Larger gains from improved management over sparing–sharing for tropical forests

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Tropical forests are globally important for both biodiversity conservation and the production of economically valuable wood products. To deliver both simultaneously, two contrasting approaches have been suggested: one partitions forests (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. We explore the delivery of biodiversity and wood products in a continuum of sparing-to-sharing scenarios, using spatial optimization with set economic returns in East Kalimantan, Indonesia—a 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, provided larger conservation gains than altering the balance between sparing and sharing, particularly for endangered species. Ultimately, debating sparing versus sharing has limited value while larger gains remain from improving forest management.

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, 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 since 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 US$15.2 billion annually to the gross domestic product (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

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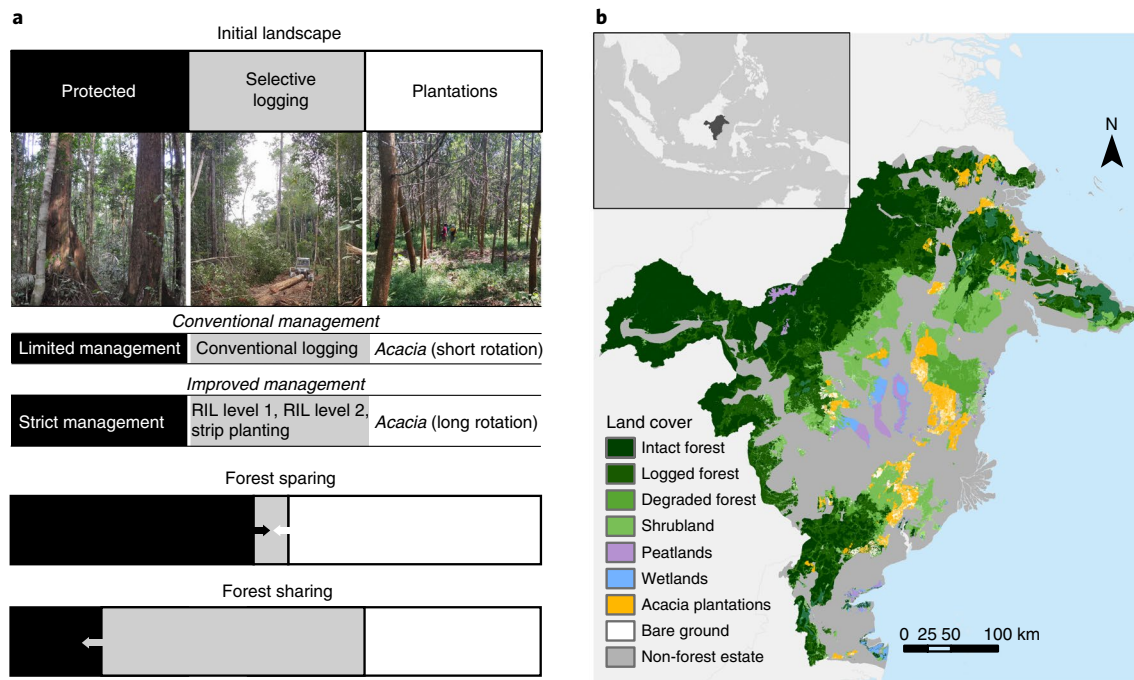
Fig. 1 | The context of the study. a, Conceptual framing of sparing and sharing strategies for tropical forests, including conventional and improved management types for each broad land-use category. Definitions of each management type are given in Table 1. Photographs are all in East Kalimantan including (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). **b**, 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 because they are not permitted within the forest estate (placed in the non-forest estate here).

the biodiversity value is derived from the spared land, since 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 broadscale 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 landscapes and seascapes are managed is at the heart of global conservation and sustainability strategies (for example, the Sustainable Development Goals[6] and the Convention on Biological Diversity[4]). In a shared landscape,

reduced-impact logging (RIL) practices can minimize the disturbances caused by logging without impacting the volume of timber extracted[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 scenario, since 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.

In this study, 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 broadscale spatial optimization of management types. The optimal spatial configuration is achieved by fixing the total economic returns across the landscape and maximizing the conservation of habitat suitable for regional mammal species and areas of high conservation value (HCV), 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 (that is, 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.

Results

Our spatial optimization of management types revealed both expected and unexpected outcomes for broadscale 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 mangium* plantations tended to be located in degraded forest, scrubland 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 (Figs. 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 mangium* 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 mangium* plantations by 25%. In contrast, increasing the NPV threshold (that is, 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). 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 (that is, 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

Table 1 | Conventional and improved forest management types considered for protected areas, selective logging and wood plantations

Management type	Description
1. Protected areas	
Conventional:	
1a. Limited management	The area is protected but there is limited control of threatening processes (for example, 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 ≥ 40 cm diameter at breast height. Logging damage averages 52.3 Mg C ha^{-1} from hauling, felling and skidding[a].
Improved:	
2b. RIL level 1 (tractor yarding)	Logging intensity matches conventional logging but the damage is 69% of conventional logging per m³ of timber extracted due to better planning and training[a].
2c. RIL level 2 (cable yarding)	Logging intensity matches conventional logging, but the damage is 54% of conventional logging per m³ of timber extracted due to better planning and training, and the use of cable yarding[a].
2d. Strip planting	Areas within 200 m of logging roads are enriched with commercial timber species along cleared lines[28]. 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 mangium* plantations with 7-year rotations that yield 160 m³ ha^{-1} of wood at each harvest, all of which is used for pulp.
Improved:	
3b. *Acacia mangium* (long rotations)	*Acacia mangium* plantations with 12-year rotations that yield 180 m³ ha^{-1} of wood at each harvest; 60% is for pulp and 40% is for saw/veneer logs.

[a]B.W.G., manuscript in preparation

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.

Discussion

We evaluated the effectiveness of sparing and sharing strategies for tropical forests using landscape-scale spatial optimization of forest management strategies. While the optimal strategy fell towards the sparing end of the continuum for all conservation objectives (Figs. 2 and 3a), our results challenge the dichotomy of the sparing versus sharing debate, since 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
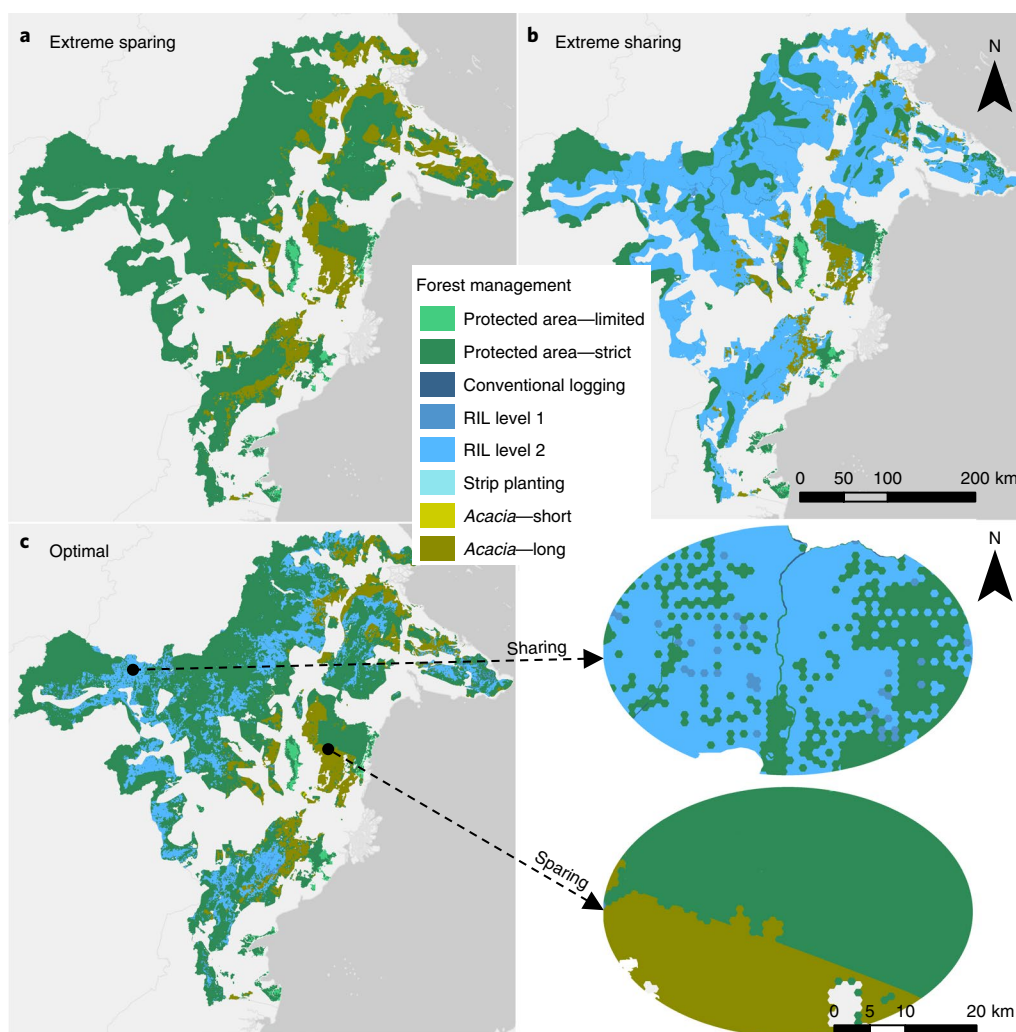
Fig. 2 | Spatial sparing and sharing scenarios. a, Extreme sparing. **b,** Extreme sharing. **c,** Optimal spatial configuration. Extreme sparing comprises 18% *Acacia mangium* plantations, with the remainder protected; extreme sharing comprises 64% selective logging, 7% *Acacia mangium* plantations, with the remainder protected; the optimal strategy comprises 21% selective logging, 12% *Acacia mangium* plantations, with the remainder protected. The optimal strategy is mixed, with elements of both sparing and sharing at finer scales.

logging, reduced-impact logging with cable yarding dominated the solutions, and long rotations were preferable for *Acacia mangium* 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 that 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 forests, they tended to also have higher harvesting and transport 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[28]. Selectively logging remaining primary forests is also generally considered to have poor outcomes for biodiversity[29]. Therefore, while logging of primary forests 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 maximizing species richness and HCV areas through large protected areas (66% of the forest estate) (Fig. 3b). It is widely recognized that large, contiguous areas of protected forest sustain natural ecological and evolutionary processes, providing a set of high-value ecosystem services, including the regulation of hydrological cycles at multiple scales and the storage of substantial carbon stocks[30]. They are also critically important for in situ biodiversity conservation, supporting the last intact forest-dependent megafaunal assemblages, wide-ranging and migratory species, and species sensitive to exploitation by or conflicts with humans[31].

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; however, the recovery of animal populations after selective logging can have substantial temporal variability[32]. While the richness of medium-to-large mammals can recover in as little as 10 years after logging[33],
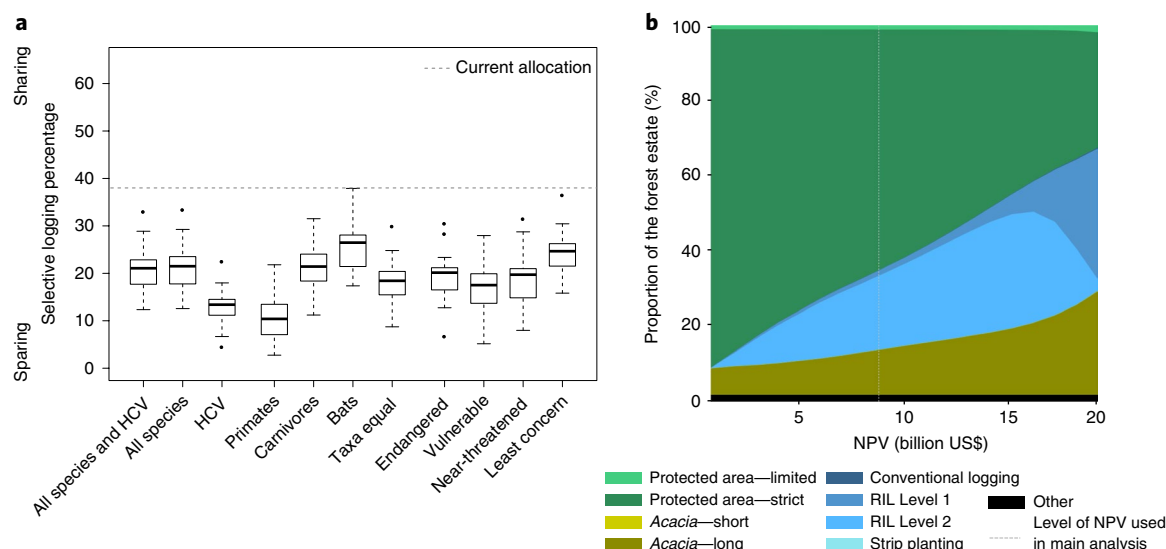
Fig. 3 | Optimal sparing or sharing strategies. a, Variation in the optimal point on the sparing-to-sharing continuum for a range of conservation objectives for a fixed NPV threshold. The variation is represented by a sensitivity analysis of conservation parameters and relative NPVs for each forest management type (Supplementary Table 5). Selective logging can comprise a maximum of 65% of the landscape because of 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. **b**, Optimal proportion of the landscape in each forest management type across a range of NPV thresholds. More than US$20 billion NPV could not be extracted from the landscape within the biophysical and administrative restrictions.

bird species that are particularly sensitive to selective logging (for example, the great argus (*Argusianus argus*) or striped wren-babbler (*Kenopia striata*)) do not show signs of population recovery 40 years after logging[34], and achieving a community composition similar to primary forest may require more than 150 years[35]. 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[35]. In addition, species richness scales with the size of a habitat patch, even within a landscape matrix of different habitat qualities[36], 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 mangium* 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 β- 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 the documented contagion effects of regional deforestation[37]. 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 capacity of the government and other owners or controllers of land (for example, concessionaires, village forest leaders) to enforce bans on forest degradation and deforestation[38].

Although we fixed 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[28]. Alternatively, in a forest 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 in this study. Future planning strategies would ideally integrate the uncertainties associated with NPV calculations, unplanned deforestation and other modelling parameters.

Also under a forest 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 would 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[39]—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 subsidize s 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[40] provide reason for some guarded optimism that the conservation benefits from sparing could be realized.

Under a sharing strategy, the expansion of selective logging requires new roads in remote forest regions, which can also catalyse
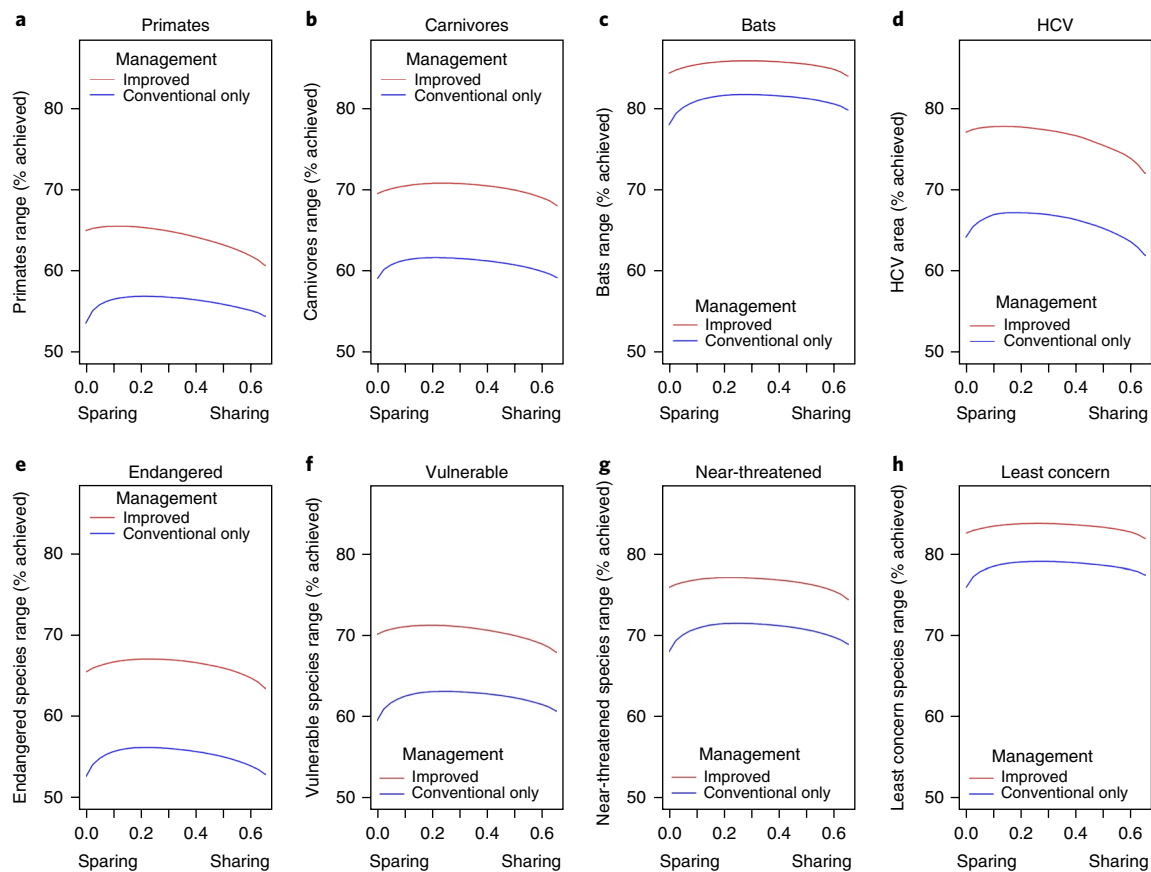
Fig. 4 | The sparing-to-sharing continuum for different taxa and IUCN red list categories when either allowing improved management (red) or constraining the problem to conventional management types (blue). a–h, The following groupings were considered: primates (**a**); carnivores (**b**); bats (**c**); HCV areas (**d**); endangered or critically endangered (**e**); vulnerable (**f**); near-threatened (**g**); least concern (**h**). 'Range % achieved' refers to the habitat quality × area (that is, 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 the difference between conventional and improved management are shown in Fig. 2a and Fig. 5, respectively.

deforestation and exploitation, especially where governance is weak[41]. Increased accessibility may also heighten the forests' susceptibility to fire and other natural disturbances[42], which can also have adverse social impacts, including exposure to hazardous levels of air pollution in the surrounding areas and beyond[43]. Conversely, a growing body of evidence indicates that legal selective logging concessions[25], particularly under certified improved management[41], 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+ (reducing emissions from deforestation and degradation) and Forest Stewardship Council 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[33]. Yet, in South East 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 (*P. pygmaeus*[44]), Sunda pangolin (*Manis javanica*) and large flying fox (*Pteropus vampyrus*)[45]. Enforcement of hunting bans coupled with programmes that provide an alternate source of protein or income for local communities should be an integral part of improved forest management[46].

Improving forest management could also bring broader socio-ecological benefits beyond timber and biodiversity. Effectively managing protected areas is likely to require additional personnel[47], thereby increasing employment opportunities, and certified selective logging can (although not always) bring social benefits by improving worker safety and job security[48]. Improved management in protected areas and selective logging concessions are also likely to have carbon co-benefits[49]. 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 broadscale emission reductions and payment schemes. Other ecosystem services, such as flood prevention and temperature regulation, have even greater relevance to local communities[50] and are also likely to be delivered through improved forest management. These broader socioecological benefits should also be considered to help ensure human well-being is attained alongside benefits to biodiversity across sparing-to-sharing landscapes[51].

Improved management, in conjunction with systematic planning[39,52], 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.
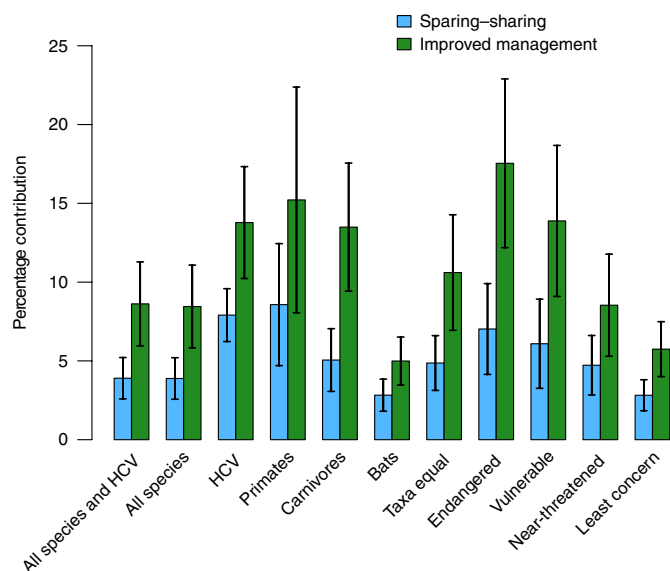
Fig. 5 | Contribution to the optimal objective value from improved management and sparing/sharing strategies across the range of conservation objectives. The contributions of sparing versus sharing were calculated as the difference between the best and worst performing points on the sparing-to-sharing continuum, as a percentage 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 percentage of the performance of the optimal solution. The error bars represent the minimum and maximum resulting from the sensitivity analysis.

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 broadscale management options to only sparing or sharing strategies risks oversimplifying the complexity of these systems, and will ultimately deliver suboptimal outcomes for biodiversity conservation. This is of particular concern since many tropical forest species are already facing extinction, and require immediate, coordinated and effective action to reverse the decline[53]. 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[54]. Land sparing was defined as intensifying production to maximize 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]. In this study, we adapted this framework by substituting intensively managed *Acacia mangium* plantations for high-yield farmland, and selective logging of natural forests for wildlife-friendly farming (Fig. 1). We defined the sparing-to-sharing continuum 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.

NPV. To determine the optimal allocation of forest management strategies, we needed to know the NPVs of the different forest management types across the

landscape to give a standardized measure of economic value. Alternative measures, such as the volume of wood harvested, were not comparable across management types because 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[55] and all values are given in US$. The NPVs of protected areas included a one-off establishment cost along with annual management costs that differed under the strict and limited management types[47]. Costs and revenue calculations for logging and plantations were informed by growth and yield modelling, information gathered from reviewing the 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 minus harvesting costs (that is, 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, above-ground biomass and forest management type (at the second harvest). For *Acacia mangium* plantations, profits were determined by calculating the harvest revenues, minus 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 forests before 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% (Supplementary Table 5). We also varied the discount rate between 3 and 10%. A detailed description of the 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 HCV areas. We used species distributions for primates, carnivores and bats from Struebig et al.[56] and HCV areas from Wells, Paoli and 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: (1) East Kalimantan is a relatively data-poor region; and (2) some of the improved forest management strategies considered in this study (Table 1) are not yet widely practised 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[57,58]. 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; this included the upper and lower bounds from the Delphi process for each species and HCV class, and also an alternative threshold for classifying species distribution (Supplementary Table 5).

Spatial optimization. For the continuum of sparing-to-sharing strategies, we aimed to maximize 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[59,60]. The general form of the problem is:

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

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

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

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

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

where: w_a is the weight allocated to objective a; r_{aik} is the standardized 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 (equation 5); equation 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), Q is the minimum area to be allocated to selective logging and P is the maximum area (equation 4).

Our aim is to maximize the objective function (equation 1), which is a weighted sum of the objectives (that is, the 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 (equation 2) ensures a minimum NPV across the landscape. This East Kalimantan-wide minimum NPV was set at US$8,764 million 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 practised[61]. 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 US$0 to US$20 billion. This allowed us to determine the sensitivity of sparing and sharing to the level of production in the landscape. The third constraint (equation 4) restricts the area allocated for selective logging (any of conventional logging, RIL Level 1, RIL Level 2 and strip planting) to be $\geq Q$ and $\leq P$. 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 km² 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 so that they could only be selected if the forest management type was legally permitted and physically possible: officially designated[62] protection forest (*Hutan Lindung*) and conservation areas (*Hutan Konservasi*) allow only protected areas; limited production forest (*Hutan Produksi Terbatas*) allows protected areas and selective logging; existing *Acacia mangium* plantations could not be logged for natural forest timber or protected; all other areas, that is, production forest (*Hutan Produksi* and *Hutan Produksi Konversi*) are unconstrained.

For comparison, we ran the optimization for two broad problems: (1) 'improved management', where any management type from Table 1 could be selected; and (2) 'conventional only', where the problem was constrained so that only the conventional management types from Table 1 were permitted. This enabled a comparison between the relative contribution of improved management and the 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 NPVs (Supplementary Table 5). We ran both broad problems across the full continuum from sparing to sharing (29 points), 11 different combinations of conservation objectives (for example, targeting specific taxa or threatened status), 3 variations on how conservation objectives were calculated and 11 different variations of the NPVs. This resulted in 4,466 scenarios for each broad problem.

Code availability

We formulated the integer linear programming problem using the R programming language[63] and solved it using the software Gurobi[64]. The R code is available from the corresponding author upon reasonable request.

Data availability

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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. conceptualized 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.

Additional information

Larger gains from improved management over sparing–sharing for tropical forests

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Supplementary Information

Larger gains delivered by improved management over sparing-sharing for tropical forests

Runting et. al. *Nature Sustainability.*

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<u>Supplementary Methods</u>

<u>Biodiversity</u>

Expert elicitation:

We conducted a Delphi expert elicitation process with the aim to quantify the expected impacts of each forest management type on biodiversity and areas of high conservation value. Human ethics approval was obtained for this process from The University of Queensland (approval no. 2017000905). The goal of the Delphi process was to elicit the impact of each forest management type on biodiversity and estimate the uncertainty associated with these impacts. When combined with spatial information on species distributions and high conservation value areas, this was used to inform the spatial optimisation of forest management types within the forest estate of East Kalimantan. Specifically we aimed to:

A. Determine the impact of each forest management type on habitat quality for mammal species (from Struebig *et al.*[1]);
    i. *Primates*, individually for 13 species,
    ii. Carnivores (*Carnivora*), individually for 22 species,
    iii. Bats (*Chiroptera*), 45 species across 3 separate subgroups based on sensitivity to disturbance (in Wilson *et al.*[2]).
    A full list of species is provided in Table S1.

B. Determine how the values and purposes of 5 HCV classes (from Wells *et al.*[3]) would be affected by each forest management type;

    i. HCV 1.1 - Areas that contain or provide biodiversity support functions for protection or conservation areas,

    ii. HCV 2.1 - Large landscapes with the capacity to maintain natural ecological processes and dynamics,

    iii. HCV 2.2 - Areas that contain two or more contiguous ecosystems,

    iv. HCV 3 - Rare or endangered ecosystems,

    v. HCV 4.1 - Areas critical for the provision of water and prevention of floods.

Table S1 | Species included in the analysis. *Chiroptera* was grouped by sensitivity to disturbance.

CARNIVORA	PRIMATES	CHIROPTERA		
		Low sensitivity	*Medium sensitivity*	*High sensitivity*
Aonyx cinereus	Cephalopachus bancanus	Cynopterus brachyotis	Balionycteris maculata	Aethalops aequalis
Arctictis binturong	Hylobates albibarbis	Cynopterus horsfieldi	Chironax melanocephalus	Hipposideros doriae
Arctogalidia trivirgata	Hylobates muelleri / funereus	Eonycteris spelaea	Dyacopterus spadiceus	Hipposideros ridleyi
Catopuma badia	Macaca fascicularis	Hipposideros diadema	Eonycteris major	Kerivoula minuta
Cynogale bennettii	Macaca nemestrina	Hipposideros galeritus	Hipposideros ater	Kerivoula pellucida
Diplogale hosei	Nasalis larvatus	Hipposideros larvatus	Hipposideros bicolor	Murina aenea
Hemigalus derbyanus	Nycticebus coucang	Kerivoula papillosa	Hipposideros cervinus	Murina rozendaali
Herpestes brachyurus	Pongo pygmaeus	Macroglossus minimus	Hipposideros cineraceus	Nycteris tragata
Herpestes semitorquatus	Presbytis chrysomelas	Megaderma spasma	Hipposideros dyacorum	Rhinolophus sedulus
Lutra sumatrana	Presbytis frontata	Megaerops ecaudatus	Kerivoula hardwickii	
Lutrogale perspicillata	Presbytis hosei	Penthetor lucasi	Kerivoula intermedia	
Martes flavigula	Presbytis rubicunda	Pteropus vampyrus	Megaerops wetmorei	
Mustela nudipes	Trachypithecus cristatus	Rhinolophus acuminatus	Murina cyclotis	
Mydaus javanensis		Rhinolophus affinis	Murina suilla	
Neofelis diardi (old nebulosa)		Rhinolophus borneensis	Phoniscus atrox	
Paguma larvata		Rhinolophus luctus	Rhinolophus creaghi	
Paradoyurus hermaphroditus		Rhinolophus philippinensis	Rhinolophus trifoliatus	
Pardofelis marmorata		Rousettus amplexicaudatus	Rousettus spinalatus	
Prionailurus bengalensis				
Prionailurus planiceps				
Prionodon linsang				
Viverra tangalunga				

We used the four-point estimation method to capture the uncertainty and confidence in experts' responses, which is the best practice for eliciting quantitative values from experts for conservation applications[4–6]. This involves eliciting experts "best guess", upper and lower bounds, and their confidence in their "best guess". Specifically, they were asked:

1) For each forest management type, what do you think is the most likely outcome in terms of habitat quality for species X (time averaged)?

2) For each forest management type, what do you think is the best outcome in terms of habitat quality for species X (time averaged)?

3) For each forest management type, what do you think is the worst outcome in terms of habitat quality for species X (time averaged)?

4) For the interval created (lower and upper bound), what is the probability between 0% and 100% that the best estimate for habitat quality will fall within these bounds?

These questions were linked to a graph for an instant visualisation of responses (Fig. S1), and were distributed via email.

(a)

HCV 1.1

	For each forest management type, what do you think is the most likely outcome in terms of maintaining the values and purpose of HCV 1.1 (time averaged)	For each forest management type, what do you think is the best outcome in terms of maintaining the values and purpose of HCV 1.1 (time averaged)	For each forest management type, what do you think is the worst outcome in terms of maintaining the values and purpose of HCV 1.1 (time averaged)	For the interval created (lower and upper bound), what is the probability between 0% and 100% that the best estimate will fall within these bounds?	
Forest management type (click/hover for definitions)	*Best estimate*	*Upper bound*	*Lower bound*	*Confidence*	*Comments/rationale/sources*
1b. Protected: Strict management	0.5	1	0	100	
1a. Protected: Limited management	0.5	1	0	100	
2b. RIL-C Level 2 (cable yarding)	0.5	1	0	100	
2c. RIL-C Level 1 (tractor)	0.5	1	0	100	
2a. Conventional Logging	0.5	1	0	100	
2d. SILIN/Strip planting	0.5	1	0	100	
3b. Acacia mangium (long rotation)	0.5	1	0	100	
3a. Acacia mangium (BAU)	0.5	1	0	100	

Back to species/HCV list

HCV 1.1: Areas that contain or provide biodiversity support functions for protection or conservation areas

Location:
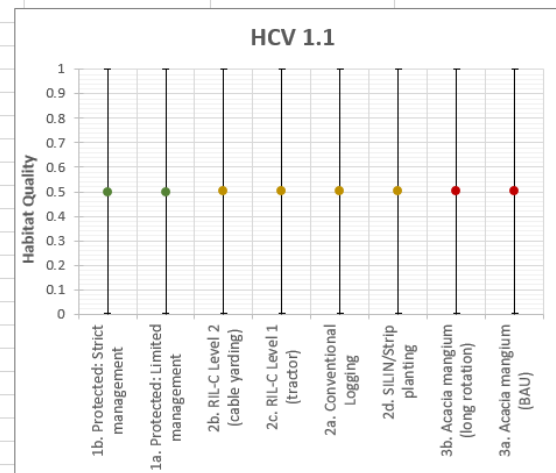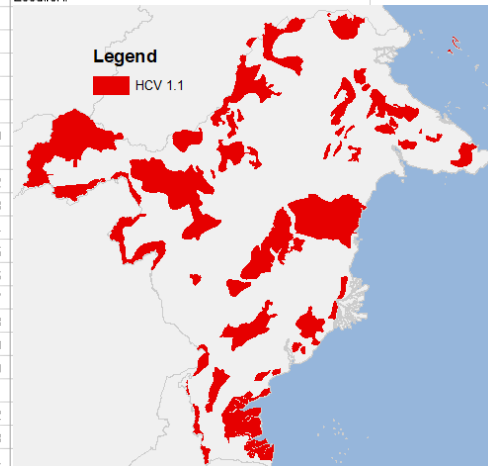
HCV 1 General information (from Pollard et al (2005))

Value	Threats	Conservation goal	Conservation method	Potential strategies
HCV1 Biodiversity concentration	• Hunting • Destructive fishing • Road construction • Felling and skidding	• Conserve populations of rare, threatened, endangered and endemic species. • Conserve overall high levels of biodiversity	• Ban hunting of specific species • Ban destructive fishing • RIL • Conservation zones	• Enforcing the ban on all hunting by SLJ staff. • Environmental awareness to encourage local communities not to hunt protected species • Further improvement of RIL techniques and skyline use to minimise environmental impact. • Representative conservation zones including examples of all ecosystems.

HCV1. Forest areas containing globally, regionally or nationally significant concentrations of biodiversity values (e.g. endemism, endangered species, refugia)

What is happening / stress	Potential impact on value	Cause/Source (likely contribution to the stress)	Notes/Examples
Species loss/extinction	Very High	• Hunting & Fishing (high) • Felling (high) • Skidding (medium) • Roading and yarding (medium) • Forest clearance/Ladang (low) • Forest clearance/other land use (medium)	The Asian two-horned rhino is now probably extinct in East Kalimantan. Contributing factors include heavy hunting pressure (Rabinowitz 1995; Meijaard 1996)
Species composition change	High	• Hunting & Fishing (high) • Felling (very high) • Skidding (high) • Roading and yarding (high) • Forest clearance/Ladang (high) • Forest clearance/other land use (very high)	Logging operations lead to an increase of the percentage of pioneer plant species (Fimbel et al 2001). Some bird species are severely impacted by logging and their populations decline (Zakaria & Francis 2001). Post logging populations of Red Muntjak (*Muntiacus muntjak*) increase and populations of Yellow Muntjak (*M. atherodes*) decrease.
Behaviour change	Low	• Felling (high) • Roading and yarding (high)	Gibbon home range size has been shown to increase after logging and they become less vocal. Possibly due to reduced food availability. (Johns 1986)

3

(b) Aonyx cinereus

Asian Small-clawed Otter

Forest management type (click/hover for definitions)	Best estimate	Upper bound	Lower bound	Confidence	Comments/rationale/sources
	For each forest management type, what do you think is the most likely outcome in terms of habitat quality for Aonyx cinereus (time averaged)	For each forest management type, what do you think is the best outcome in terms of habitat quality for Aonyx cinereus (time averaged)	For each forest management type, what do you think is the worst outcome in terms of habitat quality for Aonyx cinereus (time averaged)	For the interval created (lower and upper bound), what is the probability between 0% and 100% that the best estimate for habitat quality will fall within these bounds?	
1b. Protected: Strict management	0.5	1	0	100	
1a. Protected: Limited management	0.5	1	0	100	
2b. RIL-C Level 2 (cable yarding)	0.5	1	0	100	
2c. RIL-C Level 1 (tractor)	0.5	1	0	100	
2a. Conventional Logging	0.5	1	0	100	
2d. SILIN/Strip planting	0.5	1	0	100	
3b. Acacia mangium (long rotation)	0.5	1	0	100	
3a. Acacia mangium (BAU)	0.5	1	0	100	

Back to species list

Link to IUCN Red List information

Figure S1 | An example of the questionnaire and information provided to respondents for a HCV class (HCV 1.1) (a), and an individual species (*Aonyx cinereus*) (b).

The group consisted of 14 experts, who self-selected which species/HCV questionaries to complete based on their expertise. This resulted in 4-7 experts per taxonomic group and HCV class. Numbers were kept small to easily facilitate discussion and participants could ask clarifying questions from the facilitator (via email or phone) at any point in the process. Participants were sought from existing networks who had expertise across multiple species (rather than specialists in an individual species) to reduce potential bias. Experts were primarily based at universities (62%) or NGOs (38%) with a mean of 14.3 years experience (range: 3-24 years) in the area of tropical forests, including specific taxa (primates, carnivores, or bats) (62%) or approaches to forest management (e.g. RIL) (62%). The group included those currently working in Indonesia and/or Malaysian Borneo, along with those based in other locations (including the USA, Canada, and Europe). All experts had spent time in the field on Borneo, ranging from 3 weeks to 20 years (mean: 56 months).

After the first response round, experts' responses were collated, then visual summaries (and explanations where applicable) were provided back to the group. Experts then had an opportunity to discuss these summaries (facilitated via email). The main points of contention and discussion were surrounding: (i) whether or not a strictly managed protected area can guarantee perfect habitat quality, and (ii) the relative benefits to species from a poorly managed protected area compared to a well-managed (RIL level 2) selective logging concession. Consensus was not reached on either point, reflecting the associated with both these topics. The second response round allowed for experts to adjust their responses based on this feedback, or leave them unchanged. Half of the experts (7) adjusted their previous responses following feedback and discussion, which resulted in minor changes to the results (Fig. S2). The process stopped after two rounds, as we were aiming to characterise the uncertainty in estimates, rather than reach a consensus (which can lead to false precision). A final summary of responses for HCVs and each taxonomic group are presented in Fig. S2.
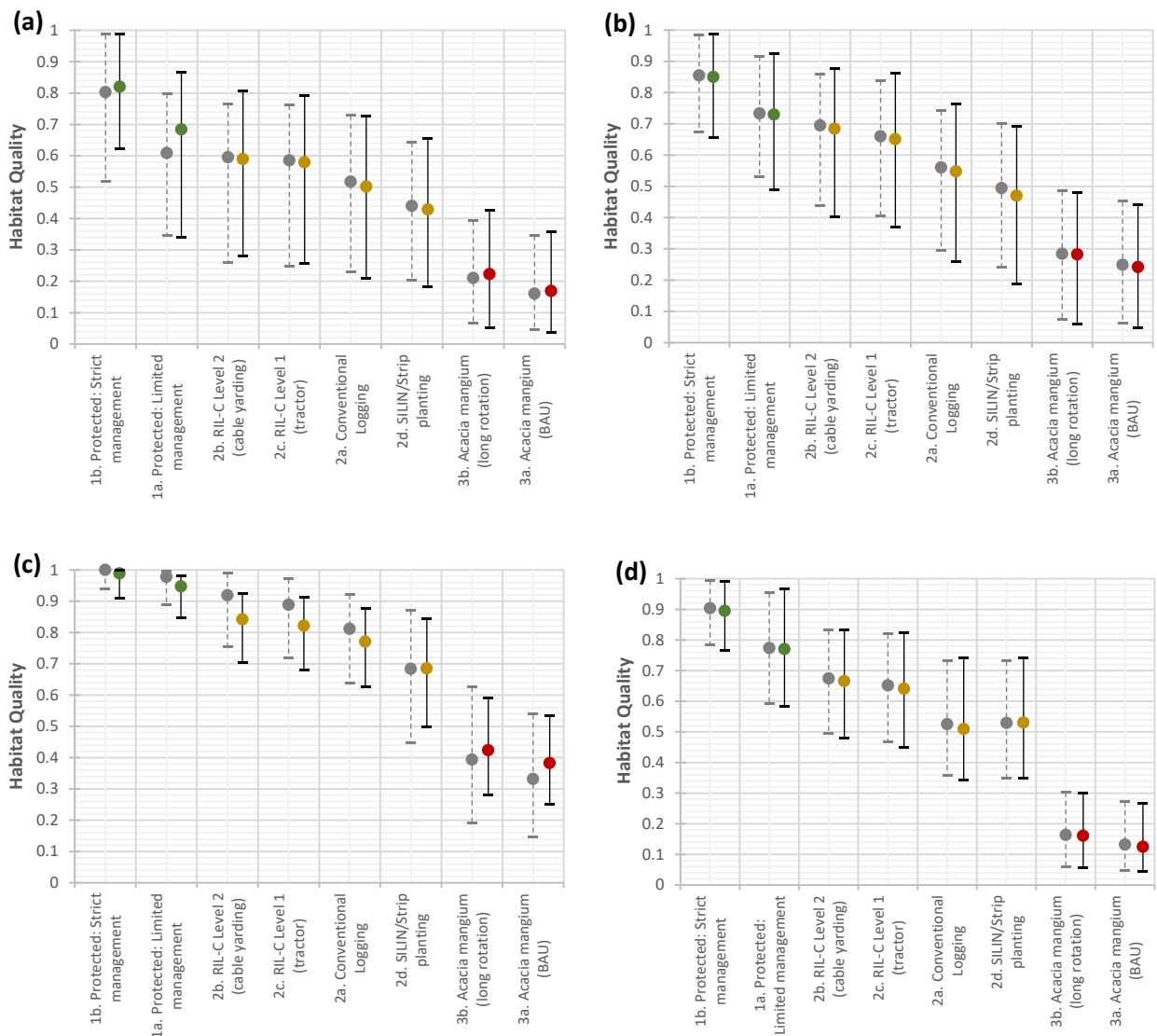
Figure S2 | A summary of the output from each round of the Delphi process for (a) primates, (b) carnivores, (c) bats, and (d) HCV areas. The upper and lower bounds represent the 80% confidence intervals. The grey symbols and dashed lines represent a summary of the responses from round 1. The coloured symbols and solid lines represent a summary of the responses from round 2 (which were used in the analysis).

Habitat quality and land-use transitions over time:

We calculated time-averaged habitat quality accounting for land-use (and management) transitions. To apply the habitat quality scores, current land use was classified as either: protected (limited management), RIL level 1, conventional logging, or *Acacia mangium* plantation (short rotation). Intact forest was assumed to be similar to protected (limited management) based on protected area expenditure reported in McQuistan *et al.*[7]; conventional logging was assumed for logged forest, except where RIL was known to occur; and short rotations were assumed for all current *Acacia mangium* plantations as longer rotations are not currently practiced in the region. We then calculated the time-averaged habitat quality over 60 years based on forest management transition durations in Table S2 and assuming a linear change.

Table S2 | The time required to recover (or lose/degrade) habitat quality for mammal species due to changes in forest management.

From	*To*	*Time (years)*	*Justification*
Acacia mangium plantation	Protected or selective logging	NA	*Acacia mangium* plantations could not be protected or logged
Acacia mangium (short rotation)	*Acacia mangium* (long rotation)	12	1/12 of the planning unit is harvested each year for long rotations, so it would take 12 years for the whole planning unit to transition to this management type.
Selective logging (any type)	Selective logging (any type)	30	A cutting cycle of 30 years means 1/30 of the planning unit is harvested in each year, taking 30 years for the whole planning unit to fully transition from one type of selective logging to another.
Selective logging (any type)	Protected (any type)	60	Within the range reported by syntheses of faunal species recovery in tropical secondary forests[8,9].
Protected or Selective logging (any type)	*Acacia mangium* (short rotation)	7	1/7 of the planning unit is harvested each year for short rotations, so it would take 7 years for the whole planning unit to transition to this management type.
Protected or Selective logging (any type)	*Acacia mangium* (long rotation)	12	1/12 of the planning unit is harvested each year for short rotations, so it would take 12 years for the whole planning unit to transition to this management type.
Protected (limited)	Protected (strict)	10	As these forests are still classified as intact, it is assumed that impacts from lax management can be recovered quickly following stricter management.
Protected (any type)	Selective logging (any type)	30	A cutting cycle of 30 years means 1/30 of the planning unit is harvested in each year, taking 30 years for the whole planning unit to transition to this management type

Net present value

All values are given in USD throughout.

Protected areas:

The ongoing annual management costs were set at $4.30 ha^{-1} for limited management and $9.17 ha^{-1} for optimal/effective management[7]. We assumed areas that were currently protected had limited management based on McQuinstan *et al.*[7]. Establishing a new protected area incurred a once-off cost of $50 ha^{-1} [2]. We also applied $9.84 ha^{-1} as a once-off administrative cost to move from current (limited) to effective management, which includes search costs, a feasibility assessment, negotiation costs, monitoring costs, and regulatory approval costs[10].

The net present value (NPV) of protection for each planning unit, *i*, was calculated as:

$$NPV_{mi} = \sum_{t=0}^{N} \left(\frac{-MC_{mit}}{(1+r)^t} \right) - EC_{mi} - TC_{mi} \tag{s1}$$

where *m* is the protected area management type (strict or limited), *t* is the time (year) of the cash flow, *N* is the total number of time periods (60 years), EC_{mi} are the establishment costs and TC_{mi} are the transition costs (each for protected area management type *m* and planning unit, *i*). The discount rate, *r*, was set at 6% to reflect the social rate of time preference for Indonesia[11]. The NPVs were re-calculated with a discount rate of 3%, and 10% as a part of the sensitivity analysis (Table S5). The 60-year time horizon was selected to resemble that typically used by decision makers, while also being feasible for modelling. Longer time horizons are of limited value with the 6% discount rate used in the main analysis. A summary of the values this produced is given in Table S3.

Table S3 | NPV for strict and limited protected area management. All values are in USD ha^{-1}. The values in brackets represent the minimum and maximum values under the sensitivity analysis (Table S5). The largest cost was produced by a discount rate of 10% in all cases. The smallest cost was produced by using a discount rate of 3% in all cases, except for limited management in areas where current protected areas were absent, in which case the smallest cost ($93) resulted from the case of reducing the East Kalimantan-wide NPV by 25%.

Current protected area	NPV limited management	NPV strict management
Present	-$77 (-$47, -$123)	-$167 (-$110, -$271)
Absent	-$124 (-$93, -$173)	-$217 (-$160, -$321)

Selective logging:

The volume of timber harvested from the first cut was constant across the different logging practices, but varied according to logging history and aboveground biomass. Where biomass was greater than 360 Mg ha^{-1}, 250*0.7 m^3 of timber was harvested irrespective of logging history. Where biomass was less than 360 Mg ha^{-1}, but greater than 65 Mg ha^{-1}, the amount harvested varied. For intact forests this was calculated as:

$$HarvestVolume = (-20.49575 + 39.88383 + 0.64071*Biomass)*0.7 \qquad (s2)$$

and for logged forests as:

$$HarvestVolume = (-20.49575 + 0.64071*Biomass)*0.7 \qquad (s3)$$

These equations are based on analyses of permanent-sample-plot data from East Kalimantan[12]. Here 0.7 is the correction factor, which represents 30% wastage from low quality timber not suitable for roundwood[13]. Where biomass was less than 65 Mg ha^{-1} the area was considered unsuitable for logging. The volume of timber harvested from the second cut (after 30 years) varied according to different logging practices, with 19, 27, and 90 m^3 ha^{-1} timber for conventional logging, RIL and strip planting respectively. The correction factor of 0.7 was also applied here. Spatial information on biomass was sourced from Ferraz *et al.*[14].

We calculated profits to the landholder by calculating the revenue from harvest, less the costs from harvesting, skidding, transport, and taxes/royalties (and planting in the case of strip planting). Roundwood price was set at \$105 m^3, and harvest cost (felling, loading etc) at \$20.9 m^3. The harvesting cost of RIL level 2 was set at \$23.2 to represent an 11% cost increase due to the use of cable yarding. Strip planting incurred additional costs due to planting (occurring in the same year as the first harvest) which were set at \$418.8 ha^{-1} ≤ 200 m from an existing road, \$460.68 ha^{-1} between 200 and 400 m, and \$628.2 if > 400 m from an existing road. Skidding costs varied according to slope with the cost set at \$10.8 ha^{-1} on slopes ≤ 30%, \$16.2 ha^{-1} on slopes > 30% and ≤ 45%, and \$21.6 ha^{-1} on slopes > 45%. Skidding costs were also increased by 11% for RIL level 2 due to the use of cable yarding. Transport costs (including road construction + hauling) were based on the (surface) distance to the nearest log pond (i.e., on the Mahakam River or its tributary the Telen River, the Berau River or its tributary the Kelai River, a coastal inlet near the Berau/Kutai Timur border, or a coastal inlet near Balikpapan). Existing roads were scored 1, while all other areas were scored 2. A value of \$0.1 m^{-3} harvested timber was applied to the resulting surface. This resulted in travel along existing roads costing \$0.1 m^{-3}, and \$0.2 m^{-3} for all other areas. Taxes were set at \$22 m^{-3}.

Although rotations are every 30 years per harvested hectare, actual harvesting within a concession would be staged, such that 1/30 of the area was logged each year. Therefore, 1/30 of the total revenue and costs for the first harvest was allocated in each year from 1-30. Subsequently, 1/30 of the total revenue and costs for the second harvest was allocated in each year from 31-60. Fixed management costs of \$385.8 ha^{-1} were applied in the first year to represent initial concessions fees, planning costs, and other administrative costs. The net present value (NPV) was calculated over 60 years at a 6% discount rate (additional rates were used in the sensitivity analysis, Table S5).

More formally, the NPV of logging for each planning unit, i, is given as:

$$NPV_{mi} = \sum_{t=0}^{N} \left(\frac{HR_{mit} - HC_{mit} - SC_{mit} - TC_{mit} - PC_{mit} - TX_{mit}}{(1+r)^t} \right) - FM_{mi} \qquad \text{(s4)}$$

where m is the forest management type (conventional logging, RIL level 1, RIL level 2, or strip planting), t is the time (year) of the cash flow, and r is the discount rate. HR_{mit} are the harvest revenues, HC_{mit} are the harvesting costs, SC_{mit} are the skidding costs, TC_{mit} are the transport costs, PC_{mit} are the planting costs (only applicable to strip planting), and TX_{mit} are the taxes and royalties - each for forest management type m, for planning unit i, at time t. FM_{mi} are the upfront fixed management costs for forest management type m and planning unit i. A spatial representation of these values is shown in Fig. S3.
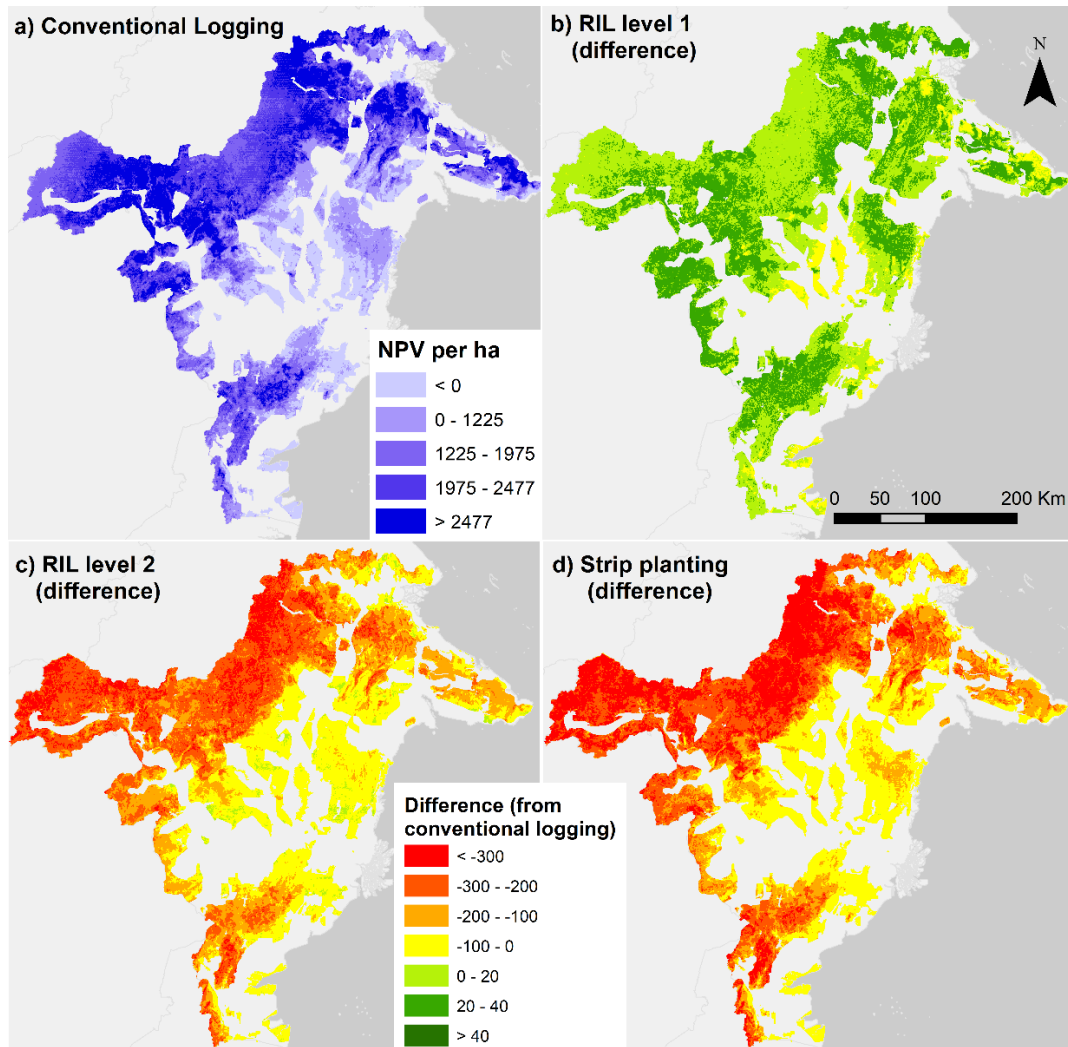
Figure S3 | NPVs of different selective logging management types. Conventional logging (a) is given in total NPV per ha. For contrast, the remaining selective logging management types (RIL level 1 (b), RIL level 2 (c), and strip planting (d)) are given as the difference from conventional logging. Over the 60 year period, RIL level 1 was typically more profitable, but RIL level 2 and strip planting were typically less profitable. These figures display the NPV for illustration purposes for all areas of the forest estate (including areas where logging was not possible, or not legally permitted, such as within current protected areas).

Acacia mangium plantations:

We restricted the area that could potentially be converted to *Acacia mangium* plantations to below 780 m above sea level, based on the upper limit of the known species distribution[15], and to slopes < 45 degrees (100%). We also excluded the conversion of water bodies, and land currently utilised for industry (including mining), urban areas, oil palm, or other agriculture. In the remaining land area, we calculated the profits to the landholder from conversion by calculating the harvest revenues, less the costs of planting, maintenance, harvesting, transport, and taxes:

- The wood volume harvested was set at 160 m^3 ha^{-1} for 7-year rotations (short), and 180 m^3 ha^{-1} for 12-year rotations (long)[16]. For short rotations, 100% of the wood was sold as pulp for \$30 m^{-3}. For long rotations 60% of the timber was sold as pulp and 40% as veneer-quality logs for \$70 m^{-3} [17].
- Harvesting costs were \$800 - \$1500 ha^{-1} based on slope (which ranged from 0-100% within the potential area for plantations). This was implemented as:
$$HarvestCost = 800 + (MeanSlope/100)*700 \qquad (s5)$$
- Initial planting and maintenance costs (i.e. planting and the first 3 years of maintenance) also varied with slope, from \$300 to \$1000 ha^{-1}:
$$PlantingCost: 300 + (MeanSlope/100)*700 \qquad (s6)$$
This cost included planting, weeding, fertilizing, and releasing from competition. After the first 3 years, maintenance costs are only for protection and patrols and are set at annual costs of 10% of the initial planting/maintenance costs.
- Transport costs (including road construction + hauling) were based on the (surface) distance to the nearest pulp mill. There are two pulp mills in East Kalimantan (in Sebulu and Tanjung Redeb). Existing roads were scored 1, while all other areas were scored 2. A value of 0.08 per m^3 was applied to the resulting surface.
- Timber taxes and royalties were set at \$5 m^{-3}. This also incorporates the concession fees.

Average annual profits from plantations on karst and peat soils were reduced to 62.5% of that on mineral soils due to the differences in growth rates and maintenance costs[18,19].

Although rotations are every 7 (short) or 12 (long) years per *lot*, actual harvesting within a *planning unit* would be staged, such that 1/7 or 1/12 of the area was harvested each year. Therefore, where plantations were already established, the total revenue and costs over the whole rotation period was calculated and allocated evenly across the number of years in the rotation to give an average annual profit. Where plantations were not yet established, the average planting and maintenance costs (only) were applied for the first 7 or 12 years, then the average annual profit (as per established plantations) was applied in subsequent years. The net present value (NPV) was calculated over 60 years at a 6% discount rate (with variations for the sensitivity analysis, Table S5).

Acacia mangium plantations also produced additional revenue from clear-felling intact and logged forest prior to plantation establishment. In forested areas that were potentially suitable for plantations, we first applied a biomass expansion factor of 0.6 to convert from Mg

biomass (as defined by Ferraz *et al.*[14]) to the total volume of timber m³ [20]. We then calculated the proportion total volume of timber in intact forest to be sold as roundwood as:

$$RoundwoodVolume = TotalVolume * 0.459 * 0.7 \qquad (s7)$$

and in logged forests as:

$$RoundwoodVolume = TotalVolume * 0.306 * 0.7 \qquad (s8)$$

These equations are based on analyses of permanent-sample-plot data from East Kalimantan[12]. 0.7 is applied to represent the 30% of the timber that is wastage or of low quality. However, additional revenue from clear-felling can be gained from selling timber unsuitable for roundwood as pulpwood. The volume of pulpwood sold from primary forests was calculated as:

$$PulpwoodVolume = ((TotalVolume * 0.459 * 0.3) + (TotalVolume * 0.541)) * 0.7 \qquad (s9)$$

and in logged forests as:

$$PulpwoodVolume = ((TotalVolume * 0.306 * 0.3) + (TotalVolume * 0.694)) * 0.7 \qquad (s10)$$

With 0.7 again representing wastage or timber that is not suitable for pulp. Revenue for roundwood and pulpwood was given as \$105 m³ and \$30 m³ respectively. Similarly harvesting costs, transportation costs (to the log pond or pulp mill), and timber royalties were applied for roundwood and pulpwood as given above.

More formally, the NPV of acacia plantations for each planning unit, *i*, is given as:

$$NPV_{mi} = \sum_{t=0}^{N} \left(\frac{(HR_{mit} - HC_{mit} - PC_{mit} - TC_{mit} - TX_{mit}) * \alpha_i}{(1+r)^t} \right) + CFR_i - CFC_i \qquad (s11)$$

where *m* is the acacia plantation management type (short or long rotation), *t* is the time (year) of the cash flow, and *r* is the discount rate. HR_{mit} are the harvest revenues, HC_{mit} are the harvesting costs, PC_{mit} are the planting costs, TC_{mit} are the transport costs, and TX_{mit} are the taxes and royalties and concession fees (each for plantation management type *m*, for planning unit *i*, at time *t*). α_i is 0.625 on karst and peat soils (and 1 otherwise) due to differences in growth rates and maintenance costs. CTR_i and CFC_i are the upfront revenues and costs (respectively) from clear-felling prior to plantation establishment. This produced NPVs for acacia plantations that varied spatially across the forest estate (Fig. S4).
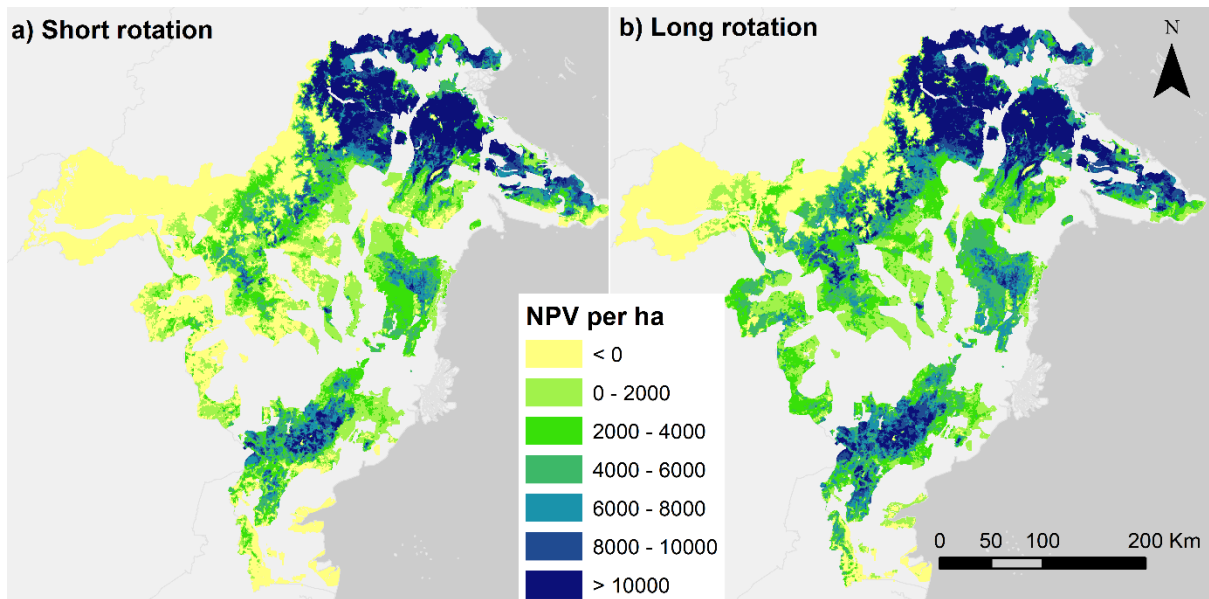
Figure S4 | NPV per hectare for (a) short and (b) long rotation acacia plantations at a 6% discount rate. Long rotations were on average slightly more profitable over the 60 year period, as some of the timber could be sold as veneer-quality logs instead of pulp. These figures display the NPV for illustration purposes for all areas of the forest estate (including areas where *Acacia* plantations are not possible or not legally permitted).

East Kalimantan-wide total NPV threshold:

Our optimisation (Eqns. 1-5) ensures a minimum East Kalimantan-wide NPV is met in each run (Eqn. 2). The mean NPV of the optimised landscapes was 0.8% higher than the minimum NPV threshold. This is to be expected as the *entire* planning unit must be allocated to a forest management type, so it is unlikely that any given threshold can be achieved exactly. Variation from this mean NPV was low across scenarios, with the standard deviation across solutions falling within 2% of the mean NPV.

Spatial limits for selective logging

Slope limits were placed on each logging method, as follows and described in Table S4. The slope of each 30 m pixel was calculated from the 30 m DEM[21].

Under all logging types, areas > 80% slope were left unlogged, due to the difficulties of yarding felled trees, and apparent avoidance by concessionaires (based on data for skid trails measured by field GPS or Lidar by Griscom *et al.*[22] and Ellis *et al.*[23], which showed logging on higher slopes was extremely rare). The lack of extractive activities in these areas was considered to be broadly equivalent to the forest management type 'Protected areas- limited management'.

For Conventional Logging (CL), we modelled CL on slopes less than 80%. Most ground-based logging equipment (i.e., bulldozers and skidders) cannot climb directly up slopes >40%, but logging often still occurs by cutting switchbacks on slopes 40-80%.

For RIL Level 1 (bulldozer/tractor yarding only), on slopes less than 40%, better planning of skid trails reduces impacts of RIL-1 compared to CL. From 40% up to a maximum of 80% slope, we assumed RIL Level 1 has impacts similar to CL (with switchbacks), because the locations of switchbacks are heavily constrained by topography[22], and their impacts cannot be substantially reduced through improved planning.

For RIL Level 2 (bulldozer/tractor and cable yarding), we assumed a 50% mix of bulldozer/tractor and cable yarding, across all slopes 0 – 80%. Cable yarding has lower impacts due to eliminating the need for skid trails between the road and felled log, as seen in the near-zero carbon emissions from skidding in areas where cable yarding was used in two concessions studied by Griscom *et al.*[22]. This logging method still requires ridge-top roads for hauling.

For strip planting, the areas of strip clearing and planting were limited to slopes <25% (as implemented by SBK Pty. in Central Kalimantan[24]), within 200 m of logging roads, and excluding riparian areas (as per government regulations). However, because our optimisation allowed for logging in areas not previously harvested, using current logging roads would be a poor approximation of the potential area for strip planting. As we allowed for new logging roads to be built, strip planting was capped at 28.6% of the loggable area (the area of strip planting is less if the area <25% slope does not reach 28.6%). The 28.6% is based on strip planting occurring within 200 m of logging roads, and logging generally occurring 700 m from logging roads[25]. Remaining areas under this forest management type were assumed to be logged using RIL level 2 practices up to the same absolute maximum slope of 80% for all logging practices.

Riparian and coastal areas – remained unlogged for all types of reduced impact logging, assuming rigorous application of buffer zones as detailed in the "Water resource buffers" section below.

Table S4 | Selective logging management types by slope class and riparian buffer areas.

	Slope < 25 %	Slope 25-40%	Slope 40-80%	Slope > 80 %	Riparian Areas
Percent of forest estate	68.30%	17.57%	13.23%	0.90%	0.84%
Conventional logging	CL	CL	CL	Protected areas (limited management)	CL
RIL Level 1 (bulldozer/tractor yarding)	RIL 1	RIL 1	*CL	Protected areas (limited management)	Protected areas (limited management)
RIL Level 2 (ground or cable yarding)	RIL 2	RIL 2	RIL 2	Protected areas (limited management)	Protected areas (limited management)
Strip Planting	Strip planting if <200 m from roads**, otherwise RIL 2	RIL 2	RIL 2	Protected areas (limited management)	Protected areas (limited management)

* In this slope range (40-80%), RIL level 1 has impacts similar to CL because bulldozer/tractor yarding requires skid trails using switchbacks. The locations of switchbacks are heavily constrained by topography [22], and their impacts cannot be substantially reduced through improved planning. In contrast, for slopes lower than 40%, better planning of skid trails does reduce impacts of RIL-1 compared to CL.

** Approximated as described the text.

Land Allocations
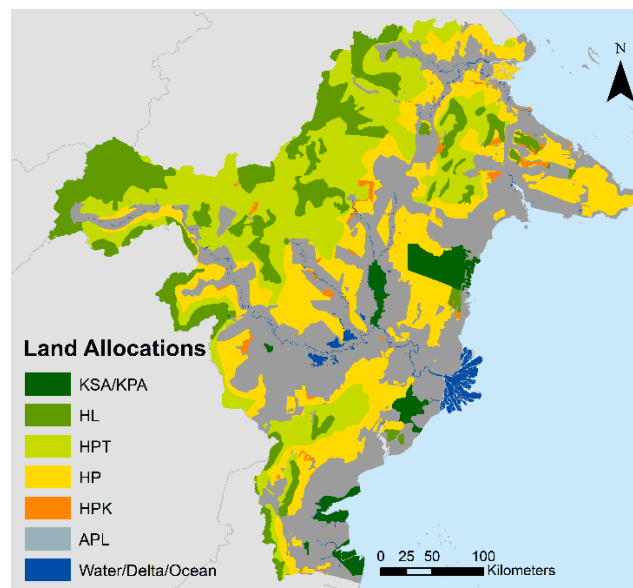
Figure S5 | Land allocations in East Kalimantan. The area included in this study (analogous to the forest estate) comprises: conservation areas (*Hutan Konservasi*, KSA/KPA) and protection forest (*Hutan Lindung*, HL), where no logging is permitted, limited production forest (*Hutan Produksi Terbatas,* HPT), where only selective logging concessions can be granted, and production forest (*Hutan Produksi*. HP) and conversion forest (*Hutan Produksi Konversi*, HPK), where concessions can be granted for both selective logging and wood-fibre plantations. The remaining area (*Areal Penggunaan Lain*, APL) is not included in our analysis. APL is land outside the forest estate designated for uses such as agriculture or settlements. Although some minor discrepancies exist (particularly at the borders of the different land allocations), these zones are largely adhered to when designating concessions.

Water resource buffers

We based water resource buffers on the following rules from the Government Regulation No. 47/1997, Presidential Decree No. 32/1990, GR No. 26 of 2008, and PP no. 38 of 2011 – Presidential regulation on Rivers (Peraturan Pemerintah Republik Indonesia Nomor 38, Tahun 2011, Tentang Sungai):

i.   Coastlines were buffered by 100 m.
ii. Large rivers with a catchment ≥ 500 km^2 were given a 100 m buffer either side from the river bank.
iii. Other rivers with a catchment of at least 200 km^2 were given a 50 m buffer either side of the river. We considered a catchment of 200 km^2 to represent substantial rivers of approximately 30 m width.

To apply these rules, we first spatially defined the coastline, 'large rivers', and 'other rivers'. *The coastline* was derived from the land-use land cover classification from the Ministry of Agriculture. Deltas and estuaries were excluded from the 'land' area and coastline. Small adjustments were made at river mouths so that the delineation between 'water body' and 'ocean' matched that used in the modelling of hydrological ecosystem services. The final linear feature representing the coastline was buffered by 100 m.

For rivers, 'large rivers' were defined as those with a catchment of at least 500 km^2 (in accordance with the legislation) using ArcHyrdo based on the 1 arc-second DEM[21]. Where the 'large rivers' from the hydrological model were proximal to the water bodies defined from 2010 Landsat data[26], these water bodies were buffered by 100 m either side. Landsat-defined waterbodies were included to ensure that the buffers extended from riverbanks, rather than the centre of the river, which is particularly important for very large rivers. Landsat-defined waterbodies that were not identified as 'large rivers' were considered to be 'other rivers' and buffered by 50 m either side. In addition, 'other rivers' were defined as those with a catchment of at least 200 km^2, but less than 500 km^2, using ArcHyrdo based on the 1 arc-second DEM[21]. We considered a catchment of 200 km^2 to represent substantial rivers of approximately 30 m width. In cases where the hydrologically defined 'other rivers' included tributaries that were not represented in the Landsat-defined waterbodies, we buffered the linear river features by 65 m either side. The additional 15 m is to account for the buffer beginning from the riverbank, rather than the centre of the river.

Land cover mapping

A LULC map at 30 m resolution was developed for East Kalimantan for the year 2015 from four primary sources (all analyses of Landsat[TM] imagery), and ancillary data on plantations, peatlands, karst limestone systems, logging concessions, dated logging roads, topographic slope, and aboveground biomass:

1. Intact and logged forest of Borneo in 2015, identified by Gaveau *et al.*[27] combining four Landsat-based analyses of forest cover and logging roads, over four decades (1973 - 2015).

2. Forest cover percentages for the year 2015, from the Global Forest Change 2015 dataset based on Landsat imagery[28]. This data was used to refine plantation classes (young or open oil palm, open lands within timber plantations) and to reclassify forest classes as shrublands (if 10-30% cover), or open lands (<10% cover).

3. The 2015 LULC map for East Kalimantan by the Ministry of Environment and Forestry (KLHK 2015), based on Landsat interpretation described by Wijaya *et al.*[29]. This provided information on forest and wetland types, mining, plantations, agriculture, settlements and industry.

4. Oil palm and Timber plantations identified by Gaveau *et al.*[27] for the year 2015, based on Landsat imagery 1973 - 2015.

5. Peatlands map compiled by the Ministry of Agriculture[30,31].

6. Karst limestone landsystems identified in the RePPProT Landsystems dataset (Kalimantan LS v2 processed by Daemeter Consulting)[32].

7. Logging concessions boundaries for the year 2016 from The Nature Conservancy.

8. Logging concessions implementing RIL, assessed by the Tropical Forest Foundation.

9. Logging roads and years of first detection in LandsatTM imagery by Gaveau et al.[27], used to identify 'RIL logged forests' as forests that lie within RIL concessions and have been logged since the mid 2000s.

10. Slope at 30 m resolution calculated from the NASA SRTM 1 arc second DEM[33], used to identify logged forests on steep slopes (40-80%), which undergo higher logging impacts due to switchbacks required for bulldozer/tractor skid trails.

11. Aboveground biomass carbon at 100 m resolution for the year 2017 (Ferraz *et al.*[14]), used to distinguish areas with AGB carbon of > 65 Mg C ha^{-1} as forests containing potentially loggable timber. Any degraded forests with <= 65 Mg C ha^{-1} were reclassed as shrublands.

Sensitivity analysis

Table S4 | The parameters varied in the sensitivity analysis. The upper and lower bounds for each species were generated using an 80% confidence interval from the Delphi process. These variations were tested against each of the 11 different targeting strategies for the conservation objectives.

Variation	Presence-absence threshold	Biodiversity response	Protected areas NPV	Selective logging NPV	Acacia plantation NPV	Conventional management NPV	Discount rate
Original	10%	Mean	-	-	-	-	6%
Species 25%	25%	Mean	-	-	-	-	6%
Species upper	10%	Upper bound	-	-	-	-	6%
Species lower	10%	Lower bound	-	-	-	-	6%
PA NPV upper	10%	Mean	+25%	-	-	-	6%
PA NPV lower	10%	Mean	-25%	-	-	-	6%
Logging NPV upper	10%	Mean	-	+25%	-	-	6%
Logging NPV lower	10%	Mean	-	-25%	-	-	6%
Plantation NPV upper	10%	Mean	-	-	+25%	-	6%
Plantation NPV lower	10%	Mean	-	-	-25%	-	6%
Conventional NPV upper	10%	Mean	-	-	-	+25%	6%
Conventional NPV lower	10%	Mean	-	-	-	-25%	6%
Low Discount Rate	10%	Mean	-	-	-	-	3%
High Discount Rate	10%	Mean	-	-	-	-	10%

Supplementary Results

Sensitivity analysis

Table S6 | Sensitivity analysis of the optimal forest management allocations to maximise all species (primates, carnivores, and bats) and areas of High Conservation Value.

Variation	Protected (strict)	Protected (limited)	RIL level 2	RIL level 1	Conventional logging	Strip planting	Acacia (long)	Acacia (short)	Other
Original	64.0%	1.2%	19.6%	1.5%	0.0%	0.0%	11.9%	0.0%	1.8%
Species 25%	61.6%	1.3%	20.1%	2.6%	0.0%	0.0%	12.4%	0.0%	1.8%
Species upper	57.7%	1.3%	26.3%	2.5%	0.1%	0.0%	10.4%	0.0%	1.8%
Species lower	70.8%	1.1%	11.3%	1.0%	0.0%	0.0%	13.9%	0.0%	1.8%
PA NPV upper	65.4%	1.1%	18.4%	1.4%	0.0%	0.0%	11.8%	0.0%	1.8%
PA NPV lower	62.6%	1.2%	20.8%	1.5%	0.0%	0.0%	12.1%	0.0%	1.8%
Logging NPV upper	62.2%	1.1%	23.0%	1.8%	0.1%	0.0%	10.0%	0.0%	1.8%
Logging NPV lower	66.5%	1.2%	15.5%	1.0%	0.0%	0.0%	13.9%	0.0%	1.8%
Plantation NPV upper	72.7%	1.1%	12.0%	0.8%	0.0%	0.0%	11.5%	0.0%	1.8%
Plantation NPV lower	52.7%	1.2%	29.8%	3.1%	0.1%	0.0%	11.2%	0.0%	1.8%
Conventional NPV upper	66.3%	1.2%	17.4%	0.3%	1.6%	0.0%	8.3%	3.1%	1.8%
Conventional NPV lower	64.0%	1.1%	19.6%	1.5%	0.0%	0.0%	12.0%	0.0%	1.8%
Low Discount Rate	70.3%	1.1%	16.7%	0.9%	0.0%	0.0%	9.0%	0.0%	1.8%
High Discount Rate	59.8%	1.8%	19.6%	1.7%	0.0%	0.0%	15.1%	0.1%	1.8%

Temporal wood and cash flows

We calculated the mean and standard deviation of the spatially heterogeneous annual cash flows for the baseline (Table S7) and optimal (Table S8) scenarios. The baseline refers to the case where all current logging and plantation concessions were fully harvested/planted, within biophysical and regulatory constraints. Here, conventional logging was assumed for logging concessions, except where RIL was known to occur, in which case RIL 1 was applied; and short rotations were assumed for all current *Acacia* plantations, as longer rotations are not currently practiced in the region. Limited management was applied in current protected and *Hutan Lindung* areas (as current management is not optimal[7]), and also incurred an establishment cost in *Hutan Lindung* as these areas as not managed as protected areas.

In the baseline and optimal scenarios (Table S7 and S8), the mean negative values in year 0 for protected areas and logging are driven by establishment costs. The large positive mean value in year 0 for *Acacia* plantations are driven by windfalls from clear-cutting to establish plantations. *Acacia* profits are lower in years 1-6 and 1-11 (for short and long rotations respectively) as new plantations are becoming established. In all cases, logging revenues are lower for the second cut (occurring form year 30), due to the reduced biomass of commercial timber species. In the optimal scenario, logging is dominated by RIL level 2 (1.59 million

ha), with a relative small area allocated RIL level 1 (0.12 million ha) where this management type is particularly lucrative. The spatial optimisation conducted for the optimal scenario preferences placing each management type where it is more profitable (and meets other considerations in the optimisation), whereas no optimisation is conducted for the baseline scenario. This explains the higher mean profits delivered in the optimal scenario.

The total volume of wood products (roundwood and pulpwood/veneer) produced in each year is similar across the baseline and optimal scenarios, with the optimal scenario producing a smaller volume (Table S9). The same total NPV can be produced with a lower volume of wood products, as the optimal scenario tends to have higher profit margins due to the spatial optimisation employed, and long rotation *Acacia* plantations produces a better quality wood product, which attracts a higher price.

The NPV for each management type in each planning unit can be downloaded (see the data availability section in the main text).

Table S7 | Mean (± s.d.) of the spatially heterogeneous annual cash flows for the baseline scenario in USD per protected/harvested/planted hectare. Our baseline refers to the case where all current logging and plantation concessions were fully active (but still within biophysical and legislative constraints). Protected (strict), RIL level 2, Strip planting, and long rotation *Acacia* plantations were not present in the baseline scenario, and therefore not shown here. The total area allocated to each management type is given in million hectares. This area is greater than the area harvested or planted, as the planning units are of variable size, and can include areas not harvested or planted due to slope, elevation or other biophysical conditions.

Year	Protected (strict)	Protected (limited)	RIL level 2	RIL level 1	Conventional Logging	Strip planting	*Acacia* (long)	*Acacia* (Short)
Area	-	3.59 M ha	-	0.09 M ha	3.01 M ha	-	-	1.29 M ha
0	-	-48.4 (±16.1)	-	-210.1 (±51.2)	-137.7 (±1316.3)	-	-	1264.2 (±3382.1)
1	-	-4.3 (±0)	-	175.7 (±51.2)	248.1 (±1316.3)	-	-	6.2 (±117.8)
2	-	-4.3 (±0)	-	175.7 (±51.2)	248.1 (±1316.3)	-	-	6.2 (±117.8)
3	-	-4.3 (±0)	-	175.7 (±51.2)	248.1 (±1316.3)	-	-	6.2 (±117.8)
4	-	-4.3 (±0)	-	175.7 (±51.2)	248.1 (±1316.3)	-	-	6.2 (±117.8)
5	-	-4.3 (±0)	-	175.7 (±51.2)	248.1 (±1316.3)	-	-	6.2 (±117.8)
6	-	-4.3 (±0)	-	175.7 (±51.2)	248.1 (±1316.3)	-	-	6.2 (±117.8)
7	-	-4.3 (±0)	-	175.7 (±51.2)	248.1 (±1316.3)	-	-	124.7 (±130.1)
8	-	-4.3 (±0)	-	175.7 (±51.2)	248.1 (±1316.3)	-	-	124.7 (±130.1)
9	-	-4.3 (±0)	-	175.7 (±51.2)	248.1 (±1316.3)	-	-	124.7 (±130.1)
10	-	-4.3 (±0)	-	175.7 (±51.2)	248.1 (±1316.3)	-	-	124.7 (±130.1)
11	-	-4.3 (±0)	-	175.7 (±51.2)	248.1 (±1316.3)	-	-	124.7 (±130.1)
12	-	-4.3 (±0)	-	175.7 (±51.2)	248.1 (±1316.3)	-	-	124.7 (±130.1)
13	-	-4.3 (±0)	-	175.7 (±51.2)	248.1 (±1316.3)	-	-	124.7 (±130.1)
14	-	-4.3 (±0)	-	175.7 (±51.2)	248.1 (±1316.3)	-	-	124.7 (±130.1)
15	-	-4.3 (±0)	-	175.7 (±51.2)	248.1 (±1316.3)	-	-	124.7 (±130.1)
16	-	-4.3 (±0)	-	175.7 (±51.2)	248.1 (±1316.3)	-	-	124.7 (±130.1)
17	-	-4.3 (±0)	-	175.7 (±51.2)	248.1 (±1316.3)	-	-	124.7 (±130.1)
18	-	-4.3 (±0)	-	175.7 (±51.2)	248.1 (±1316.3)	-	-	124.7 (±130.1)

19	-	-4.3 (±0)	-	175.7 (±51.2)	248.1 (±1316.3)	-	-	124.7 (±130.1)
20	-	-4.3 (±0)	-	175.7 (±51.2)	248.1 (±1316.3)	-	-	124.7 (±130.1)
21	-	-4.3 (±0)	-	175.7 (±51.2)	248.1 (±1316.3)	-	-	124.7 (±130.1)
22	-	-4.3 (±0)	-	175.7 (±51.2)	248.1 (±1316.3)	-	-	124.7 (±130.1)
23	-	-4.3 (±0)	-	175.7 (±51.2)	248.1 (±1316.3)	-	-	124.7 (±130.1)
24	-	-4.3 (±0)	-	175.7 (±51.2)	248.1 (±1316.3)	-	-	124.7 (±130.1)
25	-	-4.3 (±0)	-	175.7 (±51.2)	248.1 (±1316.3)	-	-	124.7 (±130.1)
26	-	-4.3 (±0)	-	175.7 (±51.2)	248.1 (±1316.3)	-	-	124.7 (±130.1)
27	-	-4.3 (±0)	-	175.7 (±51.2)	248.1 (±1316.3)	-	-	124.7 (±130.1)
28	-	-4.3 (±0)	-	175.7 (±51.2)	248.1 (±1316.3)	-	-	124.7 (±130.1)
29	-	-4.3 (±0)	-	175.7 (±51.2)	248.1 (±1316.3)	-	-	124.7 (±130.1)
30	-	-4.3 (±0)	-	28.1 (±5.8)	30.8 (±4.4)	-	-	124.7 (±130.1)
31	-	-4.3 (±0)	-	28.1 (±5.8)	30.8 (±4.4)	-	-	124.7 (±130.1)
32	-	-4.3 (±0)	-	28.1 (±5.8)	30.8 (±4.4)	-	-	124.7 (±130.1)
33	-	-4.3 (±0)	-	28.1 (±5.8)	30.8 (±4.4)	-	-	124.7 (±130.1)
34	-	-4.3 (±0)	-	28.1 (±5.8)	30.8 (±4.4)	-	-	124.7 (±130.1)
35	-	-4.3 (±0)	-	28.1 (±5.8)	30.8 (±4.4)	-	-	124.7 (±130.1)
36	-	-4.3 (±0)	-	28.1 (±5.8)	30.8 (±4.4)	-	-	124.7 (±130.1)
37	-	-4.3 (±0)	-	28.1 (±5.8)	30.8 (±4.4)	-	-	124.7 (±130.1)
38	-	-4.3 (±0)	-	28.1 (±5.8)	30.8 (±4.4)	-	-	124.7 (±130.1)
39	-	-4.3 (±0)	-	28.1 (±5.8)	30.8 (±4.4)	-	-	124.7 (±130.1)
40	-	-4.3 (±0)	-	28.1 (±5.8)	30.8 (±4.4)	-	-	124.7 (±130.1)
41	-	-4.3 (±0)	-	28.1 (±5.8)	30.8 (±4.4)	-	-	124.7 (±130.1)
42	-	-4.3 (±0)	-	28.1 (±5.8)	30.8 (±4.4)	-	-	124.7 (±130.1)
43	-	-4.3 (±0)	-	28.1 (±5.8)	30.8 (±4.4)	-	-	124.7 (±130.1)
44	-	-4.3 (±0)	-	28.1 (±5.8)	30.8 (±4.4)	-	-	124.7 (±130.1)
45	-	-4.3 (±0)	-	28.1 (±5.8)	30.8 (±4.4)	-	-	124.7 (±130.1)
46	-	-4.3 (±0)	-	28.1 (±5.8)	30.8 (±4.4)	-	-	124.7 (±130.1)
47	-	-4.3 (±0)	-	28.1 (±5.8)	30.8 (±4.4)	-	-	124.7 (±130.1)
48	-	-4.3 (±0)	-	28.1 (±5.8)	30.8 (±4.4)	-	-	124.7 (±130.1)
49	-	-4.3 (±0)	-	28.1 (±5.8)	30.8 (±4.4)	-	-	124.7 (±130.1)
50	-	-4.3 (±0)	-	28.1 (±5.8)	30.8 (±4.4)	-	-	124.7 (±130.1)
51	-	-4.3 (±0)	-	28.1 (±5.8)	30.8 (±4.4)	-	-	124.7 (±130.1)
52	-	-4.3 (±0)	-	28.1 (±5.8)	30.8 (±4.4)	-	-	124.7 (±130.1)
53	-	-4.3 (±0)	-	28.1 (±5.8)	30.8 (±4.4)	-	-	124.7 (±130.1)
54	-	-4.3 (±0)	-	28.1 (±5.8)	30.8 (±4.4)	-	-	124.7 (±130.1)
55	-	-4.3 (±0)	-	28.1 (±5.8)	30.8 (±4.4)	-	-	124.7 (±130.1)
56	-	-4.3 (±0)	-	28.1 (±5.8)	30.8 (±4.4)	-	-	124.7 (±130.1)
57	-	-4.3 (±0)	-	28.1 (±5.8)	30.8 (±4.4)	-	-	124.7 (±130.1)
58	-	-4.3 (±0)	-	28.1 (±5.8)	30.8 (±4.4)	-	-	124.7 (±130.1)
59	-	-4.3 (±0)	-	28.1 (±5.8)	30.8 (±4.4)	-	-	124.7 (±130.1)
NPV	-	-117.8 (±16.1)	-	2249.2 (±746)	3311.7 (±19206.1)	-	-	2692.8 (±3685.6)

Table S8 | Mean (± s.d.) of the spatially heterogeneous annual cash flows for the optimal scenario in USD per protected/harvested/planted hectare. The optimal scenario is depicted in Fig. 2c. Conventional logging, strip planting, and short rotation *Acacia* plantations were allocated a negligible area, and therefore not included here. The total area allocated to each management type is given in million hectares. This area is greater than the area harvested or planted, as the planning units are of variable size, and can include areas not harvested or planted due to slope, elevation or other biophysical conditions.

Year	Protected (strict)	Protected (limited)	RIL level 2	RIL level 1	Conventional Logging	Strip planting	*Acacia* (long)	*Acacia* (Short)
Area	5.2 M ha	0.09 M ha	1.59 M ha	0.12 M ha	0.00 M ha	0.00 M ha	0.97 M ha	0.00 M ha
0	-66 (±11.8)	-23.7 (±24.4)	-211.7 (±56.6)	2322.7 (±5735.2)	-	-	2941 (±5506.7)	-
1	-9.2 (±0)	-4.3 (±0)	174.1 (±56.6)	2708.5 (±5735.2)	-	-	108.7 (±182.8)	-
2	-9.2 (±0)	-4.3 (±0)	174.1 (±56.6)	2708.5 (±5735.2)	-	-	108.7 (±182.8)	-
3	-9.2 (±0)	-4.3 (±0)	174.1 (±56.6)	2708.5 (±5735.2)	-	-	108.7 (±182.8)	-
4	-9.2 (±0)	-4.3 (±0)	174.1 (±56.6)	2708.5 (±5735.2)	-	-	108.7 (±182.8)	-
5	-9.2 (±0)	-4.3 (±0)	174.1 (±56.6)	2708.5 (±5735.2)	-	-	108.7 (±182.8)	-
6	-9.2 (±0)	-4.3 (±0)	174.1 (±56.6)	2708.5 (±5735.2)	-	-	108.7 (±182.8)	-
7	-9.2 (±0)	-4.3 (±0)	174.1 (±56.6)	2708.5 (±5735.2)	-	-	108.7 (±182.8)	-
8	-9.2 (±0)	-4.3 (±0)	174.1 (±56.6)	2708.5 (±5735.2)	-	-	108.7 (±182.8)	-
9	-9.2 (±0)	-4.3 (±0)	174.1 (±56.6)	2708.5 (±5735.2)	-	-	108.7 (±182.8)	-
10	-9.2 (±0)	-4.3 (±0)	174.1 (±56.6)	2708.5 (±5735.2)	-	-	108.7 (±182.8)	-
11	-9.2 (±0)	-4.3 (±0)	174.1 (±56.6)	2708.5 (±5735.2)	-	-	108.7 (±182.8)	-
12	-9.2 (±0)	-4.3 (±0)	174.1 (±56.6)	2708.5 (±5735.2)	-	-	350 (±75.3)	-
13	-9.2 (±0)	-4.3 (±0)	174.1 (±56.6)	2708.5 (±5735.2)	-	-	350 (±75.3)	-
14	-9.2 (±0)	-4.3 (±0)	174.1 (±56.6)	2708.5 (±5735.2)	-	-	350 (±75.3)	-
15	-9.2 (±0)	-4.3 (±0)	174.1 (±56.6)	2708.5 (±5735.2)	-	-	350 (±75.3)	-
16	-9.2 (±0)	-4.3 (±0)	174.1 (±56.6)	2708.5 (±5735.2)	-	-	350 (±75.3)	-
17	-9.2 (±0)	-4.3 (±0)	174.1 (±56.6)	2708.5 (±5735.2)	-	-	350 (±75.3)	-
18	-9.2 (±0)	-4.3 (±0)	174.1 (±56.6)	2708.5 (±5735.2)	-	-	350 (±75.3)	-
19	-9.2 (±0)	-4.3 (±0)	174.1 (±56.6)	2708.5 (±5735.2)	-	-	350 (±75.3)	-
20	-9.2 (±0)	-4.3 (±0)	174.1 (±56.6)	2708.5 (±5735.2)	-	-	350 (±75.3)	-
21	-9.2 (±0)	-4.3 (±0)	174.1 (±56.6)	2708.5 (±5735.2)	-	-	350 (±75.3)	-
22	-9.2 (±0)	-4.3 (±0)	174.1 (±56.6)	2708.5 (±5735.2)	-	-	350 (±75.3)	-
23	-9.2 (±0)	-4.3 (±0)	174.1 (±56.6)	2708.5 (±5735.2)	-	-	350 (±75.3)	-
24	-9.2 (±0)	-4.3 (±0)	174.1 (±56.6)	2708.5 (±5735.2)	-	-	350 (±75.3)	-
25	-9.2 (±0)	-4.3 (±0)	174.1 (±56.6)	2708.5 (±5735.2)	-	-	350 (±75.3)	-
26	-9.2 (±0)	-4.3 (±0)	174.1 (±56.6)	2708.5 (±5735.2)	-	-	350 (±75.3)	-
27	-9.2 (±0)	-4.3 (±0)	174.1 (±56.6)	2708.5 (±5735.2)	-	-	350 (±75.3)	-
28	-9.2 (±0)	-4.3 (±0)	174.1 (±56.6)	2708.5 (±5735.2)	-	-	350 (±75.3)	-
29	-9.2 (±0)	-4.3 (±0)	174.1 (±56.6)	2708.5 (±5735.2)	-	-	350 (±75.3)	-
30	-9.2 (±0)	-4.3 (±0)	22.7 (±2.8)	31.5 (±7.6)	-	-	350 (±75.3)	-
31	-9.2 (±0)	-4.3 (±0)	22.7 (±2.8)	31.5 (±7.6)	-	-	350 (±75.3)	-
32	-9.2 (±0)	-4.3 (±0)	22.7 (±2.8)	31.5 (±7.6)	-	-	350 (±75.3)	-
33	-9.2 (±0)	-4.3 (±0)	22.7 (±2.8)	31.5 (±7.6)	-	-	350 (±75.3)	-
34	-9.2 (±0)	-4.3 (±0)	22.7 (±2.8)	31.5 (±7.6)	-	-	350 (±75.3)	-

35	-9.2 (±0)	-4.3 (±0)	22.7 (±2.8)	31.5 (±7.6)	-	-	350 (±75.3)	-
36	-9.2 (±0)	-4.3 (±0)	22.7 (±2.8)	31.5 (±7.6)	-	-	350 (±75.3)	-
37	-9.2 (±0)	-4.3 (±0)	22.7 (±2.8)	31.5 (±7.6)	-	-	350 (±75.3)	-
38	-9.2 (±0)	-4.3 (±0)	22.7 (±2.8)	31.5 (±7.6)	-	-	350 (±75.3)	-
39	-9.2 (±0)	-4.3 (±0)	22.7 (±2.8)	31.5 (±7.6)	-	-	350 (±75.3)	-
40	-9.2 (±0)	-4.3 (±0)	22.7 (±2.8)	31.5 (±7.6)	-	-	350 (±75.3)	-
41	-9.2 (±0)	-4.3 (±0)	22.7 (±2.8)	31.5 (±7.6)	-	-	350 (±75.3)	-
42	-9.2 (±0)	-4.3 (±0)	22.7 (±2.8)	31.5 (±7.6)	-	-	350 (±75.3)	-
43	-9.2 (±0)	-4.3 (±0)	22.7 (±2.8)	31.5 (±7.6)	-	-	350 (±75.3)	-
44	-9.2 (±0)	-4.3 (±0)	22.7 (±2.8)	31.5 (±7.6)	-	-	350 (±75.3)	-
45	-9.2 (±0)	-4.3 (±0)	22.7 (±2.8)	31.5 (±7.6)	-	-	350 (±75.3)	-
46	-9.2 (±0)	-4.3 (±0)	22.7 (±2.8)	31.5 (±7.6)	-	-	350 (±75.3)	-
47	-9.2 (±0)	-4.3 (±0)	22.7 (±2.8)	31.5 (±7.6)	-	-	350 (±75.3)	-
48	-9.2 (±0)	-4.3 (±0)	22.7 (±2.8)	31.5 (±7.6)	-	-	350 (±75.3)	-
49	-9.2 (±0)	-4.3 (±0)	22.7 (±2.8)	31.5 (±7.6)	-	-	350 (±75.3)	-
50	-9.2 (±0)	-4.3 (±0)	22.7 (±2.8)	31.5 (±7.6)	-	-	350 (±75.3)	-
51	-9.2 (±0)	-4.3 (±0)	22.7 (±2.8)	31.5 (±7.6)	-	-	350 (±75.3)	-
52	-9.2 (±0)	-4.3 (±0)	22.7 (±2.8)	31.5 (±7.6)	-	-	350 (±75.3)	-
53	-9.2 (±0)	-4.3 (±0)	22.7 (±2.8)	31.5 (±7.6)	-	-	350 (±75.3)	-
54	-9.2 (±0)	-4.3 (±0)	22.7 (±2.8)	31.5 (±7.6)	-	-	350 (±75.3)	-
55	-9.2 (±0)	-4.3 (±0)	22.7 (±2.8)	31.5 (±7.6)	-	-	350 (±75.3)	-
56	-9.2 (±0)	-4.3 (±0)	22.7 (±2.8)	31.5 (±7.6)	-	-	350 (±75.3)	-
57	-9.2 (±0)	-4.3 (±0)	22.7 (±2.8)	31.5 (±7.6)	-	-	350 (±75.3)	-
58	-9.2 (±0)	-4.3 (±0)	22.7 (±2.8)	31.5 (±7.6)	-	-	350 (±75.3)	-
59	-9.2 (±0)	-4.3 (±0)	22.7 (±2.8)	31.5 (±7.6)	-	-	350 (±75.3)	-
NPV	-213.9 (±11.8)	-93.1 (±24.4)	2211.9 (±824.8)	39212.7 (±83686)	-	-	6684.4 (±4890.3)	-

Table S9 | Aggregated cash flows (million USD) and the volume (million m³) of wood products (roundwood and pulp/veneer) produced across the entire East Kalimantan forest estate in each year of our analysis for the baseline and optimal scenarios. 'Total' refers to the sum of years 0-59 for wood products.

Year	Roundwood		Pulp / Veneer		Annual Profit	
	Baseline	Optimal	Baseline	Optimal	Baseline	Optimal
0	43.07	40.93	82.19	78.88	780	2128
1	10.71	6.55	9.09	6.29	423	359
2	10.71	6.55	9.09	6.29	423	359
3	10.71	6.55	9.09	6.29	423	359
4	10.71	6.55	9.09	6.29	423	359
5	10.71	6.55	9.09	6.29	423	359
6	10.71	6.55	9.09	6.29	423	359
7	10.71	6.55	29.25	6.35	569	359
8	10.71	6.55	29.25	6.35	569	359
9	10.71	6.55	29.25	6.35	569	359
10	10.71	6.55	29.25	6.35	569	359
11	10.71	6.55	29.25	6.35	569	359
12	10.71	6.55	29.25	14.5	569	579
13	10.71	6.55	29.25	14.5	569	579
14	10.71	6.55	29.25	14.5	569	579
15	10.71	6.55	29.25	14.5	569	579
16	10.71	6.55	29.25	14.5	569	579
17	10.71	6.55	29.25	14.5	569	579
18	10.71	6.55	29.25	14.5	569	579
19	10.71	6.55	29.25	14.5	569	579
20	10.71	6.55	29.25	14.5	569	579
21	10.71	6.55	29.25	14.5	569	579
22	10.71	6.55	29.25	14.5	569	579
23	10.71	6.55	29.25	14.5	569	579
24	10.71	6.55	29.25	14.5	569	579
25	10.71	6.55	29.25	14.5	569	579
26	10.71	6.55	29.25	14.5	569	579
27	10.71	6.55	29.25	14.5	569	579
28	10.71	6.55	29.25	14.5	569	579
29	10.71	6.55	29.25	14.5	569	579
30	1.23	1.01	29.25	14.5	229	332
31	1.23	1.01	29.25	14.5	229	332
32	1.23	1.01	29.25	14.5	229	332
33	1.23	1.01	29.25	14.5	229	332
34	1.23	1.01	29.25	14.5	229	332
35	1.23	1.01	29.25	14.5	229	332
36	1.23	1.01	29.25	14.5	229	332
37	1.23	1.01	29.25	14.5	229	332

38	1.23	1.01	29.25	14.5	229	332
39	1.23	1.01	29.25	14.5	229	332
40	1.23	1.01	29.25	14.5	229	332
41	1.23	1.01	29.25	14.5	229	332
42	1.23	1.01	29.25	14.5	229	332
43	1.23	1.01	29.25	14.5	229	332
44	1.23	1.01	29.25	14.5	229	332
45	1.23	1.01	29.25	14.5	229	332
46	1.23	1.01	29.25	14.5	229	332
47	1.23	1.01	29.25	14.5	229	332
48	1.23	1.01	29.25	14.5	229	332
49	1.23	1.01	29.25	14.5	229	332
50	1.23	1.01	29.25	14.5	229	332
51	1.23	1.01	29.25	14.5	229	332
52	1.23	1.01	29.25	14.5	229	332
53	1.23	1.01	29.25	14.5	229	332
54	1.23	1.01	29.25	14.5	229	332
55	1.23	1.01	29.25	14.5	229	332
56	1.23	1.01	29.25	14.5	229	332
57	1.23	1.01	29.25	14.5	229	332
58	1.23	1.01	29.25	14.5	229	332
59	1.23	1.01	29.25	14.5	229	332
Total	390.5	261.18	1687.09	844.41		

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