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Protected area effectiveness in a sea of palm oil: A Sumatran case study

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ABSTRACT

Despite the establishment of a national protected area system at the beginning of the 20th century to protect some of the world's most biodiverse forests, Indonesia has one of the highest deforestation rates in the world, due in part to the expansion of the global palm oil industry. The unique ecosystems of Sumatra, Indonesia provide habitat for critically endangered Sumatran tigers (*Panthera tigris sumatrae*), Sumatran elephants (*Elephas maximus sumatrensis*), and two species of orangutans (*Pongo abelii* and *Pongo tapanuliensis*). In this study, we use a matching method with generalized boosted models to determine the effectiveness of three nationally protected areas in preventing deforestation from 2002 to 2016. We also examine leakage – an increase in deforestation directly outside of protected areas relative to the wider landscape – to provide a clearer picture of the effects of agricultural expansion in this landscape. We found that Tesso Nilo National Park, with its lowland rain forest and conditions suitable for oil palm, offered the least protection from deforestation (avoided deforestation rate = 4.18%, $p < 0.05$ 95% CI [1.97% - 6.45%]). Bukit Tigapuluh National Park, which may experience some de facto protection (i.e. protection due to factors independent of policy) with its mountainous terrain and difficult access, had the highest avoided deforestation rate (26.36%, $p < 0.05$ 95% CI [24.17–28.55]), but had relatively high leakage (10.21%, $p < 0.05$ 95% CI [7.51–12.98]). The low avoided deforestation rate in Tesso Nilo could be due to high localized human population and/or other socio-economic factors we were unable to control for in this study. The quantitative evidence of deforestation and effectiveness of protected areas in this heavily modified landscape supports the need for increased enforcement around protected areas locally, and globally in other oil palm production regions. These actions are critical in the preservation of global, tropical endemic flora and fauna.

Indonesian abstract: Meskipun telah membangun sistem kawasan konservasi sejak awal abad ke 20 untuk melindungi hutan dengan keanekaragaman hayati yang sangat tinggi, Indonesia masih merupakan negara yang memiliki laju deforestasi yang tertinggi di dunia, akibat penkembangan industri sawit di dunia. Ekosistem-ekosistem endemic di Sumatera-Indonesia merupakan habitat bagi spesies-spesies yang memiliki status konservasi kritis yaitu harimau Sumatera (*Panthera tigris sumatrae*), gajah Sumatera (*Elephas maximus sumatrensis*), dan dua species orangutan (*Pongo abelii* dan *Pongo tapanuliensis*). Dalam penelitian ini, kami menggunakan metode *matching* dengan model *generalized boosted* untuk menentukan efektivitas dari tiga kawasan konservasi dalam mencegah terjadinya deforestasi dari tahun 2002–2016. Kami juga menilai *leakage* (kebocoran) – yang merupakan kenaikan laju deforestasi pada area yang berdekatan dengan kawasan konservasi– untuk memberikan gambaran yang utuh atas dampak industri sawit dunia. Kami menemukan bahwa Taman Nasional Tesso Nilo, dengan habitat dan kondisi hutan tropis dataran rendah, yang juga sesuai untuk tanaman sawit, merupakan kawasan konservasi yang memiliki kemampuan paling rendah dalam melindungi dari deforestasi (laju pencegahan deforestasi = 4.18%, $p < 0.05$ 95% CI [1.97% - 6.45%]). Sedangkan Taman Nasional Bukit Tigapuluh yang merupakan kawasan pegunungan memiliki laju pencegahan deforestasi tertinggi (26.36%, $p < 0.05$ 95% CI [24.17–28.55]), namun memilki nilai kebocoran yang relatif tinggi (10.21%, $p < 0.05$ 95% CI [7.51–12.98]). Fakta kuantitatif dari deforestasi dan efektivitas kawasan konservasi pada landskap yang termodifikasi sangat berat ini mengkonfirmasi adanya kebutuhan yang mendesak untuk melakukan penguatan di sekitar kawasan konservasi baik di tingkat lokal maupun global pada wilayah yang ditujukan untuk produksi sawit. Aksi-aksi tersebut sangat dibutuhkan untuk mendukung perlindungan flora dan fauna endemik di dunia.

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1. Introduction

As the global human population continues to expand, agriculture has become a primary driver of deforestation (Henders et al., 2015). Global palm oil production has recently doubled, and as the world's cheapest vegetable oil, it is projected to continue to increase (FAO, 2017; FAPRI, 2012). Indonesia and Malaysia produce > 80% of the global palm oil supply. Oil palm (*Elaeis guineensis*) is usually grown in a monoculture, which results in a lack of structural complexity compared to natural forests. Plantations contribute to significant changes in biodiversity and wildlife distributions, and reductions in species richness compared to natural forest and other types of agriculture (Fitzherbert et al., 2008; Koh and Wilcove, 2008; Barnes et al., 2017; Mendes-Oliveira et al., 2017).

Despite the establishment of a protected area (PA) system at the beginning of the 20th century to protect some of the world's most biodiverse forests, deforestation in Indonesia is still high and recently surpassed Brazil with the highest deforestation rate in the world, largely due to the expansion of the palm oil industry since the mid/late 1990's (Margono et al., 2014). While Indonesia's endemic and globally threatened species have been seen in oil palm plantations, no evidence suggests that plantations can hold a breeding population of tigers (*Panthera tigris*), elephants (*Elephas maximus*), orangutans (*Pongo spp.*), or tapirs (*Acrocodia indica*). On Sumatra, critically endangered Sumatran tigers (*Panthera tigris sumatrae*) have been shown to prefer acacia (*Acacia mangium* or *Acacia crassicarpa*) plantations and secondary forests to oil palm plantations (Sunarto et al., 2012), and the presence of oil palm surrounding protected areas can have substantial negative impacts on tiger persistence (Imron et al., 2011). Conversion from primary or secondary forest to oil palm has slowed in recent years, but oil palm is still the dominant agricultural land cover type in central Sumatra (Austin et al., 2017). Pulp and paper plantations, rubber, and eucalyptus plantations are also common, but we focus here on oil palm due to its prevalence throughout our study area.

The level of protection that PAs actually impart varies based on location, socio-economic factors, and political factors, to name a few (Joppa et al., 2018). In Indonesia, like in many other tropical developing countries where oil palm is grown, it is difficult to determine extent and level of protection of protected areas. This may be due to incorrect or unavailable spatial boundaries of PAs or due to the remote nature of some PAs. Such PAs that are remote and would be unlikely to face anthropogenic pressures even if they were not officially protected may be experiencing what is called 'de facto' protection – protection conferred by geography or topography rather than policy (Joppa et al., 2018). In addition, the establishment of a protected area may result in unfortunate consequences such as leakage. We define leakage here as higher deforestation rates directly outside a PA in comparison to the wider landscape (Santika et al., 2017). Leakage can occur for several reasons. For example, when a PA is established in the absence of addressing socio-economic needs, local communities may intensify harvest and extraction activities of natural forests just outside the PA – thus displacing the negative impacts on biodiversity that motivated the creation of the PA in the first place (McDonald et al., 2007). Oliviera et al. (2007) found that deforestation increased by 300–470% directly adjacent to a newly established protected area in the Amazon. Leakage can also occur when deforestation on the landscape has stabilized, and has expanded to the forest-development frontier, often near protected areas. Protected areas are not intended to address leakage, but intense deforestation can impact PA effectiveness if a PA system is intended to aid in landscape-wide wildlife dispersal. Thus we include leakage here in our analyses. If leakage is occurring in Sumatra, PAs are at risk of becoming isolated islands of forest in a sea of oil palm and other agricultural crops, leaving wildlife populations at higher risk of loss of genetic diversity, inbreeding depression, and extinction due to declining dispersal rates across a potentially dangerous monoculture matrix (Wright, 1965; Wildt et al., 1987).

Sumatran PA effectiveness has been studied before at an island-wide scale, where Gaveau et al. (2009, 2012) used a propensity score matching method to examine Sumatran PA effectiveness and found positive impacts of protection against deforestation. Shah and Baylis (2015) found that Tesso Nilo National Park in central Sumatra had higher deforestation inside the park than outside the park using a similar method. Compared to the broader landscape (Gaveau et al., 2009), and within a 10 km buffer around PAs to measure leakage (Gaveau et al., 2012), PAs had lower deforestation rates, island-wide, from 1990 to 2000. Now, it is important to revisit these analyses due to several factors: 1) the large increase in oil palm plantations in this province since 2000 (50% of oil palm fruit harvested in Indonesia in 2014 was planted in 2003 or later (FAO, 2017)), 2) the availability of new, finer scale (30 m × 30 m), accuracy-assessed, land cover data (Poor et al., 2019) and 3) the general lack of research in central, lowland Sumatra in comparison to other areas on Sumatra.

Riau Province, in central Sumatra, produced 26% of Indonesia's palm oil in 2015 (approximately 8 million tons out of Indonesia's 31 million ton total) (Ministry of Agriculture, 2016). Here, in our area of interest, lowland areas that once boasted unique eco-floristic zones (Laumonier et al., 2010), Sumatran tigers, elephants, orangutans, and rhinoceroses (*Dicerorhinus sumatrensis*), provide ideal oil palm growing conditions. Riau contains three geographically close protected areas, which vary in condition, habitat, and terrain. Tesso Nilo National Park was established on land suitable for oil palm (lowland), whereas Bukit Tigapuluh National Park and Rimbang Baling Wildlife Reserve are mountainous and difficult to access. Bukit Tigapuluh is surrounded by oil palm and Rimbang Baling is surrounded by pulp and paper and plantations (*Acacia spp.*) that may be affecting their protected forests. Although deforestation is currently rampant within Tesso Nilo, deforestation is also widespread across the non-protected landscape, thus the protected status of the national park may still confer some protection despite extreme human modification.

Like Rimbang Baling and Bukit Tigapuluh, PAs globally are often placed in disproportionately inaccessible areas or in areas where harvest and extraction activities are unlikely to occur (Joppa et al., 2018). Thus, simply comparing deforestation rates inside and outside of a PA will provide a biased result due to the inherent differences in landscape heterogeneity and land use constraints. Studies that use such methods have resulted in artificially high estimates of effectiveness, and to address this, statistical matching methods were developed and are now preferred (Joppa and Pfaff, 2011). Therefore, to determine whether Tesso Nilo, Bukit Tigapuluh, and Rimbang Baling are providing effective protection, we use a propensity score matching method.

Statistical matching has been used to determine the effect of a treatment (in medicine, policy, etc.) on a group of samples while controlling for covariate bias (Stuart, 2010). Matching has been adapted to natural resources assessments, most notably when combined with a logistic regression post-matching, to examine PA effectiveness (Andam et al., 2017, Shah and Baylis, 2015, Sarathchandra et al., 2018). One of the important estimates from matching is 'avoided deforestation' – i.e., the lack of deforestation occurring in a PA due to protected status, compared to deforestation occurring in similar biophysical conditions outside of the PA. A high avoided deforestation rate indicates high protection effectiveness. Here, we use matching of points similar in landscape covariate values from inside and outside of PAs, to determine whether PAs in central Riau Province have actually provided protection against deforestation from 2002 to 2016, in spite of the high human use and modification across central Riau.

2. Methods

2.1. Study area

The climate of Riau is classified in the Koppen-Geiger system as Af, tropical. Average temperature is 27 °C and average rainfall is 2696 mm

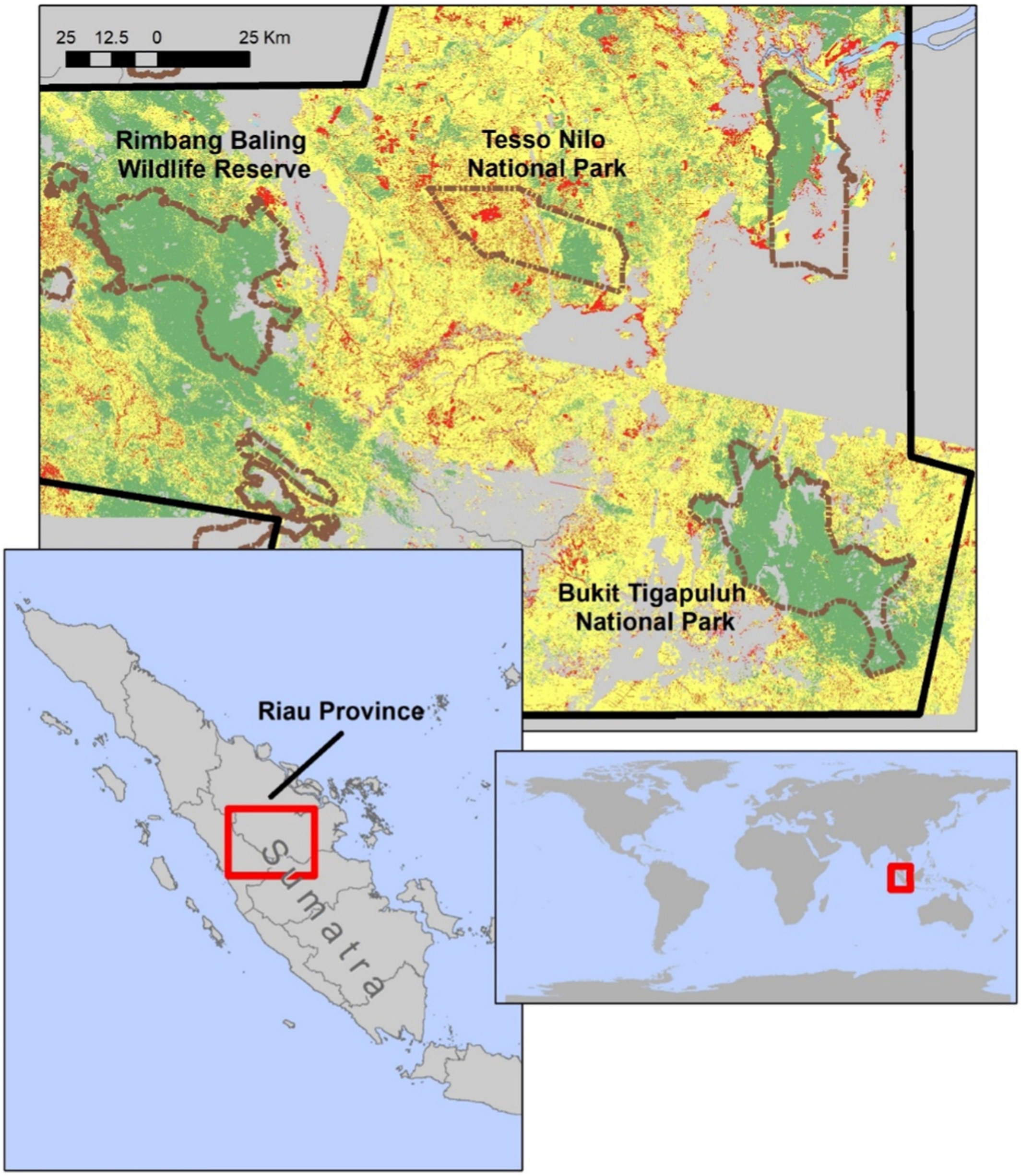

Fig. 1. Study area. Location of focal protected areas and 2016 land cover; green: forest; yellow: plantation; red: open areas. Gray areas inside black study area boundary (top) were obstructed by cloud cover during land cover classification (Poor et al., 2019). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

per year. Tesso Nilo National Park (IUCN category II) was established in 2004 and expanded to 830 km^2 in 2009 and has lost > 50% of its natural lowland forest (within its current boundary) since 2002 (Poor et al., 2019). Bukit Tigapuluh National Park (IUCN category II) was established in 1995, is 1276.98 km^2, and largely consists of tropical montane forest. While deforestation has encroached on the park's edges due to oil palm plantations, there is still a core of primary forest, which is connected to the Sumatra's western spine of forested and protected mountains (the Barisan mountain range) (Fig. 1). Bukit Tigapuluh lies partly in Jambi, but we here address only that portion within Riau due to lack of data for Jambi. Rimbang Baling Wildlife Reserve (IUCN category IV) was established in 1986 and is 1360 km^2. Rimbang Baling is connected to Kerinci Seblat National Park along Sumatra's western Bukit Barisan mountain range, which may provide forest connectivity for dispersing wildlife, but Rimbang Baling faces encroachment, largely from pulp and paper plantations along its eastern and northern edges. In all of these PAs, locals routinely enter the forest to hunt, gather resin and fruit, and fish.

2.2. Matching

With the use of matching in the context of PA effectiveness, one draws samples inside (treatment, 1) and outside (control, 0) of a PA. Then, parametric methods such as logistic regression, mahalanobis distances (Abadie and Imbens, 2006), or non-parametric methods such as a generalized boosted regression model are used to determine propensity scores (McCaffrey et al., 2004). A propensity score is the estimated probability of a sample receiving ‘treatment’, given the sample's landscape covariate values (slope, elevation, etc.). Generalized boosted regression models (gbm) are an improvement on a common non-parametric model, the genetic method (Diamond and Sekhon, 2005; Bruggeman et al., 2015), due to their incorporation of propensity scores. These scores should be ‘balanced’ across groups, that is, values of all of the chosen covariates should be as similar as possible between

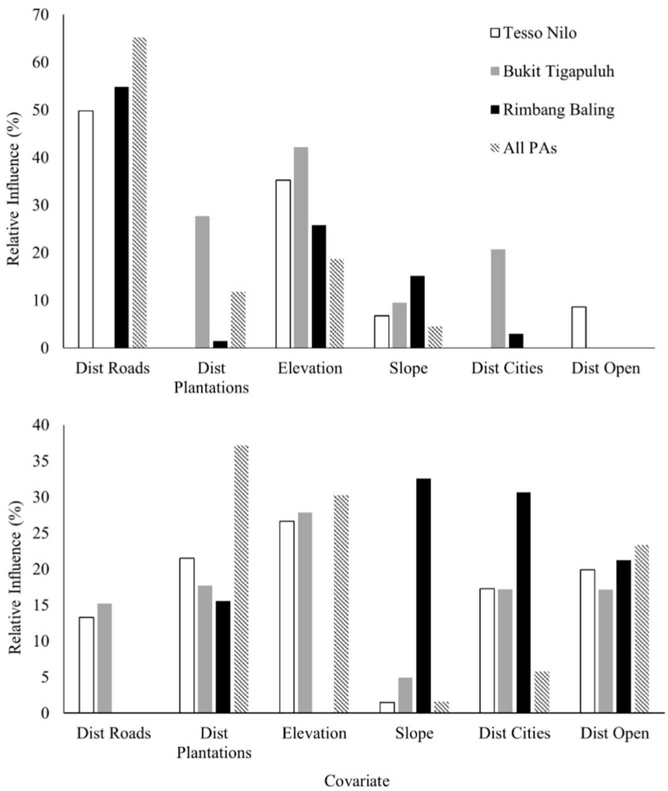

Fig. 2. Covariate contributions (absolute value). Relative covariate (distance to roads, distance to plantations, elevation, slope, distance to cities and distance to open areas) contributions (propensity scores) to central Sumatran protected area effectiveness (top) and leakage (bottom), resulting from a generalized boosted regression model. Values for individual protected area covariate contributions and the combined values are graphed (hashed bars). The direction of influence is provided in Table 1.

treatment and control groups. This process of attempting to achieve balance is termed 'matching', since the modeler is attempting to match the values of covariates at selected random locations inside a PA to those at random locations outside of a PA, thereby reducing any biases introduced by non-random locations of protected areas. If balance is not achieved, the selected model should be re-parameterized or adjusted until satisfactory balance is achieved. Further analysis such as logistic regression to determine avoided deforestation, can be completed using the matched sample set. Some samples may not match between groups and can be discarded.

To determine whether protected areas are effective, we created random points in 2002 forested areas outside and inside of PAs, excluding the areas that were obstructed by clouds in 2002 or 2016 land cover imagery. Because our analysis is based on land cover, we used a boundary derived from the extent of Landsat satellite imagery in 2016 as our study area extent from which points external to protected areas were sampled (Fig. 1). We defined forest and non-forest as described in Poor et al. (2019), where ground truth data in forest and non-forested areas and Landsat imagery from 2002 and 2016 was used to create land cover information using a supervised maximum likelihood classification algorithm. Non-forested areas were identified as open or barren lands, oil palm, and other agricultural areas. We extracted the value of six covariates; Euclidean distance to major roads, Euclidean distance to cities, Euclidean distance to open areas, Euclidean distance to plantations, slope, and elevation, for 2002, and the presence or absence of forest in 2016 (to determine whether the 2002 forest samples remained forest in 2016) at each sample location (Andam et al., 2017). Elevation and slope were derived from ASTER GDEM V2 2011 data (NASA, 2011) and roads and cities were provided by the Indonesian Survey and Mapping Authority (Badan Koordinasi Survei dan Pemetaan Nasional, 2009) (Figs. S1–S3). Potential covariates were screened for correlation prior to matching using Pearson's correlation coefficient in R (R Development Team, 2017).

To determine whether leakage was occurring outside of PAs, we used the same covariates and created random points within a 10 km buffer (Curran et al., 2004; Nepstad et al., 2006; Dewi et al., 2013; Santika et al., 2017) outside of the PAs and, based on the values of the six covariates at the random points, matched these points to points with similar covariate values in the wider landscape outside of this 10 km buffer zone. While there is no consensus on the appropriate distance used for determining leakage and results are dependent on the distance used (DeFries et al., 2005), we chose to use a 10 km buffer due to its use in other studies in this region (Dewi et al., 2013, Santika et al., 2017), allowing comparisons to past work. Covariate preparation was carried out in ArcGIS 10.5 (ESRI, 2017).

We created propensity scores, the estimated probability of a sample receiving 'treatment', given the sample's covariate values, using non-parametric generalized boosted regression models (Santika et al., 2017; Friedman, 2001), implemented in the package twang (Ridgeway et al., 2017a) in R (R Development Team, 2017). We matched 2000 sample points within each PA (treatment), and 20,000 locations for the broader landscape, outside of PAs (control). Variables that could not be matched were removed from analysis. Propensity scores were identified for the average treatment effect on the treated (ATT; the effect of protected designation on samples within a protected area), and covariate weights were compared to determine what covariates influenced deforestation. Using the gbm, samples were matched with 100,000–500,000 regression trees and the mean effect size stopping method (Ridgeway et al., 2017b). Shrinkage was 0.02–0.03 and we set interaction depth to 2. After achieving balance, we used the presence or absence of forest in 2016 at the sampling locations from 2002 to determine the effectiveness of PAs. We then used a generalized linear model, with deforestation in 2016 (0 = no deforestation, 1 = deforestation), as the dependent variable. The gbm-generated propensity scores functioned as the predictors to estimate the average treatment effect (protected versus un-protected, or, for leakage, within the 10 km buffer versus in the broader landscape) of the samples within the protected areas (ATT) on the presence or absence of forest in 2016. Results are provided as percent of forest remaining attributed to PA status – we interpret this as 'avoided deforestation' (Andam et al., 2017; Shah and Baylis, 2015).

3. Results

Maximum similarity between covariate propensity scores ('balance') was achieved using different parameters and settings for each PA (Table S1; Fig. 2). Several variables could not be matched and were not included in analysis (Table 1). Tesso Nilo showed the lowest amount of benefit from protection, with an avoided deforestation rate of only 4.19%, Rimbang Baling had 12.8% avoided deforestation, while Bukit Tigapuluh had 26.36% of forest remaining due to protection, the highest of our focal PAs (Table 1; Fig. 3). Overall, 10.35% of forest maintained from 2002 to 2016 is attributable to protection status. In all PAs except Bukit Tigapuluh, distance to roads had the highest relative influence on deforestation, with areas closer to roads experiencing more deforestation (Fig. 2). Effect of protection in Bukit Tigapuluh was most influenced by elevation (positively).

For leakage, elevation and/or slope were the most important variables (with areas of higher elevation and slope more likely to remain forested) except for Bukit Tigapuluh, where distance to plantation had the highest relative influence on leakage such that areas farther from plantations had less leakage (Fig. 2). Overall, being within closer proximity of a PA brought approximately the same amount of protection as being inside a PA (Fig. 3). There does appear to be leakage around Bukit Tigapuluh National Park, where only 10.21% of forest in the buffer existed in 2016 due to proximity to the PA (Table 1). The

Table 1
Model estimates (reported as percentages) and 95% confidence intervals (italicized; those not overlapping zero are bold) for model generalized boosted model intercept and covariates, including dependent variable, Treatment, for central Sumatran protected area effectiveness (PA) and leakage for three different protected areas (Tesso Nilo National Park (NP), Bukit Tigapuluh National Park, Rimbang Baling Wildlife Reserve) and these three protected areas together. In the leakage case, 'Treatment' is those samples within a 10 km buffer around the protected area. Missing values are those variables that could not be matched.

Covariate	Tesso Nilo NP – PA	Tesso Nilo leakage	Bukit Tigapuluh NP-PA	Bukit Tigapuluh Leakage	Rimbang Baling WR-PA	Rimbang Baling leakage	All PAs - PA	All PAs leakage
Intercept	31.7848	26.1120	43.3329	−14.4400	41.6232	4.3834	−8.2938	−1.7250
	(26.38–37.39)	***(20.0344–32.3812)***	***(39.10–47.65)***	***(−17.0999 to −11.7151)***	***(35.40–48.09)***	***(1.0019–7.8851)***	***(−9.87 to −6.6904)***	*(−3.8218–0.4206)*
Treatment	4.1852	4.5400	26.3644	10.2081	13.4282	16.7658	10.3500	8.4805
	(01.97–06.45)	***(1.9135–7.2412)***	***(24.17–28.55)***	***(7.505–12.9782)***	***(11.1394–15.6537)***	***(13.8114–19.7634)***	***(8.7293–11.9861)***	***(6.7285–10.27)***
Cities	–	−0.0003	0.0002	−0.0003	0.0001	0.0001	–	−0.0004
	–	*(−0.0047–0.0001)*	*(0.0000–0.0004)*	*(−0.0005–0.000)*	***(0.0001–0.0004)***	*(−0.0002–0.0003)*	–	***(−0.0005 to −0.0003)***
Open	−0.0490	0.0066	–	0.0098	–	0.0107	–	0.0114
	(−0.0067 to −0.00308)	***(0.0029–0.0102)***	–	***(0.0074–0.0123)***	–	***(0.0090–0.0123)***	–	***(0.0108–0.0126)***
Plantations	–	−0.0006	0.0391	0.0716	0.0345	0.0919	0.0452	0.0666
	–	*(−0.0206–0.0193)*	***(0.0341–0.0441)***	***(0.0532–0.0900)***	***(0.0264–0.0425)***	***(0.0789–0.1049)***	***(0.0399–0.0505)***	***(0.0572–0.0761)***
Roads	0.0011	−0.0004	–	0.0013	0.0011	–	0.0025	–
	(0.0007–0.0014)	*(−0.0008–0.0001)*	–	***(0.0009–0.0016)***	***(0.0010–0.0013)***	–	***(0.0023–0.0027)***	–
Elevation	−0.1539	−0.1319	0.0589	0.1211	0.0337	–	0.0849	0.0585
	(−0.1845 to −0.1222)	***(−0.1716 to −0.9155)***	***(0.0511–0.0666)***	***(0.0993–0.1428)***	***(0.0287–0.0387)***	–	***(0.0791–0.0908)***	***(0.052–0.065)***
Slope	0.2077	0.2449	0.5857	0.9757	0.0469	1.5316	0.8451	1.2781
	(−0.116–0.532)	*(−0.1422–0.6335)*	***(0.4830–0.6875)***	***(0.7229–1.2294)***	***(0.3577–0.5828)***	***(1.4089–1.6612)***	***(0.7524–0.9379)***	***(1.1463–1.4014)***

Covariate names: Cities – Distance to cities; Open – Distance to open areas; Plantations – Distance to plantations; Roads – Distance to roads.

protection of Rimbang Baling seems to be conferring additional protection to areas adjacent to the park, with 16.77% of forest near the PA existing in 2016 due to proximity to the PA (Table 1; Fig. 3).

4. Discussion

Our study is the first to use gbm matching methods in central Sumatra to examine the effectiveness of PAs within a landscape heavily modified by oil palm and pulp and paper plantations. Although authorities rely heavily on the existence of the PAs themselves (and not enforcement due to lack of resources) to confer protection of unique, endemic wildlife such as the Sumatran tiger, we found that national PAs in this system are only slightly effective at providing protection of their habitats, likely due to oil palm expansion over the past ~20 years. We suggest increased enforcement to curb further deforestation within protected areas.

To conduct this analysis, we used the land cover data created by Poor et al. (2019). We chose this land cover data set due to its relatively high resolution compared to other available data sets, and its accuracy assessment – the only known land cover data set accuracy-assessed for this area. In this land cover data set, community forests, which are not natural forests, may be confused as natural forest, thus inflating PA effectiveness. However, the use of this land cover dataset provides the most accurate measures of protected area effectiveness given its accuracy assessment in comparison with other available land cover data sets (Poor et al., 2019).

Globally, PAs fare better when empowered locals are allowed sustainable use options, or when PAs are co-managed, as opposed to management by a single, top-down authority (Oldekop et al., 2015). Other studies cite potential policies and geographic variation as cause for variation in PA effectiveness (Kubitza et al., 2018; Shah and Baylis, 2015), and though we did not incorporate socio-economic or policy data, geographic variation can be seen as a cause of variation in effectiveness in this landscape as well. We controlled for provincial level policies in this analysis by selecting PAs from one province, but neglected to examine effects at a more local level – that of regency or settlement level. We did not include any locally protected areas due to lack of data, varying degrees of on-the-ground protection despite similar policies, and our desire to focus on national protected area effectiveness. We note that effects of locally protected areas could be different than our current results for national protected areas. Matching on socio-economic and political covariates gleaned from interviews or local surveys could provide valuable information about local attitudes and their impacts on deforestation, and should be included in future research.

Bukit Tigapuluh has the highest avoided deforestation at 26.36% (Fig. 3). This may be due to many factors including the presence of multiple conservation organizations conducting research within the park, many communities living in the park, a park office located within an hour of the park, and seemingly more engaged park management that actively conducts research and monitoring. Interestingly, Bukit Tigapuluh did not have the lowest amount of leakage. Oil palm plantations ring the park on the eastern side and these are likely the cause of the lower than expected avoided deforestation rate of 10.21% ($p < 0.05$, 95% CI [7.51% - 12.98%], Table 1; Fig. 3) within 10 km of the park boundary. There are some areas on the northern side of the park where oil palm plantations have encroached, and this is likely to continue without immediate enforcement action, as the availability of new land suitable for oil palm decreases and farmers are forced to plant in less suitable areas. Though protection is currently relatively high given the other estimates of avoided deforestation in Bukit Tigapuluh, avoided deforestation is likely to decrease with increasing encroachment and we suggest further research into socio-economic drivers of deforestation that we were not able to address here.

In spite of high elevations and rugged slopes potentially conferring 'de facto' protection, Rimbang Baling Wildlife Reserve is only slightly

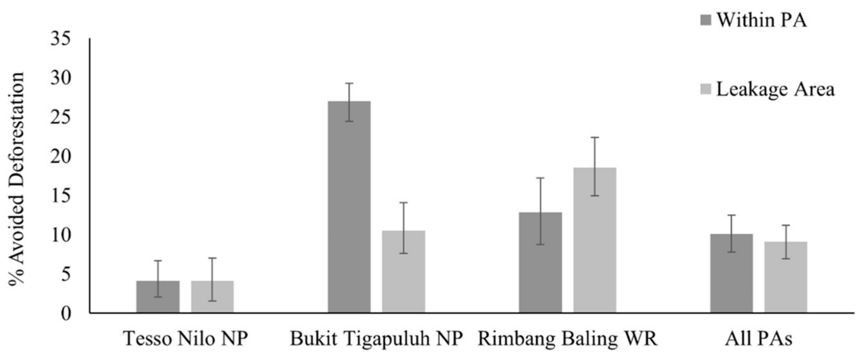

Fig. 3. Treatment effects. Average treatment effect (ATT) and avoided deforestation estimates (dark gray) for each protected area, Tesso Nilo National Park (NP), Rimbang Baling Wildlife Reserve (WR) and Bukit Tigapuluh National Park in central Sumatra, and estimates of leakage (light gray) as determined from a 10 km buffer area around each protected area, with 95% confidence intervals.

effective, with an avoided deforestation rate of 13.43%, ($p < 0.05$, 95% CI [11.14% - 15.65%], Table 1; Fig. 3). Parts of this PA included former mining concessions and are still commonly used for local extraction of timber and non-timber forest products. Rimbang Baling had the lowest level of leakage (highest percentage of forest remaining due to the protected area boundary). This could be due to the more extreme terrain, or the remaining forest and small protected areas on its western border with Western Sumatra province. This connection to neighboring forest and low leakage could be important to tiger persistence in the region into the future.

As expected, the avoided deforestation rate due to protected status was lowest in Tesso Nilo, (4.19%, $p < 0.05$ 95% CI [1.97% - 6.45%], Table 1; Fig. 3) the PA with lowest average elevation and slope, the most suitable for growing oil palm, and the most contested park in our study area. While we did control for elevation and slope in matching, we were unable to control for distance to cities, perhaps reflecting the higher population concentration around Tesso Nilo compared to other areas on the landscape, which may be influencing the amount of deforestation within the protected area. The average effect of the protected area designation (ATT) Shah and Baylis (2015) found for Tesso Nilo from 2000 to 2012 is within our 95% confidence intervals (2.69% vs. 4.10%), indicating corroboration with our results, i.e. no significant difference in estimated effectiveness between the two studies. Avoided deforestation rates inside the PA and in the 10 km buffer area were the same (4.54%), so locals are using the entire Tesso Nilo area similarly.

For both Bukit Tigapuluh and Rimbang Baling, we were unable to reach convergence for distance to open areas in our matching algorithm due to lack of open areas nearby. For Tesso Nilo, we were unable to match distance to cities for sample locations within the park and outside of the park perhaps due to the scatted and uneven distribution of cities throughout the landscape. Thus, since we were unable to control for these factors, they could play a part in protected area effectiveness. For example, Tesso Nilo may be closer to more cities and the higher population density results in higher deforestation rates as a factor of human population and not due to the effectiveness of the protected area boundary per se.

In Tesso Nilo, Rimbang Baling, and for all PAs combined, distance to roads positively impacted avoided deforestation (areas further from roads were more likely to prevent deforestation) and had the highest influence on PA effectiveness, as determined through covariate propensity score weights resulting from the gbm (Fig. 2). Only major roads (Fig. S1) were included in this study and results may change slightly if plantation roads are taken into account. Elevation and slope both had high influence throughout the landscape. Slope positively impacted avoided deforestation and elevation positively influenced avoided deforestation except in Tesso Nilo. In most of the landscape, this may be due to the relationship between high slope and elevation providing de facto protection. In Tesso Nilo, the relationship between avoided deforestation and elevation may be reversed due to the park's extremely flat landscape, low elevation areas that may be wetland (unsuitable for agriculture), with higher elevations used for oil palm. We did not incorporate every available landscape covariate and results may differ slightly depending on the variables used in matching. However, we selected these variables based on results from a related study conducted to predict deforestation (Poor et al., 2019).

Tesso Nilo, founded in 2004, has had a conflicted existence and locals did not support the formation of the PA. It is regularly used by locals for a variety of extractive purposes and there are still areas of contention between park management and oil palm plantation employees and locals. Community management has a positive impact on PA effectiveness (Santika et al., 2017). It is not surprising that while the other PAs also are regularly used by locals, that Tesso Nilo is the least effective PA on the landscape. It is unclear whether local attitudes or low elevation play a greater role in Tesso Nilo's lack of effectiveness because we were unable to incorporate socio-economic factors into our study. The government of Indonesia has proposed a 12 year plan to restore Tesso Nilo and relocate many of the locals who currently inhabit and make use of the park. However, another study estimates that very little forest will remain in Tesso Nilo in 12 years (Poor et al., 2019). The proposed restoration is unlikely to be effective unless significant education, outreach, and capacity building regarding alternative livelihoods are consistently implemented as soon as possible.

Although Rimbang Baling and Bukit Tigapuluh have greater avoided deforestation estimates than Tesso Nilo, it is still important to increase enforcement of these PAs. Tesso Nilo, has experienced high deforestation, potentially in part due to proximity to cities, and as population in Riau grows and suitable land available for agriculture decreases, Rimbang Baling and Bukit Tigapuluh may see increased deforestation as well. Leakage is occurring around both PAs, and as land becomes rare for new oil palm plantations in more ideal flat areas, encroachment into Rimbang Baling and Bukit Tigapuluh is likely to increase. The negative effects of palm oil monocultures and their associated infrastructure on biodiversity are well documented (Fitzherbert et al., 2008) and the continued expansion of oil palm in this landscape is detrimental to the native, endemic tropical forests there. Currently, Rimbang Baling and Bukit Tigapuluh are enjoying some de facto protection (Joppa and Pfaff, 2010), but may face increased threats in the future. Globally there is a growing market for palm oil (Carter et al., 2007) and thus a continued financial incentive to grow oil palm in this landscape, where it is the most lucrative crop and many locals have few other viable livelihood options. Smallholders can benefit from the booming oil palm industry, but success is often dependent on the local political context and availability of agriculture education (Rist et al., 2010). Transparency, smallholder land rights, and equal benefit sharing have been shown to increase the success of oil palm farming at the local level (Rist et al., 2010; Kubitza et al., 2018). While there could be socioeconomic benefits of the oil palm industry, bribery, lack of funding for local agencies, and illegal deforestation are common in this study area, making regulation enforcement difficult.

Biodiversity protection is a complex interdisciplinary issue globally and often is locally nuanced. Global awareness regarding the negative impacts of industrial oil palm plantations has increased, but we still see significant impacts of the industry in this landscape and as the industry continues to grow, we are likely to see similar situations worldwide, specifically in PAs with conditions suitable for oil palm and in areas where enforcement is lacking. There may be little feasible opportunity to reduce the negative impacts of plantations and their associated infrastructure, such as roads that increase forest access and poaching (Fitzherbert et al., 2008). In our study landscape, we see enforcement and restoration of current PAs as critically important to the conservation of Sumatra's unique, endemic and globally important species. The demand for palm oil is unlikely to disappear in the foreseeable future, so we must work to increase productivity of existing plantations, increase prevalence of polycropping (growing multiple crops in the same space), and work with local communities to increase production and ensure fair farming practices (Kubitza et al., 2018) while ensuring the persistence of wildlife. The establishment of forested stepping stones and corridors could allow wildlife to move more freely across mosaic landscapes (Yaap et al., 2016), while the enforcement of the boundaries of existing PAs – especially those without de facto protection – could ensure refuges for, and persistence of, wildlife in oil palm dominated landscapes. If swift action towards creating these wildlife friendly, mixed-use production landscapes is not taken, habitat will continue to decline and degrade and isolated wildlife populations will be unable to survive. Eventually, tropical wildlife in Indonesia may be swallowed into a sea of palm oil.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.biocon.2019.03.018.

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