone to
114 deforestation (Box 1; Fig. 1). Moreover, a further >121,000 km² of carbon-rich peatlands were cleared between
115 2001 and 2022, together with ~3200 km² of mangroves^{30,31}. Deforestation at both high elevation (169,964 km²

116 between 2001 and 2018³²) and low elevation³³ on the region's mountains poses new threats to habitat-restricted
117 species, particularly endemics. Consequently, the ecological communities within deforested areas are
118 characterised by a proliferation of broad-range generalist species at the expense of local specialists; a process
119 called biotic homogenisation^{34,35}. Deforestation also fragments habitat and reduces landscape connectivity,
120 resulting in isolated species populations that are increasingly vulnerable to secondary pressures, such as edge
121 effects, disturbance, and exploitation³⁶⁻³⁸.

122 Deforestation and biodiversity loss in Southeast Asia is primarily driven by agriculture^{27,28,39}. Over 1.35 million
123 km² is now cultivated across the region after agricultural land more than doubled from the 1960s⁴⁰. Although
124 the environmental impacts of oil palm in Malaysia and Indonesia dominate the research agenda⁴¹⁻⁴³, this focus
125 has overshadowed that of other 'forest-risk' commodity crops. For instance, Southeast Asia produces >90% of
126 the world's natural rubber, which is associated with deforestation in Thailand, Indonesia and, increasingly,
127 Cambodia and Vietnam⁴⁴. Vietnam is now the world's second largest coffee producer⁴⁰ after accelerating
128 production in the 1990s at the expense of central highland forests⁴⁵, and coconut cultivation in the Philippines
129 and Indonesia has long affected coastal forests and island endemics^{46,47}. The implications of rice cultivation for
130 biodiversity are also frequently ignored⁴⁸, despite the region (primarily Thailand, Indonesia, Vietnam,
131 Myanmar, and the Philippines) contributing 40% of global exports⁴⁹ and the need for new estates being
132 promoted periodically in policy agendas as a method of enhancing food security. Growth in other agricultural
133 markets is also implicated in deforestation (for example, durian in Malaysia, cashew and banana in
134 Myanmar)^{46,50,51}.

135 Land-use dynamics are complex. Variation in production systems within and among countries should not be
136 overlooked, as these systems impact biodiversity in different ways⁵². Unshaded monocultures (for example,
137 sugarcane, oil palm), particularly annual crops (such as maize), result in drastically impoverished tropical
138 biodiversity⁵³. By contrast, perennials with longer rotation periods can support comparable species numbers to
139 forest, especially when cultivated in shaded plantations or agroforests (such as cacao or coffee)⁵⁴. Land-use
140 pressures and solutions are thus often highly localised owing to inherent diversity in crop choice, rotation time
141 and management. Accordingly, the level of threat that Southeast Asia's species face from land-use change is
142 highly variable over space and time, reflecting the diversity of countries, cultures and sociopolitical systems
143 across the region (Fig. 1).

144 Not all deforestation associated with agriculture is industrial-scale. Small-holder cultivation has a long history
145 across Southeast Asia, contributing to both forest loss and gain^{55,56}. Small-holder rice cultivation began on the
146 mainland 4000 to 5000 years ago⁵⁷ and remains dominant⁵⁶. Nonetheless, a shift in livelihoods away from
147 small-scale agriculture and forest-use to commodity-driven markets is well underway. This transition can be
148 rapid, taking only ~15 years in Indonesian Borneo⁵⁸, although the pace of change is highly variable. Outside

149 the main oil palm producing areas of Borneo and Sumatra, Indonesia's central and eastern islands continue to
150 produce small-holder cash crops (including coconut, cacao, coffee and cloves), often grown in agroforestry,
151 which have comparatively better prospects for biodiversity than extensive monocultures⁹. In fact, small-holders
152 are frequently invoked as both key drivers of biodiversity loss — owing to land conversion and swidden
153 practices, high chemical use, and poor yields — as well as custodians of agrobiodiversity — through enhancing
154 tree-cover, ecosystem functioning, and species populations^{59,60}.

155 Fire, used to clear and manage land, is now a pervasive threat to Southeast Asia's forests, and the effects of
156 burning are exacerbated by disturbance, poor land management, and drought^{28,61-63}. These effects are most
157 severe in peatlands, where fires can spread belowground. Burning belowground carbon adds greatly to pollution
158 and emissions, while prevention and mitigation measures are restricted by access⁶⁴⁻⁶⁶. The transboundary haze
159 resulting from such fires is unique to the region, regularly bringing adverse outcomes for human health,
160 agriculture, and biodiversity^{64,65}.

161 Fire is a powerful ecological filter, disrupting communities and ecosystem functioning^{67,68}. Most research into
162 the impacts of fire on tropical ecosystems is conducted in South and Central America⁶¹, and relatively few
163 studies focus on Southeast Asia. However, a 16-year long investigation in a Bornean peatswamp forest
164 highlights the degree of damage fire can cause. Tree density, canopy cover, and invertebrate species diversity
165 deteriorated by 92-95% in newly burned forest, as fires immediately compromise tree reproductive phenology
166 and water quality nearby⁶⁹. Commercially valuable fish populations collapsed within three months, while
167 declines in threatened vertebrates took nine months to become apparent. Although the forest remained
168 structurally compromised long after a burn event, signs of recovery were observed after 12 years.

169

170 ***[H2] Infrastructure expansion and urbanisation***

171 Having recovered from the 1997 financial crisis, Southeast Asia experienced a development boom,
172 characterised by rapid urbanisation and growth in energy and transport sectors (Fig. S3). The region hosts three
173 of the world's 33 megacities (Bangkok, Manila and Jakarta, each comprising >10 million people), and Ho Chi
174 Minh is expected to reach this status by 2030⁷⁰. Mega-infrastructure projects include the relocation of
175 Indonesia's capital from Java to Kalimantan in Borneo, >80 new hydropower dams along the Mekong⁷¹, and
176 the China-Indochina Peninsula Economic Corridor augmenting China's Belt and Road Initiative (BRI). The
177 BRI, the largest infrastructure development in human history, will potentially bisect 21 protected areas in
178 mainland Southeast Asia, including new and upgraded roads and highways in Cambodia, Laos, Vietnam, and
179 Myanmar⁷². Road expansion exacerbates habitat fragmentation, disrupts species migration patterns, and further
180 exposes biodiversity to people (for example, through hunting and conflict)⁷², although many of these effects

181 remain poorly documented⁷³. Dam construction alters river flow and sediment movement, disrupting freshwater
182 biodiversity and downstream wetlands, resulting in negative consequences for people^{71,74–76}. The rapid
183 urbanisation of Singapore resulted in major local extinctions, and a further 20% loss of species is predicted by
184 2100⁷⁷; however, Singapore also provides prime examples of how green infrastructure can be implemented —
185 such as innovative wildlife bridges, rooftop gardens, and other nature-based solutions⁷⁸.

186 Developing infrastructure requires immense natural resource exploitation and energy that, in turn, influences
187 biodiversity. After China and India, Vietnam and Indonesia are the largest producers and consumers of Asia’s
188 cement, alongside sizeable markets in the Philippines, Thailand, and Malaysia⁷⁹. Cement is often sourced from
189 highly destructive quarrying of limestone karst habitats renowned for their exceptional endemism⁸⁰. Coal
190 mining, the largest source of energy-related carbon emissions globally, is also expanding extensively (Fig. S3),
191 resulting in land clearance and contaminated water in Indonesian Borneo⁸¹. Surface mining is common for coal,
192 gold, and other minerals, and can be highly destructive if poorly planned and regulated, particularly when
193 artisanal, leading to deforestation, soil erosion, and displacement of people^{82,83}. Although mining can generate
194 income, the environmental and social impacts of more than half the world’s mines remain undocumented,
195 especially in Myanmar and Indonesia⁸⁴. New markets are emerging for the metals that are essential to the global
196 transition to net zero (such as cobalt and nickel in Indonesia and the Philippines; Fig. S3) and, although the
197 contribution to global production is currently low, Southeast Asia (for example, Vietnam and Myanmar) holds
198 sizeable reserves of rare earth metals⁸⁵. Few large-scale mining impact evaluations are available. However, one
199 example from Sulawesi (a global centre for nickel production) showed that nickel mining amplified
200 deforestation and people’s overall well-being deteriorated, despite improvements to their living standards in
201 the short term⁸⁶.

202

203 ***[H2] Hunting and consumption of species***

204 The hunting and capturing of species has received relatively little research attention^{87,88}, despite being an
205 immediate threat to the survival of most of Southeast Asia’s endangered vertebrates⁸⁹. For instance, the Asian
206 songbird crisis is the consequence of ~1000 species being traded, particularly in Indonesia⁹⁰. Across the region,
207 species are hunted for food, pest control, sport, traditional medicine, ornaments and/or decorations, and pets^{91–}
208 ⁹³, but assessing the scale and magnitude of these activities is difficult owing to insufficient data⁸⁷ (Fig. S6).
209 Historically, people hunted mainly for subsistence, but hunting is now a widespread source of income^{92,94}, and
210 wildlife is traded across the region, particularly to fulfil large demand from China and increasingly Vietnam⁹³.
211 Overexploitation is driving species declines and extirpations leading to ‘empty forest syndrome’ (Box 2; Fig.
212 S6). Snares, a key hunting method, are particularly damaging because they are largely indiscriminate (meaning
213 they also capture non-target species) and are cheap and easy to use, meaning hundreds of snares can be set at

214 any one time. Between 2010 and 2015, >200,000 snares were removed from five protected areas in Vietnam,
215 Cambodia, and Laos alone⁹⁵. Although data on the impact of hunting on species populations in the region are
216 rare, one long-term study found snaring drove ungulate and primate declines in Cambodia⁹⁶.

217 Among local communities and indigenous peoples living in rural areas, such as in parts of Malaysia, Papua,
218 Timor-Leste, and Vietnam, the meat of wild animals (‘wildmeat’) can be an important source of nutrition^{94,97,98}.
219 However, although the extent to which wildmeat underpins food security is uncertain, in many areas it is
220 thought to be low due to wildlife depletion. Consumption of wildmeat can also be a crucial component of
221 community identity and food culture^{99,100}, and contributes to well-being¹⁰¹. In areas of Indonesian Borneo¹⁰²
222 and Cambodia¹⁰³, wildmeat is consumed less than domestic meat and fish, and professional hunting groups
223 external to local communities are largely responsible for the trade of high-value species. Wildmeat consumption
224 is observed in urban areas of Thailand, Vietnam, Cambodia, Laos, and Indonesia^{87,104–106}, where it does not
225 constitute a substantial proportion of dietary nutrients⁹². Although wildmeat can be considered a symbol of
226 status and wealth^{100,107}, this is not always the case even within the same country (for example, Vietnam¹⁰⁸).

227 A combination of species scarcity, rising consumer demand and improved market accessibility has resulted in
228 wild animal products becoming increasingly high-value commodities, luring people into targeted commercial
229 hunting. Increasing cross-border trade within Southeast Asian countries has enabled the supply of wildmeat
230 from remote rural areas to places where demand is greatest (typically China and Vietnam)¹⁰⁹. In Myanmar and
231 Vietnam, the wildmeat trade is a source for the illegal trade in wild animal body parts nationally and
232 internationally⁹². Southeast Asian diaspora also facilitate global trade in wild animal parts for traditional
233 medicine. For instance, pangolin scales and bear bile are transported between Asia and South Africa to meet
234 medicinal demand¹¹⁰.

235

236 ***[H2] Emerging threats exacerbate species losses***

237 Although the independent effects of different threats might be relatively well established^{111–114}, these drivers of
238 biodiversity loss rarely occur in isolation. Land-use change compromises habitat quality^{115,116}, while enabling
239 access for people. This combined influence increases interactions between people and wildlife, amplifying
240 persecution, overexploitation and trade^{117,118}. Trade routes and infrastructure development help invasive species
241 spread and habitat modification disrupts the resilience of ecosystems, allowing invasives to establish¹¹⁴.
242 Singapore exemplifies this situation: as a highly urbanised major trade hub, the island state has recorded at
243 least 150 invasive species, costing an estimated US\$1.72 billion to its economy since 1975¹¹⁹. Extrapolated
244 over the Southeast Asia region, costs due to invasive species near US\$17 billion.

245 Although infrequently cited as a major threat on the IUCN Red List for Southeast Asian species (Figs 2, 3), the
246 narrow thermal niches of tropical taxa make them particularly vulnerable to the effects of climate change^{120,121}.
247 Evidence from microclimatic data suggests that the stability that led to this specialisation is breaking down, as
248 mean annual temperatures beneath forest canopies in Southeast Asia are 0.37 °C warmer than in 1990¹²².
249 Logging exacerbates thermal exposure, effectively reversing the protective function of the canopy on species
250 residing in forest below¹²³. At its most severe, seasonal and phenological shifts driven by climate change could
251 force a transition of tropical dry forests to savanna in, for instance, the central mainland and the Lesser Sunda
252 islands¹²⁴. Drought conditions are already intensifying storm damage and forest fire risk across the region^{66,125},
253 and are expected to worsen in the future²⁵.

254 As coastal forests appear to be somewhat buffered from this process, the shift to novel climate conditions
255 reported from other tropical regions is less prominent in Southeast Asia owing to its insular nature¹²². Inland,
256 greater exposure to climate fluctuations and extremes is pushing species outside of their thermal optima, driving
257 some to shift to higher elevations, notably New Guinea's birds¹²⁶ and Borneo's moths¹²⁷. The potential for
258 climate-driven mountaintop extinctions is understudied in the region¹²⁸, but is perhaps greatest in Indonesia
259 and the Philippines where endemism is particularly high^{8,9}. Deforestation at low and mid-elevations compounds
260 the problem^{33,129}, exacerbating the simplification of ecological communities that is already underway³⁴. Almost
261 one-third of climate connectivity was lost across the tropics between 2000 and 2012, and degraded and
262 fragmented areas were exposed to greater temperatures¹³⁰. In turn, forest fragmentation and loss have
263 influenced land surface warming, resulting in amplified temperatures experienced several kilometres away
264 from deforestation events in Southeast Asia¹³¹. These processes also bring species into greater contact with
265 novel competitors¹²⁸ and create more frontiers for conflict with people¹³².

266

267 **[H1] Conservation solutions**

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

272

273 ***[H2] Protected area coverage and effectiveness***

274 Protected areas (PA) are crucial in biodiversity conservation, acting as important refuges for threatened species.
275 By 2020, Southeast Asia's PA network encompassed over 592,000 km² — equivalent to 13% of its land area

276 and thus falling short of the $\geq 17\%$ committed internationally at that time¹³³. However, noteworthy disparities
277 exist between countries. Cambodia protects almost 40% of its land for conservation, whereas Myanmar and
278 Vietnam protect only 7% and 8%, respectively (Table S3). Laos undertook major policy reforms and formalised
279 its PA system in 2023 to protect 19% of its land, whereas Timor-Leste's PA system began in 2016 and
280 comprises 16%. Approximately 39% of the region's PAs are in Indonesia, which has the largest PA network
281 by far. Yet, many PAs in the region were not designated for conservation, as they were established as game
282 reserves or forestry controls during the colonial era. Some habitats remain underrepresented, although less so
283 than in other Asian countries^{133,134}.

284 Despite facing some of the highest human pressures globally^{135,136}, Southeast Asia's PAs appear to be
285 successful at reducing biodiversity loss. Collectively, these PAs have experienced three times less deforestation
286 than unprotected forests¹³⁷ and, consequently, support higher bird and mammal diversity¹³⁸. However, focusing
287 on effectiveness at a regional scale masks the heterogenous, and often unintended, social-ecological outcomes
288 within countries and among individual PAs¹³⁹. Most of the avoided regional deforestation occurred in Malaysia
289 and Cambodia (15% and 11%, respectively)¹³⁷. The unintentional impacts of PAs often include leakage, in
290 which disturbances are displaced to nearby unprotected land¹⁴⁰, and restrictions on local communities. For
291 example, although PAs in Sumatra and Kalimantan have reduced deforestation (22% and 16%, respectively),
292 trade-offs with well-being in neighbouring villages has often occurred¹⁴¹. Conversely, in Cambodia,
293 communities bordering PAs had more secure forest access and better livelihoods than those further away¹⁴²,
294 but relentless pressure on two parks led to their eventual degazettement for industrial agriculture¹⁴³.

295 Although expanding the conservation estate is vital to achieving global biodiversity goals^{138,144}, improving the
296 effectiveness of existing PAs is equally important. Tools for evaluating PA management effectiveness are
297 embedded in the Kunming–Montreal Global Biodiversity Framework ([KM-GBF](#)) (Box 3), but this process
298 takes time. Only around one-quarter of PAs have been assessed globally¹⁴⁵. Although >30% of PAs in
299 Cambodia, Indonesia, and Singapore have been evaluated, <10% have been assessed in Malaysia, Myanmar,
300 and the Philippines, and none in Laos or Timor-Leste¹³³. PAs with management reporting are more likely to
301 avoid deforestation, underscoring the need to scale up evaluations¹³⁷.

302 Adequate funding, staff capacity, and enforcement are vital for effective PAs, and those that fail are often
303 characterised by corruption, land-use conflict, and contested land claims^{146–148}. Government funding is
304 inconsistent between and within countries¹⁴⁵, and is often supplemented by international finance. Thailand, for
305 instance, employs more rangers per unit area than most Asian countries combined, whereas Myanmar employs
306 among the fewest¹⁴⁹. Although PA budgets in the Philippines are substantial, funding within Cambodia and
307 Myanmar is highly unequal, and Timor-Leste's is uniformly inadequate¹⁴⁶. Investment in PAs has increased
308 substantially since the 1990s¹⁴⁹, and major improvements to patrolling, enforcement, and adaptive management

309 have been made since the introduction of the Spatial Monitoring and Reporting Tool ([SMART](#)), which is now
310 implemented in most countries. From 2007, hunting reduced and tiger density increased in Thailand’s Western
311 Forest Complex after the mainstreaming of SMART¹⁴⁶. Nevertheless, following this success, calls have been
312 made for a major scale-up in spending that would employ 7875 additional rangers at a cost of ~US\$29 million
313 in Southeast Asia’s tiger range countries alone¹⁵⁰. How authorities enforce laws and administer sanctions is
314 also important, as perceptions of fairness and the avoidance of abuses of power are key factors influencing
315 people’s willingness to adhere to PA rules¹⁵¹. Tackling these factors will be crucial to the success of PAs, and
316 could be more influential than merely focusing on more enforcement.

317

318 *[H2] Landscape approaches to conservation*

319 Focussing solely on PAs formally designated for biodiversity overlooks sizeable tracts of land that are protected
320 for purposes other than conservation and can have considerable biodiversity value (Box 3). For instance,
321 watershed protection covers 297,000 km² of forest in Indonesia (16% of the country), and large tracts of
322 biodiversity-rich forest remain outside of formal PAs in Cambodia, Laos, and Myanmar. Landscape
323 conservation approaches that incorporate such areas seek to maintain or enhance biodiversity and ecological
324 connectivity across human-modified ecosystems while also meeting livelihood and development goals¹⁵².
325 Nevertheless, governance in these alternative protected ecosystems is often weaker, and downgrading and
326 degazetting are commonplace¹⁴⁶.

327 Collaboration between multiple stakeholders through financial incentives, certification schemes, and improved
328 land tenure rights is central to promoting biodiversity in human-modified ecosystems. Southeast Asia’s large
329 and diverse private sector has an increasingly important role in these initiatives, particularly in forest restoration
330 (Box 4). In Malaysia, for example, oil palm companies are financing forest restoration of a former logging
331 concession (an area granted permission to harvest timber) to buffer threatened species from further habitat
332 loss¹⁵³. Indonesia’s ecosystem restoration licences, which lease degraded logged-over forests for 60+ years,
333 have also shown promise in achieving conservation and commercial objectives. For example, a major paper-
334 pulp company has protected 1500 km² of Sumatran peatswamp forest since 2013 through such licenses,
335 eliminating fires and enhancing carbon stocks¹⁵⁴. By 2020, >6200 km² of licenses had been awarded to
336 companies and non-governmental organisations across Indonesia, and many more are in development¹⁵⁵,
337 although some sites continue to experience pressure from agriculture and infrastructure development¹⁵⁶. Further
338 research is needed into the long-term effectiveness of using such initiatives to finance conservation.

339 Landscape conservation approaches can be strengthened by agribusinesses and extractive industries pledging
340 to eliminate deforestation from their supply chains. Indeed, >80% of Southeast Asia’s oil palm refining capacity

341 is under some form of zero deforestation commitment¹⁵⁷. Pledges typically involve avoiding clearance of
342 forests with high conservation or carbon value, not planting on peatland to minimise fire and soil-based
343 emissions, and improving well-being outcomes for workers and local communities¹⁵⁸. By 2015, oil palm
344 sustainability commitments in Indonesia had reduced deforestation by 33%, but had limited success in
345 addressing peatland clearance and fire¹⁵⁹. However, early adopters of certification (approximately 2009 to
346 2015) tended to have the least remaining forest area, so little deforestation was avoided at that time. Social
347 impacts of certification have been mixed: poverty has been alleviated in some villages but worsened in others,
348 often as a result of trade-offs between environmental and social sustainability objectives^{160,161}.

349 The forest patches left behind in production landscapes have limited biodiversity value in isolation but, if
350 managed collectively at a landscape-scale, can support the persistence and movement of threatened species
351 populations¹⁶²⁻¹⁶⁴. Riparian habitats are particularly important as they are often protected during logging
352 operations and, subsequently, in agriculture and provide refuge for many species^{165,166}. Nonetheless, without
353 adequate management these set-asides are prone to further degradation, encroachment and hunting, limiting
354 their effectiveness as habitat and dispersal corridors^{162,167}. Crucially, leveraging industry commitments to
355 follow environmental policies and best practices and incentivising smallholders to follow best practices in their
356 farmlands can lead to improved biodiversity outcomes without compromising agricultural productivity or
357 yields^{43,168}. Although voluntary certification schemes are prone to conceptual (for example, defining forests or
358 avoiding leakage) and practical (such as ensuring transparency and integrating small-holders) challenges^{169,170},
359 those in the forestry and oil palm sectors have raised governmental standards and inspired sustainability
360 initiatives in other agri-industries, including [rubber](#) and [coconut](#). Decision support tools to help identify high
361 conservation value land at a landscape-scale, ideally prior to development, continue to be needed¹⁷¹.

362

363 ***[H2] Community-led forest management***

364 Much of the intact forest of tropical countries is managed or used by indigenous people or local communities,
365 who are likely to be critical for safeguarding biodiversity^{172,173}. Participatory approaches to forest management,
366 in which local communities are given rights and responsibilities over forest resources, are used prominently in
367 Southeast Asia to address deforestation, rural poverty, and climate mitigation. Over 138,000 km² of forest is
368 under formal community management, primarily in the Philippines, Indonesia, Vietnam, and Cambodia¹⁷⁴.
369 Indonesia, Laos, and Thailand formalised forest resource rights more recently (2014–2019), and initiatives in
370 Myanmar and Malaysia continue to grow despite facing political and legal challenges^{174,175}. Community forest
371 management practices vary in different countries, as some schemes focus purely on protection whereas others
372 permit ecotourism, agroforestry, and/or the extraction of forest products (including wildmeat) for local
373 use^{175,176}. To be successful, the schemes provide indigenous people or local communities with stable income

374 through sustainable land-use practices that are compatible with conservation (Box 3), as well as access to
375 funding for restoring degraded lands (Box 4)¹⁷⁶⁻¹⁷⁸.

376 Giving indigenous people or local communities a stake in forest resources through community management
377 can incentivise sustainable practices, which is effective in many cases. Cambodia allows local communities to
378 manage forests within PAs¹⁷⁹, which has resulted in reduced deforestation and degradation¹⁸⁰. Community-
379 managed forests are also attributed with uplifting the protective function of PAs in Thailand¹⁸¹, and improving
380 canopy cover and landscape connectivity in the Philippines¹⁷⁸. In Indonesia, where multiple schemes have been
381 introduced, environmental benefits have commonly been reported^{176,177}, although not universally. A prominent
382 community-managed forest initiative successfully avoided deforestation in Kalimantan and Sumatra between
383 2009 and 2014¹⁸², although comparable outcomes have yet to be observed for this specific scheme or others
384 nationwide¹⁸³.

385 The socio-economic benefits of community forestry have not been uniformly realised^{177,184}. Effectiveness is
386 highly dependent on local governance structures and leadership, community capabilities and capacity, and
387 external support^{176,178}. Weak enforcement of forest laws and ambiguous land tenure can aggravate deforestation
388 in some community-managed forests, particularly in agricultural zones where external pressures are more
389 intense than in extensively forested areas^{182,185}. Without strong governance structures, wealthier households
390 and community leaders disproportionately benefit, while poorer households remain disadvantaged, thus
391 reinforcing existing inequities and injustices^{175,186}. Long-term, inadequate financial and technical resources can
392 lead to disillusionment. Empowering people through genuine participation in land-use decisions and locally-
393 led initiatives is challenging, but critical to delivering positive biodiversity outcomes; for example, a
394 community-led conservation scheme that co-produced management actions with local people, and designed
395 and implemented a monitoring and evaluation framework, resulted in reduced hunting, logging, and forest
396 clearance¹⁸⁷. Nonetheless, aside from a limited number of case-studies, evaluation of the biodiversity
397 credentials of community forest management remains limited^{177,184}.

398

399 ***[H2] Tackling unsustainable hunting***

400 Disincentivising wildmeat consumption in urban areas must be the prominent focus in tackling hunting for non-
401 subsistence purposes⁸⁷ because it plays a central role in overexploitation and trade dynamics. Law enforcement
402 is crucial to close illegal wildlife markets and trade routes, and increased effectiveness is required from digital
403 service platforms to reduce illegal products sold online¹⁸⁸. Meat consumption in Southeast Asia remains below
404 the global average but is increasing (Fig. S4), so ensuring this consumption is within ecologically sustainable
405 levels and from non-wild stocks is key to food security. This approach is likely to benefit biodiversity longer-

406 term by decreasing both the area of land needed for animal rearing and the demand for wildmeat. The EAT
407 Planetary Health Diet, for instance, has been specifically designed to promote sustainable food systems¹⁸⁹.

408 Preventing illegal hunting and trafficking requires a multi-pronged approach. Near PAs, interventions include
409 improving patrols, increasing penalties, and legislative reform to criminalise possession of snares^{95,190}.
410 Providing incentives for people to not hunt is yet to be adequately explored, but adoption of community-led
411 models could increase the success of this approach¹⁸⁷. For example, analogous investments into rural healthcare
412 have led to declines in illegal logging within a national park in Indonesia¹⁹¹. Strengthening transnational and
413 regional cross-border collaborations and agreements will also be necessary¹⁹².

414

415 ***[H2] Funding biodiversity through climate mitigation***

416 Despite investment, Southeast Asia's countries face substantial funding gaps for biodiversity conservation¹⁴⁶.
417 Climate change mitigation offers a promising additional source of funding, aligning the [Paris Agreement](#) with
418 various international policy commitments, such as the KM-GBF and the United Nations [Sustainable](#)
419 [Development Goals](#). Owing to its vast carbon stocks and high deforestation risk, the region is especially well
420 positioned to cost-effectively deliver on both climate and biodiversity objectives²¹ (Table S1, S3). Such nature-
421 based climate solutions include forest protection, ecosystem restoration, and sustainable land management.
422 More than 1 million km² of forests across Southeast Asia could generate at least one biodiversity or ecosystem
423 service co-benefit, alongside reducing emissions, and Thailand and Indonesia are especially important¹⁹³.
424 Optimising the spatial planning of nature-based climate solutions, so that the benefits for climate mitigation,
425 people's livelihoods, and biodiversity are maximised, is crucial for long-term success. Wetland protection is
426 particularly well-suited to Indonesia owing to its extensive tropical peatlands, where 49 tCO₂ ha⁻¹ yr⁻¹ could be
427 saved in Sumatra and Kalimantan alone^{17,193,194}. Forest restoration and agricultural improvement are ideal in
428 Thailand and the Philippines, while forest protection and sustainable land management are typically the best
429 strategies elsewhere¹⁷.

430 Among the various payment for ecosystem service schemes that exist, the UN's Reducing Emissions from
431 Deforestation and Forest Degradation ([REDD+](#)) initiative remains central to protecting forest via climate
432 finance. Although early successes have been achieved (for example, Cambodia^{195,196}), Southeast Asia's
433 complex geopolitical landscape poses considerable challenges ahead. Indonesia is the region's largest country
434 and carbon emitter (Fig. S5). Although deforestation has reduced across the country since 2017, regulatory
435 tensions between national and regional government, along with deregulation efforts, disrupted its 2011
436 moratorium on forest clearance^{197,198}. As with PAs and other area-based conservation measures, leakage can
437 be problematic, and the biodiversity and livelihood co-benefits of emissions reductions can be costly and limit

438 feasibility²¹. Discrepancies also persist between pledges and actual disbursements. For example, Norway
439 pledged US\$1 billion REDD+ to Indonesia in 2010, but had only released US\$56 million 10-years later owing
440 to delays in the measurement, reporting and verification of reduced emissions¹⁹⁹. Carbon financing also faces
441 credibility issues, such as inflated deforestation baselines used to measure progress²⁰⁰. One potential outcome
442 is that local communities and governments that have managed to successfully protect their forests in the long-
443 term might not be appropriately rewarded, despite these forests potentially having the greatest biodiversity
444 value. Developing reliable counterfactuals to evaluate the performance of interventions and addressing the high
445 costs of monitoring forests and biodiversity are sizeable issues that are being slowly overcome^{195,201,202}.
446 Strengthening inclusivity and benefit-sharing among indigenous people and local communities will be vital to
447 securing further uptake of payments for ecosystem services schemes^{203,204}, particularly if these schemes are to
448 incentivise biodiversity protection and alternatives to overexploitation²⁰⁵.

449

450 ***[H2] Policy coordination and implementation***

451 Although no single, straightforward solution exists for protecting forests and biodiversity²⁰⁶, conservation
452 activity in the region has greatly expanded since the crisis was first identified in the early 2000s⁸. Governments
453 across Southeast Asia have increased conservation investment to meet obligations under the Convention on
454 Biological Diversity and other multilateral sustainability agreements²⁰⁷. The [ASEAN Centre for Biodiversity](#),
455 established in 2005, provides regional coordination and policy guidance. The 2023 ASEAN Biodiversity
456 Outlook report noted progress among countries towards the Aichi Biodiversity Targets, including raised
457 awareness, mainstreaming biodiversity, incentivising sustainable practices, and revising National Biodiversity
458 Strategies and Action Plans (NBSAPs)²⁰⁷.

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

469 The inconsistent and often limited use of quantitative indicators is a persistent challenge — many are removed
470 or changed between reporting cycles²⁰⁸. Improved metrics are needed for habitat loss, species overexploitation,
471 climate impacts, and invasive species. Reporting of national and regional IUCN Red List data remains patchy
472 and underdeveloped. Although participation of indigenous and local communities is increasing in some
473 countries, it remains limited regionally. Weak inter-agency coordination (for example, between agriculture,
474 environment and fisheries) hampers holistic understanding of biodiversity challenges and solutions within
475 countries, and therefore implementation of the KM-GBF.

476 **[H1] Summary and Future Research Perspectives**

477 Southeast Asia’s biodiversity crisis continues owing to the intersecting pressures described above. To help
478 countries tackle the crisis, researchers should be contributing more to solutions and engaging directly in
479 implementation science, rather than merely elucidating problems²⁰⁹. Biodiversity research needs to encompass
480 a broader range of both established (for example, rubber and coconut) and emerging (for example, durian and
481 cassava) forest-risk commodities and geographies, expanding beyond the intense focus on oil palm.
482 Refocussing attention on crops where management options exist to minimise ecological damage (such as cacao,
483 coconut, coffee) — especially in agroforestry — would be particularly beneficial. Moreover, this research will
484 fill the gaps in global datasets (for example, PREDICTS, Living Planet Index; Fig. S6), thus helping to improve
485 regional biodiversity monitoring and predictions.

486 The KM-GBF has spurred on the rapid development of biodiversity credits to financially support biodiversity
487 protection and restoration. Although credits hold immense potential to attract investment for biodiversity in
488 tropical countries, establishing and validating their scientific credibility will be key to avoiding issues around
489 integrity and impact that plague carbon markets¹⁹. Unlike carbon, biodiversity is not fungible, meaning that
490 research is needed to underpin a credit system that reflects the complexity and location-specific nature of
491 biodiversity. Fundamental questions remain regarding how biodiversity gains can be reliably quantified, and
492 what metrics should be used to track biodiversity change over time^{210,211}. Practical and realistic economic
493 frameworks are vital to ensuring sufficient demand and consistent sales of credits to help direct investment
494 where it is needed most (that is, areas of high biodiversity threat, rather than easy biodiversity gain^{210,211}).
495 Furthermore, the revenue models adopted must channel the funding to indigenous peoples and local
496 communities as the stewards of biodiverse lands^{210,212}. Developing equitable and robust measurement and
497 accounting approaches will be critical to establishing biodiversity credits as trusted, impactful tools for
498 conservation finance.

499 Enhancing biodiversity monitoring requires integrating rapid, cost-effective tools alongside strengthened
500 human and technological capacity. Taxonomic expertise is vital to understanding, cataloguing, and assessing
501 biodiversity, yet remains undervalued in research^{213,214}. Although advances in remote sensing, robotics and

502 automated systems, and artificial intelligence will be transformative, reliance on technology alone is high-risk
503 and could be exclusionary or harmful to indigenous people and local communities^{18,215–217}. Instead, a hybrid
504 approach that combines technology with local ecological knowledge²¹⁸ should be adopted to deliver robust data
505 validation. To process the vast datasets technological tools generate, improved statistical methodologies and
506 integrated models to facilitate accurate biodiversity surveys are required²¹⁹.

507 Synthesis methods, such as meta-analyses, synthetic controls, and impact evaluations using rigorous
508 counterfactual designs, are key to generating the high-quality evidence needed to underpin policy and practice
509 decision-making²²⁰. The social, as well as environmental, consequences of conservation solutions must be
510 assessed within such frameworks to ensure potential socio-ecological trade-offs are fully understood^{43,221}.
511 Innovations could include assessing multiple drivers or management/policy interventions within the same
512 analysis, evaluating outcomes at smaller jurisdictional scales to better inform activities²²², and using results to
513 help target biodiversity surveys or interview-based case-studies. As the deadline for meeting the 2030 KM-
514 GBF targets approaches, the need to evaluate effectiveness of potential other effective area-based conservation
515 measures (OECMs) is paramount (Box 3).

516 Research ethics are fundamental, whether they relate to use of technology^{216,217,223} or the inclusion of people
517 within activities⁸⁷. Work on Southeast Asia’s biodiversity crisis is often dominated by high-income country
518 researchers, whereas locally valuable studies in non-English languages face barriers to broader recognition²²⁴.
519 Regional capacity continues to improve, but training opportunities are limited by funding, language, and
520 location, making them highly competitive and sometimes ill-matched to competences needed for conservation
521 (for example, planning, fundraising and project management)²²⁵.

522 Meaningful collaboration with local scientists and communities should be paramount, and parachute science
523 practices avoided, especially in the context of increased applications of artificial intelligence^{226,227}. Researchers
524 should cultivate self-awareness, expand literature searches into multiple languages, foster genuine partnerships,
525 and promote meaningful knowledge exchange²²⁸. Women, indigenous communities, and other marginalised
526 groups are vital stewards of biodiversity, but opportunities for these groups to contribute to research remain
527 underdeveloped^{229,230}. Publishers should enhance inclusivity standards, remove financial barriers, facilitate
528 multilingual dissemination, and ensure equitable representation in peer review. Funders could also remove
529 systemic obstacles by targeting investment in projects and training that strengthen research networks and
530 amplify the roles of regional experts, so that practical, culturally-nuanced research receives due recognition²²⁸.

531 Data sharing at all stages of the research process, from standardised data collection protocols and indicators
532 (for example, for [wildlife hunting, consumption, and trade](#)) through to the findings of impact evaluations, is
533 currently hindered by distrust of how data will be used and credited, and a lack of centralised open access

534 information repositories^{231,232}. Addressing these concerns would enable transparent learning from both research
535 and intervention successes and failures. To date, insufficient knowledge sharing has led to mistakes being
536 repeated and has slowed progress in tackling the terrestrial biodiversity crisis¹⁴⁶. By following these
537 recommendations, the research community will ensure that Southeast Asian nations are better positioned to
538 solve their conservation challenges and realise the more optimistic projections for biodiversity in years to come.

539

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1143 **Acknowledgements**

1144 M.J.S. and N.J.D. are supported by a Leverhulme Trust Research Leader Award (granted to M.J.S). J.S.H.L. is
1145 funded by the Climate Transformation Program, a Tier 3 Academic Research Fund from the Singapore Ministry
1146 of Education (MOE-MOET32022-0006). D.J.I. is the recipient of a UK Research and Innovation Future
1147 Leaders Fellowship (MR/W006316/1). T.S., M.J.S and Z.G.D. are supported by Research England’s

1148 ‘Expanding Excellence in England’ fund. We thank Nuwanthika Dharmaratne for providing relevant data, and
1149 Lindsay Banin for helpful feedback on forest restoration. We dedicate this paper to the late Navjot Sodhi and
1150 Tony Whitten; their contributions to highlighting the biodiversity crisis in Southeast Asia and promoting
1151 equitable conservation practice continue to be inspirational worldwide.

1152

1153 **Author contribution statement**

1154 Researching data for article: J.S.H.L., N.J.D. T.S. and D.I.J.S; substantial contribution to discussion of content:
1155 all authors; writing: all authors; review and/or editing of manuscript before submission: all authors.

1156

1157 **Competing interests**

1158 D.J.I. is a trustee of The Pangolin Project CIO (UK), a Field Science Co-Chair of the IUCN SSC Pangolin
1159 Specialist Group, and a member of the IUCN Sustainable Use and Livelihoods Specialist Group (SULi).

1160

1161 **Related links**

1162 Global Platform for Sustainable Natural Rubber: <https://sustainablenaturalrubber.org/>

1163 Roundtable on Sustainable Palm Oil: <https://rspo.org/>

1164 Sustainable Coconut Partnership: <https://www.coconutpartnership.org/>

1165 Kunming–Montreal Global Biodiversity Framework: <https://www.cbd.int/gbf>

1166 Spatial Monitoring and Reporting Tool: <https://smartconservationtools.org/>

1167 Wildmeat: www.wildmeat.org

1168 Protected planet: <https://www.protectedplanet.net/en>

1169 UN Decade on Ecosystem Restoration: <https://www.decadeonrestoration.org>

1170 Bonn Challenge: <https://www.bonnchallenge.org>

1171 New York Forest Declaration: <https://forestdeclaration.org/>

1172 Paris Agreement: <https://unfccc.int/process-and-meetings/the-paris-agreement>

1173 United Nations Sustainable Development Goals: <https://sdgs.un.org/goals>

1174 Reducing Emissions from Deforestation and Forest Degradation, REDD+: <https://redd.unfccc.int/>

1175 ASEAN Centre for Biodiversity: <https://www.aseanbiodiversity.org/>

1176

1177 **Key points**

- 1178 1. Southeast Asia’s terrestrial biodiversity crisis is driven by multiple interacting and often synergistic
1179 pressures — primarily land-use change, infrastructure development, and overexploitation — which
1180 vary in intensity across the region and demand coordinated, context-specific responses.
- 1181 2. Effective protected areas require adequate funding, staffing, enforcement, and monitoring, while
1182 carefully managing unintended consequences such as displaced deforestation and negative impacts
1183 on local communities.
- 1184 3. Maintaining biodiversity in human-modified ecosystems depends critically on financial incentives,
1185 certification schemes, and secure land tenure rights, and the forest patches that remain in the
1186 landscape need to be managed collectively to ensure species persistence and movement.
- 1187 4. Community-led forest management can align conservation and local livelihoods when supported by
1188 strong governance, leadership, community capabilities and capacity, and sustained external
1189 investment in habitat restoration.
- 1190 5. Reducing hunting for non-subsistence purposes requires a strong focus on curbing demand for
1191 wildmeat, particularly in urban areas, through enforcement to prevent illegal hunting, market
1192 closures, and disruption of physical and online trade routes.
- 1193 6. Solving the crisis requires researchers to shift from diagnosing problems to delivering actionable and
1194 equitable solutions, increased focus on forest-risk commodities beyond oil palm, developing robust
1195 metrics to underpin biodiversity credits, and inclusive collaboration with Southeast Asian scientists,
1196 indigenous people and local communities.
- 1197
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1200 **Display items**

1201

1202 **Figures**

1203 Figure 1. **Geography of Southeast Asia’s biodiversity crisis.** Bivariate map showing spatial overlap between
1204 forest condition and the extinction vulnerability of IUCN-evaluated vertebrates (881 amphibian, 1,451 reptile,
1205 1,569 bird and 880 mammal species). Forest condition was derived from aboveground vegetation biomass maps
1206 reclassified using ecological thresholds of the aggregated response of 1,681 species to habitat degradation
1207 (Supplementary Methods). The thresholds were used to define three degradation classes: intact forest (71-100%
1208 biomass retained); degraded forests (32-70% biomass retained); and heavily-degraded forests (0-32% biomass
1209 retained). Red polygons indicate deforestation hotspots identified through 26 years of forest cover change
1210 assessments from global imagery (derived from ref.²⁷). Photographic arrows denote the dominant drivers of
1211 deforestation across a selection of these disturbance frontiers. The map illustrates the sensitivity of biodiversity
1212 to forest degradation in Southeast Asia’s lowland forests owing to the proliferation of commodity agriculture,
1213 plantation forestry and mining, but highlights substantial areas of intact forests and ecological communities in
1214 high-altitude, remote regions.

1215

1216 Figure 2. **Threats to biodiversity in Southeast Asian countries.** Country-specific appraisals showing the
1217 proportion of plant, fish, amphibian, reptile, bird and mammal species that are considered threatened according
1218 to the IUCN Red List (upper panels with blue bars), the prominent threats facing biodiversity, forest condition,
1219 and protected area (PA) coverage (lower panels with stacked bars). ‘Threats’ represents the percentage of key
1220 threats cited in the IUCN Red List database, aggregated across all 7,334 taxa assessed; ‘Forest condition’ is the
1221 percentage of overall forest cover considered intact (71-100% biomass retained), degraded (32-70% biomass
1222 retained), and heavily-degraded (0-32% biomass retained) (Supplementary Methods) as used in Fig. 1. ‘PA
1223 coverage’ denotes land protected as a percentage of total terrestrial surface area. White vertical bars indicate
1224 progress towards meeting the UN Convention on Biological Diversity Aichi Biodiversity Target 11 (17% of
1225 land protected by 2020; dashed white vertical line) and the Kunming–Montreal Global Biodiversity Framework
1226 Target 3 (30% of land protected by 2030; solid white vertical line) through protected areas. Countries within
1227 mainland Southeast Asia are presented on the top row, while insular countries are located on the bottom row.
1228 Considerable variation exists in threatened species, forest condition and progress towards the 30x30 protection
1229 target both within and between regions.

1230

1231 Figure 3. **Threat hierarchies, interactions and mitigation. a** | Dominance hierarchies for established and
1232 emerging threats to Southeast Asia’s biodiversity, as listed on the IUCN Red List for vertebrates and plants.
1233 The ranges of 7,334 species are partially or fully contained within at least one Southeast Asian country, and

1234 their conservation status is linked to threats in the Red Listing process. The area of the circle for each threat
1235 reflects the proportion of incidences the threat is cited across these species, noting that a species may be
1236 subjected to multiple threats across its range; larger circles therefore indicate that a greater number of species
1237 are impacted by the threat across the region. The lines linking pairs of threats reflect the co-occurrence of
1238 threats for species and the potential for these threats to interact: thicker lines represent more co-occurrences.
1239 Established threats comprise land-use change, logging, infrastructure development, exploitation and fire, and
1240 emerging threats include climate change and invasive species. Threats have been reclassified to aid presentation
1241 and match the main themes covered in the text (Table S2). **b** | Overview of conservation solutions prominent
1242 across Southeast Asia, along with the common barriers to implementation.

1243

1244 *Boxes*

1245 Box 1 | **Tipping points in biodiversity responses to forest degradation**

1246 Approximately 25% (>4 million km²) of the world's tropical forests are designated for forestry²³³. Logging is
1247 widespread in Southeast Asia, targeting commercially valuable mature trees. This selective logging is
1248 particularly lucrative in the dipterocarp forests of insular Southeast Asia (primarily Indonesia, Malaysia, and
1249 Brunei), which support an unusually high diversity of timber tree species. Indeed, average timber yields of
1250 >100 m³ ha⁻¹ in Southeast Asia tend to be much greater than those achieved in other tropical regions, with
1251 second or even third harvests (albeit diminished) possible after a nominal rotation time²³⁴. Forests are therefore
1252 often cut several times before they become financially unviable, resulting in a gradual deterioration of forest
1253 biomass and structure^{235,236}.

1254 A major analysis of 1,681 species responses to logging disturbance in Malaysia found the removal of
1255 aboveground biomass from forests during successive rounds of logging led to a turnover of specialists to
1256 generalists, terrestrial to arboreal, and large to small taxa²³⁷. Lightly logged forests (<29% vegetation biomass
1257 removed) retained high species and functional composition, while the most heavily degraded areas (>68%
1258 biomass removed (left photograph) had much lower biodiversity value. Counter to the impression provided by
1259 IUCN Red List assessments (Fig. 2; Table S2), populations of almost one-third of the species were enhanced
1260 after logging, leading to higher levels of overall biodiversity in logged forest and a 2.5-fold increase in total
1261 resource consumption by both mammals and birds⁴² (middle and right photographs of a sun bear *Helarctos*
1262 *malayanus* and blue headed pitta *Hydrornis baudi*, respectively). Thus, not all biodiversity impacts from
1263 logging are equal, and a large area of Southeast Asia's logged forests hold considerable conservation value²³⁸
1264 while being highly prone to conversion (Fig. 1).

1265 The capacity of logged forests to support biodiversity depends on the intensity and extent of disturbance²³⁹, the
1266 number of felling cycles²⁴⁰, and the extraction techniques used²⁴¹. Efforts to minimise damage through reduced-

1267 impact logging techniques go a long way to lessen habitat degradation and promote biodiversity in production
1268 forests^{241,242}, as does limiting secondary disturbances from encroachment and road building (so called ‘ghost
1269 roads’⁷³). Such practices are central to voluntary forest management certification schemes, which have reduced
1270 deforestation, firewood dependence, malnutrition, and respiratory infections in parts of Indonesia²⁴³. Reduced-
1271 impact logging generally leads to better outcomes for forests, people, and biodiversity across the tropics,
1272 although understanding the potential interaction between logging disturbance and hunting in certified or non-
1273 certified forests remains a major research gap²⁴⁴.

1274

1275 Box 2 | **Defaunation of tropical forests**

1276 Defaunation is the decline and/or local extinction of animal species due to human activities from land-use
1277 change, habitat disturbance, and hunting (for example, wildmeat, fish and songbirds in the left, middle and
1278 right photographs, respectively). These extinctions and declines pose a growing threat to biodiversity and
1279 carbon-rich tropical forests globally^{245,246} and can result in ‘empty forest syndrome’²⁴⁷. The loss of large fauna,
1280 in particular, can disrupt critical ecological functions such as seed dispersal and carbon storage^{248–250}. The long-
1281 term consequences of defaunation remain contentious. Declines in animal populations are shifting forest
1282 community composition towards smaller-fruited or wind-dispersed trees with lower wood density and reduced
1283 aboveground biomass, undermining ecosystem resilience and carbon storage potential^{205,249,251}. For instance,
1284 nearly one-third of Thailand’s forest biomass comprises trees reliant on large-bodied frugivores for seed
1285 dispersal. Simulating their removal via hunting revealed statistically significant tree community turnover and
1286 a 2.4–3.0% aboveground carbon reduction²⁵². However, as most of the high-carbon trees of Asian forests are
1287 wind dispersed, defaunation impacts on carbon dynamics might be less severe in the region than for other parts
1288 of the tropics²⁵¹.

1289 Despite the global significance of defaunation, research has predominantly focused on temperate zones and
1290 Latin America, leaving Southeast Asia comparatively underexplored^{111,249,253}. Regional defaunation projections
1291 are based on very few empirical datasets^{111,253} (Fig. S6). Addressing these gaps requires increasing the number
1292 of field-based studies to refine predictive models and identify defaunation drivers, and better open-access data-
1293 sharing to facilitate larger-scale or meta-analyses that should be designed to inform conservation strategies.

1294 Defaunation is driven by both ecological and social factors, often in tandem, but few studies integrate these
1295 perspectives well. Researchers often emphasise habitat loss or degradation and their cascading effects on fauna,
1296 even in otherwise intact sites^{254,255}. Rapid demographic and socioeconomic changes also shape human–wildlife
1297 interactions, but these have proven challenging to characterise at scale. Economic growth can reduce reliance
1298 on forests for subsistence and well-being^{101,256,257}, but wealthier, expanding populations tend to require more

1299 land and resources, amplifying pressures on biodiversity¹. In Vietnam, Laos, and Malaysian Borneo, hunting
1300 pressures have driven higher functional extinction rates than habitat degradation²⁵⁸. Defaunation should
1301 therefore be treated as a socioecological problem, requiring an interdisciplinary approach that integrates land-
1302 use management, socio-economic dynamics and local livelihoods.

1303 **Box 3 | Target 3 of the Kunming–Montreal Global Biodiversity Framework**

1304 Protected areas (PAs) are the cornerstone of traditional global biodiversity conservation efforts, and now
1305 comprise [~16%](#) of land globally. However, PAs have not been successful in halting biodiversity declines. To
1306 lessen their social and economic impacts, state-governed PAs have been disproportionately located where
1307 human population density and land costs are low²⁵⁹. This has limited their expansion and impacted marginalised
1308 people who live in such remote locations. Recognising these imbalances and the need for transformative action,
1309 the concept of ‘other effective area-based conservation measures’ (OECMs) has gained prominence since
1310 2022^{260,261}. OECMs comprise geographically defined areas other than PAs that achieve positive long-term
1311 outcomes for biodiversity and, where applicable, cultural, spiritual, socio-economic, and other locally relevant
1312 values, despite conservation not being their primary objective.

1313 In 2022, the 195 government signatories to the Convention on Biological Diversity agreed to expand PA and
1314 OECM coverage across to the world to at least 30% by 2030 (‘30x30’)²⁶². This pledge is part of Target 3 of the
1315 Kunming-Montreal Global Biodiversity Framework, which also states these sites should be effectively
1316 managed, equitably governed, ecologically representative, and well-connected. The premise is that OECMs
1317 can offer novel mechanisms to ensure that privately or community-governed areas important for biodiversity
1318 deliver conservation value and enhance ecological connectivity²⁶³. The obligation to equitable conservation
1319 means that OECMs are likely to provide recognition to, and empower, indigenous people and local
1320 communities who are stewards of large areas of land²⁶⁴.

1321 Many of the emerging conservation initiatives in Southeast Asia (see ‘Conservation solutions’), including
1322 ecosystem restoration licences (left photograph), conservation set-asides (middle photograph) and community
1323 forest areas (right photograph), have the potential to be formally designated OECMs²⁶⁵. Importantly, official
1324 recognition of OECMs needs to have the free and informed consent of the people governing and stewarding
1325 each area, some of whom might be concerned about associated potential land-use restrictions²⁶⁶. Care must be
1326 taken during implementation to ensure no adverse impacts on food security occur²⁶⁷, lessons are learnt from
1327 past mistakes with PAs²⁶⁸, and that conservation funds are not too thinly distributed that management
1328 effectiveness is undermined²⁶⁹.

1329 However, just a few countries have formally incorporated OECMs into their National Biodiversity Strategies
1330 and Action Plans (NBSAPs). Indeed, only Thailand and Laos, out of six Southeast Asia countries assessed,

1331 have pledged in their NBSAPs to deliver 30x30 within their national borders (Table S3). This regional picture
1332 is indicative of a wider global pattern, in which 51% of nations have either committed to protect a lower
1333 percentage of land cover or failed to make any specific commitment²⁷⁰.

1334

1335 **Box 4 | Restoring Southeast Asia’s degraded landscape**

1336 Restoration is high on the global sustainability agenda thanks to the [UN Decade on Ecosystem Restoration](#) and
1337 the [Paris Agreement](#). Additionally, the [Bonn Challenge](#) and [New York Forest Declaration](#) aim to restore 3.5
1338 million km² of degraded forest by 2030. Great potential exists to upscale restoration in Southeast Asia, although
1339 action lags behind other regions owing to several unique socioecological challenges^{271,272}.

1340 Southeast Asian forests are often dominated by dipterocarp trees, which have limited dispersal ability and are
1341 highly prized for timber (Box 1), making natural regeneration difficult^{271,273}. The most common restoration
1342 intervention is therefore planting nursery-grown saplings (left photograph), supplemented by other treatments
1343 such as weeding, cutting climbers, and thinning. The availability of seeds (middle photograph) for regeneration
1344 or saplings for active planting is also restricted by infrequent mast fruiting events and limits to the supply of
1345 seeds²⁷¹. Upper estimates for merely starting restoration in the tropics and subtropics range from US\$3,880-
1346 25,830 per hectare, depending on whether natural or active regeneration is used²⁷⁴. Peatland restoration brings
1347 additional challenges and costly interventions as hydrological processes need to be reinstated and fire
1348 eliminated^{194,273}. The cost of restoring peatlands to offset oil palm impacts in Kalimantan could exceed US\$3
1349 billion alone²⁷⁵. Private finance, comprising mechanisms that learn from past failures, is clearly needed to
1350 address the scale of the challenge^{276,277}.

1351 To deliver on restoration commitments, environmental challenges and trade-offs between objectives and
1352 competing land-uses need to be resolved²⁷⁸. Restoration activities are diverse, spanning forest recovery,
1353 regeneration of abandoned farmland, and plantation development. Restoration also has different meanings for
1354 different people. For instance, local communities might prioritise income from fruiting trees or non-timber
1355 forest products, returning some ecosystem functions over full ecosystem recovery. Early efforts to mitigate
1356 climate change through plantation forestry in Cambodia were associated with land grabs and forest clearance,
1357 contradicting their stated goals²⁷⁹. However, when implemented in appropriate locations with suitable
1358 approaches and investments, restoration can bring ecosystem and livelihood benefits²⁸⁰. Despite these
1359 challenges, multi-sectorial efforts are ongoing to make restoration work for people and environment, and
1360 include activities central to country commitments for climate-change mitigation. Initiatives such as the
1361 Roundtable on Sustainable Palm Oil provide remediation mechanisms for restoring high conservation value
1362 areas within agricultural land, some of which is channelled to social forestry²⁸¹. Almost 295 million people live
1363 on land suitable for tropical forest restoration, many of whom are in Southeast Asia²⁸². Empowering these local
1364 communities to restore, manage, monitor (bottom right photograph) and derive livelihood benefits from forests
1365 can align global goals for climate mitigation, conservation, environmental justice, and sustainable development.

1366
1367

1368 **ToC blurb**

1369 The terrestrial ecosystems of Southeast Asia are both globally important reservoirs of biodiversity, and a
1370 provider of resources and livelihoods for millions of people across the region. This Review summarises the
1371 threats to biodiversity in Southeast Asia, and the conservation solutions required to ensure successful outcomes
1372 for biodiversity and people.