

Struebig, Matthew J., Aninta, Sabhrina Gita, Davies, Zoe G., Lo, Michaela, Voigt, Maria, Beger, Maria, Bani, Alessia, Barus, Henry, Brace, Selina, Brauwer, Maarten de and others (2022) Safeguarding imperiled biodiversity and evolutionary processes in the Wallacea center of endemism. BioScience, 72 (11). pp. 1118-1130. ISSN 0006-3568.

Downloaded from

<https://kar.kent.ac.uk/96640/> The University of Kent's Academic Repository KAR

The version of record is available from

<https://doi.org/10.1093/biosci/biac085>

This document version

Author's Accepted Manuscript

DOI for this version

Licence for this version

UNSPECIFIED

Additional information

For the purpose of open access, the author(s) has applied a Creative Commons Attribution (CC BY) licence to any Author Accepted Manuscript version arising.

Versions of research works

Versions of Record

If this version is the version of record, it is the same as the published version available on the publisher's web site.
Cite as the published version.

Author Accepted Manuscripts

If this document is identified as the Author Accepted Manuscript it is the version after peer review but before type setting, copy editing or publisher branding. Cite as Surname, Initial. (Year) 'Title of article'. To be published in **Title of Journal**, Volume and issue numbers [peer-reviewed accepted version]. Available at: DOI or URL (Accessed: date).

Enquiries

If you have questions about this document contact ResearchSupport@kent.ac.uk. Please include the URL of the record in KAR. If you believe that your, or a third party's rights have been compromised through this document please see our [Take Down policy](https://www.kent.ac.uk/guides/kar-the-kent-academic-repository#policies) (available from <https://www.kent.ac.uk/guides/kar-the-kent-academic-repository#policies>).

SAFEGUARDING IMPERILED BIODIVERSITY AND EVOLUTIONARY PROCESSES IN THE WALLACEA CENTER OF ENDEMISM

	<u>AUTHOR</u>	<u>MAIN AFFILIATION</u>	<u>EMAIL</u>
1	Matthew Struebig*	Durrell Institute of Conservation and Ecology (DICE), University of Kent, Canterbury CT2 7NR, UK	M.J.Struebig@kent.ac.uk
2	Sabhrina Gita Aninta*	School of Biological and Behavioural Sciences, Queen Mary University of London, E1 4NS, UK	s.g.aninta@qmul.ac.uk
3	Maria Beger	School of Biology, University of Leeds, Leeds, LS2 9JT, UK	M.Beger@leeds.ac.uk
4	Alessia Bani	School of Life Sciences, University of Essex, Wivenhoe Park, Colchester, CO4 3SQ, UK	ab18858@essex.ac.uk
5	Henry Barus	Agriculture Faculty of Tadulako University, Jl. Soekarno Hatta km 09, Tondo, Palu 94118	henbarus@hotmail.com
6	Selina Brace	Department of Earth Sciences, Natural History Museum, London, UK, SW7 5BD	S.Brace@nhm.ac.uk
7	Zoe Davies	Durrell Institute of Conservation and Ecology (DICE), University of Kent, Canterbury CT2 7NR, UK	z.g.davies@kent.ac.uk
8	Maarten De Brauwer	School of Biology, University of Leeds, Leeds, LS2 9JT, UK	Maarten.Debrauwer@csiro.au
9	Karen Diele	Centre for Conservation and Restoration Science, School of Applied Sciences, Edinburgh Napier University, Edinburgh EH11 4BN, UK	k.diele@napier.ac.uk
10	Cilun Djakiman	Maritime and Marine Science Center of Excellence, Pattimura University, Indonesia	cilun.djakimann@gmail.com
11	Rignolda Djamaluddin	Faculty of Fishery and Marine Science, Sam Ratulangi University, Indonesia	rignolda@unsrat.ac.id
12	Rosie Drinkwater	School of Biological and Behavioural Sciences, Queen Mary University of London, E1 4NS, UK	r.drinkwater@qmul.ac.uk
13	Alex Dumbrell	School of Life Sciences, University of Essex, Wivenhoe Park, Colchester, CO4 3SQ, UK	adumb@essex.ac.uk
14	Darren Evans	School of Natural and Environmental Sciences, Newcastle University, Newcastle Upon Tyne, NE1 7RU UK	Darren.Evans@newcastle.ac.uk
15	Marco Fusi	Centre for Conservation and Restoration Science, School of Applied Sciences, Edinburgh Napier University, Edinburgh EH11 4BN, UK	M.Fusi@napier.ac.uk
16	Leonel Herrera-Alsina	School of Biological Sciences, University of Aberdeen, Aberdeen, UK	leonel.herreraalsina@abdn.ac.uk
17	Djoko Iskandar	School of Life Sciences and Technology, Institut Teknologi Bandung, Indonesia	iskandar@sith.itb.ac.id
18	Jamaluddin Jompa	Faculty of Marine Science and Fisheries, Universitas Hasanuddin, Makassar, South Sulawesi, Indonesia	jamaluddin.jompa@gmail.com
19	Berry Juliandi	Department of Biology, Bogor Agricultural Institute, Bogor, 16680, Indonesia	bjuliandi@apps.ipb.ac.id
20	Lesley T. Lancaster	School of Biological Sciences, University of Aberdeen, Aberdeen, AB24 2TZ, UK	lesleylancaster@abdn.ac.uk

21	Gino Limmon	Department of Marine Science, Pattimura University, Ambon, Indonesia	gino.limmon@gmail.com
22	Lindawati	Department of Chemical and Green Process Engineering, Surya University, Tangerang, Indonesia	lindawati@surya.ac.id
23	Michaela Lo	Durrell Institute of Conservation and Ecology (DICE), University of Kent, Canterbury CT2 7NR, UK	mgyl2@kent.ac.uk
24	Pungki Lupiyaningdyah	Research Center for Biosystematics and Evolution, National Research and Innovation Agency (BRIN), Cibinong, West Java, 16911, Indonesia	pungkilupi@gmail.com
25	Molly McCannon	School of Biology, University of Leeds, Leeds, LS2 9JT, UK	mollymccannon@hotmail.co.uk
26	Erik Meijaard	Borneo Futures, 8th Floor, PGGMB Building, Jalan Kianggeh, Bandar Seri Begawan BS8111, Brunei Darussalam	e.meijaard@gmail.com
27	Simon Mitchell	Durrell Institute of Conservation and Ecology (DICE), University of Kent, Canterbury CT2 7NR, UK	simonleomitchell@gmail.com
28	Sonny Mumbunan	Research Center for Climate Change, Gedung Lab Multidisiplin, 7 th floor, Universitas of Indonesia, Jalan Margonda, Depok 16242, Indonesia	mumbunan@gmail.com
29	Darren O'Connell	School of Biology and Environmental Science, University College Dublin, Dublin D04 N2E5, Ireland	darren.oconnell@ucd.ie
30	Owen Osborne	Molecular Ecology and Evolution Bangor, Environment Centre Wales, Bangor University, Bangor, UK, LL57 2UW	o.osborne@bangor.ac.uk
31	Alex Papadopoulos	Molecular Ecology and Evolution Bangor, Environment Centre Wales, Bangor University, Bangor, UK, LL57 2UW	a.papadopoulos@bangor.ac.uk
32	Joeni S. Rahajoe	Research Center for Ecology and Etnobiology, National Research and Innovation Agency (BRIN), Cibinong, 16911, West Java, Indonesia	srjoeni@gmail.com
33	Rosaria	Department of Biology, University of Oxford, Oxford, UK	rosaria.rosaria@ox.ac.id
34	Stephen Rossiter	School of Biological and Behavioural Sciences, Queen Mary University of London, E1 4NS, UK	s.j.rossiter@qmul.ac.uk
35	Rugayah	Herbarium Bogoriense, National Research and Innovation Agency (BRIN), Cibinong, 16911, West Java, Indonesia	titikrugayah@yahoo.com
36	Himmah Rustiami	Herbarium Bogoriense, National Research and Innovation Agency (BRIN), Cibinong, 16911, West Java, Indonesia	hrustiami@gmail.com
37	Ulrich Salzmann	Department of Geography and Environmental Sciences; Northumbria University, Newcastle upon Tyne, NE1 8ST, UK	ulrich.salzmann@northumbria.ac.uk
38	Sheherazade	PROGRES (Sulawesi Regional Ecological Conservation Initiative), Jl. Hos Cokroaminoto No. 7, Luwuk Banggai, Central Sulawesi, Indonesia	sheherazade.jayadi@gmail.com
39	I Made Sudiana	Research Center for Applied Microbiology, National Research and Innovation Agency, Cibinong Km 46, Indonesia	imad003@brin.go.jp
40	Endang Sukara	Graduate School, Universitas Nasional (UNAS), Jl. Sawo Manila No 61, Pejaten Pasar Minggu, South Jakarta 12520 Indonesia	endangsukara@gmail.com

41	Johny S. Tasirin	Department of Forest Sciences, Universitas Sam Ratulangi, Manado, Indonesia	jtasirin@unsrat.ac.id
42	Aiyan Tjoa	Agriculture Faculty of Tadulako University, Jl. Soekarno Hatta km 09, Tondo, Palu 94118	aiyenb@yahoo.com
43	Justin Travis	School of Biological Sciences, University of Aberdeen, Aberdeen, UK. AB242TZ.	justin.travis@abdn.ac.uk
44	Liam Trethowan	Herbarium Kew, Royal Botanic Gardens Kew, London, TW93AE	l.trethowan@kew.org
45	Agus Trianto	Department of Marine Science, Universitas Diponegoro, Central Java, Indonesia	agustrianto.undip@gmail.com
46	Tim Utteridge	Herbarium Kew, Royal Botanic Gardens Kew, London, TW93AE	t.utteridge@kew.org
47	Maria Voigt	Durrell Institute of Conservation and Ecology (DICE), University of Kent, Canterbury CT2 7NR, UK	M.Voigt@kent.ac.uk
48	Nurul Winarni	Research Center for Climate Change, Gedung Lab Multidisiplin, 7 th floor, FMIPA-Universitas of Indonesia, Jalan Margonda, Depok 16242, West Java, Indonesia	nwinarni@gmail.com
49	Zulianto Zakaria	Department of Biology, Gorontalo University, Gorontalo city, Sulawesi, Indonesia	zuliyanto_zakaria@ung.ac.id
50	David Edwards	School of Biosciences, University of Sheffield, Sheffield, S10 2TN, UK	david.edwards@sheffield.ac.uk
51	Laurent Frantz	School of Biological and Behavioural Sciences, Queen Mary University of London, E1 4NS, UK	laurent.frantz@qmul.ac.uk
52	Jatna Supriatna	Research Center for Climate Change, Gedung Lab Multidisiplin, 7 th floor, FMIPA-Universitas of Indonesia, Jalan Margonda, Depok 16242, West Java, Indonesia	jatna.supriatna@gmail.com

* Matthew J. Struebig and Sabhrina G. Aninta contributed equally as co-lead authors to this work.

ABSTRACT

Wallacea - the meeting point between the Asian and Australian fauna - is one of the world's largest centers of endemism. Twenty-three million years of complex geological history have given rise to a living laboratory for the study of evolution and biodiversity, highly vulnerable to anthropogenic pressures. Here we review the historic and contemporary processes shaping Wallacea's biodiversity and explore ways to conserve its unique ecosystems. While remoteness has spared many Wallacean islands from the severe overexploitation that characterizes many tropical regions, industrial-scale expansion of agriculture, mining, aquaculture and fisheries is damaging terrestrial and aquatic ecosystems, denuding endemics from communities, and threatening a long-term legacy of impoverished human populations. An impending biodiversity catastrophe demands collaborative actions to improve community-based management, minimize environmental impacts, monitor threatened species and reduce wildlife trade. Securing a positive future for Wallacea's imperiled ecosystems requires a fundamental shift away from managing marine and terrestrial realms independently.

Islands offer fascinating insights into the world's evolutionary processes. Perhaps nowhere is this more evident than the archipelagos of Wallacea where the Asian and Australasian biogeographic regions collide. Wallacea, comprising the islands of Sulawesi, the Moluccas and Lesser Sunda in Indonesia and Timor Leste, supports the highest levels of endemism worldwide (Mittermeier et al. 2011), including 62 endemic vertebrate genera and iconic oddities such as the babirusa (*Babirousa* spp.), maleo (*Macrocephalon* spp.), and komodo dragon (*Varanus komodoensis*). Recognizing that the fauna was so strikingly different from that of neighboring Borneo and Papua, 19th Century naturalist Alfred Russel Wallace changed the course of evolutionary theory by delineating what ultimately became a distinct biogeographic region (figure 1). Although the bounds of Wallacea have at times included other islands, it is the central transition zone between the Sahul and Sunda land masses in Indonesia that has long captured scientific attention (Lohman et al. 2011, Ali and Heaney 2021).

With new marine and terrestrial species discoveries still occurring across the region, the importance of Wallacea as a treasure trove of biodiversity is increasingly evident (Rheindt et al. 2020, Esselstyn et al. 2021). Nonetheless, Wallacea's ecosystems face considerable pressure from a growing human population (33.7 million people in 2021; <https://www.bps.go.id/>). Economic development and people's livelihoods have largely centered on the exploitation of the region's natural resources, yet the consequences of mining, forestry, agriculture, hunting, tourism, and fisheries for biodiversity, and particularly the endemics that make Wallacea so unique, are concerning. Here, we review the historic and contemporary processes shaping Wallacea's unique ecosystems and explore ways to conserve its hyperdiversity.

Wallacea: a natural laboratory for the study of evolution

The abrupt biogeographic transitions of the Wallacean fauna, as demarcated by Wallace's Line to the west and Lydekker's Line to the east, are the result of long-term isolation of the archipelago from Asia and Australasia, respectively (Lohman et al. 2011, Ali and Heaney 2021). Faunal migration and speciation were shaped by a complex geological history, involving rifting of the Makassar Strait during the Eocene, collisions of Sunda margins with the Australian continent during the Miocene, and tectonic movement during the early Neogene (Hall 2013). While most of the small islands in the southeast, as well as Timor and Seram, emerged around five million years ago (Mya), the largest island Sulawesi originally formed as a series of smaller land masses that only amalgamated into its current form around 1 Mya (Vaillant et al. 2011, Hall 2013, Nugraha and Hall 2018). This merger created distinct volcanic ridges, mountains and ancient lakes that characterize the island today. Although the formation of Sulawesi as a single island is relatively recent, deep ocean trenches to the east and west have separated it, as well as the wider Wallacea region, from the Sunda and Sahul continental shelves throughout the past 23 million years (Hall 2013).

This complex geological history and subsequent diverse environments makes Wallacea a natural laboratory for testing the roles of dispersal, geographic isolation, and adaptation in driving evolution, speciation and ecological diversification. The evolutionary history of the many endemic species that are found in the region's terrestrial and freshwater ecosystems (figure 2) illustrate well how the rise and fall of geological barriers can promote the evolution of species (tables S1, S2). The ancestors of many endemic lineages arrived long after the region became isolated from Asia and Australia in the Eocene (Stelbrink et al. 2012), indicating that migration through rafting and

island hopping likely played a strong role in the assembly of Wallacea's unique terrestrial ecosystems. There are now more than 120 endemic fishes (e.g. Telmatherininae, sail-fin silversides) and invertebrates (e.g. *Tylomelania* snails and *Syntipsa* crabs) that have subsequently diversified in Sulawesi's ancient lakes, and colonization and isolation in montane regions have triggered further speciation in mammals (*Crocidura*), frogs (*Limnonectes*) and plants (*Cyrtandra*) (table S2). While Wallacea covers less than 2% of the world's oceans, its marine ecosystems contain ~76% of the world's hard coral species and >2000 shallow non-cryptic coral reef fishes (Veron et al. 2009).

In some taxa, populations and species likely diversified in isolation on separate paleo-islands, perhaps with occasional dispersal across the paleo-archipelago. Subsequent periods of large-scale uplift over the past four million years (Nugraha and Hall 2018) had further impacts on biodiversity by connecting previously separated regions (Frantz et al. 2018). Indeed, this uplift may have reunited previously isolated (sub)species of terrestrial taxa, including tarsiers, shrews, macaques, snails, frogs, lizards, crickets, and damselflies (table S3), generating distinctive phylogeographic patterns (figure 3), and some generalized zones of terrestrial endemism (Michaux 2010; figures 1 and 2, table S1). Yet, there are many lineages that buck these trends. For example, many freshwater lineages (e.g. *Tylomelania* snails *Caridina* shrimps, Gecarcinucid crabs and Telmatherinid fish) have undergone adaptive radiations in the island's ancient lake systems (von Rintelen et al. 2012), and plant diversification (e.g. *Cyrtandra* and *Nepenthes*) may be more heavily influenced by soil types, elevation, and other ecological barriers (Bouchenak-Khelladi et al. 2015).

Wallacea's complex geological history, combined with its location and the extent of its coastline at the confluence of the Pacific and Indian Oceans, also promoted the evolution of exceptionally biodiverse coastal marine ecosystems (Tittensor et al. 2010, Wicaksono et al. 2017). The archipelagos of the region lie in the center of the Coral Triangle, the global epicentre for marine diversity including corals, fishes, and mollusks (Veron et al 2009). Different biogeographical hypotheses have been proposed for how this high biodiversity came to be (Veron et al. 2009; Huang et al. 2017). The region's unstable tectonic environment continually creates diverse shallow habitats. During past sea level changes, these often remained connected to deep water, creating refuges that formed both a buffer from extinction as well as opportunities for divergent evolution of endemic species. The consistent movement of water and eddies created by the Indonesian throughflow ocean current increases the chance of subsequent larval dispersion at different rates across geological timescales (e.g. Linsley et al. 2010).

Wallacea's paleontological record bears witness to these complex evolutionary processes and to the emergence of large numbers of island endemics (figure 2). While less is known about Wallacea's fossil record compared to that of neighboring Java, the oldest terrestrial fauna recorded (~2.5 Mya) from south Sulawesi includes giant suids (*Celebochoerus*), giant tortoises (*Geochelone atlas*), and two dwarf elephants (*Elephas celebensis* and *Stegodon sompoensis*) (van den Bergh et al. 2001). Most of these megafauna became extinct at the end of the Pleistocene or the early Holocene. The paleontological record is also rich in hominid (non-*Homo sapiens*) fossils and artifacts, which first appeared in the Pleistocene ca. 1 Mya (van den Bergh et al. 2001). Given that the region was never connected via a land-bridge to neighboring continental shelves, these hominids would have had to complete sea-crossings across treacherous waters to reach Wallacean

islands with limited technologies, most likely from Borneo (Shipton et al. 2020). Wallacea was likely inhabited by at least two early hominid species, including *Homo floresiensis* and, potentially, *Homo erectus* (van den Bergh et al. 2001), both of which disappeared by the end of the Pleistocene, together with other megafauna (Sutikna et al. 2018). Archeological evidence for the presence of modern humans (*Homo sapiens*) indicated that they may have lived on Wallacean islands around ~50-30 thousand years ago (Shipton et al. 2020), with evidence of their activities including some of the earliest prehistoric cave paintings dated to at least 40,000 ya (Brumm et al. 2021).

The activities of hominins, including modern humans, likely had a strong impact on the region for thousands of years. Even prior to the introduction of farming, at least 40 taxa were thought to have been translocated across Southeast Asia to Wallacean islands, including game species such as deer, pig, buffalo, and junglefowl (Heinsohn 2003). These translocations likely increased with the arrival of modern humans in the archipelago (Kealy et al. 2017), probably for hunting stock or ceremonial purposes. The process further intensified with the introduction of domesticated taxa, including pigs, dogs, and chickens, which then became feral during the expansion of farming cultures from mainland Asia (Piper 2017).

Contemporary human pressures

More than 160 years after Wallace wrote of the rich marine diversity of Ambon, the coast of this Moluccan island has been dredged, overfished, and polluted (Limmon and Marasabessy 2019). This provides just one example of the multiple stressors that have impacted Wallacean environments in recent decades. Yet the remoteness of Wallacea, especially its eastern islands, has

spared much of the region from the severe overexploitation of marine, freshwater and terrestrial ecosystems characteristic of other parts of Southeast Asia. For instance, the rugged interior forests of most Wallacean islands remain relatively intact (Voigt et al. 2021), having avoided the pervasive conversion to large-scale plantations typical of western Indonesia, Malaysia, and southern Thailand. Indeed, between 2001 and 2019 the annual deforestation rate across Wallacea (0.39%) was half of that of neighboring Borneo (0.76%) and a quarter of that of Sumatra (1.52%) (Gaveau et al. 2022) (figure 1), reflecting the continued dominance of small-scale farming and agroforestry over large-scale extractive industries (figure 4, figure 5). Compared to industrial agriculture, these low-intensity farmlands support high species diversity, especially when close to forest and where habitat heterogeneity and canopy cover is maximized (Waltert et al. 2011). Nonetheless, forest specialists and endemic species are disappearing from these communities, often being replaced by wide-ranging generalists following a process of biotic homogenization across the archipelago (Maas et al. 2009, Mitchell et al. 2022).

A deforestation surge over the last ten years, primarily in Central Sulawesi and northern Maluku, has been linked to the expansion of mining and industrial oil palm plantations (Supriatna et al. 2020). While the region's oil palm industry is at an early stage, mineral extraction has rapidly expanded since 2010 following a new mining governance regime in Indonesia. This led to more than 95% of the country's nickel coming from Wallacean islands (mainly Sulawesi and Halmahera), and around half of its gold (figure 4). Elsewhere, key agricultural commodities, such as coconut and cacao (figure 4), have resulted in small-scale but widespread encroachment of forest areas (Supriatna et al. 2020, Voigt et al. 2021), while mangroves have been replaced by commercial shrimp farms (Richards and Friess 2016, Malik et al. 2016).

Land-cover changes also leave Wallacea's islands particularly susceptible to ecological invasion. Human-mediated establishment of invasive species can occur by either facilitating dispersal across islands after natural arrival or introducing those species from elsewhere. For example, genetic analyses suggest seven amphibian and reptile taxa that are now widespread in human settlements and croplands of the Lesser Sundas colonized these islands relatively recently (<100 years) (Reilly et al. 2019). Invasion of the poisonous Asian common toad (*Duttaphrynus melanostictus*) is a key concern since the species has benefited from the absence of toads in the region and expanded quickly throughout. The large snakes and varanid lizards at the top of Wallacea's food chains are particularly susceptible to poisoning from eating this prey, since as naïve predators they are incapable of processing the toad's toxins (Reilly et al. 2017). Sulawesi's lake ecosystems have also been adversely affected by introduced species, including flowerhorn cichlids, nile tilapia, and common carp (Serdiati et al. 2021). For example, in Matano, one of South Sulawesi's ancient lakes, adult flowerhorn cichlids prey upon native fish and invertebrates endemic to this ancient lake (Hilgers et al. 2018). In Central Sulawesi's Lake Poso, this predation and competition is so severe that the number of non-native fish species (17) now exceeds the native fish fauna (13) (Herder et al. 2022).

The infrastructure development that often accompanies deforestation has facilitated hunting and wildlife trade throughout Wallacea, which is challenging to counter in more remote islands where patrols, communication, and enforcement are weak. Wild meat is routinely sold in markets and supermarkets in North Sulawesi, for example, and ca. 500 metric tons of bats are imported to the province annually from across the island (Sheherazade and Tsang 2015). Egg collection of Sulawesi's famed maleo birds (*Macrocephalon maleo*) has led to a rapid

abandonment of nesting grounds and the species elevated to Critically Endangered status by the IUCN (<https://www.iucnredlist.org/species/22678576/194673255>). In Maluku, trade in endemic birds for the pet and songbird trade is prolific, having caused an 80% crash in salmon-crested cockatoo (*Cacatua moluccensis*) populations in a decade (<https://www.iucnredlist.org/species/22684784/93046425>). Since Wallacea is characterized by relatively few large-bodied terrestrial vertebrates, unsustainable extraction levels disproportionately impact a small set of these highly threatened species (Scheffers et al. 2019).

Landscape change and overexploitation have important ramifications for Wallacea's aquatic ecosystems. Hydroelectric dams and mining pose huge threats to the integrity and functioning of freshwaters, culminating in Sulawesi ancient lakes (von Rintelen et al. 2012). A gold rush in North Sulawesi, for example, led to elevated mercury concentrations in nearby rivers and high bioaccumulation in fish (Limbong et al. 2003). Run-off from agricultural practices and urbanization has reduced downstream water quality in Ambon Bay to the extent that the sediment load smothers corals and has shifted reef communities towards sediment-tolerant species (Limmon and Marasabessy 2019). Pollution of the marine environment tends to be stronger close to major population centers, such as Makassar and Manado in Sulawesi, which also attract substantial fishing pressure. In contrast, the eastern islands of Maluku are less exposed to commercial fisheries, but artisanal fishing is widespread, and impacts are poorly understood. Many of these islands still host the highest reef fish biomass in Indonesia (Campbell et al. 2020). However, broad-scale, destructive fishing practices are evident even in remote reefs, leaving a long-term legacy of damaged reef structure and overexploited populations (e.g. overfishing of Endangered Banggai

Cardinalfish, *Pterapogon kauderni* for the aquarium trade,
<https://www.iucnredlist.org/species/63572/12692964>).

Climate change further threatens Wallacean biodiversity, with at least two recent coral bleaching and mortality events degrading structural coral habitats, fisheries, and thus income opportunities (Moore et al. 2017). The reefs around Buton and Spermonde islands off Sulawesi, for instance, show a community shift from a dominance of branching corals (e.g. *Acropora* spp.) towards more heat-tolerant species (Yusuf and Jompa 2012). Climate change also pushes terrestrial species outside of their thermal optima, changing phenology and seasonality that could drive transitions towards savanna (Siyum 2020), making dry forest ecosystems of the Lesser Sunda islands (e.g. Sumbawa, Flores; Box 1) particularly vulnerable. In the absence of adaptation or behavioral and phenological changes, species will have to move to track their thermal envelopes, and much of that movement on Wallacea's rugged and convoluted islands is expected to be upslope (Harris et al. 2014). While this high landscape complexity provides potential refuge areas that may help buffer some species against the most adverse impacts of climate change (Trew and Maclean 2021), the high numbers of species endemic to single islands or small island chains means that the potential for mountaintop extinctions is high should these refuges prove insufficient. This is particularly concerning for species with limited dispersal capabilities or those highly dependent on intact habitat or water resources on drier and more seasonal islands in the east. These issues point towards the need for integrated land and coastal management to retain connectivity of protected forests, mangroves, and coral reefs across thermal gradients.

Wallacea at a crossroads

Sustainable use of natural resources is needed to ensure biodiversity, evolutionary processes, and ecosystem functioning are maintained, while accounting for rapidly growing human pressures and accelerating climate change. The situation is further exacerbated in Wallacea by incentivizing development policies that encourage unsustainable practices in agriculture, mining, and fisheries, and thus the continued overexploitation of terrestrial and marine ecosystems. On the one hand, low-intensity cultivation tends to have fewer major impacts on the local environment relative to large-scale agriculture (Waltert et al. 2011), and deforestation has been much slower in Wallacea than in other regions as a result (Voigt et al. 2021). On the other hand, the income potential of these livelihoods is often insufficient, making some parts of Wallacea (e.g. Maluku, Gorontalo in Sulawesi, and East Nusa Tenggara) among the poorest in Indonesia, while those that are better oriented to market-based livelihoods (e.g. North and South Sulawesi) prosper (<https://www.bps.go.id/>; figure 4). Forested landscapes are often poorly suited to farming, with limited transportation and infrastructure networks, leaving residents facing high costs to access markets, education, and healthcare (Angelsen et al. 2014). Coastal communities face similar challenges with accessing markets and social facilities, particularly on isolated islands. These considerations, combined with weak law enforcement, mean that solutions to Wallacea's emerging biodiversity crisis are not as simple as lobbying for further habitat protection.

Currently, only 9% of Wallacea's land and 3% of its marine zone is formally protected for biodiversity conservation (figure 1; <https://www.protectedplanet.net/country/IDN>), although Indonesia has ambitious targets for protected area expansion by 2030. Similarly, while formally protected terrestrial reserves have curbed deforestation in endemic-rich areas (Voigt et al. 2021), they are limited in Buru and Flores, and many of the smaller islands. Protected areas, particularly

marine ones, face many logistic, managerial, and funding challenges to be effective (Kamil et al. 2017). Moreover, expanding strictly protected areas places substantial burdens on natural resource users, and are often viewed as threatening livelihoods, despite, for instance, the need for no-take zones to support sustainability of fisheries (Mills et al. 2010). It is therefore imperative to work with local communities when establishing protected areas or other conservation interventions. Much of the current conservation activity in Wallacea focuses around protected areas and where international non-governmental organizations operate. Diversifying conservation resources, as well as increasing them, will help empower grassroots organizations and multiple stakeholders so that conservation could be more locally led.

Community-based management has a long history on land and at sea, and in Indonesia is manifested as highly localized customary *adat* practices. Since 2015, these customary rights have been embodied within Indonesia's social forestry program and extended to other local communities, regardless of cultural or ethnic background. Among the multiple social forestry schemes available, those that permit some limited timber extraction and agroforestry for local use can help improve social welfare while minimizing deforestation (Rakatama and Pandit 2020). However, uptake across the Wallacean region has been slow relative to the western islands of Indonesia (Santika et al. 2019). Correspondingly, marine community-based management (e.g. Territorial Use Rights in Fisheries) typically allows some resource extraction and can achieve sustainable fish biomass. Culturally embedded conservation practices of the sea or land in Maluku pertain to local dynamic closures that prohibit and allow fishing. Contextualizing these practices within traditional marine tenure and belief systems —*sasi*—has been effective in reducing overfishing (Halim et al. 2020).

Community involvement and local leadership are also vital for restoring ecosystem function and diversity. Some of the best examples come from the coastal-marine zone, where communities have been instrumental in restoring reefs and mangroves, albeit after many failed attempts (Box 2). On land, Indonesia also pioneered the use of ecosystem restoration licenses through which degraded forests are leased by the government for restoration-compatible business development (Harrison et al. 2020). Licenses are granted typically for 60-100 years, allowing activities such as conservation, ecotourism, management of non-timber forest products, and tree protection for carbon sequestration. Once legally harvestable timber volumes have been restored and environmental safeguards met, a license-holder may log the forest. Around one third of Indonesia's ecosystem restoration licenses (4,325,649 ha by 2020, <https://phl.menlhk.go.id/tabular>) are so far allocated for the Wallacea region, with most of these located in Sulawesi and Maluku.

Conclusions and future research directions

There remains immense potential for emerging scientific and technological tools to further document, monitor, and help prioritize Wallacea's unique and imperiled biodiversity for conservation actions. For example, combining traditional morphological analyses with bioacoustic, genetic, and genomic data led to the description of 12 new bird taxa from Sulawesi's satellite islands, more than double the number typically described per year globally (Rheindt et al. 2020, O'Connell et al 2019). Molecular methods, including environmental DNA (eDNA), and large-scale collaborations to catalog the genetic code of thousands of organisms are also facilitating a revolution in biodiversity monitoring. This is particularly notable in coastal

ecosystems where microbial surveys in sediment and water help assess their roles in ecosystem functioning (DiBattista et al. 2020) and conservation (Bani et al. 2020). The science of restoration is also being served by population genomic and ‘meta-omic’ approaches, which can be used to reveal new genotypes and the potential for genetic biocontrol of pest populations as well as for monitoring purposes (Breed et al. 2019). It is now possible to construct highly resolved food webs, moving beyond the study of specific plants or animals, towards a holistic understanding of direct and indirect species-interactions that links biodiversity with ecosystem functioning (O’Connell et al. 2022).

As well as taking full advantage of scientific advances, there needs to be a fundamental shift away from managing marine, freshwater and terrestrial realms independently. This can lead to inefficiencies and inaction, particularly where interactions and threats occur between ecosystems, such as the influence of land-use change on coastal sediment exposure (Beger et al. 2010). Taking a ‘ridge-to-reef’ approach should lead to lower opportunity costs and improved outcomes for conservation in Wallacea. To be future-proof, land-use and conservation planning should also ensure these ecosystems, and the endemic biodiversity they support, are climate resilient (Struebig et al. 2015, Dixon et al. 2021).

Scenario planning with multiple, diverse groups of stakeholders, where a range of ‘what if’ future land-use/marine-use scenarios are explored, can be helpful in identifying and understanding different viewpoints, key knowledge gaps, and the nature of interactions between inputs and outcomes (e.g. do tipping points exist beyond which ecological recovery is unlikely?). While research can only approximate complex and non-linear interactions, it can help to avoid inappropriate policy/practice decisions. Other sources of knowledge, such as views on traditional

management practices, can also help steer landscape/seascape planning in a direction where people with the greatest role in implementing sustainable practices (i.e. Wallacea's vast and growing rural communities) are given a voice regarding managing their local ecosystems. Indonesia's national planning processes now incorporate scenario tools, and there are moves to expand this to sub-national development planning, starting with Sulawesi (Bappenas 2019).

As poverty remains a major driver of unsustainable natural resource use in Wallacea, this needs to be tackled head on. We need a much better grasp of what evidence and which decisions underpin optimal outcomes for community wellbeing, ensuring that socio-economic gains from the region's development are not undermined by socio-ecological losses. For example, the oil palm industry, still in its infancy in Wallacea, has largely helped improve living standards elsewhere in Indonesia, but also resulted in social conflict and pollution (Santika et al. 2021). There is huge scope for Indonesia's mining boom to follow the same trajectory if environmental and social safeguards are not adequately followed. While government requires all mining permit holders to follow good mining principles and plan for post-mining reclamation before they can begin operations, land reclamation is ecologically challenging and mostly oriented towards restoring soils and basic vegetation (Pratiwi et al. 2021). Minimizing the ecological footprint and engaging nearby communities in the first place (e.g. by optimizing land-use planning using the High Conservation Value approach, <https://www.hcvnetwork.org/>) is clearly a more cost effective strategy to minimize the impacts of mines and maximize the benefits they bring (Budiharta et al. 2018). Improved monitoring and evaluation of mining and post-mining operations are needed, to help identify best management practices that can be promoted broadly across the country. After all, Wallacea's central role producing the nickel needed to help the global transition to low carbon

technologies should bring investments that benefit local communities, and not the land disputes and environmental damage reported from some sites (Hudayana et al. 2020).

As part of these efforts, community-based and locally led approaches that have been effective elsewhere in Indonesia (Santika et al. 2019) should be further promoted in Wallacea, with communities empowered to derive sustainable livelihoods from these schemes and contribute to conservation. For instance, terrestrial and marine wildlife tourism is already an important source of income for Wallacean communities on Komodo island (Ardiantiono et al. 2018) and in North Sulawesi (Towoliu 2014). In Bangka Island, North Sulawesi, the combined actions of local communities and tourism operators successfully stopped illegal mining activities in favor of sustainable jobs and subsistence fishing (Kalalo 2019). However, tourism is not without challenges as excessive diving also affects reef conditions (Towoliu 2014). Likewise, a key need for Wallacea's terrestrial and marine community-managed areas will be to evaluate sustainable extraction rates and integrate these appropriately in management plans alongside incentives and rewards for sustainable activities. For example, maleo numbers experienced a population recovery in Tompotika, Central Sulawesi after villages were engaged by local conservationists and received community benefits (financial and non-financial) in exchange for ceasing egg poaching (Tasirin et al. 2021).

While Ecosystem Restoration Licenses appear to be a promising tool, the high costs of restoration have yet to be sufficiently offset via harvestable products, carbon markets, or other payments for ecosystem service schemes (Harrison et al. 2020). The success of Ecosystem Restoration Licenses could be improved if ecosystem services (e.g. carbon, biodiversity, water) were adequately valued and the payments were allocated fairly. Ensuring that payments reach

people closest to and most dependent upon ecosystem services remains politically challenging. However, Indonesia's government has taken steps in the right direction through its recognition of traditional land and natural resource use rights, and a willingness to transfer management rights from the state to rural communities (Rakatama and Pandit 2020). Clear rights and appropriate rewards may provide people with the security that prevents short-term over-exploitation of resources to protect longer-term benefits. Without such changes in thinking, the environmental costs of natural resource management in Wallacea, as elsewhere in the World, will ultimately negate most socio-economic gains.

Box 1: Characterizing the forests of Wallacea

Mapping and monitoring forests is essential for countries to meet their sustainability commitments, such as conserving biodiversity and ecosystem processes and tackling climate change (e.g. Bappenas 2019). Yet monitoring the fate of Wallacea's forests is surprisingly difficult, even with advances in remote sensing. In 2018 the islands of Sulawesi, Maluku, and Nusa Tenggara comprised 141,080 km² of forest according to Global Forest Change data, a reduction of 10,231 km² since 2000 (Voigt et 2021). However, like any mapping assessment (e.g. Austin et al. 2019), this coverage remains prone to error because of ongoing challenges in distinguishing forest from regrowth and forest-like vegetation, particularly agroforestry (e.g., Sulawesi, Halmahera and Seram; figure 6a,b). This is compounded in the islands of southern Maluku and Nusa Tenggara where the tropical moist forests characteristic of equatorial Southeast Asia become much drier seasonal ecosystems (figure 6c). Because seasonal forests have different spectral properties to tropical forests, their extent is likely underestimated in large-scale mapping assessments that rely solely on standard forest definitions (Staver et al. 2011).

The islands of the Lesser Sundas (i.e. Nusa Tenggara) lie within a climatic zone that could support both dry forest and savanna (Staver et al. 2011). The flora are tolerant to drought and the fauna are somewhat adapted to the phenology of these predominantly-deciduous forests. Unlike savanna, seasonal forests of Nusa Tenggara comprise a closed canopy and no grass layer (Pennington et al. 2018) (figure 6d). Baseline taxonomic knowledge of Wallacea's seasonal forests lags far behind similar ecosystems in the American tropics, where plant diversity is known to rival that of Amazonia's prominent wet tropical forests (Pennington et al. 2018).

Current estimates suggest around 300 plant species endemic to the Lesser Sundas can be found in Nusa Tenggara's seasonal forest, but this list continues to grow (e.g. Sunarti et al. 2022).

Key threats to Wallacea's seasonal forests include mining and encroachment from small-scale agriculture (Voigt et al. 2021; Austin et al. 2019), as well as highly-localized collection of firewood, timber, plants and wildlife (figure 6e,f). While in tropical Southeast Asia agricultural plantings tend to be long-term cash crops, the low rainfall of the Lesser Sunda islands limits irrigation. Seasonal forests thus tend to be replaced by rotating cultivation systems, which over time may return to forest vegetation (Monk et al. 1996). Unfortunately, the dry local climate makes seasonal forests highly vulnerable to these activities. A single stressor – such as fire used to clear land – can rapidly alter the stable state of forest to that of savanna. While both savanna and seasonal forest plants can cope with drought, differences in fire regimes between these two ecosystems mean they support fundamentally different species (Pellegrini et al. 2021). Seasonal forest plants tend to be highly intolerant to fire, meaning that any switches to savanna are less reversible, thus posing a great risk in the highly threatened seasonal forests of Nusa Tenggara.

Box 2: Restoring Wallacea's blue ecosystems

Wallacea has among the highest mangrove, seagrass and coral biodiversity and biomass globally (Veron et al. 2009, Alongi et al. 2016), providing extensive ecosystem services. Yet these 'blue' ecosystems face unprecedented pressures as aquaculture and farmland replace mangroves, disruptive fishing techniques and tourism affect seagrass meadows and reefs, and ocean warming kills corals. These pressures have impacted commercially important fisheries, increased erosion, decreased coastal stabilization, and reduced water quality (Camp et al. 2016), substantially degrading valuable ecosystem services.

Mangrove restoration programs involving monospecific plantations often fail due to a poor choice of foundation species and/or lack of hydrological restoration. However, in Wallacea, the government, businesses, NGOs and local communities have had some success in restoring blue ecosystems. For example, in Bunaken National Park, local communities broke down the walls of abandoned shrimp ponds and dug trenches to re-establish tidal flow, supporting natural recruitment of mangrove propagules and associated organisms (figure 6; Djamaruddin et al. 2019). The resulting mixed-species regeneration, facilitated by the hydrological interventions (i.e. 'ecological restoration') supported diverse faunal communities and interaction networks that more closely resembled old-growth areas than monoculture plantings of similar age (O'Connell et al. 2022).

There are similar coral reef restoration success stories for the region. Novel community-based reef restoration efforts in Spermonde, South Sulawesi resulted in a rapid increase in live coral cover compared to unrestored areas (Williams et al. 2019). Modular metal structures

stabilized coral rubble to facilitate natural coral recruitment and structurally support transplanted coral fragments (figure 6). There have been fewer efforts to restore degraded seagrass meadows in Wallacea, although experiments in Spermonde showed that incorporating species diversity into restoration efforts, rather than re-planting a single foundation species, had positive effects on ecosystem function and services (Williams et al. 2017). Successful examples of larger-scale seagrass restoration are known from two sites in Java, where meadows of *Enhalus* and *Thalassia* species were replanted and have since persisted for more than a decade (Thorhaug et al. 2020)

Future restoration needs to be implemented at a much larger scale across Wallacea to support the targets of the UN 2021-2030 Decade of Ecosystem Restoration. However, this requires broad consensus across different sectors of society, to help remove barriers such as tenure issues with other land and sea users. Upscaling coral reef and seagrass restoration to the levels required to counteract Indonesia's bomb-fishing legacy and climate change mortality is infeasible, making prevention of ecosystem degradation a better overall strategy than restoration once the damage is done. Indeed, protected natural capital assets will always be better, both ecologically and economically, than restoration. Complementary protocols for long-term monitoring and evaluation of restoration outcomes, including biodiversity, ecosystem functioning, and livelihood benefits, are also needed.

Acknowledgements

This work was enabled through the Newton Fund Wallacea Programme, a research collaboration funded by the UK Natural and Environmental Research Council (NERC; grants NE/S006990/1, NE/S007067/1, NE/S006923/1, NE/S006893/1, NE/S006958/1, NE/S006931/1, NE/S007059/1) and the Ministry of Research Technology and Higher Education, Indonesia (grants 7/E1/KP.PTNBH/2021, 7/AMD/E1/KP.PTNBH/2020, NKB-2892/UN2.RST/HKP.05.00/2020 and 1/E1/KP.PTNBH/2019, 2488/IT3.L1/PN/2020, 3982/IT3.L1/PN/2020, and 257-15/UN7.6.1/PP/2021). All authors contributed ideas to the article in a workshop held in Bogor, Indonesia in July 2019, and subsequently were involved with drafting subsections and/or editing the manuscript. Matthew J Struebig was also supported by a Leverhulme Trust Research Leadership Award to further collaboration between University of Kent and Universitas Indonesia.

Figure legends

Figure 1. Maps of Wallacea showing its location in Southeast Asia (a), zones of endemism on land (b) and in coastal marine environments (c) – see tables S1 and S2 for further information on the zones. In panel (b), the shading represents Indonesia's primary forest cover in 2018 compiled from Margono *et al.* (2014) and data from www.globalforestwatch.org. Forest according to this definition cannot be reproduced consistently for Timor-Leste, so forest is not displayed for this country. Note also that forests are difficult to map consistently in the drier parts of Wallacea, notably the Lesser Sunda islands (Nusa Tenggara) – Box 1. Mangrove cover is derived from Bunting *et al.* (2018), and corals from <https://allencoralatlas.org/>.

Figure 2. Patterns of terrestrial endemism – as inferred by range restricted reptile, mammal, bird and amphibian species in the IUCN database – for the eight zones presented in figure 1. Zones are outlined by Michaux (2010) and expanded to include other areas of Sulawesi (figure 1; table S1). Each plot shows the proportion of terrestrial vertebrate species that are range-restricted according to <https://www.iucnredlist.org/>. The assessment is limited to those taxa formally recognized as species and so may underrepresent endemism within species complexes, particularly in parts of Sulawesi (figure 3) and along the island chains of Nusa Tenggara. The shaded background to each plot denotes the percentage of land forested in 2019, and pie charts indicate progress made in each region (percent in orange/light shade) to meet the country's target of protecting 17% of land by 2020 (based on IUCN categories I-IV for protected areas from <https://www.protectedplanet.net/>).

Figure 3. The origins of Sulawesi and some of the resulting contact zones among endemic species/populations in Sulawesi as determined using genetic data. Examples of separated taxa include macaque (*Macaca spp.*), tarsier (*Tarsius spp.*) and gliding lizard (*Draco spp.*). Divergent subpopulations include the Celebes toad (*Ingerophrynus celebensis*), babirusa (*Babiroussa celebensis*) and swift fruit bat (yellow: *Thoopterus nigrescens*). Schematic based on Nugraha and Hall (2018). Photo credits: Sulawesi babirusa from Simon Mitchell, 2015; swift fruit bat Klaus Rudloff, 2014; other images from Wikimedia commons.

Figure 4. Livelihood systems, cultivated crops and mining commodities in Wallacea compared to other parts of Indonesia. In panel (a), the primary livelihoods at the village-level are shown according to Indonesia's 'Village Potential' census in 2018. Subsistence livelihoods include the subsistence agriculture, swidden agriculture, hunting and gathering of forest products and capture fisheries; market-orientated livelihoods include monoculture, horticulture, logging, animal breeding, aquaculture, and commercial fisheries. Western Indonesia includes Java, Sumatra, and Kalimantan; Wallacea is Sulawesi, Maluku and Nusa Tenggara; Eastern Indonesia includes Papua, West Papua and nearby islands. Panel (b) shows the total cultivated area of the 10 dominant agricultural commodities in Wallacea and Indonesia more widely, according to the Directorate General of Estate Crops Indonesia (2019). Panel (c) shows the total concession area under production for the 10 most dominant mineral commodities in Wallacea before and after mining policy changes in 2010, derived from the Ministry of Energy and Mineral Resources (ESDM, 2020).

Figure 5. Forest and forest uses in Wallacea. (a, b) Agroforestry practiced in community managed forest of Seram, Maluku raises the question of how to define a forest from aerial imagery. (c, d) Seasonal forests in Sumbawa, Nusa Tenggara are mostly deciduous and fragmented by small-scale agriculture. (e, f) Examples of the many uses of forests for local communities include timber extraction (here, Seram, Maluku) and subsistence hunting (Flores, Nusa Tenggara). Photo credits: Aris Santaya (a), Ulat Ifansasti (b,e) and Aulia Erlangga (c, f), courtesy of CIFOR.org, and Gemma Bramley, Royal Botanic Gardens Kew.

Figure 6. Intact (a) and degraded (b) coral reef in Bunaken National Park, North Sulawesi, and 2-years of restoration in Spermonde, South Sulawesi (c). Old growth (d) and degraded (e) mangrove forests in North Sulawesi, followed by community-based hydrological restoration (f) - i.e. a channel that was reopened to connect the old shrimp pond area to the sea. Photo credits: Maarten De Brauwer (a-b), Dominic Muenzel (c), Karen Diele (d, e), Rignolda Djamaluddin (f).

References

Ali JR, Heaney LR. 2021. Wallace's line, Wallacea, and associated divides and areas: history of a tortuous tangle of ideas and labels. *Biological Reviews* 96: 922–942.

Alongi DM, Murdiyarso D, Fourqurean JW, Kauffman JB, Hutahean A, Crooks S, Lovelock CE, Howard J, Herr D, Fortes M, Pidgeon E, Wagey T. 2016. Indonesia's blue carbon: a globally significant and vulnerable sink for seagrass and mangrove carbon. *Wetlands Ecology and Management* 24: 3–13.

Angelsen A, Jagger P, Babigumira R, Belcher B, Hogarth NJ, Bauch S, Börner J, Smith-Hall C, Wunder S. 2014. Environmental income and rural livelihoods: a global comparative Analysis. *World Development* 64: S12–S28.

Ardiantiono, Jessop TS, Purwandana D, Ciofi C, Jeri Imansyah M, Panggur MR, Ariefiandy A. 2018. Effects of human activities on Komodo dragons in Komodo National Park. *Biodiversity and Conservation* 27: 3329–3347.

Bani A, De Brauwer M, Creer S, Dumbrell AJ, Limmon G, Jompa J, von der Heyden S, Beger M. 2020. Informing marine spatial planning decisions with environmental DNA. Pages 375–407 in. *Advances in Ecological Research*, vol. 62. Elsevier.

Bappenas. 2019. Low carbon development: a paradigm shift towards a green economy in Indonesia. Ministry of National Development Planning/National Development Planning Agency (Bappenas). <https://lcdi-indonesia.id>.

Beger M, Linke S, Watts M, Game E, Treml E, Ball I, Possingham HP. 2010. Incorporating asymmetric connectivity into spatial decision making for conservation. *Conservation Letters* 3: 359–368.

van den Bergh G, de Vos J, Sondaar PY. 2001. The Late Quaternary palaeogeography of mammal evolution in the Indonesian Archipelago. *Palaeogeography, Palaeoclimatology, Palaeoecology* 171: 385–408.

Breed MF, Harrison PA, Blyth C, Byrne M, Gaget V, Gellie NJC, Groom SVC, Hodgson R, Mills JG, Prowse TAA, Steane DA, Mohr JJ. 2019. The potential of genomics for restoring ecosystems and biodiversity. *Nature Reviews Genetics* 20: 615–628.

Brumm A, Oktaviana AA, Burhan B, Hakim B, Lebe R, Zhao J, Sulistyarto PH, Ririmasse M, Adhityatama S, Sumantri I, Aubert M. 2021. Oldest cave art found in Sulawesi. *Science Advances* 7: eabd4648.

Bouchenak-Khelladi Y, Onstein RE, Xing Y, Schwery O, Linder PH. 2015. On the complexity of triggering evolutionary radiations. *New Phytologist* 207: 313-326.

Bunting P, Rosenqvist A, Lucas RM, Rebelo L-M, Hilarides L, Thomas N, Hardy A, Itoh T, Shimada M, Finlayson CM. 2018. The Global Mangrove Watch—a new 2010 global baseline of mangrove extent. *Remote Sensing* 10: 1669.

Camp EF, Suggett DJ, Gendron G, Jompa J, Manfrino C, Smith DJ. 2016. Mangrove and seagrass beds provide different biogeochemical services for corals threatened by climate Change. *Frontiers in Marine Science* 3.

Campbell SJ, Darling ES, Pardede S, Ahmadia G, Mangubhai S, Amkieltiela, Estradivari, Maire E. 2020. Fishing restrictions and remoteness deliver conservation outcomes for Indonesia's coral reef fisheries. *Conservation Letters* 13: e12698.

DiBattista JD, Reimer JD, Stat M, Masucci GD, Biondi P, De Brauwer M, Wilkinson SP, Chariton AA, Bunce M. 2020. Environmental DNA can act as a biodiversity barometer of anthropogenic pressures in coastal ecosystems. *Scientific Reports* 10: 8365.

Dixon AM, Forster PM, Beger M. 2021. Coral conservation requires ecological climate-change vulnerability assessments. *Frontiers in Ecology and the Environment* 19: 243–250.

Djamaluddin R, Brown B, Iii R. 2019. The practice of hydrological restoration to rehabilitate abandoned shrimp ponds in Bunaken National Park, North Sulawesi, Indonesia. *Biodiversitas* 20.

Esselstyn JA, Achmadi AS, Handika H, Swanson MT, Giarla TC, Rowe KC. 2021. Fourteen new, endemic species of shrew (Genus *Crocidura*) from Sulawesi reveal a spectacular island radiation. *Bulletin of the American Museum of Natural History* 454.

Frantz LAF, Rudzinski A, Nugraha AMS, Evin A, Burton J, Hulme-Beaman A, Linderholm A, Barnett R, Vega R, Irving-Pease EK, Haile J, Allen R, Leus K, Shephard J, Hillyer M, Gillemot S, van den Hurk J, Ogle S, Atofanei C, Thomas MG, Johansson F, Mustari AH, Williams J, Mohamad K, Damayanti CS, Wiryadi ID, Obbles D, Mona S, Day H, Yasin M, Meker S, McGuire JA, Evans BJ, von Rintelen T, Ho SYW, Searle JB, Kitchener AC, Macdonald AA, Shaw DJ, Hall R, Galbusera P, Larson G. 2018. Synchronous diversification of Sulawesi's iconic artiodactyls driven by recent geological events. *Proceedings of the Royal Society B: Biological Sciences* 285: 20172566.

Gaveau D, Locatelli B, Salim M, Husnayaen H, Manurung T, Descals A, Angelsen A, Meijaard E, Sheil D. 2022. Slowing deforestation in Indonesia follows declining oil palm expansion and lower oil prices. *PLoS ONE* 17: e0266178.

Halim A, Loneragan NR, Wirawan B, Fujita R, Adhuri DS, Hordyk AR, Sondita MFA. 2020. Transforming traditional management into contemporary territorial-based fisheries management rights for small-scale fisheries in Indonesia. *Marine Policy* 116: 103923.

Hall R. 2013. The palaeogeography of Sundaland and Wallacea since the Late Jurassic. *Journal of Limnology* 72: 1-17.

Harris JBC, Putra DD, Gregory SD, Brook BW, Prawiradilaga DM, Sodhi NS, Wei D, Fordham DA. 2014. Rapid deforestation threatens mid-elevational endemic birds but climate change is most important at higher elevations. *Diversity and Distributions* 20: 773–785.

Harrison R, Swinfield T, Ayat A, Dewi S, Silalahi M, Heriansyah I. 2020. Restoration concessions: a second lease on life for beleaguered tropical forests? *Frontiers in Ecology and the Environment* 18: 567–75.

Heinsohn T. 2003. Animal translocation:long-term human influences on the vertebrate zoogeography of Australasia (natural dispersal versus ethnophoresy). *Australian Zoologist* 32: 351–376.

Herder F, Möhring J, Flury J, Utama I, Wantania L, Wowor D, Boneka F, Stelbrink B, Hilgers L, Schwarzer J, Pfaender J. 2022. More non-native fish species than natives, and an invasion of Malawi cichlids, in ancient Lake Poso, Sulawesi, Indonesia. *Aquatic Invasions* 17: 72–91.

Hilgers L, Herder F, Hadiaty RK, Pfaender J. 2018. Alien attack: trophic interactions of flowerhorn cichlids with endemics of ancient Lake Matano (Sulawesi, Indonesia). *Evolutionary Ecology Research* 19: 575–590.

Huang D, Goldberg EE, Chou LM, Roy K. 2018. The origin and evolution of coral species richness in a marine biodiversity hotspot. *Evolution*, 72: 288-302.

Hudayana B, Suharko, Widyanta AB. 2020. Communal violence as a strategy for negotiation: Community responses to nickel mining industry in Central Sulawesi, Indonesia. *The Extractive Industries and Society* 7: 1547–1556.

Kalalo FP. 2019. Revisiting the mining controversy of Bangka Island, Minahasa Regency, North Sulawesi, Indonesia. Paper presented at Proceedings of the 1st Warmadewa Research and Development Seminar (WARDs), 30 October 2018, Denpasar-Bali, Indonesia. 2019, Bali, Indonesia.

Kamil KA, Hailu A, Rogers A, Pandit R. 2017. An assessment of marine protected areas as a marine management strategy in Southeast Asia: A literature review. *Ocean & Coastal Management* 145: 72–81.

Kealy S, Louys J, O'Connor S. 2017. Reconstructing palaeogeography and inter-island visibility in the Wallacean archipelago during the likely period of Sahul colonization, 65–45 000 years ago. *Archaeological Prospection* 24: 259–272.

Limbong D, Kumampung J, Rimper J, Arai T, Miyazaki N. 2003. Emissions and environmental implications of mercury from artisanal gold mining in north Sulawesi, Indonesia. *Science of The Total Environment* 302: 227–236.

Limmon GV, Marasabessy AM. 2019. Impacts of sedimentation on coral reefs in Inner Ambon Bay, Indonesia. *IOP Conference Series: Earth and Environmental Science* 339: 012035.

Lohman DJ, de Bruyn M, Page T, von Rintelen K, Hall R, Ng PKL, Shih H-T, Carvalho GR, von Rintelen T. 2011. Biogeography of the Indo-Australian archipelago, *Annual Review of Ecology, Evolution, and Systematics*, 42: 205-426.

Maas B, Putra DD, Waltert M, Clough Y, Tscharntke T, Schulze CH. 2009. Six years of habitat modification in a tropical rainforest margin of Indonesia do not affect bird diversity but endemic forest species. *Biological Conservation*, 142: 2665-2671.

Malik A, Mertz O, Fensholt R. 2017. Mangrove forest decline: consequences for livelihoods and environment in South Sulawesi. *Regional Environmental Change* 17: 157–169.

Michaux B. 2010. Biogeology of Wallacea: geotectonic models, areas of endemism, and natural biogeographical units. *Biological Journal of the Linnean Society* 101: 193–212.

Margono BA, Potapov PV, Turubanova S, Stolle F. 2014. Primary forest cover loss in indonesia over 2000-2012. *Nature Climate Change* 4: 730-735.

Mills M, Pressey RL, Weeks R, Foale S, Ban NC. 2010. A mismatch of scales: challenges in planning for implementation of marine protected areas in the Coral Triangle. *Conservation Letters* 3: 291–303.

Mitchell SL, Edwards DP, Martin RW, Deere NJ, Voigt M, Kastanya A, Karja A, Akbar PG, Jordan K, Tasirin J, Zakaria Z, Martin T, Supriatna J, Winarni N, Davies ZG, Strubig MJ. 2022. Severity of deforestation mediates biotic homogenisation in an island archipelago. *Ecography*: e05990.

Mittermeier RA, Turner WR, Larsen FW, Brooks TM, Gascon C. 2011. Global biodiversity conservation: the critical role of hotspots. Pages 3–22 in Zachos FE and Habel JC, eds. *Biodiversity Hotspots*. Springer Berlin Heidelberg.

Monk KA, Fretes Y de, Reksodiharjo-Lilley G. 1997. *The Ecology of Nusa Tenggara and Maluku*. Oxford University Press.

Moore A, Ndobe S, Jompa J. 2017. Fingerprints of the Anthropocene: the 2016 coral bleaching event in an equatorial archipelago. *Proceedings of the 4th International Marine and Fisheries Symposium*, Makassar, 2 October 2017.

Nugraha AMS, Hall R. 2018. Late Cenozoic palaeogeography of Sulawesi, Indonesia. *Palaeogeography, Palaeoclimatology, Palaeoecology* 490: 191–209.

O'Connell DP, Kelly DJ, Lawless N, O'Brien K, Marcaigh FÓ, Karya A, Analuddin K, Marples NM. 2019. A sympatric pair of undescribed white-eye species (Aves: Zosteropidae: *Zosterops*) with different origins. *Zoological Journal of the Linnean Society* 186: 701–724.

O'Connell DP, Fusi M, Djamaruddin R, Rajagukguk BB, Bachmid F, Kitson JJN, Dunnett Z, Trianto A, Tjoa AB, Diele K, Evans DM. 2022. Assessing mangrove restoration practices using species-interaction networks. *Restoration Ecology* 30: e13546.

Pellegrini AFA, Refsland T, Averill C, Terrer C, Staver AC, Brockway DG, Caprio A, Clatterbuck W, Coetsee C, Haywood JD, Hobbie SE, Hoffmann WA, Kush J, Lewis T, Moser WK, Overby ST, Patterson WA, Peay KG, Reich PB, Ryan C, Sayer MAS, Scharenbroch BC, Schoennagel T, Smith GR, Stephan K, Swanston C, Turner MG, Varner JM, Jackson RB. 2021. Decadal changes in fire frequencies shift tree communities and functional traits. *Nature Ecology & Evolution* 5: 504–512.

Pennington RT, Lehmann CER, Rowland LM. 2018. Tropical savannas and dry forests. *Current Biology* 28: R541–R545.

Piper PJ. 2017. The origins and arrival of the earliest domestic animals in mainland and island Southeast Asia: a developing story of complexity. Pages 251–273 in. *New Perspectives in Southeast Asian and Pacific Prehistory*, vol. 45. Australian National University.

Pratiwi, Narendra BH, Siregar CA, Turjaman M, Hidayat A, Rachmat HH, Mulyanto B, Suwardi, Iskandar, Maharani R, Rayadin Y, Prayudyaningsih R, Yuwati TW, Prematuri R, Susilowati A. 2021. Managing and reforesting degraded post-mining landscape in Indonesia: A review. *Land*. 10: 658.

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

Reilly SB, Wogan GOU, Stubbs AL, Arida E, Iskandar DT, McGuire JA. 2017. Toxic toad invasion of Wallacea: A biodiversity hotspot characterized by extraordinary endemism. *Global Change Biology* 23: 5029–5031.

Reilly SB, Stubbs AL, Karin BR, Arida E, Iskandar DT, McGuire JA. 2019. Recent colonization and expansion through the Lesser Sundas by seven amphibian and reptile species. *Zoologica Scripta* 48: 614–626.

Rheindt FE, Prawiradilaga DM, Ashari H, Gwee CY, Lee GWX, Wu MY, Ng NSR. 2020. A lost world in Wallacea: Description of a montane archipelagic avifauna. *Science* 367: 167–170.

Richards DR, Friess DA. 2016. Rates and drivers of mangrove deforestation in Southeast Asia, 2000–2012. *Proceedings of the National Academy of Sciences* 113: 344–349.

Santika T, Wilson KA, Budiharta S, Kusworo A, Meijaard E, Law EA, Friedman R, Hutaibarat JA, Indrawan TP, John FAVS, Struebig MJ. 2019. Heterogeneous impacts of community forestry on forest conservation and poverty alleviation: Evidence from Indonesia. *People and Nature* 1: 204–219.

Santika T, Wilson KA, Law EA, St John FAV, Carlson KM, Gibbs H, Morgans CL, Ancrenaz M, Meijaard E, Struebig MJ. 2021. Impact of palm oil sustainability certification on village well-being and poverty in Indonesia. *Nature Sustainability* 4: 109–119.

Scheffers BR, Oliveira BF, Lamb I, Edwards DP. 2019. Global wildlife trade across the tree of life. *Science* 366: 71–76.

Serdiati N, Arfiati D, Sri Widodo M, Lelono TD, Ndobe S, Mansyur K, Moore AM. 2021. Perspectives on sustainable management of the Poso Lake (Indonesia) endemic ricefish, *Oryzias nigrimas* (Actinopterygii: Adrianichthyidae). *Revista de Biología Tropical* 69: 139–152.

Sheherazade, Tsang SM. 2015. Quantifying the bat bushmeat trade in North Sulawesi, Indonesia, with suggestions for conservation action. *Global Ecology and Conservation* 3: 324–330.

Shipton C, O'Connor S, Kealy S. 2020. The biogeographic threshold of Wallacea in human evolution. *Quaternary International*. 574: 1-12.

Siyum ZG. 2020. Tropical dry forest dynamics in the context of climate change: syntheses of drivers, gaps, and management perspectives. *Ecological Processes* 9: 25.

Staver AC, Archibald S, Levin SA. 2011. The global extent and determinants of savanna and forest as alternative biome states. *Science* 334: 230–232.

Stelbrink B, Albrecht C, Hall R, von Rintelen T. 2012. The biogeography of Sulawesi revisited: is there evidence for vicariant origin of taxa on Wallace's 'anomalous island'? *Evolution* 66: 2252–2271.

Struebig MJ, Fischer M, Gaveau DLA, Meijaard E, Wich SA, Gonner C, Sykes R, Wilting A, Kramer-Schadt S. 2015. Anticipated climate and land-cover changes reveal refuge areas for Borneo's orang-utans. *Global Change Biology* 21: 2891–2904.

Sunarti S, Rugayah, Low YW, Lucas EJ. 2022. *Syzygium nusatenggaraense* (Myrtaceae), a new rainforest tree species with a calyprate calyx from the Lesser Sunda Islands, Indonesia. *Telopea* 25: 1–6.

Supriatna J, Shekelle M, Fuad HAH, Winarni NL, Dwiyahreni AA, Farid M, Mariati S, Margules C, Prakoso B, Zakaria Z. 2020. Deforestation on the Indonesian island of Sulawesi and the loss of primate habitat. *Global Ecology and Conservation* 24: e01205.

Sutikna T, Tocheri M, Faith T, Jatmiko, Awe R, Meijer H, Wahyu E, Roberts R. 2018. The spatio-temporal distribution of archaeological and faunal finds at Liang Bua (Flores, Indonesia) in light of the revised chronology for *Homo floresiensis*. *Journal of Human Evolution* 124.

Tasirin JS, Iskandar DT, Laya A, Kresno P, Suling N, Oga VT, Djano R, Bawotong A, Nur A, Isfanddri M, Abbas W, Rihu NA, Poli E, Lanusi AA, Summers M. 2021. Maleo Macrocephalon maleo population recovery at two Sulawesi nesting grounds after community engagement to prevent egg poaching. *Global Ecology and Conservation* 28: e01699.

Thorhaug A, Belaire C, Verduin JJ, Schwarz A, Kiswara W, Prathee A, Gallagher JB, Huang XP, Berlyn G, Yap T-K, Dorward S. 2020. Longevity and sustainability of tropical and subtropical restored seagrass beds among Atlantic, Pacific, and Indian Oceans. *Marine Pollution Bulletin* 160: 111544.

Tittensor DP, Mora C, Jetz W, Lotze HK, Ricard D, Berghe EV, Worm B. 2010. Global patterns and predictors of marine biodiversity across taxa. *Nature* 466: 1098–1101.

Towoliu R. 2014. Coral reef condition in several dive points around Bunaken Island, North Sulawesi. *Aquatic Science & Management*. 2: 44–48.

Trew BT, Maclean IMD. 2021. Vulnerability of global biodiversity hotspots to climate change. *Global Ecology and Biogeography*. 30: 768–783.

Vaillant JJ, Haffner GD, Cristescu ME. 2011. The ancient lakes of Indonesia: Towards integrated research on speciation. *Integrative and Comparative Biology* 51: 634–643.

Veron JEN, Devantier LM, Turak E, Green AL, Kininmonth S, Stafford-Smith M, Peterson N. 2009. Delineating the coral triangle. *Galaxea, Journal of Coral Reef Studies* 11: 91–100.

Voigt M, Supriatna J, Deere NJ, Kastanya A, Mitchell SL, Rosa IMD, Santika T, Siregar R, Tasirin JS, Widjanto A, Winarni NL, Zakaria Z, Mumbunan S, Davies ZG, Struebig MJ. 2021. Emerging threats from deforestation and forest fragmentation in the Wallacea centre of endemism. *Environmental Research Letters*. 16: 094048

Von Rintelen T, Von Rintelen K, Glaubrecht M, Schubart C, Herder F. 2012. Aquatic biodiversity hotspots in Wallacea: The species flocks in the ancient lakes of Sulawesi, Indonesia. In D. Gower, K. Johnson, J. Richardson, B. Rosen, L. Rüber, S. Williams (Eds.), *Biotic Evolution and Environmental Change in Southeast Asia* (Systematics Association Special Volume Series, pp. 290-315). Cambridge University Press.
doi:10.1017/CBO9780511735882.014

Waltert M, Bobo KS, Kaupa S, Montoya ML, Nsanyi MS, Fermon H. 2011. Assessing conservation values: Biodiversity and endemicity in tropical land use systems. *PLOS ONE* 6: e16238.

Wicaksono SA, Russell JM, Holbourn A, Kuhnt W. 2017. Hydrological and vegetation shifts in the Wallacean region of central Indonesia since the Last Glacial Maximum. *Quaternary Science Reviews* 157: 152–163.

Williams SL, Ambo-Rappe R, Sur C, Abbott JM, Limbong SR. 2017. Species richness accelerates marine ecosystem restoration in the Coral Triangle. *Proceedings of the National Academy of Sciences* 114: 11986–11991.

Williams SL, Sur C, Janetski N, Hollarsmith JA, Rapi S, Barron L, Heatwole SJ, Yusuf AM, Yusuf S, Jompa J, Mars F. 2019. Large-scale coral reef rehabilitation after blast fishing in Indonesia. *Restoration Ecology* 27: 447–456.

Yusuf S, Jompa J. 2012. First quantitative assessment of coral bleaching on Indonesian reefs. *Proceedings of the 12th International Coral Reef Symposium*, Cairns, Australia, 9-13 July 2012.
