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Designing multifunctional landscapes for forest conservation

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Abstract

A multifunctional landscape approach to forest protection has been advocated for tropical countries. Designing such landscapes necessitates that the role of different land uses in protecting forest be evaluated, along with the spatial interactions between land uses. However, such evaluations have been hindered by a lack of suitable analysis methodologies and data with fine spatial resolution over long time periods. We demonstrate the utility of a matching method with multiple categories to evaluate the role of alternative land uses in protecting forest. We also assessed the impact of land use change trajectories on the rate of deforestation. We employed data from Kalimantan (Indonesian Borneo) at three different time periods during 2000–2012 to illustrate our approach. Four single land uses (protected areas (PA), natural forest logging concessions (LC), timber plantation concessions (TC) and oil-palm plantation concessions (OC)) and two mixed land uses (mixed concessions and the overlap between concessions and PA) were assessed. The rate of deforestation was found to be lowest for PA, followed by LC. Deforestation rates for all land uses tended to be highest for locations that share the characteristics of areas in which TC or OC are located (e.g. degraded areas), suggesting that these areas are inherently more susceptible to deforestation due to foregone opportunities. Our approach provides important insights into how multifunctional landscapes can be designed to enhance the protection of biodiversity.

1. Introduction

Protecting forest and reducing deforestation is central to mitigating the impacts of climate change and averting the loss of biodiversity and the services provided by natural ecosystems [1]. However, for most of the developing tropics, this is challenged by socio-economic pressure to clear land, development agendas arising from government policy, and the opportunity costs of forest protection [2, 3]. Many protected areas (PA) are isolated and situated in a matrix of agricultural land uses, thus reducing their effective size and capacity to maintain the biological diversity that they were originally designated to protect [4]. Therefore, PA alone, despite their growing extent, are unlikely to be sufficient to conserve biodiversity and other ecosystem services [5, 6]. These considerations have led to a shifted conservation paradigm from a focus solely on PA to the integration of PA within wider multifunctional landscapes [7–9]. Under this new paradigm, PA remain a cornerstone of biodiversity conservation policy, but the landscape matrix also becomes important for achieving broader conservation and development objectives [10, 11]. This approach will likely also increase the robustness and resilience of forest protection strategies, especially under a changing climate [12, 13].

A multifunctional landscape approach to forest protection is cognizant of the interrelationships among different land uses across the landscape matrix [8, 11, 13]. These land use types and spatial locations are determined by planning processes that divide a territory into zones with different rules and regulations, management practices and land covers. The locations assigned to different land uses often have dominant characteristics. For example, in tropical regions PA have historically been located in remote and mountainous areas [14], natural forest logging concessions (LC) are generally established where timber resources are most abundant and easily extracted, and agricultural plantations are generally established in locations with suitable climate and soil conditions and accessible to human population centers. Land uses can be defined based on their use, i.e. conservation or extraction, or the users, e.g., community forests or concessions [15]. A variety of land use systems exist in tropical forested areas, although LC, agricultural plantation concessions, mining permits, and PA are the principal forms of government-controlled land use [16, 17]. Small-scale agriculture under community control predominates on remaining lands [18].

The shift in the conservation paradigm from a focus on PA to multifunctional landscapes necessitates a comprehensive approach for evaluating the performance of forest protection policies that accounts for the contribution of multiple land uses [19]. However, this presents critical methodological challenges. First, it requires evaluation of the dynamic change in both forest cover and land use configurations through time [20, 21]. The data required to support such analyses are often not available over extended time periods and at broad spatial extents. Second, past evaluations of the effectiveness of PA in abating deforestation rely on reduced-form empirical estimates. These estimates appraise whether or not PA and the surrounding landscape matrix were able to maintain forests based on an aggregated measure of effectiveness (e.g. average deforestation rate), but rarely address why and how different land uses contribute to forest protection [22]. Ideally evaluation methods should seek to identify the underlying causes and mechanisms that determine effectiveness, and appraise the associated interplay among different land uses [23].

With the lack of historical land use change data, past evaluations of the effectiveness of PA and other land uses in abating deforestation have had to rely on static land use maps that are typically based on the most current land use configurations [24–26]. This approach can potentially lead to an incomplete understanding of the effectiveness of different land uses for reducing deforestation. This is particularly the case for the developing tropics, which are characterized by rapid changes in land use and land cover in response to global demand for food, fiber and fuel [27–29], and often facilitated by a combination of decentralization of government authority [30–32] and weak and changing land tenure systems [33]. Land disputes and overlapping permits for forest use are common [34, 35], and can include overlap between LC or agriculture plantation concessions and PA [36, 37]. Ignoring the existence of such overlaps can potentially confound measures of the effectiveness of single land uses. Furthermore, recent studies from Indonesia that were based on static land use data have shown that the deforestation rate in LC in Indonesia were generally low and comparable to PA [24, 26]. This suggests that selectively harvested LC can potentially provide a secondary source of forest protection [26]. This is contrary to other studies that have found commercial logging to be the main contributor to deforestation [37], initiating the trajectory of forest degradation that eventually leads to conversion of land to agricultural plantations [38–40]. In these earlier studies, however, the impact of timber harvest on deforestation was assessed irrespective of its legality, i.e. whether or not the removal of trees was selectively planned and performed within the boundary of an LC and within cutting limits, or illegally outside of an LC or including trees below a minimum diameter [39]. To date, there has not been a comprehensive evaluation of the contribution of LC to deforestation that explicitly accounts for both the change in land use and forest cover.

In this paper, we assessed the conservation role of different land uses to inform the design of multifunctional landscapes. We also assessed how land use change trajectories affect the pattern of deforestation. To illustrate our approach we used data from Kalimantan, the Indonesian part of Borneo, over three time periods: 2000–2004, 2004–2008, and 2008–2012. We first determined the relationship between the spatial assignments of each land use and a suite of geographical and soil variables. On the basis of these relationships we calculated the likelihood of a grid cell to be assigned to a single land use type. We then applied a matching method adapted for multiple land use categories [41, 42] and the deforestation rate for each land use was compared based on the matched datasets. Our approach offers an improved method for assessing the effectiveness of PA by enabling the contribution of multiple land uses to mitigating deforestation to be evaluated simultaneously and explicitly accounting for the spatial interplay between land uses.

2. Methods

2.1. Study area

Kalimantan covers an area of approximately 533 500 km^2. Between 2000 and 2012, approximately 17.6% of the total land area was allocated to LC, i.e. parcels of forest leased out to companies to selectively extract timber on a long-term basis. About 13.1% of the total land area was allocated to oil-palm (*Elaeis guineensis*) plantation concessions (OC), and 5.3% was allocated to timber plantation concessions (TC) of fast-growing species, primarily for pulp, paper and rubber production (*Acacia mangium*, *Hevea*, or *Eucalyptus spp*.). About 19.1% of Kalimantan's land area was designated as PA, including strict PA (IUCN PA Category I–III) and district-managed watershed protection forest (*Hutan Lindung*). During this period,

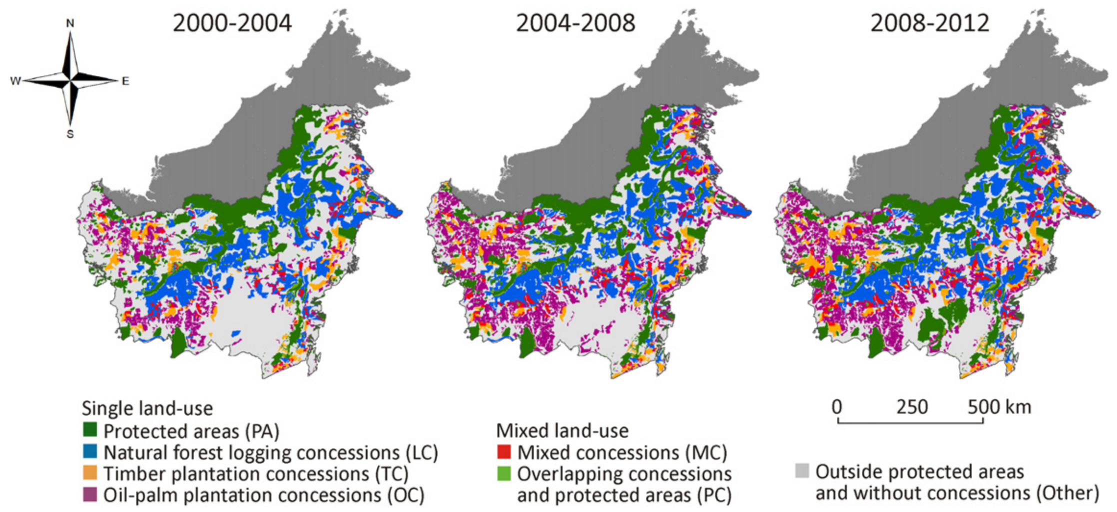

Figure 1. The distributions of single land uses (including protected areas (PA), natural forest logging concessions (LC), timber plantation concessions (TC), and oil-palm plantation concessions (OC)), mixed land uses (including mixed concessions (MC), i.e. areas with multiple overlapping concessions) and concessions within protected area boundaries (PC)), and areas outside protected areas and without concessions (Other) in Kalimantan for 2000–2004, 2004–2008 and 2008–2012.

land use change driven by economic and political demands has accelerated the rate of deforestation [38, 43]. Gaveau *et al* [26] found that between 2000 and 2010, 1.2% of the forest area in Kalimantan's PA was deforested, while forests in areas granted to LC were reduced by 1.5% and forests in areas granted to OC were reduced by 14.1%.

2.2. Data and analysis

2.2.1. Land use

Maps of PA, including strict PA and watershed protected forest (*Hutan Lindung*), and concession types, i.e. OC, TC (IUPHHK-HT), and LC (IUPHHK-HA), for 2000–2004, 2004–2008, and 2008–2012 were obtained from the Indonesia's Ministry of Forestry (MoF) and Department of Estate Crops within the Ministry of Agriculture. The assignments of PA and concession types for the three different time periods are shown in figure 1. The study area was assigned a grid of land parcels with a spatial resolution of 1×1 km^2 and at least one land use was assigned to each grid cell.

2.2.2. Extent of natural forest in 2000 and annual forest loss between 2000 and 2012

The extent of natural forest in 2000 was obtained from Indonesia's MoF [44]. Natural forest constitutes undisturbed old-growth forests (primary forest in the MoF classification) and forests degraded by logging (secondary forest in the MoF classification). We overlaid the natural forest extent with forest cover data for 2000 obtained from the LANDSAT based Global Forest Change dataset [45]. The forest cover data has a spatial resolution of 30×30 m^2 and comprises continuous values where 0% represents bare land and 100% represents dense forest. Since we were interested in the loss of intact forest across different land use types, we only included grid cell that were completely covered by natural forest (i.e. 100 hectares) in the beginning of each time period (i.e. 2000, 2004, and 2008). Following Hansen *et al* [45], we used a threshold of 30% to define a pixel as forested in each subsequent time period.

Data on the annual rate of forest loss between 2000 and 2012 were also derived from the Global Forest Change dataset. The annual loss data has a spatial resolution of 30×30 m^2 and comprises binary values, where '1' denotes clearing of forest within a 30×30 m^2 grid cell and '0' otherwise. We first overlaid the forest loss data with the aforementioned natural forest extent data to obtain a map of the annual rate of forest loss. We then calculated the total loss of forest in hectares in each 1×1 km^2 grid cell for each time period $t\in$ {2000–2004, 2004–2008, 2008–2012} and this was represented by the variable DEFOR$_t$. Thus, DEFOR$_t$ ranged between 0 and 100, where 0 represents the absence of forest loss and 100 represents that the entire area of forest within the grid cell had been cleared during the four year period.

2.2.3. Spatial assignment of land uses

For each time period t, where $t\in$ {2000–2004, 2004–2008, 2008–2012}, we accounted for three categories of land use: (1) the dominant single land uses within the region SLU$_t$ (i.e. PA, LC, TC, and OC); (2) mixed land uses MLU$_t$ (mixed concessions where two or more concessions overlap (MC) and areas where either LC, TC, or OC overlapped with PA (PC)), (3) and all other land uses outside the single and the mixed land uses (Other).

The spatial characteristics of different land uses for each time period SLU$_t$ were assessed using a multinomial logistic regression model incorporating a suite of geographical and soil predictor variables [46]. The geographical predictor variables included the change in the human population density and the governing district [47, 48] and static variables of altitude, slope, travel distance to the nearest city, travel distance to the nearest arterial road and long-term mean annual rainfall (table S1). The soil predictor variables included soil type, drainage, depth, and acidity (table S1). These data are the best available soil data for Kalimantan and have been used in other recent research [49, 50]. The multinomial logistic regression model for each time period was applied using the multinom function in the nnet R-package [51] and linear, quadratic, and cubic functions were tested for each variable. Using the derived relationships for each time period, we predicted the likelihood that a grid cell would be assigned to each single land use (SLU_t) [52]. We assessed the predictive performance of the multinomial logistic models by comparing the predicted land use assignments with the actual land uses, measured using the overall percentage success (OPS) and Gwet's AC1 statistic [53]. Gwet's AC1 statistic modifies the usual Cohen's kappa agreement measure [54] and is more robust to data prevalence [53]. The AC1 value ranges between 0 and 1, where a value larger than 0.6 represents substantial agreement [55].

2.2.4. Deforestation in different land uses

The propensity score of a grid cell was determined by the probability associated with each land use as predicted by the multinomial logistic regression. We then identified grid cells with similar propensity score values to match locations in terms of their geographical and soil characteristics. We applied the nearest neighbor with calipers method to obtain the optimal matched data, by setting a caliper width of 0.2 of the standard deviation of the propensity score's logit function [56]. We used the *nn*2 function in the RANN R-package [57] to perform the nearest neighbor search. For each time period, we then compared the average deforestation rate per km^2 across different land uses using the matched datasets. We also calculated the deforestation rate over the entire landscape for each land use category (referred to herein as the 'naïve' approach).

3. Results

3.1. Spatial assignment of land uses

Spatial assignments of land uses in Kalimantan for 2000–2004, 2004–2008, and 2008–2012 are shown in figure 1. PA are predominantly located in remote areas at high altitude, with a small proportion of these areas located in densely populated areas at low altitude (figure S1). Conversely, LC are largely located in areas at moderate altitude and distant from cities and arterial roads (figure S1). TC and OC are predominately located in lowland areas in close proximity to cities and arterial roads (figure S1). Moderately shallow (11–50 cm deep), strongly acid, and well to excessively drained soils characterizes soil found inside the boundaries of PA (figure S2). Conversely, well-drained ultisols, inceptisols or alfisols soil types characterize LC. TC have either extremely acid (pH 4.0–4.5) or neutral (pH 6.6–7.3), deep to very deep (75–150 cm) alfisols or oxisols soil types (figure S2). On the other hand, very deep (>100 cm) and extremely acid (pH 4.0–4.5) histosols, oxisols or spodosols are the dominant soil type of OC (figure S2). This suggests that OC have generally been assigned to areas with naturally infertile soil with high soil acidity, whereas TC, have generally been assigned to areas with either naturally fertile or infertile soil [58]. Oil-palm is considered moderately tolerant to a wide range of soil types and acidities, as long as it is well watered [59–61].

Of all 1×1 km^2 grid cells within a single land use category (i.e. PA, LC, TC and OC), at least 73% were correctly predicted as the current land use assignment in each time period (figure S3). Gwet's AC1 for each time period was greater than 0.63 (figure S3), indicating strong agreement between the actual and predicted land uses and also that the land use types have been assigned in a predictable way across the landscape. The proportion of land parcels assigned to LC and OC has increased through time, with the models exhibiting better performance in the later time periods for these land uses (table S2).

3.2. Comparative deforestation rates among land uses

Based on the combined Global Forest Change datasets and the MoF natural forest extent, we estimated that in 2000 the extent of natural forest in Kalimantan was about 300 000 km^2 (table S3). However, by 2012 the extent of natural forest had been reduced to 276 000 km^2 (table S3), equating to 7.9% loss of the 2000 extent, and conforming with the findings of an earlier study [39]. Between 2000 and 2012, natural forest accounted for 81.7% of the area designated as PA and 80.8% of the area designated as LC (or 28.5% and 25.9% of Kalimantan's total natural forest area respectively, table S3). Between 2000 and 2012, 28.5% of the area designated as TC and 24.9% of the area designated as OC comprised natural forest, equating to 2.8% and 6.1% of the total area of natural forests, respectively (table S3).

Based on spatially-matched data, PA had the lowest deforestation rate per km^2 every four years (1.6 hectares on average) followed by LC (2.5 hectares), TC (5.4 hectares), and OC (9.9 hectares) (figure 2(a)). The deforestation rate inside PA where concessions have also been assigned (2.3 hectares) was higher than inside PA without overlapping concessions. In comparison, using the naive approach, the rate of deforestation for each land use was predicted to be lower for PA and LC, but higher for TC and OC. Between 2000

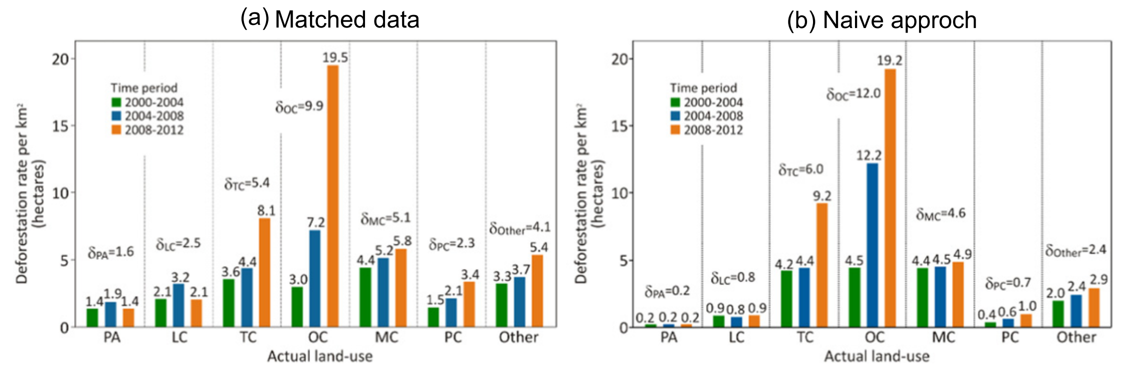

Figure 2. Comparison of the deforestation rate per km^2 across different land uses based on (a) matched data and (b) naive approach for three different time periods between 2000 and 2012. δ_i represents the mean deforestation rate across different time periods for land use category *i*.

and 2012, the deforestation rate every four years per km^2 for PA was predicted to be 0.2 hectares on average, for LC the rate was 0.8 hectares, for TC the rate was 6.0 hectares, and for OC the rate was 12.0 hectares (figure 2(b)). Inside PA where concessions have also been assigned, the deforestation rate was 0.7 hectares.

The spatially-matched data reveals a shift in deforestation trends through time (figure 2(a)). Between 2000 and 2004 the deforestation rate was greatest in mixed concessions (4.4 hectares), TC (3.6 hectares), and OC (3.0 hectares). Between 2004 and 2008, the deforestation rate was greatest inside OC (7.2 hectares) and mixed concessions (5.2 hectares). Between 2008 and 2012 the deforestation rate was greatest inside OC (19.5 hectares). This suggests that deforestation in early 2000 was motivated mainly in response to demand for timber production, whereas it is now largely motivated by oil-palm establishment. Additionally, the deforestation rate has increased through time, particularly for OC, suggesting that there is a growing pressure to clear forest in this region.

For all land uses, we found that the deforestation rate for each time period was greater in locations that share characteristics typically associated with TC or OC (figure 3). For example, inside PA, in the locations that share characteristics typically associated with plantation concessions the deforestation rate per km^2 every four years was 3.1 hectares on average, whereas for other locations that do not share these characteristics the rate was 0.2 hectares (figure 3).

3.3. Land use change trajectories and deforestation of intact forest

Since 2000, Kalimantan has undergone a rapid expansion of concessions as well as complex alteration of land uses. In 2000, about 48.2% of the total land area had not been assigned to any concession or PA, or was assigned to the 'Other' land use category (table S3). By 2008, 14.2%, 9.2% and 1.4% of this concession-free area were granted to OC, LC and TC, respectively (table S4(a)). The expansion of concessions continued and by 2012 about 11.9% of the concession-free area was converted to LC, TC or OC (table S4(b)). Between 2000 and 2012, some of the existing LC and TC were either converted to OC or the concession was removed. For example, about 2.8% of LC that existed in 2000 were converted to OC by 2008 (table S4(a)). At the same time, 18.0% of LC and 3.9% of TC lost their concession permit (table S4(a)). By 2012, 5.3% of LC were converted to OC (table S4(b)).

Of all locations currently assigned to OC (i.e. assigned to this land use between 2008 and 2012), 29.1% comprised intact forest in 2000 (table S5). Almost a third of this intact forest was assigned to OC as early as 2000, while a little over a half was without a concession (or concession-free) and a small proportion (3.4%) was originally allocated to LC. When the concession-free areas and the LC were later converted to OC, about 84.3% comprised intact forest (with >90% forest cover) (figure S4(a)). Similarly, of all locations currently assigned to TC (i.e. assigned to this land use between 2008 and 2012), 34.0% comprised intact forest in 2000 (table S5). About 46.3% of this intact forest was assigned TC to as early as 2000, while 53.2% were concession-free. When the concession-free area were later converted to TC, about 82.3% was intact prior to conversion (figure S4(a)). This suggests forest degradation was unlikely to be the main reason for the conversion of concession-free areas or LC to TC or OC during 2000–2012. However, among LC that were later converted to OC, the proportion of areas with excessively acid soil (pH $\leqslant$ 4.0) was high (32%) (figure S4(b)). High soil acidity (pH $\leqslant$ 4.5) was also found in a relatively large proportion of concession-free areas that were later converted to TC or OC (figure S4(b)). This suggests that conversion from natural forest LC or areas without concessions to plantation concessions were more likely to be motivated by the perceived inherent land capability rather than forest degradation.

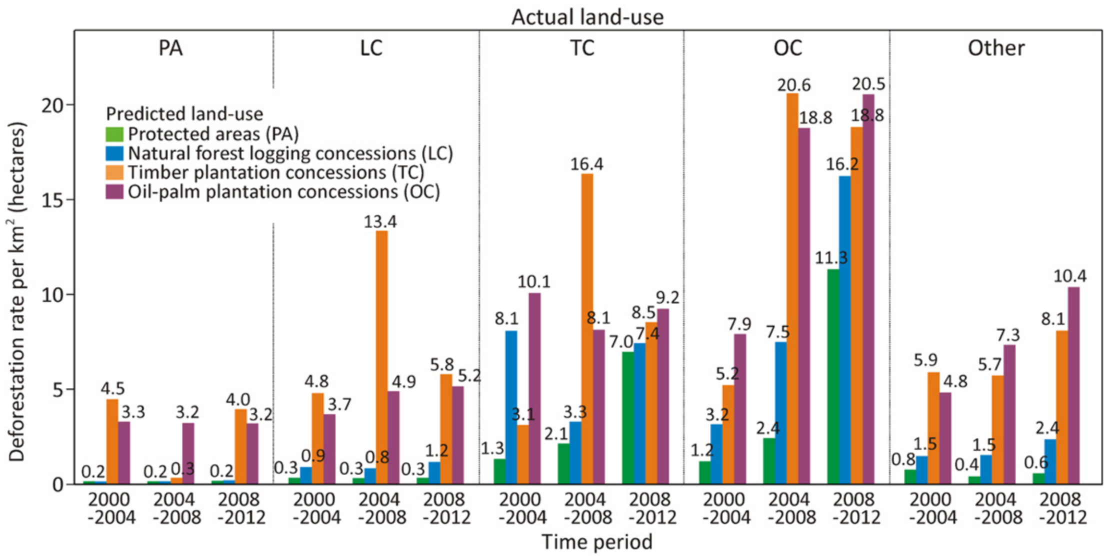

Figure 3. The deforestation rate per km^2 for grid cells that were predicted to be other land uses based on matched data for three time periods (2000–2004, 2004–2008, and 2008–2012).

4. Discussion

In recent years, there has been an increasing awareness of the importance of multifunctional landscapes for conserving biodiversity [62]. This necessitates that evaluations of the performance of conservation policy shift from focusing on the effectiveness of PA alone (at a site level) to appraising the role of all land uses (at a landscape scale) [26]. Aggregated measures of the effectiveness of different land uses for mitigating deforestation [22], such as the overall deforestation rate, fail to reveal the underlying mechanisms of deforestation within a land use [23]. While the deforestation rate for PA and LC revealed by our analysis reflects the overall deforestation rate found by an earlier study [26], the vulnerability to deforestation varies between land uses and locations, particularly in relation to potential foregone opportunities for agriculture or timber extraction (figure 3). For example, while the deforestation rate for LC with a high potential for agriculture or plantation establishment during 2000–2010 was about 6.3 hectares per km^2, the deforestation rate inside PA that shared similar characteristics was half this rate (3.1 hectares per km^2). This indicates that PA are mitigating some of the impacts of deforestation in this region.

TC and OC have tended to be located in areas in close proximity to cities. However, these concessions are also located in areas with naturally infertile soils, such as on peat swamps and dry lands with acidic soil. These marginal areas [63] are usually unoccupied as a result of their low value for small-holder agriculture [64]. The reclamation of peat swamps or dry land is a lucrative alternative to transporting crops from remote areas, especially if the cost of reclamation can be subsidized from the sale of timber by clearing forest [65]. The vulnerability of such areas to deforestation, therefore, highlights the importance of appropriate management interventions, such as policies that increase the value of forest (e.g. through biodiversity and ecosystem service payments) [66] as well as enforcement of environmental regulations.

Logging activities have been viewed as the initial step in the trajectory towards forest degradation that ultimately leads to oil-palm plantation establishment [67], although we found evidence to the contrary. Based on a detailed analysis of land use change trajectories during 2000–2012, we found that among sites currently assigned as TC or OC, nearly a third comprised intact forest in early 2000, confirming an earlier report focused on forest conversion [68]. About half of the concessions assigned within this intact forest were already granted TC or OC in early 2000 and the other half were either without a concession (or concession-free) or assigned as LC. However, when these concession-free areas or LC were later converted to TC or OC in the mid to late 2000s, over 80% had >90% forest cover. This suggests that forest degradation was unlikely to be the main reason for conversion of LC or concession-free areas to plantation concessions, at least during 2000–2012. Instead, we found a large proportion of these areas were located on highly acid soils, suggesting that perceived land capability was more likely to be the key reason for conversion. This finding is consistent with the fact that the term of 'degraded land' is used by the Indonesian government to represent a wide variety of land conditions, including degraded forest (areas that have been severely logged [49]), critical lands (areas that have been subject to intensive agricultural practices) and marginal lands (areas considered to be unproductive with high soil acidity, including peat swamp and dry land on acid soil) [63].

As anticipated, the deforestation rate within TC and OC was two to four times higher than the rate in LC. Our analysis also reveals that the deforestation rate within OC has increased through time. Interestingly, the deforestation rate in LC was lower than areas without a concession, revealing the impacts of illegal logging activities. The capacity for LC to reduce the rate of deforestation compared to both plantation concessions and concession-free areas in Kalimantan supports recommendations for reclassifying LC as PA under the IUCN Protected Area Category VI [26]. In addition, such reclassification could lessen the impacts of current government policy that results in the conversion of LC to OC, particularly in areas perceived to be unproductive or marginal. Instead the rehabilitation and restoration of these areas should be encouraged [69]. Such reclassification could also benefit biodiversity conservation, with many endangered species residing inside LC [70].

Our analysis has revealed locations where multiple types of concessions overlap and locations where concessions overlap with PA. In the latter, the deforestation rate was higher than in PA as a single land use type (figure 2). Therefore, this underlines the value of accounting for overlapping land use allocations when assessing the effectiveness of PA. Overlapping land uses are not unique to Indonesia and have been reported in countries in South America and Africa [32, 71, 72]. In Indonesia, overlapping land uses not only occur due to weak land use planning systems, but also as a consequence of the discrepancy in maps developed at different levels of government [73]. This is particularly evident for the province of Central Kalimantan where PA boundaries considered by the local government differ from the ones assigned by the Ministry of Environment and Forestry [74]. In an attempt to reconcile these conflicting maps, the Indonesian government has recently launched the 'One Map' initiative that aims to resolve land disputes and overlapping concession permits [75].

Our study advances past evaluations of the effectiveness of PA by accounting for the spatial interplay between alternative land uses and explicitly accounting for the dynamic change in land use through time. Our findings suggest that a mix of different forest conservation strategies is needed in Kalimantan that integrates different levels of protection and resource use by local communities [76]. Formally reclassifying LC as PA under the IUCN Protected Area Category VI could enhance biodiversity protection, increase social welfare, and provide economic opportunities for local people and businesses. Furthermore, combining PA with LC when planning for multi-functional landscapes could ensure the protection of larger areas of intact forest than possible via PA alone.

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