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The future of forests and orangutans (*Pongo abelii*) in Sumatra: predicting impacts of oil palm plantations, road construction, and mechanisms for reducing carbon emissions from deforestation

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Abstract
Payments for reduced carbon emissions from deforestation (RED) are now attracting attention as a way to halt tropical deforestation. Northern Sumatra comprises an area of 65 000 km^2 that is both the site of Indonesia's first planned RED initiative, and the stronghold of 92% of remaining Sumatran orangutans. Under current plans, this RED initiative will be implemented in a defined geographic area, essentially a newly established, 7500 km^2 protected area (PA) comprising mostly upland forest, where guards will be recruited to enforce forest protection. Meanwhile, new roads are currently under construction, while companies are converting lowland forests into oil palm plantations. This case study predicts the effectiveness of RED in reducing deforestation and conserving orangutans for two distinct scenarios: the current plan of implementing RED within the specific boundary of a new upland PA, and an alternative scenario of implementing RED across landscapes outside PAs.

Our satellite-based spatially explicit deforestation model predicts that 1313 km^2 of forest would be saved from deforestation by 2030, while forest cover present in 2006 would shrink by 22% (7913 km^2) across landscapes outside PAs if RED were only to be implemented in the upland PA. Meanwhile, orangutan habitat would reduce by 16% (1137 km^2), resulting in the conservative loss of 1384 orangutans, or 25% of the current total population with or without RED intervention. By contrast, an estimated 7824 km^2 of forest could be saved from deforestation, with maximum benefit for orangutan conservation, if RED were to be implemented across all remaining forest landscapes outside PAs. Here, RED payments would compensate land users for their opportunity costs in not converting unprotected forests into oil palm, while the construction of new roads to service the marketing of oil palm would be halted.

Our predictions suggest that Indonesia's first RED initiative in an upland PA may not significantly reduce deforestation in northern Sumatra and would have little impact on orangutan conservation because a large amount of forest inside the project area is protected *de facto* by being inaccessible, while lowland forests will remain exposed to the combined expansion of high-revenue plantations and road networks. In contrast, RED would be more effective in terms of its conservation impact if payments were extended to all remaining carbon-rich tropical forests, including lowland peat swamp forests, the preferred habitat for dense populations of orangutans, and if the construction of new roads was halted.

Keywords: tropical deforestation, predictive models, orangutan, oil palm plantations, road construction, RED, Sumatra

S Supplementary data are available from stacks.iop.org/ERL/4/034013

1. Introduction

Tropical forests are currently being lost at rates of ~58 000 km^2 yr^{-1} (Achard *et al* 2002). Losses of Southeast Asia's tropical lowland forests are particularly acute (Curran *et al* 2004, Fuller *et al* 2004, Gaveau *et al* 2009a, Hansen *et al* 2009), yet these forests hold globally important carbon stores (Page *et al* 2002), and represent prime habitat for threatened species such as orangutans (Wich *et al* 2008). Anthropogenic clearing of lowland forests in Indonesia, Malaysia, and Papua New Guinea, reinforced by increased droughts and forest fires, has become a major source of global carbon emissions (Field *et al* 2009, Page *et al* 2002, van der Werf *et al* 2008). So, the conservation of tropical lowland forests warrants a sense of urgency, both to mitigate climate change and to conserve species.

In order to curb losses in forest cover, governments and conservation organizations have established networks of protected areas (PAs) that restrict human access through law enforcement (Chape *et al* 2005, Gaveau *et al* 2009b). However, existing PA networks cover <17% of the total land surface in Southeast Asia (Chape *et al* 2005). Furthermore, these PA networks have largely been established in less biodiversity- and carbon-rich highland areas (Gaveau *et al* 2009a), because conserving Southeast Asia's biodiversity- and carbon-rich lowland forests lacks support among political elites when faced with the absence of payments for conservation, and with near-term opportunities to engage in high-revenue extractive industries, such as plantations and logging (Curran *et al* 2004, Fitzherbert *et al* 2008, Venter *et al* 2009).

Payments for environmental services, such as reduced carbon emissions from deforestation (RED), are attracting interest as possible mechanisms that could halt deforestation both outside and inside PA networks. Outside PAs, such payments would compensate agents of deforestation, whether rural communities or plantation companies, for their opportunity costs in not clearing unprotected forests (Hall 2008, Humphreys 2008, Wunder 2007). However, the greatest challenge for RED outside PAs is increasing demand for high-revenue crops (Butler *et al* 2009, Laurance 2008). In such situations, RED may not halt deforestation if the compensation to conserve unprotected forests is less than the estimated earnings per ha from agricultural commodities (Humphreys 2008, Karsenty 2008). In Southeast Asia, the most important threats to lowland forests are likely to be the combined expansion of high-revenue oil palm plantations and road networks required to move palm oil from remote areas to their market destinations (Butler *et al* 2009, Chomitz *et al* 2007, Chomitz and Gray 1996, Ewers *et al* 2008, Fitzherbert *et al* 2008, Laurance *et al* 2001, Soares-Filho *et al* 2006, Venter *et al* 2009).

An alternative may be to implement payments for reduced carbon emissions within defined PAs. Here, a considerable proportion of RED payments would be used by governments to monitor and enforce forest protection within PA boundaries. In effect, this approach under a RED regime would resemble the approach already followed in many existing conservation projects. This alternative could lead to the establishment of new PAs, but would still leave some forests open to agricultural expansion and road construction. Therefore, a key question is whether RED will significantly reduce deforestation and conserve species (Angelsen *et al* 2008, Venter *et al* 2009). We seek to illustrate this question for northern Sumatra, the site of Indonesia's first RED initiative and the stronghold of the critically endangered Sumatran orangutan (*Pongo abelii*) (Wich *et al* 2008), yet where there are competing investments in expanding oil palm plantations and new road construction.

To illustrate this question, we have produced the first accurate fine-scale deforestation map for northern Sumatra, using LANDSAT satellite imagery from 1990 to 2000 to 2006, and developed a predictive model that projects deforestation from 2006 to 2030 for three possible scenarios: (1) a baseline scenario without RED intervention; (2) a RED scenario implemented in a newly established upland PA; and (3) a RED scenario implemented on landscapes outside PAs. We display our models in cartographic form, and show the forest that would be lost to deforestation, and the forest that would be saved through avoided deforestation, as a result of expanding or limiting plantations, constructing or halting new roads, and implementing or foregoing RED initiatives. Our three scenarios incorporate the following:

(1) the baseline, or 'business-as-usual' scenario incorporates a high rate of deforestation to model rapid expansion of mainly palm oil plantations in northern Sumatra. Roads currently scheduled for construction will be built. Existing PAs, including national parks, wildlife and hydrological reserves, will mitigate deforestation by law enforcement. However, no RED scheme will be implemented.

(2) the second scenario also incorporates a high rate of deforestation, while roads scheduled for construction will also be built. However, RED will be implemented within a newly established upland PA that seeks to mitigate deforestation like existing PAs. In other words, a considerable part of RED payments will be used to follow the common conservation approach of restricting human access through law enforcement carried out within the boundaries of a defined PA.

(3) the third scenario incorporates a low rate of deforestation to model the limited expansion of plantations, which will be achieved by implementing RED across landscapes outside PAs. Thus, RED payments will serve to compensate rural communities and plantation companies for their opportunity costs in not converting unprotected forests to oil palm. Roads scheduled for construction will be halted, and no new PAs will be created. However, existing PAs will continue to mitigate deforestation within their boundaries through law enforcement.

These scenarios were combined with detailed maps of orangutan populations to measure the biodiversity outcome of RED in northern Sumatra. Our projections of forest and orangutan loss are conservative because they do not consider forest degradation, including the effects of forest patch size, and habitat connectivity, nor the poaching of wildlife. We chose to run our predictions to the year 2030, to match the Organization for Economic Co-operation and Development (OECD) Environmental Outlook to 2030.

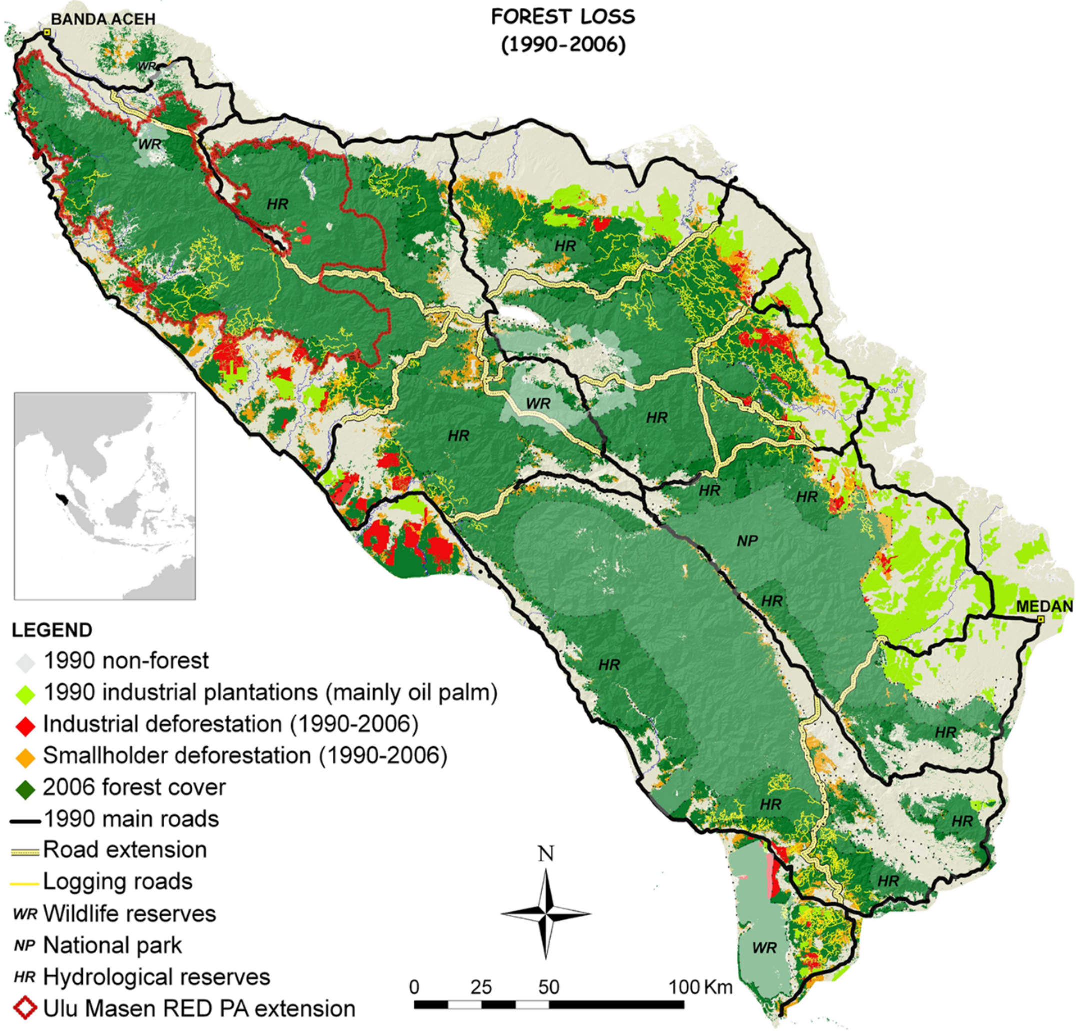

Figure 1. Map of deforestation (1990–2006), logging roads, and remaining 2006 forest cover in northern Sumatra derived using LANDSAT satellite imagery with hill shade overlay to reveal the terrain topography. Existing protected areas are shown. Main roads refer to all-weather roads, whether paved or semi-paved. Road extension refers to main roads recently built, currently under construction or planned. A recent field survey by the non-governmental organization Fauna Flora International indicates that more roads are under construction than are shown on this map. Ulu Masen RED PA extension refers to Indonesia's first RED initiative to be implemented within the boundaries of a newly established, 7500 km^2 protected area (PA) comprising mostly upland forest. Map available in GoogleEarth format at http://sumatranforest.org/northernSumatra.php.

2. Study area

Our northern Sumatra study area comprises 65 000 km^2. This region includes the Ulu Masen and Leuser ecosystems in Aceh and Sumatra Utara provinces, and holds around 6100 or 92% of the remaining 6600 Sumatran orangutans (Meijaard and Wich 2007, Wich *et al* 2008). Northern Sumatra's forests are threatened by oil palm expansion, and particularly so the lowland peat swamp areas (Marks 2009) estimated still to be home to >2250 or 37% of northern Sumatra's orangutans (Wich *et al* 2008). Furthermore, Aceh province has been devastated both by the tsunami of 26 December 2004, and by 30 years of armed conflict between an independence movement and Indonesia's national government (Reid 2006). Since the tsunami, the international community has helped rebuild infrastructure and peace in Aceh by providing over US$ 4 billion in humanitarian and reconstruction aid (Benthall 2008). The Indonesian government has earmarked some of the funds to planned extensions of northern Sumatra's road network, both to rebuild Aceh and to attract investments in oil palm plantations. An estimated >500 km of this new road network is planned to extend through the interior of northern Sumatra at fourteen different locations (figure 1). Using other funds, the local government of Aceh and conservation agencies plan to establish a RED project to conserve the 7500 km^2 Ulu Masen forest ecosystem (Ulu Masen Project Design Note 2007), 65% of which comprises upland forest >500 m a.s.l. that holds no orangutans (Wich *et al* 2008). The government hopes to generate >$100 million in carbon financing over the next 30 years by preventing logging and conversion of Ulu Masen's forests to plantations through increased law enforcement and some community development (Ulu Masen Project Design Note 2007). A large proportion of RED payments will serve, in part to recruit guards to conduct forest monitoring and forest patrols (Mann and Surya 2009).

3. Methods

3.1. Mapping past deforestation

We processed and analyzed 26 corresponding LANDSAT TM and ETM + satellite images with a $\sim$800 m^2 (28.5 m $\times$ 28.5 m) resolution to map forest cover change across northern Sumatra from approximately 1990 to 2000 to 2006. Areas of forest, non-forest, water, and deforestation were mapped. 'Forest' referred to old-growth natural forest, either undisturbed or partially degraded by selective logging or thinning. This definition corresponds closely to those forests defined by the FAO as closed broadleaved forests (Achard *et al* 2002, FAO 1993). Second-growth forest was classified as non-forest because it was impossible to detect this land cover class without extensive ground data that we lacked. Therefore, re-growth of forest from 1990 to 2000 to 2006 was not quantified, but this is likely to be minimal because land for permanent agriculture is in high demand in Sumatra (Tomich *et al* 2001). Furthermore, second-growth forests will probably not be included in future international RED agreements, so the omission of this land cover class matters little. Based on these classifications, changes in forest cover only include 'deforestation' comprising the long-term removal of old-growth natural forest cover. Industrial plantations and logging trails in 1990, 2000 and 2006 were digitized manually, by on-screen digitizing. Oil palm plantations were identified from Indonesia's Ministry of Forestry Planning Agency land-use maps (Minnemeyer *et al* 2008), and from our field knowledge.

Processing methods—which are similar to those used to map deforestation Sumatra-wide (Gaveau *et al* 2009a)—and map validation procedures can be found in appendix S1 in supporting information available at stacks.iop.org/ERL/4/034013/mmedia/. A map of 1990–2006 deforestation across northern Sumatra is presented in figure 1.

3.2. Predictive modeling

Our approach to modeling the spatial distribution of deforestation follows the principle of the land-rent theories. In general, agents of deforestation, whether smallholder farmers or plantation companies act to maximize profits by allocating any parcel of land to the use that earns the highest rent (Angelsen 1999, Mertens and Lambin 2000). Geographic accessibility, agricultural suitability and protection status determine, to a large extent the spatial distribution of land rent. Based on the literature on tropical deforestation, the main variables that capture accessibility are: topography (slope and elevation), distance to forest edge, roads and logging roads (Kaimowitz and Angelsen 1998). Soil and forest type determine whether a parcel of land is worth logging or converting to agriculture. Therefore, slope and elevation, distance expressed as travel times to forest edge, to industrial plantations, to roads and logging roads, and protection status were selected as input variables to predict the spatial distribution of deforestation. The main forest types were determined by elevation, with high quality timber mostly found at low elevations (Laumonier 1997). Soil type was not included for two reasons. First, small-scale, often migrant landless farmers tend to clear forests based mainly on accessibility as they do not have intimate knowledge of soil types (Benoit *et al* 1989). Second, timber and plantation industries tend to clear forests regardless of soil type (Uryu *et al* 2008). Human population density was included as the only spatially explicit socio-economic driver of deforestation. Processing methods for extracting the variables can be found in appendix S2 in supporting information available at stacks.iop.org/ERL/4/034013/mmedia/.

We performed a logistic regression analysis on the 1990–2000 deforestation map to test whether the selected variables explained the presence or absence of deforestation across the landscape under consideration (Mertens and Lambin 2000, Wilson *et al* 2005). We retained the 2000–2006 map as an independent dataset to validate the model (Mertens and Lambin 2000). Four hundred points were selected on the surface that was deforested between 1990 and 2000, and 400 points were selected on the surface that remained forested in year 2000. All points were sampled at random but were separated by a minimum distance of 10 000 m to reduce the likelihood of spatial autocorrelation in the dataset. Therefore, the results of this study are based upon a sample dataset rather than upon an analysis of all changes in forest cover across all of northern Sumatra.

We measured the magnitude of the variables at each sampled point, and analyzed this dataset using SPSS statistical software. We tested for the presence of multi-collinearity among the variables before including them as inputs in the logistic regression model to avoid bias in the model's parameter estimates (Aguilera *et al* 2006). One pair of variables, comprising travel time to roads and travel time to forest edge, showed a high degree of correlation (Pearson's $r = 0.84$), so this pair was combined in a single variable using principal components (Aguilera *et al* 2006). This single variable explained most (95%) of the variance observed between travel time to roads and travel time to forest edge, and subsequently replaced the pair as one input in the model instead of two. All other pairs showed moderate levels of multi-collinearity, below the acceptable level of 0.65 (Green 1979), and so did not require further data reduction.

We used an information theoretic selection process to determine the most parsimonious model of a suite of candidate models, by comparing the Akaike's information criterion (AIC) values and Akaike's weights (w_i) of all the models under consideration (Burnham and Anderson 2002). The model that was within two AIC units (ΔAIC) of the top ranked model and that had the fewest number of parameters was considered as the most parsimonious, and final, model. We then tested for the presence of spatial autocorrelation in the final model's residuals by calculating Moran's I statistic using Crime-Stat (version 1.1). Finally, the performance of the model was evaluated by calculating the R-squared, and the area under the curve of the receiver operating characteristics (ROC).

The final, most parsimonious model produced a base probability map of deforestation, $P(x, y)$ with probability values ranging from 0 to 1, with values close to 1 indicating areas of native forest highly vulnerable to deforestation, according to the following equation:

$$P(x, y) = \frac{e^{\beta_0 + \sum_{i=1}^{n} \beta_i X_i(x,y)}}{1 + e^{\beta_0 + \sum_{i=1}^{n} \beta_i X_i(x,y)}}. \quad (1)$$

This probability map had a spatial resolution of 8100 m^2 (90 m × 90 m) to match the topographic datasets derived from the NASA SRTM digital elevation model (DEM) (appendix S2 available at stacks.iop.org/ERL/4/034013/mmedia/). $X_i(x, y)$ are the statistically significant variables, weighted by their respective model coefficient, β_i.

We compared the base probability map to the forest cover changes observed between 2000 and 2006 to validate the model. This sought to ensure that the model's calibration data (1990–2000) were independent of the validation data (2000–2006). The validation was performed by quantifying the proportion of the observed deforestation (expressed as an annual deforestation rate) taking place along the range of probability values, following a procedure developed by (Mertens and Lambin 2000). The obtained probability values were partitioned into thirty intervals of equal spacing (width = 0.03), which subsequently classified the study area into thirty geographic zones. The deforestation rates for 1990–2000, and 2000–2006 were then calculated for each zone ($N = 30$), to obtain a calibration curve and a validation curve.

The estimated model coefficients were assumed to be time invariant to allow inclusion of the new >500 km road network, and of the new 7500 km^2 RED PA in the model. Incorporating modified road and PA networks produced modified probability maps. These modified maps were compared to the base probability map to display, in cartographic form, probabilities of deforestation, which would result from constructing or halting new roads, and establishing or foregoing a new RED PA. We modeled the rapid expansion of plantations by determining the area of forest that would be cleared by 2030 using a high rate of deforestation measured during 1990–2000. We modeled the slow expansion of plantations by determining the area of forest that would be cleared by 2030 using a low rate measured during 2000–2006. We considered that a successful outcome for northern Sumatra's RED initiative would be to limit future deforestation to the lowest recorded rate, which we assumed could be achieved by compensating the agents of deforestation for their opportunity costs in not clearing forests outside PAs.

The area of future deforestation was projected by identifying a probability threshold below which forest would remain, and above which forest would disappear. We determined this threshold value in two steps. First, we assumed that forest pixels (each measuring 90 m × 90 m) with high probability values would be lost first. Second, we aggregated those forest pixels with the highest probability values until the cumulative sum equaled the area of deforestation calculated for the low rate of deforestation. We repeated this two-step procedure for the high rate. Two probability thresholds were thus identified, for the low and high rates, respectively. We then utilized the threshold probability values to measure the increased rate of deforestation under a road extension scenario and the decreased rate of deforestation under a RED project scenario resulting in the creation of a new PA.

3.3. Estimating losses in orangutan habitat and numbers

Orangutans live at fairly low population densities. In Sumatra, orangutan density usually ranges between 0 and 3 individual km^{-2}, although locally this density can sometimes reach up to 7 individuals km^{-2} (van Schaik *et al* 1995). The highest population densities are found in the western lowlands of northern Sumatra <50 m a.s.l. where peat swamp forests have high levels of year-round fruit availability.

Nest counts were conducted along transects in locations that varied from lowland forests to montane forests to determine orangutan population density in northern Sumatra (Singleton *et al* 2004, van Schaik 2004, Wich *et al* 2004). Methods for determining orangutan population density can be found in appendix S3 in supporting information available at stacks.iop.org/ERL/4/034013/mmedia/. These field data resulted in an up-to-date elevation- and region-specific map of orangutan population density (Singleton *et al* 2004, Wich *et al* 2008), which we used to determine losses that might occur in orangutan numbers as a result of habitat loss. Habitat loss directly reduces the survival of females and their offspring because of their limited home range and subsequent inability to move out of deforested areas (van Schaik 2004). Orangutan males might move to remaining forest areas, which will lead to more intense competition among individuals, until those over-crowded areas return to carrying capacity (van Schaik 2004). Therefore, where orangutan densities are known, the net effect is that area of habitat lost can be used to extrapolate likely losses in orangutan numbers. There is no hunting of orangutans for food in the predominantly Islamic area in which this study was conducted, but orangutans are caught for trade and often killed by farmers in agricultural areas (Rijksen and Meijaard 1999). The impact of trade and killing in agricultural areas on orangutans are not addressed in this study due to lack of data. Furthermore, we did not include effects of forest patch size and habitat connectivity to determine reductions in orangutan numbers, again as there are no sufficient data to include in this model. Therefore, the conservation outcomes presented for the orangutan are likely to be conservative predictions of their future status.

4. Results and discussion

4.1. Historical deforestation baseline

In 1990, forests covered 39 447 km^2, or 61% of the 65 000 km^2 study area. An estimated 3295 km^2(>8%) had been lost by 2006 (figure 1), at the same proportional rate of loss of 0.52% yr^{-1} as the rest of the Earth's humid tropical forests (Achard *et al* 2002). Throughout the 1990s, extensive investments were made in extractive industries, of mainly oil palm and logging. It was conservatively estimated that >40% of the deforested area was converted to large-scale plantations, mainly of oil palm. Indeed, over two-thirds (71%) of the biodiversity-rich lowland forests (<500 m a.s.l.) were lost to large-scale plantations. Mechanized logging carved out a 5400 km logging trail network into the forest, indicating extensive forest degradation (figure 1). By contrast, logging and plantations development greatly reduced from

Table 1. Logistic regression models describing the relationship between landscape variables and deforestation across northern Sumatra. (Note: *Response* denotes the presence or absence of deforestation, PA denotes protected areas.)

Model	K	ΔAIC	W_i	ROC	R^2
1 *Response* $\sim$ (road & edge)[a] + slope + plantation[b] + PA	5	0.00	0.633	0.858	0.504
2 *Response* $\sim$ (road & edge)[a] + slope + PA	4	1.09	0.367	0.856	0.501
3 *Response* $\sim$ (road & edge)[a] + slope	3	26.41	0.000	0.842	0.472
4 *Response* $\sim$ (road & edge)	2	32.00	0.000	0.840	0.464
5 *Response* $\sim$ road	2	121.62	0.000	0.803	0.361

[a] Denotes the first principle component between travel times to roads and travel time to forest edge.
[b] Denotes travel time to industrial plantation borders as of 1990.

Table 2. Parameter estimates of the final, most parsimonious model (model 2, table 1).

Variables	Coefficients	Std. error	Chi-square	Significance
(Road & edge)[a]	−0.153	0.016	91.408	0.000
Slope	−0.021	0.010	4.017	0.045
National park	−1.137	0.348	10.682	0.001
Wildlife reserves	−1.871	0.475	15.532	0.000
Hydrological reserves	−0.603	0.216	7.804	0.005
Constant	2.378	0.191	155.398	0.000

[a] Denotes the first principle component of travel time to roads and travel time to forest edge.

2000 to 2006 because of resurgence in armed conflict in Aceh province and, latterly, due to tsunami-related destruction of infrastructure (Reid 2006). Less than 2% of the area deforested from 2000–2006 was converted to large-scale plantations, while mechanized logging had carved less than 12 km of logging trails, and re-growth had occurred along older trails. Therefore, deforestation rates were five times slower (58 versus 294 km^2 yr^{-1}) during 2000–2006 than during 1990–2000.

4.2. Predictive model

Five logistic regression-based spatial models of deforestation were calibrated using the 1990–2000 dataset (table 1). The most parsimonious model (model 2, table 1) was chosen, which had the fewest parameters and was within two AIC units (ΔAIC) of the top ranked model (model 1, table 1). The model explained 77% of the original observations. The residuals of the final, most parsimonious regression model were not affected by spatial autocorrelation (Moran's $I = -0.006$, $P > 0.1$). The model had an R^2 of 0.501 and an ROC value of 0.856, indicating a very good fit to the model. The chi-square statistics, which indicate the relative weights of the explanatory variables in the model, showed that the single variable combining travel time to roads and the forest edge was the most important explanatory variable, followed by protection status, and finally by slope (table 2). By choosing not to select the top ranked model, the small but significantly positive effect that travel time to the border of 1990 industrial plantations had on deforestation was ignored (table 1). Forest areas located near roads and near the forest edge were found to be highly vulnerable to deforestation. Steep slopes and inclusion within PAs mitigated the effect of roads. Human population density in 1990, elevation and travel time to logging roads were not statistically significant, and so were not included in the model (table 3).

Table 3. Variables excluded from the model. (Note: The score statistic is based on the gradient of the likelihood function. The steeper the gradient, the stronger it suggests this covariate affects the likelihood and hence should be in the model. When it is small, there is no evidence that the covariate is required.)

Variables	Score statistics	Significance
Logging road	0.608	0.435
Population density	0.171	0.679
Elevation	0.038	0.845

These results mirror previous research on land cover change, showing that roads promote deforestation (Chomitz and Gray 1996, Laurance 2001, Soares-Filho *et al* 2006), while PAs reduce tropical deforestation (Bruner *et al* 2001, Gaveau *et al* 2009a). Including the construction of new roads as an explanatory variable in the model greatly increased the probability of deforestation ($P > 0.8$), by 40% compared to the scenario of halting the construction of new roads. By penetrating the remote forest interior, the planned construction of new roads further risks habitat fragmentation (figure 2). Including the RED project area as an extension to the current PA network in the model decreased the cover of natural forest at high probability of deforestation by 15%.

In general, high rates of deforestation have been observed in areas predicted to have a high probability of deforestation, for both the calibration (1990–2000) and validation periods (2000–2006) (figure 3). In particular, forested areas with $P > 0.8$ are most at risk under both curves. Therefore, it can be concluded that the model has predicted the risk of deforestation relatively well, in so far as probability values represent a valid relative index of deforestation. However, deforestation rates decreased more sharply with decreasing probability during the validation than during the calibration period because rates of deforestation were five times slower during the validation period. Despite the reduction in deforestation, the validation

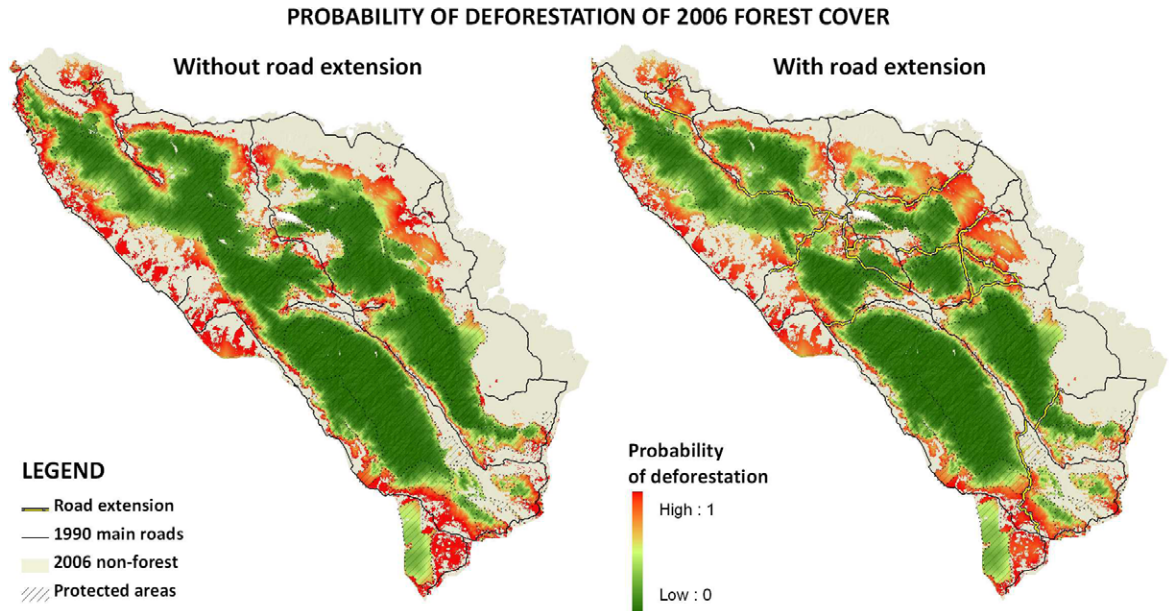

Figure 2. Probability map of an area being cleared of forest without further road extension (A), and with road extension (B). Areas that are highly vulnerable to deforestation are in red. Areas that are not at risk remain in dark green.

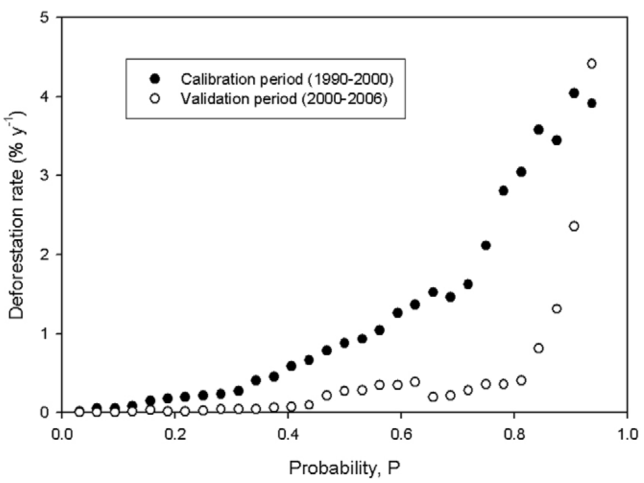

Figure 3. Calibration and validation curves for rates of deforestation in northern Sumatra, with increasing probability of deforestation.

curve still demonstrates good predictability, further reinforcing the validity of the model.

At one extreme, the worst-case baseline scenario without RED intervention incorporates the high rate of deforestation measured during 1990–2000 to model the rapid expansion of plantations into forest areas. Deforestation rates would increase from 294 to 385 km^2 yr^{-1} because new roads currently scheduled for construction would be built. Existing PAs would only mitigate deforestation as they did during 1990–2000 through law enforcement. Forest cover present in 2006 would shrink by >25% (9226 km^2) by 2030 (scenario 1, figure 4(a)). Orangutan habitat would reduce by 16% (1137 km^2), resulting in the conservative loss of an estimated 1384 Sumatran orangutans, or 25% of the current global population, while those remaining would face increased threats from encroachment, conflicts with humans and extensive habitat fragmentation. These predicted losses of orangutans would largely arise from extensive losses (56%) of forest cover in lowland forests (<500 m a.s.l.).

A plausible RED scenario incorporates the high rate of deforestation measured during 1990–2000 to model rapid expansion of plantations. Roads currently scheduled for construction would be built, but deforestation rates would decrease from 385 to 329 km^2 yr^{-1} because a new PA would be created under RED and would mitigate deforestation as with existing PAs. The model assumes that a considerable proportion of RED payments would be used by the government to enforce forest protection inside this new PA. Thus, inclusion of the 7500 km^2 PA extension of Ulu Masen into our predictive model would save 1313 km^2 from deforestation (scenario 2, figure 4(b)). However, this would represent a limited conservation success because forests outside PAs would shrink by 7913 km^2. Furthermore, there would be no benefit for orangutan conservation, given that much of Ulu Masen ecosystem comprises upland not favored by orangutans (Wich *et al* 2008). Either way, approximately 5000 wild Sumatran orangutans would be left in the wild by 2030, with or without this RED project because the combined expansion of high-revenue plantations and road networks would still threaten large tracts of unprotected lowland forests.

At the opposite extreme, the best-case RED scenario incorporates the low rate of deforestation measured during 2000–2006 to model the limited expansion of plantations. Roads currently scheduled for construction would be halted. Existing PAs would mitigate deforestation as they did during 1990–2000, but there would be no further extension of the PA network. Instead, this scenario assumes that RED payments to local communities or oil palm companies for their opportunity costs in not clearing unprotected forests outside PAs would trigger a reduction of deforestation rates across northern Sumatra from 329 to 58 km^2 yr^{-1}. Forest cover present in

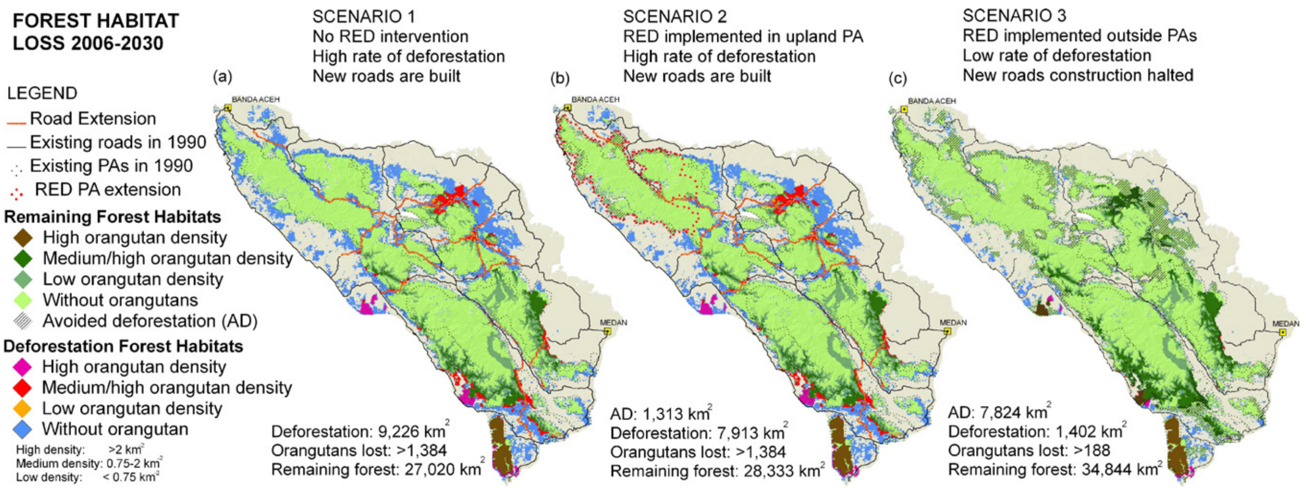

Figure 4. Forest habitat lost to deforestation, and forest habitat saved through avoided deforestation, and resulting losses in orangutans numbers by 2030 under: (a) a business-as-usual scenario without RED intervention; (b) RED implemented within a newly established upland PA; and (c) RED implemented across all remaining forest landscapes outside PAs.

2006 would shrink by <4% (1402 km^2) by 2030 (scenario 3, figure 4(c)). An estimated 7824 km^2 of forest would be saved from deforestation, some six fold more than the scenario with the RED project focused only on Ulu Masen (scenario 2, figure 4(b)). Furthermore, favored orangutan habitat in lowland forests would reduce by only 2% (138 km^2), resulting in the conservative loss of 180 orangutans, or less than 3% of the current global population.

The assumptions and parameters that define each scenario are shown in table 4.

4.3. Policy implications

This study has established an accurate historical deforestation baseline in northern Sumatra, which is the site of Indonesia's first RED initiative, but where data on forest loss had been previously lacking. It has developed a predictive model that displays, in map form, the forest that would be lost to deforestation, and the forest that would be saved through avoided deforestation, as a result of expanding or limiting plantations, constructing or halting new roads, and implementing or foregoing RED interventions. Like most models, ours is a simplified representation of reality. In particular, our model does not include important socio-economic drivers of deforestation, e.g. prices of agricultural commodities, and assumes that its coefficients are stationary, which may not be the case if socio-economic drivers vary over time (Mertens and Lambin 2000). However, our model bases its legitimacy on concurring with the past history of deforestation in northern Sumatra and through our aims of testing whether Indonesia's first RED initiative will significantly reduce deforestation and help conserve orangutans. Thus, we have measured the potential effectiveness of RED in reducing deforestation and conserving orangutans under two distinct implementation scenarios.

On the one hand, current plans are to implement RED within the boundaries of a newly established PA, where a considerable proportion of RED payments would serve to carry out monitoring and law enforcement activities (scenario 2, figure 4(b)). Alternatively, RED could be implemented across all remaining forest landscapes outside PAs (scenario 3, figure 4(c)). Here, RED payments would serve to compensate rural communities and plantation companies for their opportunity costs in not clearing unprotected forests. The provincial government of Aceh, the authority that will ultimately decide how RED will be implemented across northern Sumatra, would signal its intention to conserve the largest possible swathes of remaining carbon- and biodiversity-rich forest if it chose to implement RED across landscapes outside PAs, as in scenario 3 (figure 4(c)). Thus, scenario 3 would provide maximum conservation benefits for orangutans, and generate greater sales of carbon credits, with which to compensate rural communities and plantation companies for foregoing economic benefits that would otherwise be derived from developing plantations outside the PA network. However, scenario 3 requires voluntary participation from all land users and owners to trigger the same reductions in deforestation rates as did civil unrest during 2000–2006, which could only be sustained if the compensation to conserve unprotected forests is substantially more than the estimated per hectare earnings from agricultural commodities. The biggest investments in extracting natural resources in northern Sumatra are likely to be made in high-revenue oil palm plantations (Fitzherbert *et al* 2008). Crude palm oil prices have risen sharply since 2006 (World Bank 2008). In reality, RED revenues may actually be substantially less than profits from conversion to oil palm under voluntary carbon markets (Butler *et al* 2009), in particular if new roads are built to lower transportation costs of palm oil. In this context, scenario 3 would fail to trigger drastic reductions in deforestation rate.

Given the high economic return from oil palm investments, it is not surprising that the Indonesian national government recently announced it will press ahead with a plan to convert millions of hectares of lowland forests into oil palm plantations across Indonesian Borneo and Sumatra, despite its support for RED (Butler 2009). Therefore, future RED

Table 4. Assumptions and parameters that define each scenario.

Parameters and assumptions	Scenario 1 Without RED intervention	Scenario 2 RED implemented within specific boundary of a new upland PA	Scenario 3 RED implemented across all remaining forest landscapes outside PAs
Protected areas	Existing PAs (29 892 km^2) mitigate deforestation like during 1990–2000 through law enforcement	Existing PAs (29 892 km^2) and the 7500 km^2 RED PA extension mitigate deforestation like during 1990–2000 through law enforcement	Existing PAs (29 892 km^2) mitigate deforestation like during 1990–2000 through law enforcement
Roads	New roads are built and promote deforestation like existing roads during 1990–2000	New roads are built and promote deforestation like existing roads during 1990–2000	New roads construction is halted. Existing roads promote deforestation like during 1990–2000
Topography	Steep slopes mitigate deforestation	Steep slopes mitigate deforestation	Steep slopes mitigate deforestation
RED payments assumptions	None	Payments serve to monitor and enforce forest protection within boundary of RED PA extension	Payments serve to compensate land users for opportunity costs in not converting forests to oil palm
Oil palm plantations	High deforestation measured during 1990–2000 used to model rapid expansion of oil palm	High deforestation measured during 1990–2000 used to model rapid expansion of oil palm	Low deforestation measured during 2000–2006 used to model limited expansion of oil palm
Probability of deforestation threshold	$P = 0.549$	$P = 0.549$	$P = 0.837$
Deforestation rates	Deforestation rates increase from 294 to 385 $km^2\ yr^{-1}$ because of new roads	Deforestation rates decrease from 385 to 329 $km^2\ yr^{-1}$ because of the PA extension	RED payments to local communities or oil palm companies across in land outside formally protected areas trigger a reduction of deforestation rates across northern Sumatra from 329 to 58 $km^2\ yr^{-1}$

schemes in Indonesia will almost certainly be implemented within defined areas of land, including newly established PAs, because this approach would leave some areas of forest open to plantation development, and road construction. In essence, RED may simply end up resembling other types of conservation project that promote the establishment of PAs, where conservation funds help finance monitoring and law enforcement within PA boundaries. It is currently the case that guards will be recruited to conduct patrols and enforce forest protection in the 7500 km^2 upland area of the Ulu Masen ecosystem in Aceh province (Ulu Masen Project Design Note 2007). A considerable proportion of the project costs will be spent on forest monitoring and law enforcement activities (Mann and Surya 2009). This RED approach illustrated by scenario 2 suggests that Indonesia's first RED initiative will not significantly reduce deforestation in northern Sumatra and will have little impact on orangutan conservation because a large amount of forest inside Ulu Masen is protected *de facto* by being inaccessible, while much of northern Sumatra's lowland forests will remain exposed to the combined expansion of high-revenue plantations and road networks. New roads are currently under construction in northern Sumatra (Al-Fachri *et al* 2009), while oil palm companies are converting lowland forests into oil palm (Marks 2009). This would represent a dire scenario for the only great ape species occurring in Southeast Asia and would bring it even closer to extinction. RED would be more effective in terms of its conservation impact if RED was implemented at the provincial level across all remaining forest landscapes outside PAs, which could only be achieved if RED revenues were substantially more than profits from agricultural commodities. This may be feasible if post-2012 global climate agreements legitimize the trading of carbon credits from avoided deforestation on the compliance market (Butler *et al* 2009). Meanwhile, a recent study found that RED revenues under voluntary markets would be substantially more profitable than oil palm conversion in lowland peat swamp forests with high carbon density (Venter *et al* 2009), also the preferred habitat of orangutans (Wich *et al* 2008). If indeed it proved possible to translate RED payments into a profitable currency, Indonesia could alter the current economic logic that is driving the rapid destruction of its lowland tropical forests, and demonstrate that climate change mitigation, the conservation of orangutans, and economic development can operate without causing trade-offs between apparently competing demands.

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