Where the wild things are: Conserving tropical biodiversity via market forces and spatial targeting.

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Abstract

The recent report from the Secretariat of the Convention on Biological Diversity (*Global Biodiversity Outlook 3*, Montréal, 2010) acknowledges that ongoing biodiversity loss necessitates swift, radical action. Protecting undisturbed lands, while vital, is clearly insufficient, and the key role of unprotected, private land owned is being increasingly recognized. Seeking to avoid common assumptions of a social planner backed by government interventions, the present study focuses upon the incentives of the individual land owner. We use detailed data to show that successful conservation on private land depends on three factors: conservation effectiveness (the impact upon target species); private costs (especially reductions in production); and private benefits (the extent to which conservation activities provide compensation, for example by enhancing the value of remaining production). By examining the high-profile issue of palm-oil production in a major tropical biodiversity hotspot, we show that the levels of both conservation effectiveness and private costs are inherently spatial; varying the location of conservation activities can radically change both their effectiveness and private cost implications. We also use an economic choice experiment to show that consumers' willingness-to-pay for conservation-grade palm-oil products has the potential to incentivize private producers sufficiently to engage in conservation activities supporting vulnerable IUCN Red Listed species. However, these incentives vary according to the scale and efficiency of production and the extent to which conservation is targeted to optimize its cost-effectiveness. Our integrated, interdisciplinary approach shows how strategies to harness the power of the market can usefully complement existing, and to-date insufficient, approaches to conservation.

Significance statement

Protected public lands are insufficient to halt the loss of global biodiversity. However, most commercial land owners need incentives to engage in conservation. Through an interdisciplinary study examining palm-oil plantations in Sumatra we demonstrate that (1) joint consideration of both biodiversity and economic relationships permits the spatial targeting of areas that enhance conservation of IUCN Red Listed species at relatively low cost to the land owner, and (2) the potential exists for funding such private costs of conservation through a price premium on a conservation certified good. Such an approach avoids the need to assume intervention from an international social planner while establishing the potential for profitable conservation on private lands, providing an important additional route for sustaining endangered species.

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Introduction

The urgency of the global biodiversity crisis has been well-documented, with one-fifth of the world's assessed vertebrates being at imminent risk of extinction (1) and many more less-understood species thought to be under similar threat (2). The overwhelming cause of this biodiversity loss is land use change (3, 4), driven in major part by the expansion and intensification of agriculture and plantations (5, 6). Some of the most dramatic changes have occurred within forests (7), which are being lost at an estimated rate of around 13 million hectares annually (8). Such loss is particularly prevalent in the tropics of southeast Asia where the overall rate of deforestation between 2000 and 2010 was 1% per annum (9), with annual peaks in excess of 5% in areas such as the naturally biodiverse lowlands of Sumatra where much of this loss has been due to the growth of oil palm plantations (10).

Despite the tremendous loss of primary forests, recent findings from southeast Asia suggest that much of the region's fauna can persist in logged 'secondary' forests, and that it is the subsequent clearance of such areas and conversion to plantations of crops such as oil palm that causes major losses of biodiversity (11, 12). However, even in lowland areas where logging of primary forests has been substantial, subsequent clearance of secondary forests has not been complete. The region is thus a mosaic of land-use types, primarily composed of secondary forests, cleared land and palm oil plantations (13), rather than uniform crop monocultures. From a conservation perspective, it is therefore imperative to incentivize land owners to conserve as much of the remaining secondary (and of course primary) forests as possible (14).

The international community has recognized the problem of global biodiversity loss, and through the Convention on Biological Diversity (CBD), committed to achieving a significant reduction in the rate of loss by 2010 (11). Unfortunately, not only was the CBD target missed, but recent assessments have shown that the overall rate of biodiversity loss is not even slowing (15, 16). Reasons for this policy failure are varied, but in southeast Asia, it appears that inadequate international public sector funding (17), and a focus on conserving extensive tracts of primary forest which now no longer exist (7), have been major contributors. To effectively halt biodiversity decline in the tropical forest regions of southeast Asia, conservation strategies must recognize the importance of large private landowners and that, at present, there is little incentive for such landowners to conserve biodiversity. Indeed, conservation incurs significant costs in terms of foregone income (18, 19), which, given the lack of sufficient national and international public sector funding, needs to be addressed if biodiversity on that majority of land which resides in the private sector is to be conserved.

Here, we provide the first interdisciplinary, scientific assessment of a private sector, market-based approach to large-scale conservation in the tropical forest regions of southeast Asia. We use data from our four-year field study of a 32,000-hectare palm-oil concession and its environs in central Sumatra to calculate cost-effectiveness and opportunity costs of conservation in one of the world's richest areas of biodiversity (20). Our biodiversity surveys were conducted across the study period through more than 670 km of transect walks across a mosaic of palm plantations, palm nurseries, secondary forest, and recently cleared lands (Fig 1a). Our analysis focuses on the various species of IUCN Red List mammals that were observed during the course of these walks (analyses of other species being given in Supplementary Information). These data permitted the estimation of models relating the probability of observing these mammals to the spatial distribution of land uses and other features within and surrounding the concession.

Data necessary to calculate the opportunity costs of conservation (foregone profits) were obtained through unconstrained access to all company financial records, including costs and revenues for all operations on each of the roughly 400 planted and unplanted sub-compartments of the concession, geo-referenced and recorded monthly for the entire study period. This was supplemented by information on the direct costs of restoring degraded land in tropical areas obtained from a review of previous studies (see SI). The combined dataset allowed a spatially explicit analysis of the overall cost-effectiveness of conservation in terms of both biodiversity benefits and private costs. We complete our analysis by examining the impacts upon company revenues of a conservation-grade price premium (assessed via a multi-treatment choice experiment (21, 22)) and comparing this to the costs of conservation to reveal the net effects upon profitability.

Our approach considers three interrelated issues: (i) conservation potential (assessed via spatial modelling of the impacts of land use in and around the concession on the presence of threatened species); (ii) conservation costs (again spatially modelled from unconstrained access to all company financial records) and (iii) potential price premium (analyzed via choice experiments of the value of goods produced using certified conservation grade palm oil). Other comparable studies typically operate at broad scales and at a resolution beyond that which is relevant to the individual landowner responding to market forces can do when faced with a potential profit-conservation tradeoff (23, 24). Applications that simultaneously collect primary cost and biophysical data are still few and far between, and our access to such fine-grained corporate financial data is particularly rare, given the sensitivities involved in providing such data to third parties. Here, by focusing on how the private benefits of consumers may offset the private costs of conservation grade palm oil production, our study also circumvents problems associated with studies that assume the intervention of a "social planner", typically backed by national or international government tax transfers to offset conservation costs (23-25).

Results

Biodiversity effectiveness of conservation

The species of IUCN Red Listed mammal observed were: agile gibbon (*Hylobatres agilis*), pig tailed macaques (*Macaca nemestrina*), long tailed macaque (*Macaca gascicularis*), East Asian porcupine (*Hystrix brachyuran*), smooth coated otter (*Lutrogale perspicillata*), siamang (*Symphalangus syndactylus*) and pangolin (*Manis javanica*). Models were built relating observations of these different mammals to land uses, natural and physical features both in the immediate vicinity of the observation and across the landscape mosaic within and surrounding the concession (see methods and SI for details). These models are used to predict the probability of sighting different species at each location (200m grid cell) across the study. Fig. 1b shows the total number of Red List species for which the probability of sighting (or 'potential presence') is equal to or greater than fifty per cent for a daily 200m walk at that location aggregated over a year (again see methods and SI for details).

Comparing our predictions of the probability of sighting Red List species with the land use information shown in Fig. 1(a) clearly shows the highly negative impact of intensive oil palm plantation upon such endangered mammals (illustrated by the low probabilities of sighting dominating the central plantation area of the concession). These mammals also fare poorly in highly fragmented landscapes characterized by substantial elements of both plantation and recently cleared land (as in the western arm of the concession). However, the same species perform much better within secondary forest, as shown in the southern area of the concession (contrasting this with the low probabilities of observation shown on the north-eastern edge of the concession, bordering farmland and plantation, clearly shows the impact of surrounding land use). Such findings conform well with previous observations (26) and illustrate the vital importance of spatial targeting for conservation effectiveness.

The costs of conservation

Variation in land use and other features result in substantial diversity in biodiversity across the concession. However, relative homogeneity in terrain, soils and other natural determinants of oil palm output meant that productivity levels were found to be reasonably similar across the plantation. Despite this lack of spatial variation, the introduction of improved management practices raised output of crude palm oil (CPO) across the plantation from around 220 to just over 300 kg/ha/month over the period of our study. Such a range will clearly affect our estimates of the opportunity costs of conservation and, given that concessions operate at a variety of efficiency levels, we decided to use these extremes as examples of 'low' and 'high' production regimes in our subsequent analysis. These rates of output were applied to both currently planted and unplanted areas with the costs of road development being modelled for those latter areas which were not currently served by roads (see SI).

Combining our estimates of the opportunity costs of foregone profits with information on the direct costs of land restoration (see SI) allowed us to generate an opportunity cost of conservation (OCC) surface for the entire concession by using a GIS to bring together spatially referenced data on the location of planted areas, other habitat types, existing roads and the processing mill. Assuming the high productivity scenario we obtain the OCC results illustrated in Figure 1(c). This shows that the OCC is highest within existing, mature palm plantations near to the processing plant (where transport costs are lowest). We also observe that the presence of existing roads raises the OCC as there is less need for road construction in such areas and potential profits are higher. Even allowing for the loss of potential future profits inherent in dedicating present secondary forest to permanent conservation, such costs are 3-5 times higher (depending on output levels) if conservation land were to be located on present productive plantation areas (see detailed analysis in SI).

The cost-effectiveness of conservation

Integrating our biodiversity effectiveness and cost assessments allows us to undertake a cost-effectiveness analysis for conservation across the concession. This is achieved for each hectare by dividing the predicted biodiversity effectiveness of conversion to conservation (Figure 1(b)) by the cost of that conversion (Figure 1(c)). We then rank the resulting 'value for money' measure from highest to lowest. Figure 1(d) illustrates the resulting cost-effectiveness map with darker shading indicating areas that deliver higher value for money invested in conservation. Inspection of this map shows that the most cost-effective areas for conservation are situated towards the south and west edges of the concession, in areas both in and near to extensive secondary forest within and surrounding the concession, and outside the mature oil palm plantation where conversion costs would be highest. Corresponding population effects were estimated using scaling models (27) which suggested that conservation in such areas had the potential to make a substantial contribution to the viability of the species concerned (see Methods and SI).

We now turn to consider the adequacy of incentives to undertake such conservation actions by assessing the likely scale of a conservation-grade price premium and its net effect upon profitability.

Private benefits of conservation: ***price premium for conservation grade products***

While cost-effectiveness analysis significantly reduces the costs of conservation, these remain non-trivial and therefore incentives are needed to ensure uptake of such schemes on commercially used private lands. Consideration of the alternatives available for incentivizing producers (discussed in Methods) suggested that these might best be delivered through a price premium associated with certified 'conservation grade' products. Certification might reasonably be provided through an extension of existing initiatives such as the Roundtable on Sustainable Palm Oil (RSPO) Certified Sustainable Palm Oil (CSPO) scheme (28, 29). To assess the extent to which such certification of products might result in a price premium we designed a multi-treatment choice experiment (30), implementing this through a field survey of developed world supermarket shoppers (see SI for details).

Our study presented shoppers with choices between pairs of a common household good (margarine) which were physically identical except for whether the palm-oil they contained was conservation-grade or conventionally produced. The price differential between the two goods was varied across shoppers allowing us to observe the premium that consumers were prepared to pay for the conservation-grade good. Multiple treatments revealed that the absolute level of price premium was greatest for higher quality products. Taken together our results indicate that people would be willing to pay a conservation grade premium ranging from 15% to 56% with a central value of 36% (full details given in SI and (22)); values that we used in our subsequent analysis of impacts upon profitability.

The profitability of cost-effective conservation schemes in the presence of a price premium.

Our cost-effectiveness analysis illustrated that substantial reductions in the private costs of conservation can be achieved through spatial targeting. However, residual costs remain non-trivial and will deter many private land owners unless adequately compensated by higher prices for certified, conservation-grade production. To investigate this we compare the additional costs faced by firms undertaking cost-effective conservation schemes (as per Figure 1(d)), with the higher revenues associated with conservation-grade production for each of the price premiums identified in our consumer survey. The resulting net benefits (i.e. change in profitability) to the firm are summarized in Figure 2. Here Figure 2(a) considers a concession of the same size as that studied (32,000 ha), showing that larger conservation schemes progressively remove areas of productive palm plantation, raising costs and causing the net benefit curve to decline. Nevertheless, even at the lowest price premium, conservation areas of up to 6,000 ha increase profits. Concessions with higher productivity make larger profits from such levels of conservation as the price premium attaches to their higher levels of output. However, this differential switches with larger conservation areas as higher levels of productivity mean that reductions in the size of oil palm plantation result in a greater loss of output. As expected higher price premiums incentivize larger conservation schemes but even given the most favorable conditions the firm still devotes the majority of land towards production.

Of course not all concessions are of the same size as the one we studied. Figure 2(b) shows the net benefits associated with a conservation scheme of 5,000 ha as the concession area increases (assuming that the distribution of habitat types at our study site is representative of other concessions). Our results show that both the level of price premium and concession size are important determinants of the private incentives for conservation. Higher price premiums again improve the incentives for conservation, but for small plantations of less than 10,000 ha. even the highest price premium fails to make conservation schemes financially attractive. Indeed, at the smallest price premium only concessions larger than 25,000 ha have an incentive to engage in this (albeit substantial) level of conservation. The impact of higher levels of productivity also vary by concession size, being positive for larger concessions for which high output levels reap greater rewards from the price premium. Overall the analysis reveals that larger, high productivity firms generally have substantially greater incentives to engage in conservation activities. Given this, the engagement of smaller producers might require co-operative agreements spanning groups of similar sized firms.

Discussion

By jointly considering the spatial variability of both the effectiveness and opportunity costs of conservation, and linking these with the price premiums that developed world consumers are willing to pay, we have demonstrated the potential for a mixture of market forces, spatial targeting and certification to incentivize private producers to engage in levels of conservation effort that are relevant to sustaining populations of the IUCN Red Listed vertebrates observed in our case study. The principle of trying to use incentives to increase the provision of habitat on private lands and hold back the conversion of secondary forest into intensive plantation seems vital in areas where primary forests have already been reduced to low levels. However, for this potential to be realized the certification of conservation-grade production requires careful design both to avoid the creation of fragmented ribbons of habitat (isolated within intensive plantations and yielding little biodiversity value (31, 32)), and to reduce conversion of secondary forest to oil palm (which remains a vulnerability of the current RSPO scheme (33, 34)). The downward sloping net benefit curves illustrated in Figure 2(a) indicate that the profit maximizing strategy of the private producer is to engage in the minimal level of conservation consistent with certification. It is therefore imperative that any certification scheme should not only prohibit the inclusion of newly deforested areas but also require a minimum conservation area. Furthermore, the higher profits accruing to high productivity larger concessions means that there is scope to augment this minimum area threshold with a requirement for increases in absolute conservation areas for larger concessions and still maintain the profit incentive. The analysis conducted above provides some useful results in this respect, showing that areas which substantially exceed the minimum thresholds for conservation suggested by prior studies (35) can still be profitable if suitably incentivized by price premiums.

Although drawing upon a substantial amount of economic, consumer and biodiversity data, the findings presented in this paper need to be replicated across a diversity of geographical sites and economic conditions. Consequently, our study cannot be considered as definitive in terms of the precise level of economic returns, but it nevertheless demonstrates the potential for adding a further complementary approach to addressing the vitally important issue of biodiversity loss. Given this, the fact that our results suggest that such an approach might be sufficient to incentivize conservation is encouraging, particularly as we see this as a supplement to, rather than replacement for, other initiatives such as REDD+ which, to date, appear underfunded (12). Furthermore, some relatively simple extensions should substantially enhance both the incentives and biodiversity effectiveness of conservation schemes on private lands. Allowing the establishment of contiguous conservation areas that span concessions may further reduce costs and improve incentives for land owners to participate in such undertakings. Simple design principles that trade-off improvements in the overall size, spatial coherence (including linkage with surrounding forested areas) and contiguity of conservation areas (36, 37) against reductions in the land contribution made by each participating concession provide win-win outcomes for both biodiversity and land-owners. The potential for such gains to be further enhanced through the funding of even larger off-site conservation reserves (38) is also worthy of consideration.

In conclusion, our findings directly address the joint challenge that ecosystem science needs to become both operational and integrated within its wider socio-economic context if it is to change decisions and resource use (2, 39-40). Through analyses such as the cost-effectiveness and conservation profitability assessments reported here, we demonstrate that the integration of both ecological and economic research yields insights which neither can illuminate alone. Moreover, through the integration of financial, ecological and environmental information in a concise, consistent and comparable format, we have provided an approach which addresses calls to provide business with tools and metrics to understand the benefits that nature can bring to their operations (41).

Materials and methods

Biodiversity effectiveness of conservation

Data regarding the relationship between species and the matrix of land uses within and surrounding the study area were gathered from a series of 16 transects located across the concession to sample all of its land use types from secondary forest to intensive palm-oil plantation. Transects had a mean length of 1.5 km and were walked on average 28 times over the sampling period, including both day and night, across all months of the year and in a range of weather conditions. This provided a total of about 670 km of transect walks. To allow for variation in spatial characteristics along a walk, each transect was divided into 200 m segments yielding more than 3,300 such segments in all.

A variety of species were observed, including the IUCN Red List mammals listed previously and a number of other species analyzed in SI. The location of each observation was recorded using a GPS (Global Positioning Systems) device with an approximate resolution accuracy of 3 m. A GIS was used to integrate the location of observations with data from local map and satellite images to generate a range of more than 30 variables that might reflect determinants of species observations, including the predominant habitat within each transect segment, distance and area based habitat measures, human disturbance indicators, etc. (details in SI).

Models of the probability of observing different IUCN Red Listed species were estimated using a generalized linear model with a logistic link function and a binomial distribution (details in SI). Observation data were structured as a panel data set to account for repeated sampling of transect segments and fit with robust standard errors to account for spatial and temporal autocorrelation. Explanatory variables were obtained from observations or calculated in the GIS (e.g. distance to each habitat type). Model selection was based upon theoretical considerations in conjunction with a quasi-likelihood criterion to compare nested specifications. Models were then used to predict the probable presence of different species across the study area. To do this, the concession was divided into 200 x 200 m grid cells, corresponding to the spatial resolution of the regression model, predictor variables obtained from the GIS and model coefficients used to yield predictions.

Our various IUCN mammal models are used to predict the probability of sighting different species at each location (200m grid cell) assuming a single daily walk across that cell over the duration of one year. Fig. 1b shows the total number of species for which the probability of a sighting is equal to or greater than fifty per cent. This is constructed by using the models to predict the probability of sighting a given species and assigning a value of 1 if the probability of a sighting is equal to or greater than fifty per cent and zero otherwise. These values are then summed for all Red List species to yield the probability measure given in Fig. 1b.

The presence of a species within an area does not imply its long term survival but, all other things being equal, larger conservation areas should deliver larger populations of species. Estimates of this relationship were provided by mechanistic scaling models (27), linking expected population to animal body mass, trophic level and the various extents of conservation area considered in our study and shown in Fig.1(d) (see SI for details). The application of such models is at best a rough approximation of response, as this may vary substantially across locations and consequently results should not be over-interpreted. Accepting this, these models suggest that the various conservation areas are expected to yield populations of Red Listed species ranging from less than one hundred for larger carnivorous mammals to well over 5,000 individuals for some herbivores (see SI for results). At various times it has been suggested that populations of the order of 50, 500 and 5,000 might enable long term persistence (42, 43), although Flather et al (44) question whether data or theory support such generalizations. It has also been suggested that for species such as those reported here with a body mass of 5-23 kg that the minimum area requirement to contribute to the viability of species is of the order of 10,000 ha (45). We do not claim that the conservation measures taken here would ensure the viability of the species' populations. However, it is clear from the population estimates and the area of land being set aside for conservation in this analysis that the measures advocated here have the potential to make a substantial contribution to the viability of the species concerned. Furthermore, we would not expect that profitable schemes (as outlined subsequently) would be confined to single concessions and the potential for enhanced conservation coordinated across multiple sites enhances the likelihood that they would deliver sustainable populations for the species concerned.

Production and financial data

The concession contained large areas of mature and immature oil palm plantation, secondary forest and bamboo-dominated scrubland. To the northern edge of the concession, farming, small settlements and government oil palm plantations create an agricultural mosaic (see SI). By contrast the southern edge was mainly secondary forest. The private revenues and costs associated with the production of CPO in both planted and unplanted areas were assessed by applying the principles of agricultural economics (46). The concession management granted full access to all cost and revenue data broken down to the field unit for the years 2002-2006. This data consisted of highly disaggregated, spatially referenced, financial and physical quantity information, environmental characteristics and meteorological condition records for each of the nearly 400 sub-compartments (averaging around 30 ha each) of the concession (planted and unplanted). More than 90 variables were provided for each sub-compartment with these data being collected every month throughout the study, yielding a total of more than 1.5 million data records over the full period. These data included: Average price at which the concession sold its CPO; Total kilograms of oil palm fresh fruit bunches (FFB) harvested; Total number of kg of CPO sold; Income from CPO sales; Administrative costs; Fixed costs of the processing mill; Debt servicing and other outgoings; Cost of producing CPO from FFB at the mill; General maintenance costs such as pruning, weeding, fertilizing and censuses; Wages; Cost of transporting FFB to the mill; Field office costs; Area of productive oil palms; etc. Further statistics such as productivity measures were calculated from this data. Selected summary statistics aggregated at an annual level are presented in SI.

Opportunity costs of conservation

The OCC of each area of the concession was comprised of the following components: (a) the actual (for planted areas) or predicted potential (for unplanted areas) gross margin (revenue minus variable costs other than those mentioned subsequently) for that area; (b) transport cost from the area to the processing mill; (c) the annuitized predicted cost of road construction to that area from the existing road network; (d) the restoration cost for area. Further details on these calculations are given in SI.

While output varied substantially in response to changes in inputs such as fertilizer, an analysis of FFB data showed insignificant spatial variation in yield across the planted areas of the concession. While this is unsurprising given the absence of substantial differences in soil, elevation, watershed and other physical characteristics over that area, research from other contexts shows that where such variation does occur analysts should expect and allow for a yield response (see for example (47)). Given the results of this analysis, in calculating the potential profitability (and hence OCC) of currently unplanted areas it was assumed that, if converted to plantation, they would provide similar levels of output to existing planted areas. Expected FFB output was then related to data on the proportion of fruit mass converted to oil to calculate monthly output of CPO. Combining this with data on prices provided our revenue estimates. Cost data on inputs, maintenance, development and processing were combined with spatially disaggregated estimates of site specific transportation costs, the latter being predicted by using GIS to apply per kilometer cost estimates to road network data. As part of this calculation we incorporated, within the potential profits of unplanted areas, the costs of constructing new roads. We took local construction cost values from the literature and account for the fact that, as an unplanted area is developed, new roads will spur off each other. Subtracting the sum of these costs from revenues provided our predicted profits for both planted and currently unplanted areas. Overall cost estimates were completed by adding in local restoration costs again taken from the literature which also provided indications of the relevant time profiles and discount rates for Indonesian investment projects. Details of calculations and information sources are provided in SI.

Private benefits of conservation

A variety of approaches can be identified as potential means for incentivizing producers to engage in conservation. One approach would be to fund such incentives through a social planner backed by international transfers. However, such approaches are vulnerable to problems such as the corrupt divergence of funds, failure of donors to pay and changes in donor priorities (48, 12). In this paper we consider the potential for alternative (or, ideally, supplementary) incentives provided by the price premium attached to ‘conservation grade’, ‘fair-trade’, ‘certified’ and similar goods. Such differentiated goods have arisen in response to demand, primarily from developed world consumers, who are prepared to pay a premium for preferred methods of production and the perceived positive externalities that they bring (49). Given that Europe, the United States and Australia alone consume close to 20% of the world’s palm oil (50), the potential exists for a substantial portion of that production to generate conservation grade price premiums.

The choice modelling valuation technique was employed to estimate the price premium that might be attached to products containing ‘conservation-grade’ as opposed to conventionally produced palm oil. Survey subjects were presented with a choice between two standard size (500 g) tubs of vegetable margarine, chosen because it has high consumer recognition and palm oil is a major ingredient. The questionnaire was extensively piloted (n = 150) and field data (n = 600) were collected using survey techniques applied at UK supermarkets. 'Next-to-pass' interviewing techniques were applied to ensure a random sample. The price and quality of the two products as well as the degree of information about the conservation-grade good were all varied independently across subjects (details provided in SI). Treatments themselves were randomized such that each respondent had an equal probability of facing any permutation of our experiment. Individuals were asked a number of other questions regarding their socioeconomic and demographic characteristics as well as various other issues which might affect preferences. These factors were controlled for in subsequent analyses.

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Figure legends

Figure 1: Study area and analysis results. (a) Distribution of predominant habitat types across the concession (Areas shown as oil palm are principally plantation; Secondary forest is typified by areas where large trees had been logged but were otherwise relatively undisturbed; Recently cleared areas include land under preparation for potential planting with oil palm or cleared as a result of illegal settlement (burnt and in preparation for crop planting), typically having little vegetation cover, although some grasses and herbaceous plants occur amongst the tree stumps). (b) The predicted number of IUCN Red Listed species with a greater than 50% probability of being observed on a given 200m transect walked once each day for a year. (c) The opportunity cost of conservation (assuming high productivity management regime) shown in thousands of Indonesian Rupiah per hectare per month. (d) Optimal cost-effective allocation of land to three sizes of conservation scheme.

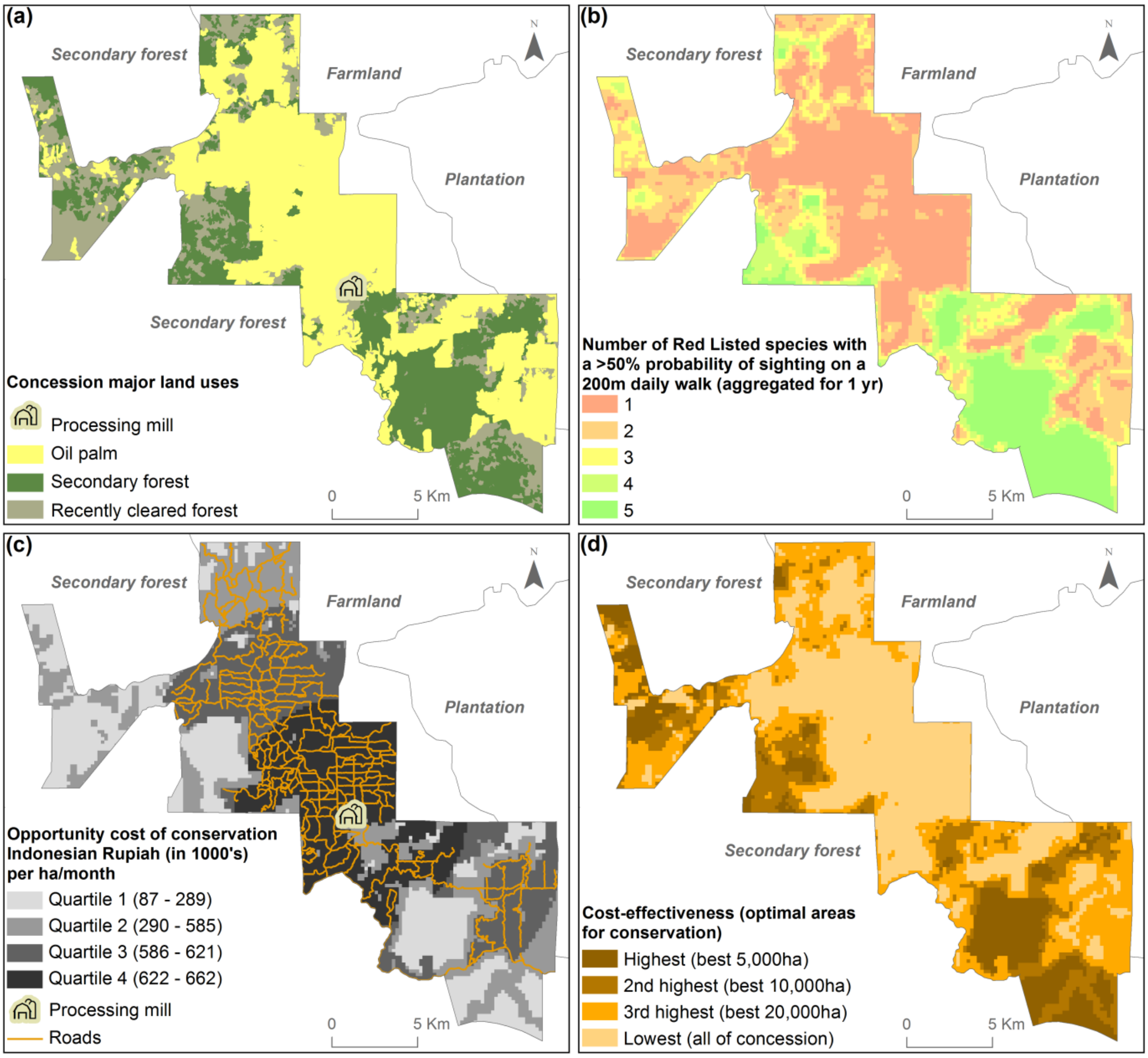
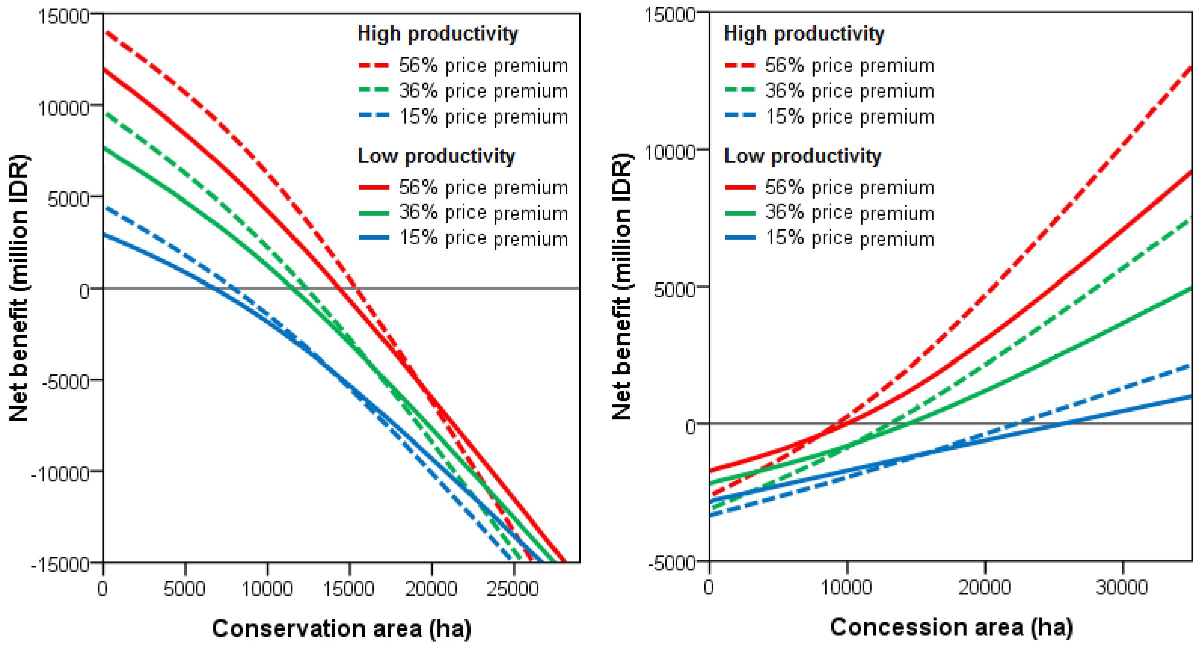


Figure 2: The profitability of cost-effective conservation schemes in the presence of differing price premiums and productivity levels. (a) The net benefit (change in profits) accrued by a concession of a constant size (32,000ha) with varying conservation areas. (b) The net benefit accrued by concessions of differing sizes with a constant conservation area (5,000 ha).



Supplementary Information

Biodiversity effectiveness of conservation

Data

In addition to details given in the main paper, of the 16 transects established across the plantation, six were situated in areas dominated by oil palm with the remainder in locations of primarily secondary forest or recently cleared land with some seasonally flooded areas and palm nurseries also being represented across the sampling scheme (see Fig. S1). Distances to different surrounding land uses were also varied. Transects where walked diurnally (starting at 7am), and nocturnally (starting at 7pm) in rotation across all months of the year and in a range of weather conditions. Transects were walked a minimum of 20 times each over the course of the study, with a mean of 28 walks per transect. A trained team of 12 assistants was employed and observers walked in groups of 2-3. As noted, additional data were gathered from GIS analysis of local map and satellite images. These latter data gathering exercises included measures which extend into the area surrounding the concession (e.g. the distance to secondary forest may be much shorter to areas outside rather than inside the concession). These surrounding land use types are illustrated in Fig. S1. All explanatory variables were generated at the same 200m resolution as the transect segment data yielding the set of explanatory variables detailed in Table S1.

Figure S1: The concession and surrounding area.

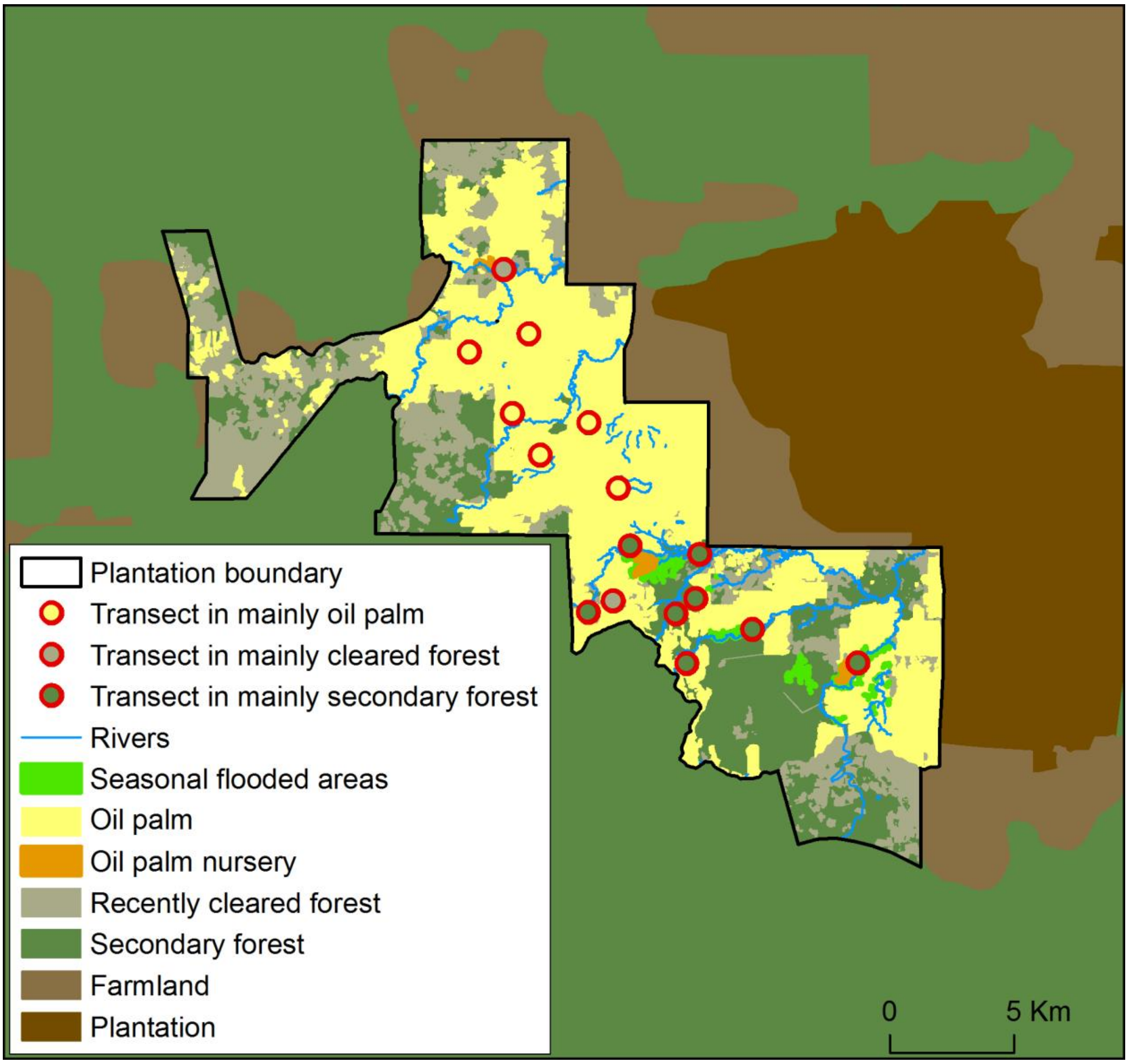


Table S1: Description of independent and explanatory variables used to examine variation in mammal numbers across the plantation, including the data sources from which they were derived within the GIS.

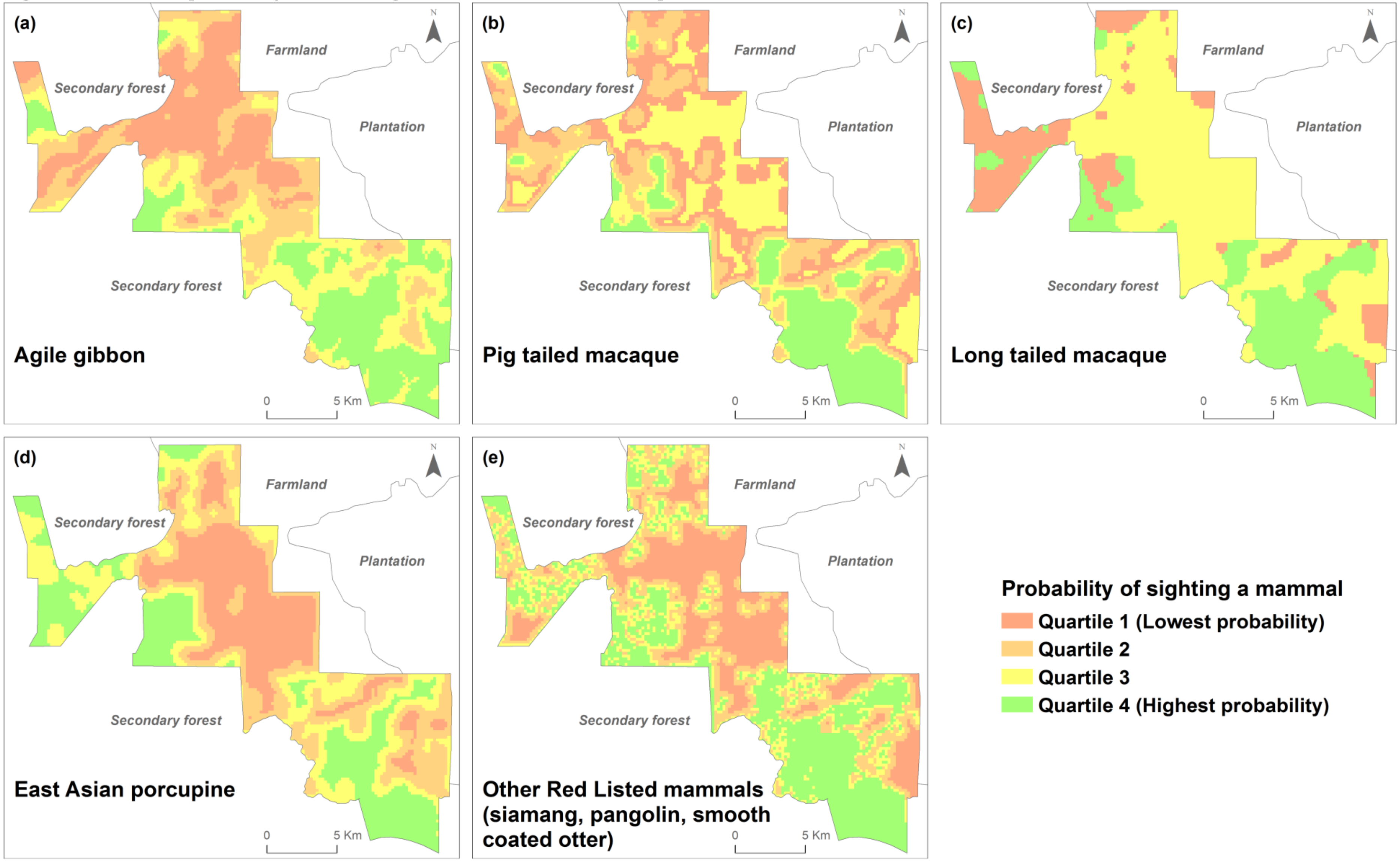
Variable Categories	Variable Names	Units	Sources of Data
Mammal	Agile gibbon sighted Pig tailed macaques sighted Long tailed macaques sighted East Asian porcupine sighted Siamang, pangolin or smooth coated otter sighted Leopard cat sighted Wild pig sighted Tree shrew sighted Palm civet sighted Mouse deer sighted	0=no 1=yes	Recorded in the field by visual observation.
Predominant habitat within each transect segment	Oil palm Recently cleared forest Secondary forest	0=no 1=yes	The distribution of habitats was identified from satellite images (obtained from the plantation management) and Jambi Government GIS data (obtained under license from the Jambi Government). The predominant habitat of each transect segment was calculated using a GIS. Secondary forest is typified by areas where large trees had been logged but were otherwise relatively undisturbed. Recently cleared areas include land under preparation for potential planting with oil palm or cleared as a result of illegal settlement (burnt and in preparation for crop planting). These areas typically had little vegetation cover, although some grasses and herbaceous plants occur amongst the tree stumps.
Distance based habitat measures	Distance to edge of the plantation Distance to oil palm Distance to recently cleared forest Distance to secondary forest Distance to primary forest Distance to the nearest tree nursery Distance to farmland Distance to secondary forest if predominant habitat is oil palm	Kilometers	The distribution of habitats was identified from satellite images and Jambi Government GIS data. All distances were calculated using a GIS.
Area and presence based habitat measures (area or presence of each habitat type within a 1km^2 zone around each transect segment)	Area of oil palm Area of recently cleared forest Area of secondary forest Area of primary forest Area of tree nurseries Area of farmland	kilometres^2	The distribution of habitats was identified from satellite images and Jambi Government GIS data. The area of each habitat within a 1km^2 zone around each transect segment was calculated using a GIS.
	Presence of oil palm Presence of recently cleared forest Presence of secondary forest Presence of primary forest Presence of tree nursery Presence of farmland	0=no 1=yes	The distribution of habitats was identified from satellite images and Jambi Government GIS data. Habitats present within a 1km^2 zone around each transect segment were identified using a GIS.
Water features	Distance to rivers Distance to seasonally flooded areas	Kilometers	Rivers were identified from satellite images and Jambi Government GIS data. All distances were calculated using a GIS.
Season	Rainy season	0=no 1=yes	Weather data was obtained from plantation records. The rainy season was defined as the wettest months of the year from October to April.
Weather conditions	Rain Heavy rain	0=no 1=yes	Recorded in the field by visual observation.
Time of day	Night	0=no 1=yes	Recorded in the field by visual observation.
Measures of human disturbance	Distance to major roads Distance to minor roads Distance to harvest roads Distance to any road (major, minor or harvest) Distance to settlements	Kilometers	Roads and settlements were identified from satellite images and Jambi Government GIS data. All distances were calculated using a GIS.

As noted in the main paper, models of the probability of observing different IUCN Red Listed species were estimated using a generalized linear model with a logistic link function and a binomial distribution. Observation data were structured as a panel data set to account for repeated sampling of transect segments and fit with robust standard errors to account for spatial and temporal autocorrelation. Table S2 presents the various models as estimated. These models were then employed to generate predictions of the probability of observing different species for each 200 x 200 m grid cell across the concession. Maps of these predictions are given in Fig. S2.

Table S2: Odds ratios for sighting different IUCN Red Listed mammals in relation to habitat availability.

Independent variables	Coef. (β)	s.e.	Odds ratio (OR)	p-value
Agile gibbon				
Constant	-3.43	0.62	0.032	<0.001
Night	-20.55	5.78	1.19E-09	<0.001
Distance to seasonally flooded areas (km)	-0.39	0.21	0.677	0.068
Oil palm area within 1km^2	-1.31	1.48	0.270	0.376
Pig tailed macaque				
Constant	-6.86	0.62	0.001	<0.001
Secondary forest area within 1km^2	7.45	3.88	1720.920	0.055
Distance to oil palm (km)	4.44	3.66	84.463	0.225
Predominant habitat is secondary forest	-6.21	2.27	0.002	0.006
Long tailed macaque				
Constant	-7.98	0.80	0.000	<0.001
Night	-2.14	1.05	0.117	0.042
Predominant habitat is secondary forest	3.01	0.56	20.297	<0.001
Predominant habitat is oil palm	2.10	0.56	8.180	<0.001
East Asian porcupine				
Constant	-4.67	1.05	0.009	<0.001
Night	1.27	0.62	3.548	0.040
Oil palm area within 1km^2	-2.85	1.21	0.058	0.019
Siamang, pangolin and smooth coated otter				
Constant	-5.73	0.61	0.003	<0.001
Distance to secondary forest (km)	-3.30	0.54	0.037	<0.001

Figure S2: Predicted probability of observing different IUCN Red Listed species across the concession



Examining the models and maps of the probability of observing IUCN Red Listed species, it is clear that continuous forest is preferred to oil palm, recently cleared land or fragmented mixtures of land use types, a finding which concurs with the extant literature (1-3). Preferences between non-forest land uses vary across species with most finding oil palm the most adverse habitat but macaques preferring oil palm to recently cleared land, a result which accords with the findings of Chung (4) who notes that these mammals feed on oil palm fruits. However all land use types remain clearly inferior to forest. The latter finding is echoed through the synthesis analysis of Fig 1b in the main paper which is obtained by using the models of Table S2 to predict the probability of sighting a given species and assigning a value of 1 for probabilities equal to or greater than fifty per cent and zero otherwise. These values are then summed for all Red List species to yield the probability measure given in Fig. 1b.

Alongside the various IUCN Red List species observed on site a number of other mammals were observed in our transect studies. Table S3 and Fig. S3 present models and maps of these species, derived as described previously.

Table S3: Odds ratios for sighting non-IUCN Red Listed mammals in relation to habitat availability.

Independent variables	Coef. (β)	s.e.	Odds ratio (OR)	p-value
Leopard cat				
Constant	-8.55	0.98	0.000	0.000
Secondary forest present within 1km2	0.54	0.23	1.709	0.020
Oil palm area within 1km2	5.72	1.02	304.735	0.000
Distance to village (km)	-0.57	0.19	0.565	0.003
Night	1.29	0.10	3.613	0.000
Greater mouse deer				
Constant	-30.20	7.43	7.685E-14	0.000
Secondary forest area within 1km2	14.55	5.32	2.088E6	0.006
Oil palm area within 1km2	11.93	4.77	1.517E5	0.012
Number of land uses within 1km2	2.69	0.86	14.796	0.002
Night	2.04	1.03	7.725	0.048
Distance to any road (km)	8.56	2.48	5224.997	0.001
Common palm civet				
Constant	-13.88	3.14	9.395E-7	0.000
Secondary forest present within 1km2	-0.90	0.55	0.405	0.102
Secondary forest area within 1km2	7.17	3.12	1304.248	0.021
Oil palm area within 1km2	8.48	2.93	4816.534	0.004
Distance to village (km)	0.69	0.37	1.989	0.060
Number of land uses within 1km2	0.85	0.29	2.340	0.004
Common tree shrew				
Constant	-7.45	1.15	0.001	0.000
Distance to village (km)	1.18	0.44	3.242	0.007
Number of land uses within 1km2	0.56	0.24	1.742	0.022
Night	-2.29	0.66	0.102	0.001
Distance to any road (km)	4.09	2.11	59.633	0.053
Wild pig				
Constant	-739.59	329.71	63.20E-32	0.025
Distance to oil palm (km)	-3.36	1.78	0.035	0.059
Oil palm area within 1km2	-1.70	0.727	0.183	0.019
Year	0.37	0.16	1.444	0.025
Distance to village (km)	0.42	0.21	1.517	0.052
Number of land uses within 1km2	0.22	0.10	1.250	0.023

Figure S3: Predicted probability of observing different non-IUCN Red Listed species across the concession

Comparison of Figs S3 and S2 reveal some clear contrasts between Red Listed and other species. As expected, in all habitats numbers of all the latter species significantly exceed those of Red Listed mammals. Nevertheless the patterns of variation show some differences. While tree shrews and wild pigs clearly prefer secondary forest and can cope with fragmented landscapes, generalists such as the leopard cat, mouse deer and (not surprisingly) palm civet all fare well and indeed flourish amongst oil palm, feeding off either the fruits or other species (such as rodents) attracted to the area. Note that, while they are not themselves considered of conservation interest, wild pigs form a significant element of the diet of the endangered Sumatran tiger (*Panthera tigris sumatrae*) which we observed on the concession via camera traps, although not in sufficient numbers for modeling purposes. As can clearly be seen in Fig. S3, the conversion of secondary forest into oil palm plantation is associated with substantial reductions in the population of wild pigs; which would in turn reduce food supplies for the Sumatran tiger. Conversely, again as shown in Fig. S3 avoiding the loss of secondary forest not only helps secure the food supply of the tiger, but also conserves the IUCN Red List Species which were the focus of our modelling exercise. Insufficient data precludes us from examining whether or not this would be sufficient to conserve the tiger, but clearly securing its food supply is a prerequisite for such conservation.

Conducting transect surveys raises a question as to whether data concerning different species of mammal collected across different habitats are comparable. Oil palm plantation provides relatively little in the way of visual obstruction and it might be expected that a relatively high proportion of those species which are present in such areas will be observed during transect surveys. Conversely, in more obstructed, closed environments, such as secondary forest, it might be that a lower proportion of those species that are present will be observed. Furthermore, one might expect any bias to be relatively greater for smaller as opposed to larger mammals.

To assess the presence and significance of any bias surveyors estimated detection distances for various species. Table S4 reports mean detection distance for three species; the relatively large wild pig, the smaller leopard cat and the yet smaller common palm civet. These mean distances are shown for surveys conducted within and beyond oil palm areas.

Table S4: Mean survey detection distance (m) for different mammals across two environments. Figure in parentheses are standard deviations.

Survey areas	Wild Pig	Leopard cat	Common Palm Civet
Oil Palm	15.88 (9.34)	15.01 (10.32)	14.36 (9.52)
Non Oil Palm	8.58 (3.63)	7.40 (2.88)	8.15 (5.27)

Results show that, within either environment, there is no significant difference in average detection distances across the three species. Similarly, for any given mammal, there is no significant difference in detection differences across the two environments. Furthermore, even if the detection distances had proved to be significantly higher in oil palm habitats (suggesting that our estimate of mammal numbers in secondary forest was lower than might actually be the case), then any resulting bias would mean that, if anything, we would have actually understated the likely conservation benefits of preventing the conversion of land from secondary forest into palm oil plantation. This in turn would suggest that our conclusions are, if anything, conservative in terms of the wildlife benefits that would be generated by the schemes considered in our main analysis. However, as noted, these differences proved insignificant and therefore such an argument remains unsupported.

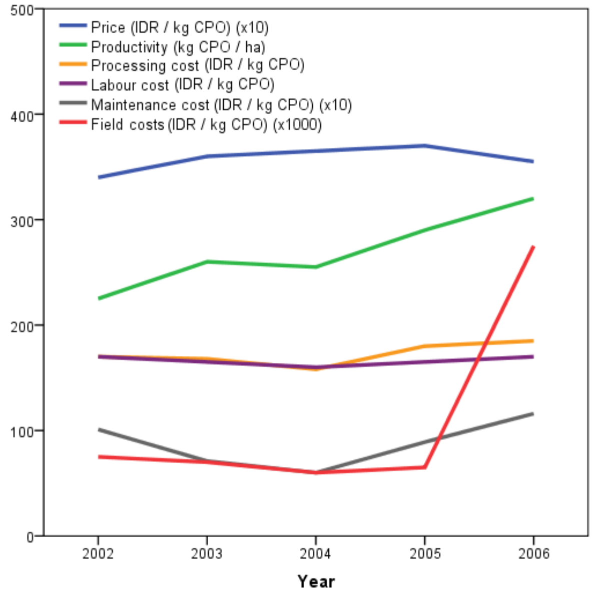
Opportunity cost of conservation

The principal element of the opportunity cost of conservation on productive private lands is foregone profit. Therefore is it useful to initially consider the nature of palm oil production.

Oil palm (*Elaeis guineensis Jacq.*) is a perennial crop that is primarily produced in intensive plantations. Seedlings are initially grown in nurseries for the first two years of their life after which they are planted out into management blocks of around 30 ha at a density of between 130-143 palms per hectare. The young palms are classed as immature until they start to produce fruit, usually 3 years after planting out. The fruit is dark orange with a thick, fibrous, oily outer flesh with a large seed from which palm kernel oil is produced. Fruits range from <2cm to 5 cm long, are ovoid in shape and grow in large compact fruit bunches weighing between 40-60 kg. Fruit takes approximately 6 months to ripen from pollination and is produced continually throughout the year, each palm producing between 6-12 fruit bunches per year. Harvesting occurs at regular intervals of between 5 and 12 days to ensure fruit is cut at the optimum time, not all palms would be harvested in a rotation. Oil palms are generally replanted every 15 to 20 years due to the difficulty of effectively harvesting older, taller plants. Continuous upkeep and maintenance of the crop is required, most of which is conducted by manual laborers. This involves fertilizer regimes, weeding, pruning and pesticide application. Once harvested the fruit needs to be processed quickly in order to minimize the rapid esterification of its oil content. For this reason large plantations will often have a primary processing mill on site or nearby, as is the case of our study site. In the mill the fruit is pressed to extract the crude palm oil (CPO), which is the primary sale product.

In order to establish the opportunity costs of conservation we first need to follow basic principles of agricultural economics to establish the distribution of gross margins across the concession for our low and high productivity periods. Gross margins differ from profits in that they omit fixed costs such as those associated with road construction. For several decades now, gross margin analysis has been the standard approach for assessing agricultural operations (6,7) as fixed cost levels can vary very substantially across operations often for historical reasons and prevent the generation of generalizable results. The basic data required for calculation of gross margins is summarized in Figure S4 which clearly demonstrates the noticeable increase in productivity (with an accompanying increase in field costs) over the period.

Figure S4: Plantation level trends in price, output and costs of palm oil production; 2002-2006.



Notes: Productivity is measured in kg CPO per hectare per month. All other variables are measured in Indonesian Rupiah (IDR) per month.
In Table S2 we convert overall conservation costs to US$ values using an exchange rate of 1 IDR = 0.000117 US$, which was typical for the period which these costs relate to).

The gross margin calculations were undertaken using monthly figures for enhanced accuracy. Prior to the calculation of revenues, an analysis of yield data showed no significant spatial variation across the plantation. Despite the size of the concession and the diversity of current land cover, this finding was not surprising as the study site occupies a relatively flat area with homogenous soils and environmental conditions. We therefore do not spatially differentiate revenues, although this may be necessary if transferring results to other or larger areas (an approach to such an analysis for timber production is set out in (8)). By taking data on the proportion of fruit mass converted to oil we calculate output of CPO in kilograms produced per month. Bringing in data on monthly prices then yields our revenue estimates. All values were initially calculated in nominal Indonesian Rupiah (IDR) and subsequently deflated to 2006 values (overall inflation was 12 % between January 2002 and December 2006 (9)).

Costs include inputs, maintenance, field administration, wages, plant nursery, development and planting costs as well as processing charges, all of which do not vary spatially. However, this is clearly not the case for harvesting costs which have a substantial transportation element. As harvesting costs were not disaggregated to individual sub-compartments a digital representation of the road network within the concession was constructed using road data obtained from the Jambi Government. Network routing algorithms were used in the GIS to identify the most direct (least cost) route along the road network to the processing mill located in the center of the plantation and to calculate the total distance for that route. This provided us with a distance measure for each 200m x 200m grid cell within the concession and was used to provide a measure of cell specific transport costs scaled by information on overall transport costs (additional costs of road construction for currently unplanted cells are discussed below).

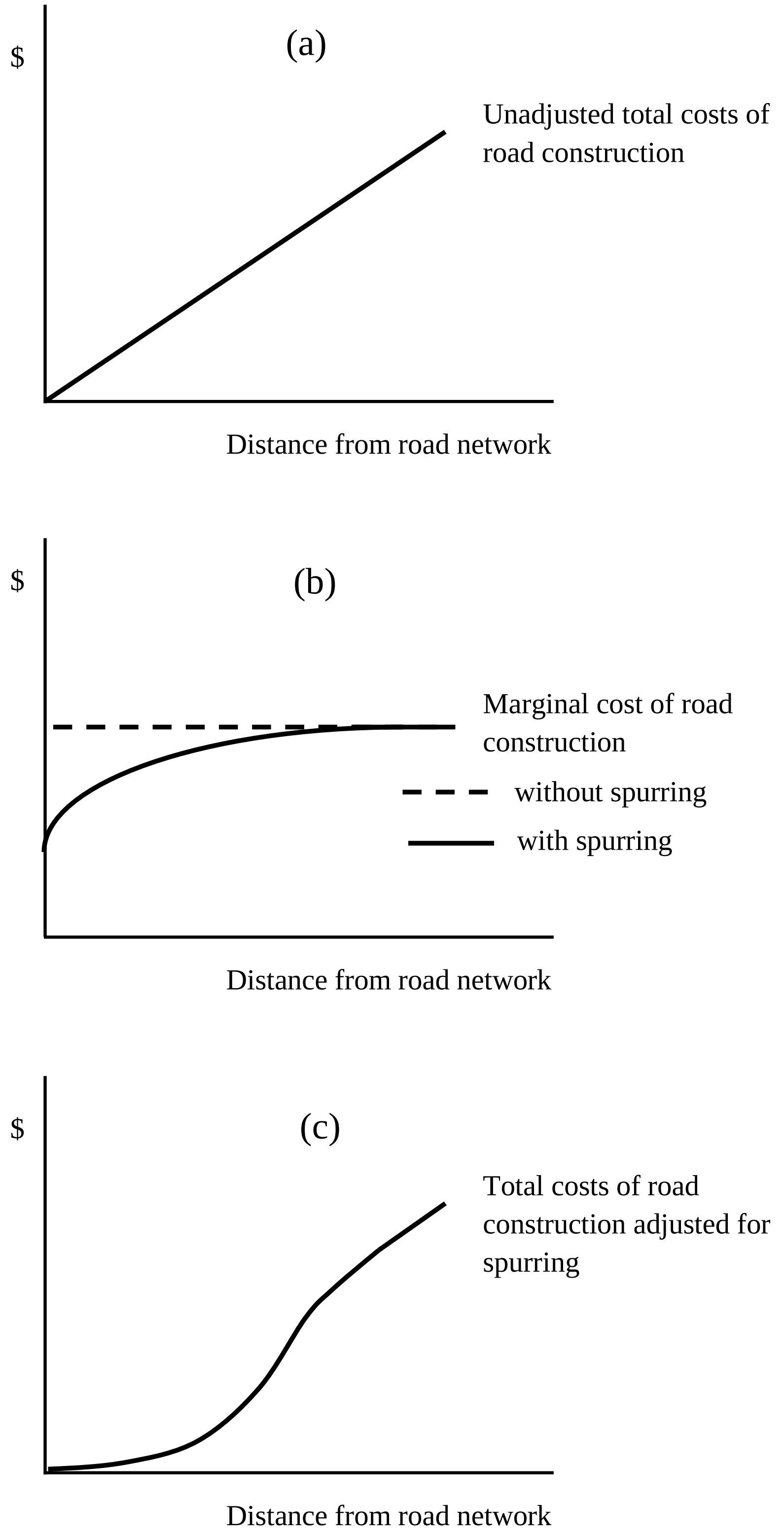
“

Comparison of revenue and cost streams provides our assessment of gross margin within currently planted areas. This declines with increasing distance from the processing plant due to higher transport costs. However, this does not give us our full estimate of the opportunity cost of conservation (OCC) within such areas as existing palms would have to be felled, the land ploughed and restored and a variety of costs incurred to encourage the re-establishment of high quality forest cover. Estimates of restoration costs were taken from (10) who also supplied indications of the relevant time profile for such projects allowing us to annuitize costs using formulae provided by (10) and discount rates (of 10%) for Sumatra given in (12) and (13). Adding this restoration cost to the foregone gross margin gives us our estimates of OCC within presently planted areas.

Of course it is likely that any profit maximizing plantation manager will be loath to rip up mature palms if there are unplanted areas within their concession. However, the OCC for unplanted areas is far from zero as they have a potential gross margin. This will also vary spatially because of the transport costs described previously. However, part of the reason why these areas are often currently unplanted is because at present they do not have roads running to them (indeed road density is closely linked to land development, habitat fragmentation, deforestation and the disappearance of wild-lands and wildlife (14, 15)). The potential gross margin of presently unplanted lands has, therefore, to be adjusted for the need to extend the road network to reach those areas. To estimate per kilometer road construction costs we again consulted the wider literature, taking values from the Indonesian studies of (16) and annuitizing as before. A problem in this calculation is to allow for the fact that as an unplanted area is developed so new roads will spur off each other. Calculating the cost of constructing a unique, new road to any given unplanted area, therefore, risks overestimation of those costs. A simple, theoretically driven, model is therefore adopted which assumes that the closer a potential palm planting areas is to an existing road, the higher is the probability of reducing road construction costs by spurring off that existing road, i.e. the marginal per-kilometer costs of roads will be reduced in such locations. However, as we progressively consider areas further from the road network, so the chances of being able to spur off the existing network decline and hence the expected marginal costs of road construction are not reduced.

Expected relationships are sketched in Fig. S5. Here in panel (a) we show total construction costs for a unique new road to a given area assuming constant marginal costs per kilometer and no spurring from existing roads. Panel (b) shows both the constant marginal costs (dashed line) implicit in the preceding panel and the lower marginal costs for locations near to, and hence spurring off, the existing road network (solid line). Panel (c) shows the adjusted total cost curve assuming diminishing marginal costs for locations near to the existing road network.

Figure S5: Sketch of relationships adjusting for spurring effects in road construction costs.



Parameterization of the functions sketched in Fig. S5 requires the calculation of a road construction cost adjustment factor (SPUR_ADJ). To define this we modelled the proportion of oil palm contained within a 1 km^2 buffer around each grid cell mid-point (PROP_OP) using the single explanatory variable LnDIST (the natural logarithm distance in kilometers from each grid cell to the road network). Because PROP_OP is measured as a proportion we used a Tobit regression model to estimate this relationship (17); the results are reported in the upper part of Table S5 with adjusted linear predictor values (18) given in the lower part of that table.

Table S5. Tobit regression model of the proportion of oil palm in areas as distance from the processing mill varies.

	Coef.	s.e.	t	Sig. (p)	Lower 95% CI	Upper 95% CI
Unadjusted parameters						
LnDIST	-0.26	0.01	-35.02	<0.001	-0.28	-0.25
Constant	0.98	0.02	59.27	<0.001	0.95	1.01
Sigma	0.44	0.01			0.43	0.10
N = 8180						
LL = -5546.76						
Adjusted values						
	dF/dx	s.e.	Z	Sig. (p)	Lower 95% CI	Upper 95% CI
LnDIST	-0.22	0.01	-35.02	<0.001	-0.23	-0.21
Constant	0.81	0.01	59.27	<0.001	0.79	0.84

The results given in Table S5 confirm that the proportion of oil palm to unplanted land falls significantly and logarithmically as distance from the processing mill increases. This provides the shape for our SPUR_ADJ function which can then be used to calculate road construction costs as sketched in Figure S5. These were annuitized as previously.

We can now estimate the OCC for any given area *i* at any time period *t* as per Equation (1):

$$OCC_{it} = GM_{it} - Trans_{it} - Construct_{it} + Restore_{it} \qquad (1)$$

where:

OCC_{it}	= opportunity cost of conservation for area *i* at time *t*
GM_{it}	= the (potential) gross margin for area *i* at time *t*
$Transport_{it}$	= Transport cost from area *i* to the processing mill at time *t*
$Construct_{it}$	= Annuitized cost of road construction from existing road network to area *i* at time *t* adjusted for spurring probability (=0 for existing oil palm plantation)
$Restore_{it}$	= Restoration cost for grid cell *i* at time *t* (= 0 for currently unplanted areas)

Calculating an OCC_{it} value for each grid cell then describes the spatial distribution of costs of setting aside each cell across the plantation for conservation. The OCC will clearly vary according to the location of any conservation area. Most particularly, the OCC will be substantially higher for conservation occurring on existing oil palm plantation than when targeted towards unplanted areas using spatial cost-effectiveness analysis. Cost estimates for such alternative strategies are presented in Table S6. The difference between conversion strategies is greatest for smaller conservation scheme as larger schemes necessarily include some oil palm even when targeted using cost-effectiveness analyses. OCC is also always greater for higher productivity regimes as any loss of plantation area incurs a greater reduction of output than for low efficiency producers.

Table S6. Mean opportunity cost of conservation (OCC) per hectare for various sizes of conservation scheme implemented under two productivity levels and via two alternative spatial targeting methods.

		Spatial targeting →	Mature oil palm		Cost-effective	
		Productivity level →	Low	High	Low	High
Area converted to conservation	'small' scheme 5,000 ha	IDR ('000) per month	502	639	87	212
		US $ per month	59	75	10	25
		US $ per year	704	897	122	298
	'medium' scheme 10,000 ha	IDR ('000) per month	494	620	131	247
		US $ per month	58	72	15	29
		US $ per year	693	870	183	347
	'large' scheme 20,000 ha	IDR ('000) per month	483	594	267	379
		US $ per month	57	70	31	44
		US $ per year	679	835	375	532

Note: For each of the three scheme sizes (small, medium, and large) and the two approaches to spatial targeting (on mature oil palm or targeted to maximize cost-effectiveness), Table S6 shows the mean opportunity cost of conservation per hectare presented in three different monetary units: (i) IDR ('000) per month, (ii) US$ per month, and (iii) US$ per year. The original data that our opportunity costs were calculated from was available in IDR per month for each of the 400 or so sub-compartments of the concession. After we had calculated the opportunity cost of conservation in IDR ('000) per month, we then converted these values to US$ per month and per annum using the exchange rate 1 IDR = 0.000117 US$, which was the typical exchange rate during the study period, being reasonably stable (with one peak) over that period. The exchange rate has since fluctuated somewhat and stood at 1 IDR = 0.000085 US$ as of 9th September 2014. Researchers wishing to use these figures in the future should apply time series purchasing power parity adjustments (19) to adjust from the study period and location.

The analysis given in Table S6 is sufficient to show that private incentives will mean that landowners will be highly resistant to the conversion of productive palm-oil plantation to conservation purposes. Indeed it would be a highly inefficient use of any price premium to pay for such conversion. However, the cost-effective solution incurs much lower costs which, as demonstrated in the main paper, have for appropriately side conversion areas, the potential to be more than adequately compensated for by the induced price premium. Comparison of the location of cost-effective conversion areas (Fig 1d) with the opportunity cost of conservation (Fig 1c) show that these are highly correlated. This suggests that, at least for the present concession, this addresses the problem of asymmetric information between the land-owner and the conservationist. It is in the land owner's private interest to adopt the cost-effective solution in this case.

Cost-effectiveness analysis: Calculation of potential populations

Estimates of the numbers of mammals corresponding to the different conservation area are derived by using results reported by (19). This derives the minimum area required by some number (N) of a given mammal with respect to their diet and mass (M) according to the power equation $N = \alpha M^{\beta}$ where the values of α and β are as given below:

Diet category	α	β
Herbivore	1.01	0.76
Omnivore	3.62	0.73
Carnivore	34.43	0.86

Source: (19)

Table S7 applies the findings of (19) to derive estimates of the number of mammals corresponding to the different conservation extents considered in our analysis. Note that the equations reported by (20) may not apply to isolated and unconnected pockets of conservation land. However, as Figure S1 shows, the conservation areas are linked either directly or through the surrounding secondary forest area. The work of (20) is based on a global scale data set of mammal population densities (21). As many threatened species are poorly studied (22), it is possible that population size estimates derived from (20) may differ from those of the threatened Sumatran species cited here and should therefore be treated as first order approximation. We cannot say whether these populations would persist in the long term as the concept of a universal minimum viable population size is questioned (23). Nevertheless, these numbers are substantial and indicate that the conservation benefits of applying the procedures advocated in this paper would be considerable in terms of promoting population viability. As noted in the main paper, the areas conserved are considered significant and a sophisticated approach to certification design would incentivize the creation of larger conservation areas across adjoining concessions.

Table S7: The predicted population of each Red List mammal under three conservation area scenarios (based upon allometric relationships described in (19)).

Species		IUCN Red List Category	Mass (kg)	Diet	Individual Area (ha)	Population numbers within different conservation areas		
Common name	Latin name					5,000 ha	10,000 ha	20,000 ha
Agile gibbon	*Hylobatres agilis*	3	5.6	herbivore	4	1337	2673	5347
Pig tailed macaque	*Macaca nemestrina*	2	12	herbivore	7	749	1498	2996
Long tailed macaque	*Macaca gascicularis*	3	5	herbivore	3	1457	2914	5828
East Asian porcupine	*Hystrix brachyuran*	2	8	herbivore	5	1019	2039	4077
Siamang	*Symphalangus syndactylus*	3	23	herbivore	11	457	914	1828
Pangolin	*Manis javanica*	3	6	carnivore	161	31	62	124
Smooth coated otter	*Lutrogale perspicillata*	2	9	carnivore	228	22	44	88

Price premium for conservation grade products

It important to clarify that we do not suggest that the price premium for conservation grade goods reflects the true underlying value of biodiversity to individuals. Rather this is merely the uplift in prices that consumers are prepared to pay for a preferred mode of production which in turn has the potential to promote conservation. Importantly this does not encapsulate what economists refer to as the non-use value of conserving a species (24).

With this in mind, a choice experiment was designed to test for the size and potential determinants of any price premium for developed world consumers (palm oil being traded internationally, with the EU and USA being in the top five largest consumers in the world (25)). Supermarket shoppers were presented with a choice between two tubs of margarine in which palm oil was a major ingredient. Both were described as physically and chemically identical except that one used conventionally produced palm oil while the other used conservation grade palm oil.

Information on the biodiversity effects of conservation focused upon the iconic and highly endangered Sumatran tiger (*Panthera tigris sumatrae*) which, as previously noted, was observed on the concession via camera traps, although not in sufficient numbers for modeling purposes. This focus on the charismatic species which benefits from conservation reflects the findings of prior choice experiments which reveal these to be the main objects of value by developed country respondents and a prime motivator of conservation support (26). However, as shown in our modelling results (Fig. S3), avoiding the conversion of secondary forest to oil palm not only helps secure food supplies for the tiger (e.g. wild pigs), it also conserves IUCN Red List species.

The choice presented to shoppers was varied across individuals, in some cases presenting pairs of high quality products while in others a pair of regular quality margarines was presented. Furthermore, again across shoppers, three different levels of marketing information were used. One third of the sample (the *LowInfo* treatment) was simply informed that purchasing the conservation-grade good would protect the land where tigers hunt. Another third of the sample was additionally informed (*MedInfo*) that over the previous 30 years tiger numbers had halved to only about 500 individuals. The remainder of the sample (*HiInfo*) was given the prior information and also shown color images of tiger adults and cubs. All of this information is deliberately brief and intended to represent the highly accessible mix of general, quantitative and visual image marketing information likely to be used in a mass-market commercial setting.

Table S8 reports a model of the propensity of individuals to choose the conservation grade (CG) product over the conventionally produced alternative. This shows expected relationships with the preference for the CG good declining as its price (*PriceCG*) increased and being significantly higher when the choice was between two high quality (*HiQuality*) alternatives. Compared to the *LowInfo* base case, the addition of marketing information in the *MedInfo* treatment significantly increased the propensity to choose the CG good, an effect that was further enhanced by the *HiInfo* treatment.

Table S8: Logit model of propensity to choose the conservation grade (CG) good.

	$\hat{\beta}$	s.e.	*P*
PriceCG	-2.021	.230	.000
HiQuality	2.408	.235	.000
MedInfo	0.546	.248	.028
HiInfo	1.388	.267	.000
Constant	-0.074	.214	.728

Dep. Var = 1 if respondent chose the conservation grade good and 0 otherwise. χ^2 = 230.1 ($p<.001$); LL = 565.78; Nagelkerke R^2 = .434). Base case level of marketing (low) = *LowInfo*

Table S9 reports mean willingness to pay for the conservation grade good which, in all treatments, reveals a significant price premium over the conventionally produced alternative. This increases with the level of marketing as expected. While the willingness to pay is highest in absolute terms at the upper end of the market, in relative terms the conservation grade premium is greatest for the lower quality product. Further details of this aspect of the study are given in (27)

Table S9: Mean willingness to pay for the conservation grade good: Quality and marketing effects (parentheses show 95% confidence interval and percentage price premium compared to the conventionally produced good; $p<0.05$ throughout).

Level of marketing	Lower quality product (conventional good price = £0.75)	Higher quality product (conventional good price = £1.12)
LowInfo	£1.03 (0.98 – 1.07; 37%)	£1.29 (1.24 – 1.33; 15%)
MedInfo	£1.10 (1.05 – 1.15; 47%)	£1.35 (1.30 – 1.40; 21%)
HiInfo	£1.17 (1.11 – 1.23; 56%)	£1.52 (1.47 – 1.57; 36%)

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