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Improved management is more important than sparing-sharing strategies for tropical forests

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Abstract

Tropical forests are globally significant for both biodiversity conservation and the production of economically valuable wood products. Two contrasting approaches have been suggested to simultaneously produce timber and conserve biodiversity; one partitions forests to deliver these objectives separately (sparing), the other integrates both objectives in the same location (sharing). To date, the 'sparing or sharing' debate has focused on agricultural landscapes, with scant attention paid to forest management. Here we explored the sparing-to-sharing continuum through spatial optimisations with set economic returns for the forests of East Kalimantan, Indonesia – a global biodiversity hotspot. We found that neither sparing nor sharing extremes are optimal, although the greatest conservation value was attained towards the sparing end of the continuum. Critically, improved management strategies, such as reduced-impact logging, accounted for larger conservation gains than altering the balance between sparing and sharing, particularly for endangered species. Ultimately, debating sparing versus sharing has limited value while large gains remain from improving forest management.

Introduction

Over half of the world's species live in tropical forests[1], ecosystems that also help mitigate climate change[2] and provide critical ecosystem services to local communities, including clean water and reduced heat stress[3]. These values have led to a number of international policies that support the preservation and better management of tropical forests. The 2020 Strategic Plan for Biodiversity, for example, aims to halve deforestation rates by 2020 and substantially reduce forest degradation[4], goals reinforced by the New York Declaration on Forests[5] and the United Nations' Sustainable Development Goals[6]. The 2015 Paris Agreement highlights the importance of tropical forests for limiting future global temperature increase to below 2°C above pre-industrial levels[7], and recent research shows that conservation, restoration, and improved management of tropical forests can deliver 21% of the emission reductions required between now and 2030 to reach this goal[2]. Furthermore, the provision of structural wood is potentially an important part of the climate mitigation solution as it can be used to replace steel and concrete in construction - two products that generate substantial CO_2 emissions[8].

At the same time, the forestry industry – which ranges from selective logging in natural forests to the intensive management of short-rotation wood fibre plantations – contributes to regional economies in almost all forested tropical countries[9]. For example, forestry in Indonesia contributes USD15.2 billion annually to the GDP (1.7%) while directly employing nearly half a million people[10]. While forestry provides clear benefits for socio-economic development in tropical countries, industrial-scale exploitation is well known to reduce the structural complexity of forested landscapes, and in turn reduces forest-dependent biodiversity[11]. Meanwhile, conversion of native forests to monoculture wood fibre plantations is a major cause of deforestation globally, and the largest driver of deforestation in Indonesia[12].

A major question for how to best maintain the production of wood products while conserving biodiversity values is whether these forests are best managed through intensive or extensive forest management strategies[13]. Intensification, either through increased harvest intensities in natural forests or the development of industrial wood fibre plantations, allows for production to be sourced from a smaller area, thereby potentially 'sparing' from degradation a larger portion of the forest estate for biodiversity and other ecosystem services. In a forest sparing landscape, the vast majority of the biodiversity value is derived from the spared land, as intensively managed stands, especially plantations, have limited biodiversity value[11]. In direct contrast, forest 'sharing' approaches aim to maintain biodiversity within extensive areas of forest that are harvested at lower intensities. This approach reflects the understanding that selectively logged tropical forests can maintain a large fraction of the biodiversity found in natural forest stands[14]. Previous studies have examined the spectrum of tropical forestry intensification aspatially at the stand or concession level[15–17], but no study has yet investigated the broad-scale performance of tropical forest sharing versus sparing strategies in a spatially heterogeneous landscape.

Discussion of highly modified agricultural landscapes dominates the land-sparing versus land-sharing debate, and the general conclusion is that sparing better protects biodiversity while maintaining agricultural yields[18]. This result could be driven by the fact that even low-intensity agriculture usually involves conversion of forests and other native ecosystems (or at least prevents their recovery), which limits the conservation potential of sharing in agricultural landscapes. As such, the documented benefits from land sparing in agricultural landscapes are linked to high-impact and high-yielding cropping systems[19], which may not carry over to other production systems with comparatively lower impact, such as timber production landscapes[13], where production does not necessarily imply conversion. As forests occupy nearly three times the land area of agriculture globally (41.5 M km^2 [20] compared to 15 M km^2 [21]), exploring forest-sharing versus forest-sparing could have vast implications for global biodiversity.

However, tropical forests are highly complex systems with considerable scope for improved management beyond the spectrum of intensification. Improving how land and seascapes are managed is at the heart of global conservation and sustainability strategies (e.g., the Sustainable Development goals[6] and the Convention on Biological Diversity[4]). In a shared landscape, reduced impact logging (RIL) practices can minimise the disturbances caused by logging without impacting the volume of timber extacted[22]. Alternatively, conservation outcomes from plantation management can be improved through practices such as longer rotations[23]. Improved management is also pertinent in the 'spared' land, as strictly enforcing protected areas (through, for example, increasing patrols) can have greater biodiversity benefits than expanding the reserve system when there is poor enforcement[24,25]. Consequently, it is imperative to include improved management strategies within the sparing or sharing framework for forest systems.

Here we consider forest sparing, sharing and improved management in the East Kalimantan Province of Indonesian Borneo. Indonesia exports more wood products than any other tropical country[9], yet the region is a major evolutionary hotspot[26], contains high species richness and endemism, and includes charismatic and critically endangered species such as the Bornean orangutan (*Pongo pygmaeus*). Our analysis includes East Kalimantan's entire forest estate (~8.1 million ha), which is an area managed by the national-level Ministry of Environment and Forestry where only forested land-uses are permitted (including selective logging and wood fibre plantations) (Fig. 1b). We aim to determine the effectiveness of sparing and sharing strategies, while accounting for the role of improved management, using a broad-scale spatial optimisation of management types. The optimal spatial configuration is achieved by fixing the total economic returns across the landscape and maximising the conservation of habitat suitable for regional mammal species and areas of high conservation value, which include large areas that are important for threatened ecosystems and maintaining ecological processes[27]. Rather than treating sparing and sharing strategies as a dichotomy, we consider a continuum from sparing to sharing, defined by the proportion of selective logging in the forest estate (relative to protected areas and plantations) (Fig. 1a). For example, an extreme sparing scenario would contain no selective logging, with all forests being either in protected areas or intensively managed wood fibre plantations. To incorporate the role of improved management, we select at least one conventional and one improved management type for each broad land-use category (i.e., protected areas, selective logging, and plantations) (Fig. 1a, Table 1). Including improved management allows us to determine the relative contribution of these management types to delivering conservation outcomes.

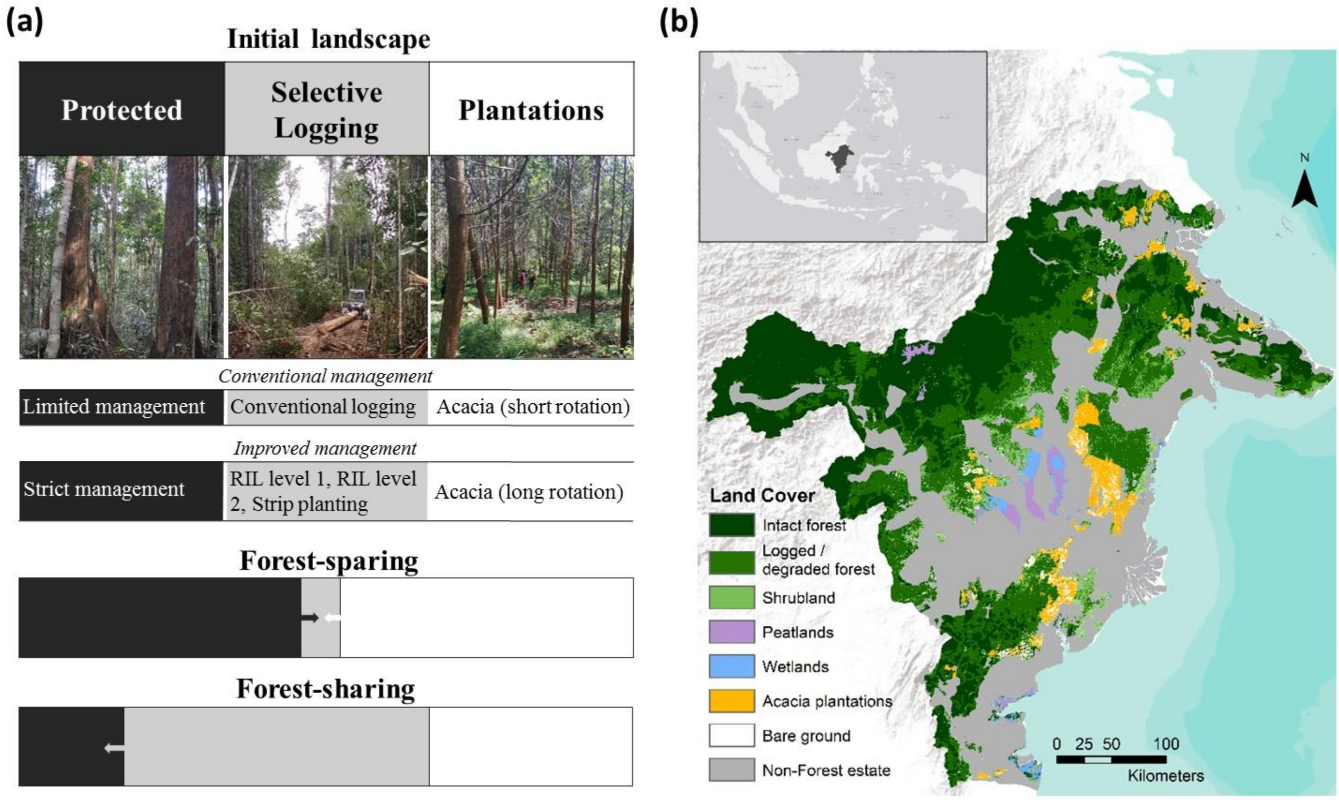

Figure 1 | The context of the study. Panel (a) shows the conceptual framing of sparing and sharing strategies for tropical forests, including conventional and improved management types for each broad land-use category. Definitions of each management type are given in Table 1. Photographs are all in East Kalimantan including (left to right): Wehea Protected Area, East Kutai Regency (E.T. Game); Rizki Kacida Reana logging concession, Berau Regency (R.K. Runting); and Tanjung Redeb Hutani fibre plantation, Berau Regency (R.K. Runting). Panel (b) shows the location of the 8.1 M ha forest estate within East Kalimantan, Indonesia, and the dominant land cover types (Supplementary Information). All mining, industrial, oil palm and settlement areas are excluded as they are not permitted within the forest estate (placed in the non-forest estate here).

Table 1 | Summary of the conventional and improved forest management types considered for protected areas, selective logging, and wood plantations.

Management	*Summary*
1. Protected areas	
Conventional:	
1a. Limited management	The area is protected, but there is limited control of threatening processes (e.g., hunting, illegal logging, and fire) resulting in some habitat degradation and loss.
Improved:	
1b. Strict management	The effective management of protected areas. Most threatening processes are controlled and habitat is maintained.
2. Selective logging	
Conventional:	
2a. Conventional Logging	Selective logging of commercial timber species ≥40cm DBH. Logging damage from hauling, felling, and skidding averages 52.3 Mg C ha^{-1} [28].
Improved:	
2b. RIL level 1 (tractor yarding)	Logging intensity matches conventional logging, but the damage is 69% of conventional logging per m^3 of timber extracted due to better planning and training[28].
2c. RIL level 2 (cable yarding)	Logging intensity matches conventional logging, but the damage is 54% of conventional logging per m^3 of timber extracted due to better planning, training, and the use of cable yarding[28].
2d. Strip planting	Areas within 200 m of logging roads are enriched with commercial timber species along cleared lines[29]. Timber production increases due to rapid growth of residual and planted trees. The remaining area follows RIL level 2 practices.
3. Wood fibre plantations	
Conventional:	
3a. *Acacia mangium* (short rotations)	*Acacia* plantations with 7-year rotations that yield 160 m^3 ha^{-1} of wood at each harvest, all of which is used for pulp.
Improved:	
3b. *Acacia mangium* (long rotations)	*Acacia* plantations with 12-year rotations that yield 180 m^3 ha^{-1} of wood at each harvest. 60% is for pulp and 40% is for saw/veneer logs.

Results

Our spatial optimisation of management types revealed both expected and unexpected outcomes for broad-scale forest management. As expected, extreme sparing and extreme sharing produced vastly different spatial configurations (Fig. 2). The sharing strategy necessitated large expanses of selective logging, with only 40% of planning units allocated to the same zones as in the sparing strategy (primarily within existing protected areas (Fig. 2)). Importantly, our results show that neither the extremes of sparing nor sharing were identified as the optimal solution. Instead, the optimal solution involved a mixed land-use configuration that tended towards the sparing end of the continuum, while containing elements of both sparing and sharing at finer scales (Fig. 2). In the optimal scenario, the expansion of *Acacia* plantations tended to be located in degraded forest, shrubland, or bare areas (63%), whereas selective logging was split between previously logged (79%) and intact forest (21%).

The finding that the optimal spatial configuration tended towards the sparing end of the continuum held true across a range of objectives and parameter combinations (Fig. 3a and 4). The parameter case that caused the largest change along the sparing-to-sharing continuum from the base parameter combinations was if the net present value (NPV) of *Acacia* plantations was decreased by 25%. This scenario represents the uppermost outlier across all conservation objectives, with an optimal landscape shifted towards sharing (although this strategy was generally still towards the sparing end of the continuum (Fig. 3a)). Increasing or decreasing the discount rate used to calculate the NPV shifted the solution towards sharing or sparing respectively, but these changes were minor compared to other parameters in the sensitivity analysis. Towards the sparing end of the spectrum, the largest shifts were seen by using the lower bounds for habitat quality from the Delphi expert elicitation (Supplementary Information), or increasing the NPV of *Acacia* plantations by 25%. In contrast, increasing the NPV threshold (i.e., the minimum NPV to be produced from the whole landscape) resulted in a greater mix of strategies, moving the solution towards sharing (Fig. 3b).

Our results reveal the strong benefits of improved management strategies irrespective of the degree of forest sparing and sharing. Improved management types dominated all spatial solutions, with only minor contributions from conventional management types (Fig. 2), and this result remained true even when varying the level of economic value required from the landscape (NPV thresholds, Fig. 3b). Whether or not we constrained the problem to conventional management had little impact on the balance between sharing and sparing across all threatened status' and taxonomic groups (i.e., primates, carnivores and bats) (Fig. 4). However, allowing improved management types, relative to solutions constrained to conventional management, could improve outcomes by 17.5% of the optimal conservation objective value when targeting endangered species (Fig. 5). For every different weighting of conservation objectives, the gains from improved management were larger than the contributions from selecting the optimal point on the sparing-to-sharing continuum (Fig. 5). In fact, for all conservation objectives (Fig. 3a-h), even selecting the worst point on the sharing-to-sparing continuum for improved management still leads to greater benefits than selecting the best point on the continuum for conventional management scenarios. This result highlights the far greater importance of improving land management than selecting the right proportion of land-use intensities in the landscape.

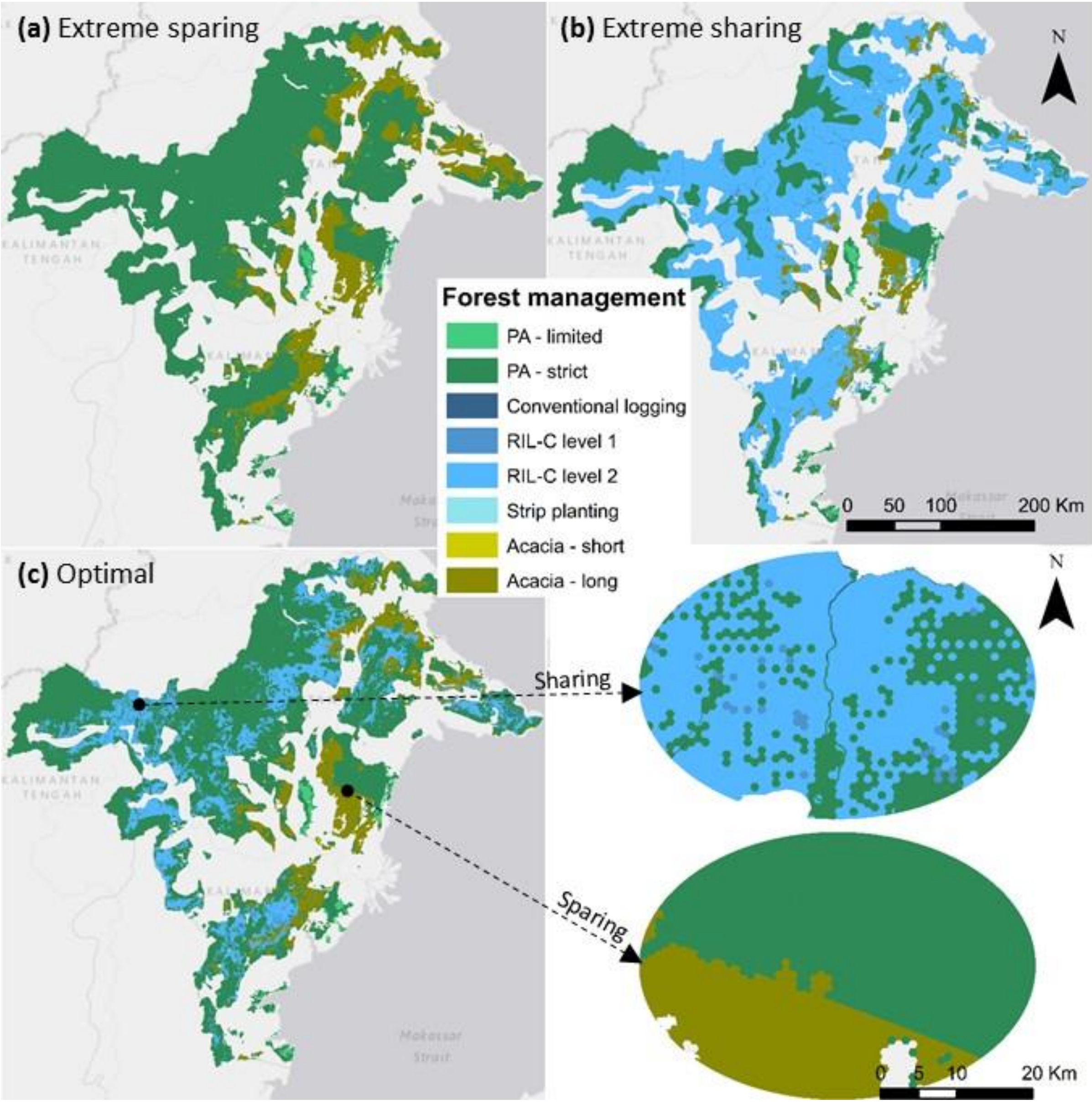

Figure 2 | Spatial sparing and sharing scenarios: (a) extreme sparing, (b) extreme sharing, (c) the optimal spatial configuration. Extreme sparing (a) comprises 18% *Acacia* plantations, with the remainder protected; extreme sharing (b) comprises 64% selective logging, 7% *Acacia* plantations, with the remainder protected; and the optimal strategy (c) comprises 21% selective logging, 12% *Acacia* plantations, with the remainder protected. The optimal strategy is mixed, with elements of both sparing and sharing at finer scales.

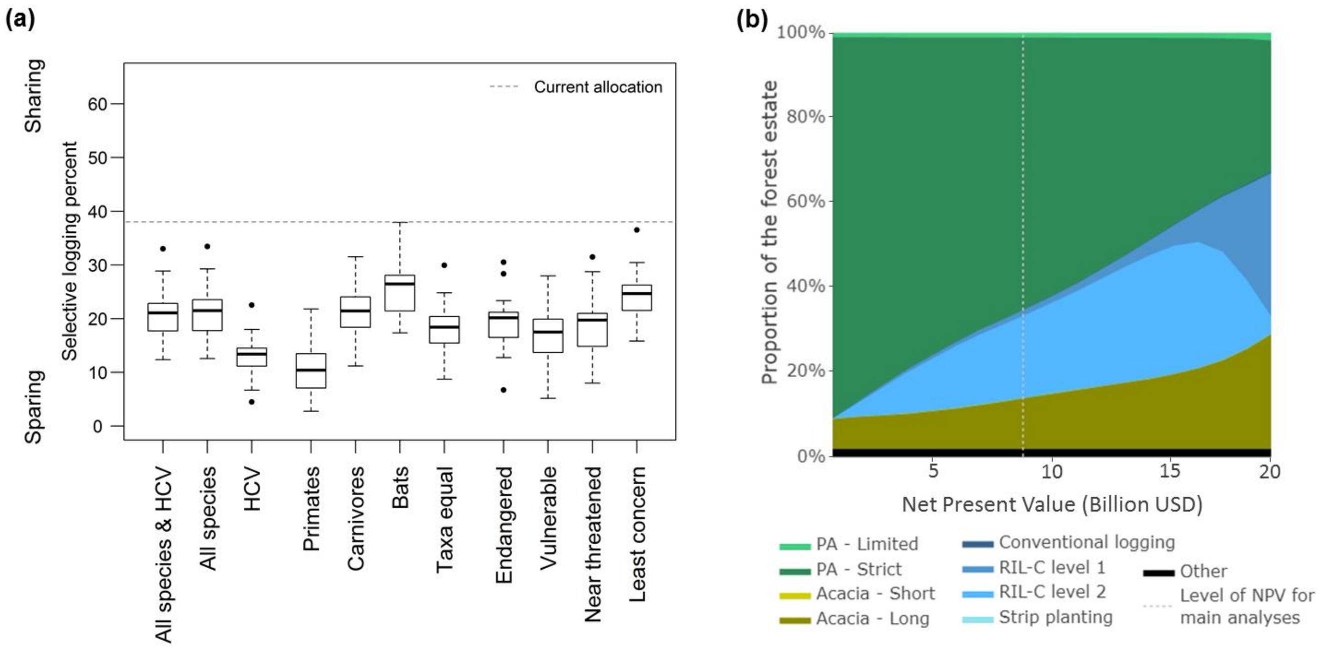

Figure 3 | Optimal sparing or sharing strategies. Panel (a) shows the variation in the optimal point on the sparing-to-sharing continuum for a range of conservation objectives for a fixed NPV threshold. The variation is represented by a sensitivity analysis of conservation parameters and relative NPVs for each forest management type (Table S5). Selective logging can comprise a maximum of 65% of the landscape due to biophysical and administrative constraints, thus we consider 65% selective logging to be the 'extreme' sharing scenario. The current proportion of selective logging, if all concessions are active, is 38% of the landscape (dashed grey line). "Taxa equal" represents a conservation objective where each taxon was weighted equally, regardless of the number of species it contained. Panel (b) shows the optimal proportion of the landscape in each forest management type across a range of NPV thresholds. PA refers to protected areas. More than $20 billion NPV could not be extracted from the landscape within the biophysical and administrative restrictions.

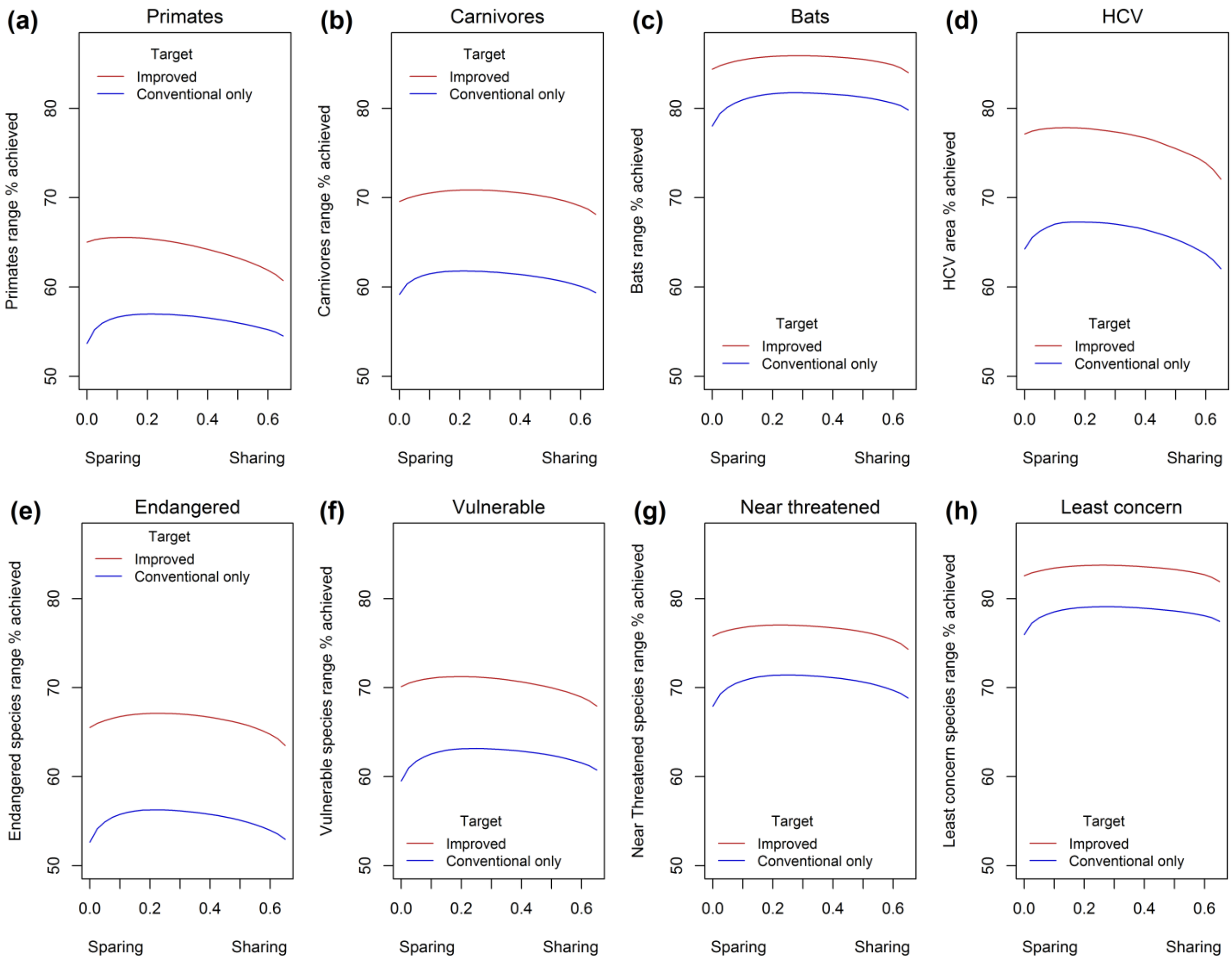

Figure 4 | The sparing-to-sharing continuum for different taxa and IUCN red list categories when either: allowing improved management (red) or constraining the problem to conventional management types (blue). The following groupings were considered: (a) primates, (b) carnivores, (c) bats, (d) areas of high conservation value, (e) endangered or critically endangered, (f) vulnerable, (g) near threatened, (h) least concern. "Range % achieved" refers to the habitat quality x area (i.e., pristine habitat for all species across the entire forest estate would represent 100%). The x-axis represents the proportion of selective logging in the landscape, with 0.65 representing the maximum possible. The uncertainties in the optimal position along the sparing-to-sharing continuum and difference between conventional and improved management are shown in Fig. 2a and Fig. 5 respectively.

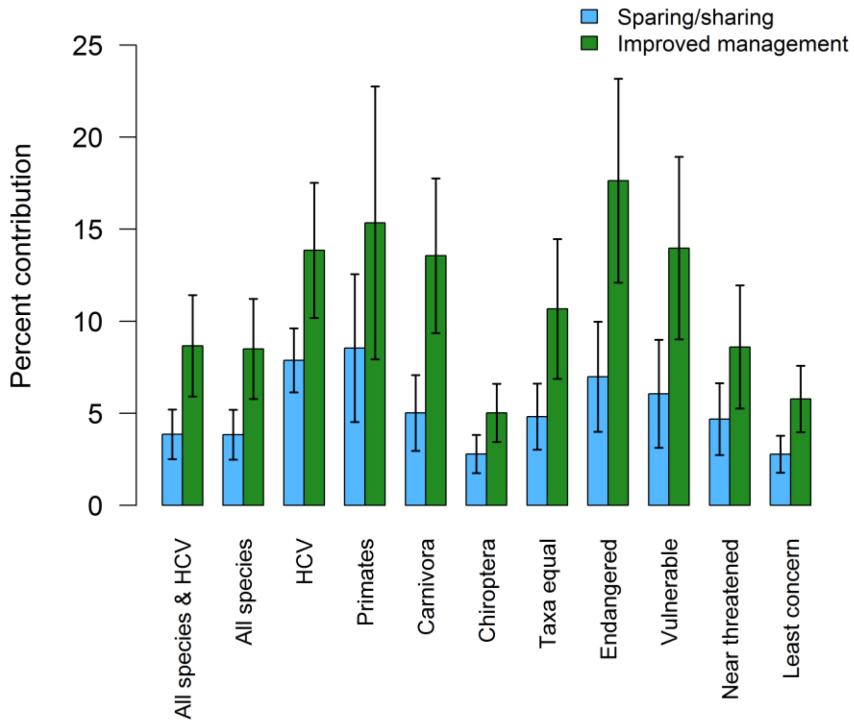

Figure 5 | Contribution to the optimal objective value from improved management and sparing/sharing strategies across the range of conservation objectives. The contributions of sparing versus sharing were calculated as the difference between the best and worst performing points on the sparing-to-sharing continuum, as a percent of the performance of the optimal solution. The contribution of improved management was calculated as the optimal improved management solution less the optimal solution when restricted to conventional management types, as a percent of the performance of the optimal solution.

Discussion

We evaluated the effectiveness of sparing and sharing strategies for tropical forests using landscape-scale spatial optimisation of forest management strategies. While the optimal strategy fell towards the sparing end of the continuum for all conservation objectives (Fig. 2, Fig. 3a), our results challenge the dichotomy of the sparing versus sharing debate, as the optimal strategy contains elements of both sparing and sharing strategies at finer scales. Where areas were designated as protected, strict management was almost always the most cost-effective way of delivering better outcomes, despite the higher costs per unit area (Fig. 2). Likewise, in areas allocated to selective logging, reduced impact logging with cable yarding dominated the solutions, and long rotations were preferable for *Acacia* plantations (Fig. 2). Crucially, the collective gains from improved management outperformed any improvement from moving along the sparing to sharing spectrum. Ultimately, it was more important to improve management, for any management type, than to shift the landscape towards a sparing strategy. Given these results, we recommend future studies of sparing and sharing also consider improved management strategies to avoid an unrealistic simplification of landscape management and planning.

The optimal landscape configuration contained a relatively small amount of selective logging (21% of the landscape, compared to 38% currently held in logging concessions), and most of this (79%) was allocated to previously logged forests. While intact forests often had higher timber stocks than previously logged or degraded forest, they tended to also have higher harvesting and transportation costs due to steeper slopes and the lack of existing roads. In addition, timber yields at the first and second harvests may not be sustainable in the long-term, even if cutting cycles are extended to 60 years[29]. Selectively logging remaining primary forests is also generally considered to have poor outcomes for biodiversity[30]. Therefore, whilst logging of primary forest can, at times, provide an initial financial windfall, these revenues are unlikely to be sustained, and the widespread adoption of this practice is not justified.

We discovered that a relatively small increase in wood fibre plantations (to 12.1% of the forest estate from 5.6% currently) was required to substitute the economic losses from protecting forests that are currently selectively logged, thus maximising species richness and areas of high conservation value through large protected areas (66% of the forest estate) (Fig. 3b). It is widely recognised that large, contiguous areas of protected forest sustain natural ecological and evolutionary processes, providing a suite of high-value ecosystem services, including the regulation of hydrological cycles at multiple scales, and the storage of substantial carbon stocks[31]. They are also critically important for *in situ* biodiversity conservation, supporting the last intact forest-dependent mega-faunal assemblages, wide-ranging and migratory species, and species sensitive to exploitation by or conflicts with humans[32].

However, our measure of biodiversity (time-averaged habitat quality for mammal species) may not be indicative for all species. For example, we assumed that habitat quality would recover over 60 years following the cessation of logging, on average, but the recovery of animal populations after selective logging can have substantial temporal variability[33]. While the richness of medium-large mammals can recover in as little as 10 years after logging[34], bird species that are particularly sensitive to selective logging (e.g., *Argusianus argus* or *Kenopia striata*) do not show signs of population recovery 40 years after logging[35], and achieving a community composition similar to primary forest may require more than 150 years[36]. Other taxonomic groups may also face different recovery rates: tree species richness is likely to recover within 50 years, compared with more than 100 years for epiphyte richness[36]. In addition, species richness scales with the size of a habitat patch, even within a landscape matrix of different habitat qualities[37], so we would expect a patch of forest within a large protected area to have a higher likelihood of mammal species survival than, for example, a similarly sized protected forest patch within an *Acacia* plantation. While we did not explicitly account for this, both the extreme sparing and extreme sharing scenarios, along with the optimal solution, contain large contiguous protected areas (Fig. 2). Incorporating the uncertainty in population recovery along with alternative measures of biodiversity (such as including contiguity and beta diversity) within a spatial planning framework is an important area of future research.

It is important to note that both sharing and sparing strategies could increase the risk of future deforestation.

Under a sparing strategy, direct expansion of forest conversion – in the form of intensive plantations – can increase the risk of further forest conversion due to increased economic returns at the forest frontier[12,16] and documented contagion effects of regional deforestation[38]. Consequently, it is essential for protected areas to be strongly enforced in any application of a sparing land-use strategy for forests. Moreover, the requirements and challenges of protection will vary with factors including accessibility, the opportunity costs of forest protection to a range of actors, and both the willingness and the capacity of the government and other owners or controllers of land (e.g., concessionaires, village forest leaders) to enforce bans on forest degradation and deforestation[39].

Although we fix total economic returns in terms of NPV, the reality is that the economic costs and revenues from wood production would flow at different times, and to different sectors. For instance, in a forest sharing strategy, selective logging companies would be the main economic beneficiaries, but revenues would decline after the first cutting cycle in many cases[29]. Alternatively, in a sparing strategy, private plantation owners would receive a large share of the profits, with much of these flowing towards the beginning of the time period when forest conversion occurs. These temporal fluctuations in wood production would also impact local markets and prices, adding uncertainty to the NPV calculations used here. Future planning strategies would ideally integrate the uncertainties associated with NPV calculations, unplanned deforestation, and other modelling parameters.

Also under a sparing strategy, while plantation owners would profit, the government and local communities would bear most of the economic burden. The upfront financial cost of establishing and enforcing protected areas would largely fall to the government, and the opportunity costs of foregone small-scale forest extraction could be borne by local communities. Critically, these different groups are likely to have different economic utility – a given increase in wealth is likely to be of greater relative benefit to a local community than to the government or large plantation owners. In cases of weak governance in tropical developing countries, this may result in limited management of protected areas and forest conversion which would undermine conservation gains and the benefits of a sparing strategy. To avoid this perverse outcome we recommend integrating conservation and production goals in land-use planning[40] - as we have done here - and ensuring the plan is implemented through close partnerships with local actors, particularly local forest-dependent communities and the agricultural sector. Alternatively, intensification could be linked to strict protection through innovative finance mechanisms (such as levies on production) that could subsidise programs that offset the lost livelihoods and other opportunity costs of the strict management of protected areas. In the case of Indonesia, East Kalimantan's Green Growth Compact and Governor's decree to halt new logging and plantation permits[41] provide reason for some guarded optimism that the conservation benefits from sparing could be realised.

Under a sharing strategy, the expansion of selective logging requires new roads in remote forest regions, which can also catalyse deforestation and exploitation, especially where governance is weak[42]. Increased accessibility may also heighten the forests' susceptibility to fire and other natural disturbances[43], which can also have adverse social impacts, including exposure to hazardous levels of air pollution in the surrounding areas and beyond[44]. Conversely, a growing body of evidence indicates that legal selective logging concessions[25], particularly under certified improved management[42], can often reduce the risk of unplanned deforestation better than protected areas. Our analysis suggests that improved forestry practices across all management types account for both larger and more reliable conservation gains than any sharing or sparing strategy described here. Therefore, we recommend strengthening ongoing efforts to improve forest management in the tropics, such as through REDD+ and FSC certification (where additionality can be established), and community forest management initiatives.

For forests to provide viable habitat for biodiversity, it is of utmost importance to prevent hunting for bushmeat consumption and the wildlife trade, which can be a bigger threat than the direct habitat disturbance from logging for many species[34]. Yet, in Southeast Asia, an unprecedented defaunation of forests is underway due to hunting, especially for the trade of birds as pets, but also for mammals including the Bornean orangutan (*Pongo pygmaeus*[45]), pangolins (*Manis javanica*) and large flying foxes (*Pteropus vampyrus*)[46]. Enforcement of hunting bans coupled with programs that provide an alternate source of protein or income for local communities should be an integral part of improved forest management[47].

Improving forest management could also bring broader socio-ecological benefits beyond timber and biodiversity. Effectively managing protected areas is likely to require additional personnel[48], thereby increasing employment opportunities, and certified selective logging can (although not always) bring social benefits by improving worker safety and job security[49]. Improved management in protected areas and selective logging concessions is also likely to have carbon co-benefits[50]. While carbon sequestration has primarily global benefits, it is also of particular relevance to East Kalimantan, which has been selected as a World Bank REDD+ implementation site to pilot broad-scale emission reductions and payment schemes. Other ecosystem services, such as flood prevention and temperature regulation, have even greater relevance to local communities[51] and are also likely to be delivered through improved forest management. These broader social-ecological benefits should also be considered to help ensure human well-being is attained alongside benefits to biodiversity across sparing-to-sharing landscapes[52].

Improved management, in conjunction with systematic planning[40,53], can maintain economic production from tropical forests while delivering substantial biodiversity outcomes at a broad scale. Our results indicate that these conservation gains could be greater than those achieved from altering the balance between sparing or sharing in the landscape, despite the higher costs often involved in better management. These gains are also likely to be more reliable in practice – improving management through investment in managing protected areas and innovative logging methods can resist the forest conversion pressures[25] associated with intensification. Based on our findings, it is time to question the utility of framing forest management within the sparing versus sharing dichotomy. Tropical forests are highly diverse systems with immense conservation value and production potential. Restricting broad-scale management options to only sparing or sharing strategies risks oversimplifying the complexity of these systems, and will ultimately deliver sub-optimal outcomes for biodiversity conservation. This is of particular concern as many tropical forest species are already facing extinction, and require immediate, co-ordinated, and effective action to reverse the decline[54]. This highlights the vital importance of bolstering ongoing efforts to improve forest management throughout the tropics. Ultimately, debating sparing versus sharing may only serve to distract research and management efforts while large gains from improving forest management go untapped.

Methods

Framework and context

The land sparing versus land sharing framework was initially defined for agricultural landscapes, considering food production and biodiversity as primary objectives[55]. Land sparing was defined as intensifying production to maximise agricultural yield within a fixed area, and dedicating other land to biodiversity conservation. Conversely, land sharing (or 'wildlife-friendly farming') aimed to maintain biodiversity within less intensively farmed agricultural landscapes[18]. Here, we adapted this framework by substituting intensively managed *Acacia* plantations for high-yield farmland, and selective logging of natural forests for wildlife-friendly farming (Fig. 1). We defined the continuum of sparing-to-sharing by the proportion of selective logging in the landscape (relative to protected areas and wood plantations). However, these broad categories (protected areas, selective logging, and plantations) overlook the potential to improve the way tropical forests can be managed. Therefore, we selected at least one conventional and one improved management type for each broad category, resulting in eight different management types in total (Table 1). These management types are relevant to the forest estate within the East Kalimantan Province, while also including aspirational – yet feasible – options for improvement.

Net Present Value

To determine the optimal allocation of forest management strategies we need to know the Net Present Values (NPVs) of the different forest management types across the landscape to give a standardised measure of economic value. Alternative measures, such as the volume of wood harvested, were not comparable across management types, as wood destined for hardwood products is more valuable than wood destined for pulp and paper. For each management type, the NPV was calculated over 60 years at a 6% discount rate[56] and all values are given in USD. The NPVs of protected areas included the one-off establishment cost along with annual management costs that differed under the strict and limited management types[48]. Costs and revenue calculations for logging and plantations were informed by growth and yield modelling, information gathered from reviewing relevant literature, and data obtained from internal company reports during visits to nine logging concessions in East Kalimantan in April and May 2017. For selective logging management types, we determined profits to the landholder by calculating the revenue from harvest less harvesting costs (i.e., felling, skidding, and hauling), taxes, and for the enrichment planted stands, the costs of planting and tending. We modelled 30-year cutting cycles, assuming that 1/30 of the harvestable area within each planning unit was logged in each year (on average). The costs were modified by slope and accessibility, while the volume of timber harvested varied with logging history, aboveground biomass, and forest management type (at the second harvest). For *Acacia mangium* plantations, profits were determined by calculating the harvest revenues, less the costs of planting, maintenance, harvesting, transport, and taxes, while accounting for slope, elevation and soil type (peat or mineral). In some cases, *Acacia mangium* plantations also produced additional revenue from clear-felling intact and logged forest prior to plantation establishment.

Given the uncertainty in parameter estimation for NPV calculations, and the potential for future changes (such as market prices), we determined the impact of potential variation in the relative NPVs between the sparing and sharing strategies, and between conventional and improved management strategies. Specifically, we varied the relative NPVs between protected areas, selective logging, and *Acacia mangium* plantations by ± 25%, and separately varied the conventional management strategies by ± 25% (Table S5). We also varied the discount rate between 3% and 10%. A detailed description of NPV calculations is given in the Supplementary Information.

Conservation objectives

Our conservation objectives are to preserve suitable habitat for mammal species and maintain the values and purpose of High Conservation Value (HCV) areas. We used species distributions for primates, carnivores, and bats from Struebig *et al.*[57] and HCV areas from Wells, Paoli, & Suryadi[27]. To quantify the potential impact of each forest management type on species' habitats and HCV areas, we conducted a Delphi expert elicitation process (Supplementary Information). We chose this process over more formal data analysis for two reasons: (i) East Kalimantan is a relatively data-poor region; and (ii) some of the improved forest management strategies considered in this study (Table 1) are not yet widely practiced in the region, which limits our ability to statistically correlate management with impact. The Delphi method includes feedback to respondents over multiple rounds, which can reduce biases[58,59]. Participants scored the impact of each management type on the habitat quality for each species, and the extent to which each management type maintained the values and purpose of each HCV. We then calculated the time-averaged habitat quality over 60 years, accounting for transitions between different management types (Supplementary Information). A sensitivity analysis was conducted which included the upper and lower bounds from the Delphi process for each species and HCV class, and also an alternative threshold for classifying the species distribution (Table S5).

Spatial optimisation

For the continuum of sparing-to-sharing strategies, we aimed to maximise the amount of habitat suitable for each mammal species and for HCV areas, subject to the landscape producing a set economic value. We formulated our approach as an integer linear programming problem, similar to Marxan with Zones[60,61]. The general form of the problem is:

Maximise: $$\sum_{a=1}^{A} w_a \sum_{k=1}^{K}\sum_{i=1}^{N} r_{aik} x_{ik} \qquad (1)$$

subject to: $$\sum_{k=1}^{K}\sum_{i=1}^{N} v_{ik} x_{ik} \geq T \quad , \qquad (2)$$

$$\sum_{k=1}^{K} x_{ik} = 1 \quad , \forall i , \; i = 1.... N , \qquad (3)$$

$$P \geq \sum_{k=3}^{6}\sum_{i=1}^{N} s_i x_{ik} \geq Q \quad \text{, and} \qquad (4)$$

$$x_{ik} \in \{0,1\} \qquad (5)$$

Where:

- w_a is the weight allocated to objective *a,*
- r_{aik} is the standardised value of objective *a* for planning unit *i* in zone *k*,
- x_{ik} is a binary decision variable that is 1 when planning unit *i* is assigned to zone *k* and 0 otherwise (Eqn. 5); Eqn. 3 ensures every planning unit is assigned to one zone only,
- v_{ik} is the NPV of assigning planning unit *i* to zone *k*,
- *T* is the minimum NPV that must be produced from the final zone allocation,
- s_i is the size (area) of planning unit *i*,
- zones *k* = 3…6 are the selective logging management types (conventional logging, RIL Level 1, RIL Level 2, and strip planting), and
- *Q* is the minimum area to be allocated to selective logging, and *P* is the maximum area (Eqn. 4).

Our aim is to maximise the objective function (Eqn. 1) which is a weighted sum of the objectives (i.e., amount of suitable habitat for mammal species and HCV areas) across the landscape. In subsequent scenarios, we altered this objective to focus on species only, HCV areas only, specific taxonomic groups, or IUCN Red List statuses to determine if this altered the impacts of sparing-to-sharing strategies. The first constraint (Eqn. 2) ensures a minimum NPV across the landscape. This East Kalimantan-wide minimum NPV was set at $8,764 million USD to match the amount that could be extracted if all current logging and plantation concessions were fully active (but still within biophysical and legislative constraints). To calculate this figure, conventional management was assumed except for some logging concessions in which RIL is known to be practiced[62]. Given the likely increases in future demands for both timber and pulp, we tested the sensitivities of our findings to different province-wide NPVs from forest and plantation land by varying East Kalimantan-wide minimum NPV from $0 to $20 billion. This allowed us to determine the sensitivity of sparing and sharing to the level of production in the landscape. The third constraint (Eqn. 4) restricts the area allocated for selective logging (any of conventional logging, RIL Level 1, RIL Level 2, and strip planting) to be greater than or equal to *Q* and less than or equal to *P*. This range was iterated in increments representing 2.5% of the landscape to force varying degrees of sparing and sharing. For instance, a value of zero allocated to *P* represents extreme sharing, with only wood fibre plantations (long or short rotation *Acacia mangium*) or protected areas (with strict or limited management) permitted.

Planning units were created using 1 km^2 hexagons, further divided by riparian zones and official land allocations (Supplementary Information). This resulted in 101,875 planning units that averaged 79.8 ha each. We then restricted these planning units such that they could only be selected if the forest management type was legally permitted and physically possible: officially designated[63] protection forest (*Hutan Lindung*, HL) and conservation areas (*Hutan Konservasi*, KSA/KPA) allow only protected areas; limited production forest (*Hutan Produksi Terbatas,* HPT) allows protected areas and selective logging; existing *Acacia* plantations could not be logged for natural forest timber or protected; and all other areas (i.e. production forest [*Hutan Produksi*. HP, and *Hutan Produksi Konversi*, HPK]) are unconstrained.

For comparison, we ran the optimisation for two broad problems: (i) “improved management”, where any management type from Table 1 could be selected; and (ii) “conventional only”, where the problem was constrained such that only the conventional management types from Table 1 were permitted. This enabled a comparison between the relative contribution of improved management and gains from altering the balance between sparing or sharing. We also conducted a sensitivity analysis using a range of parameter combinations to calculate conservation objectives and NPV (Table S5). We ran both broad problems across the full continuum from sparing-to-sharing (29 points), 11 different combinations of conservation objectives (e.g., targeting specific taxa or threatened status), three variations on how conservation objectives were calculated, and 11 different variations of the NPVs. This resulted in 4,466 scenarios for each broad problem.

Data availability

The datasets analysed in this paper are available via *[DOI to be inserted upon acceptance]*.

Code availability

We formulated the integer linear programming problem using the R programming language [64], and solved it using the software Gurobi[65]. The R code is available from the corresponding author upon reasonable request.

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Author Contributions

B.G., O.V., R.K.R., E.T.G., Z.B., F.E.P., R., J.A.W., P.E., S.M.L., and M.S. conceptualised the manuscript. R.K.R., R., M.J.S., M.S., and J.A.W. developed the spatial data inputs. R.K.R. led the expert elicitation with input from E.M., M.J.S., O.V., N.J.D., A.W., E.T.G., S.M.C., M.S., A.J.M., B.G., F.A.A.K., M.A., and Z.B.. R.K.R. conducted the analyses. All authors interpreted the results and contributed to writing the paper.

Competing interests

The authors declare no competing interests.

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