Conservation Letters
A journal of the Society for Conservation Biology · Open Access

WILEY

LETTER

Land-cover and land-use change trajectory hopping facilitates estate-crop expansion into protected forests in Indonesia

Yu Xin[1] | Laixiang Sun[1,2] | Matthew C. Hansen[1]

[1]Department of Geographical Sciences, University of Maryland, College Park, Maryland, USA

[2]School of Finance & Management, SOAS University of London, London, UK

Correspondence
Laixiang Sun, Department of Geographical Sciences, University of Maryland, 2181 Samuel J. LeFrak Hall, 7251 Preinkert Drive, College Park, MD 20742, USA.
Email: LSun123@umd.edu

Abstract

Protected areas (PAs) have been regarded as a critical strategy to protect natural forest (NF) and biodiversity. Estate-crop expansion is an important driver of deforestation in Indonesia. Yet, little is known regarding the temporal dynamics of PA effectiveness in preventing estate-crop expansion into NF. We employ Cox proportional hazard models and their extensions to characterize the dynamics of estate-crop expansion into NF in Indonesia during 1996–2015. The results show that PA effectiveness in Sumatra decreased over time and became insignificant in 2012–2015. A multistate modeling analysis shows that hopping in land-cover and land-use change (LCLUC) trajectories with shrub and/or bare ground as intermediates has decreased PA effectiveness and facilitated the expansion. Preventing LCLUC trajectory hopping becomes crucial to biodiversity conservation because it tends to occur at lowland forest, diminishing natural habitat area and increasing NF isolation.

KEYWORDS
deforestation, estate-crop expansion, Indonesia, multistate modeling, protected area

1 | INTRODUCTION

Protected areas (PAs) are regarded as crucial for reducing deforestation and conserving biodiversity, but their effectiveness remains disputed. At the national level, PAs have been shown to experience lower deforestation rates than unprotected areas (Andam et al., 2008; Geldmann et al., 2013). However, PA effectiveness varies widely over space depending on anthropogenic pressures and resource availability for protection (Geldmann et al., 2019; Jones et al., 2018). Land-use change is the dominant factor for biodiver-

sity loss (Caro et al., 2022) and has been known to reduce PA effectiveness (Bailey et al., 2016).

Indonesia, with the richest biodiversity and highest conservation priorities in the world (Pouzols et al., 2014), faces the highest deforestation rates (FAO, 2016). Estate-crop expansion, dominated by oil palm, is believed to be the greatest immediate threat to biodiversity in Indonesia (Wilcove et al., 2013), as it is one of the major drivers of deforestation during the last few decades (Austin et al., 2019; Carlson et al., 2012) and is among the land-use types supporting the least biodiversity (Poor et al., 2019;

Wilcove et al., 2013). As global demand for estate-crop commodities, especially oil palm products, grows (Purnomo et al., 2020), estate-crop expansion is expected to continue, driving forest loss (Austin et al., 2019; Taheripour et al., 2019; Xin et al., 2021) and increasing pressure on PAs in the country (Curran et al., 2004; Poor et al., 2019). Evaluating PA effectiveness in preventing estate-crop expansion into natural forest (NF) is critical for improving conservation efforts. However, existing evaluations are sparse and limited to the province scale (Poor et al., 2019), do not account for variations in estate-crop expansion patterns across different islands (Xin et al., 2021), and have limited generalizability. This study quantifies the PA effectiveness across Sumatra and Kalimantan, where over 90% of Indonesia's estate-crop expansion occurred (Xin et al., 2021).

Partially attributed to rapid estate-crop expansion, Indonesia has experienced the largest increase in human pressure since the 21st century, even within PAs (Geldmann et al., 2019; Graham et al., 2021). Understanding how PA effectiveness changes over time in response to increasing human pressure is vital for cost-effective resource allocation and maximizing conservation benefits. Although the importance of examining the time-variant PA effectiveness is recognized (Geldmann et al., 2015), empirical research investigating how the PA conservation outcomes evolves over time remains scarce in the literature. Existing research focuses on evaluating PA effectiveness in reducing deforestation, which commonly relies on techniques such as matching methods (Gaveau et al., 2012; Geldmann et al., 2013, 2019; Graham et al., 2021), multifactor regressions (Brun et al., 2015), and Before–After Treatment–Intervention (Gaveau et al., 2007; Shah & Baylis, 2015). However, these methods do not account for temporal details, and are thus unable to capture the temporal dynamics of PA effectiveness.

Survival analysis, which is specialized for event data modeling and explicitly deals with the occurrence and timing of events, is able to address the temporal complexities in longitudinal studies (Wang et al., 2013). Extending by including covariates interacted with time, it can address the possible time-dependent effects under rapid land changes (Chen et al., 2016). We employ the extended survival analysis to address the potential changes of PA effectiveness in preventing estate-crop expansion into NF over time. Standard survival analysis concentrates on the timing of a single event of interest; however, there are many examples in which a subject may experience a variety of intermediate events during the study period. This is especially true for dynamic landscapes in Sumatra and Kalimantan (Jamaludin et al., 2022), where land-cover and land-use change (LCLUC) is typically featured by a sequence of changes along the temporal trajectory

(Carlson et al., 2012). In several cases, deforestation is not immediately followed up with cultivation, but with degraded land of relatively low biomass as intermediate states (Jamaludin et al., 2022). Conversion of NF to estate-crop plantation could either occur directly (rapid conversion) or with trajectory hopping (NF → intermediate states → estate-crop plantation). Therefore, we adopt the multistate model, which is capable of jointly considering all initial, intermediate, and final states, to address the complexities along with LCLUC trajectories.

In this research, we assess the dynamics of PA effectiveness in preventing estate-crop expansion into NF over 1996–2015, with temporal details and varying LCLUC trajectories, in Sumatra and Kalimantan. The estimation results of the Cox proportional hazard models and their extensions indicate that PA effectiveness in Sumatra decreased over time and became insignificant in 2012–2015; the temporal trend was not significant in Kalimantan as Kalimantan is a latecomer with relatively abundant land resources. By applying multistate models, we demonstrate that PA effectiveness is reduced by LCLUC trajectory hopping with shrub and/or bare ground (BG) as intermediates in both Sumatra and Kalimantan.

2 | METHODS

We acquired land-cover and land-use (LCLU) maps of 1996, 2000, 2003, 2006, 2009, 2012, and 2015 from the Indonesian Ministry of Environment and Forestry (MoEF) to analyze the LCLUC trajectories in Indonesia, focusing on Sumatra and Kalimantan. We reclassified LCLU classes to six categories—NF, shrub, dry agriculture (food crops except for paddy), estate crop (dominated by oil palm), BG, and others (Figure 1)—and quantified the LCLUC among the categories in each 3- or 4-year period. The description of maps and processing methods are presented in Supporting Information (Note S1.1; Table S1). LCLUC occurred within 3(or 4)-year intervals are defined as direct conversions, since it usually takes 2–4 years to have sufficient plant growth to be detected by remote sensing (Austin et al., 2019). Sankey diagrams (Note S1.2) were used to visually display the LCLUC trajectories of deforestation. Deforestation, synonymous with forest loss, is defined as the transformation of forests to a nonforest state at the mapping scale.

We use survival analysis to quantify the extent and timing of estate-crop expansion. We run the models on 1×1 km grid cells with over 90% NF coverage in 1996 (Note S1.3). We define the estate-crop expansion transition in a grid cell as a single event, with hopping to intermediate states (e.g., BG in NF → BG → estate-crop process) being treated as part of survival time. In this way, whether
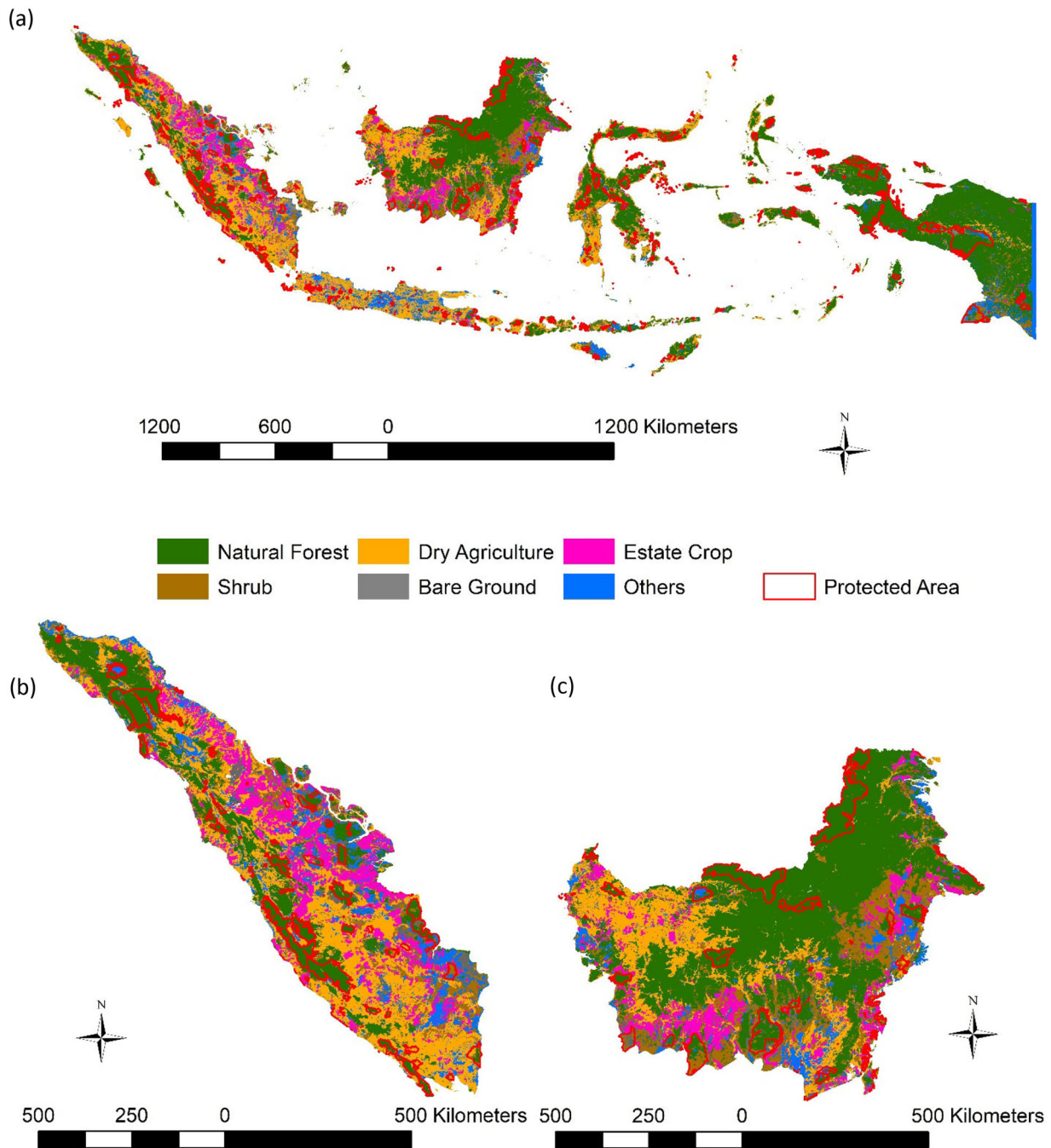
FIGURE 1 Land-cover and land-use map of Indonesia (a), Sumatra (b), and Kalimantan (c) in 2015. Data sources: Ministry of Environment and Forestry (MoEF) of Indonesia; World Database on Protected Areas (WDPA).

the estate-crop expansion into NF occurred directly or with intermediates makes no difference and both are included in the analysis. We used the Cox proportional hazard model to calculate the hazard rate—the risk of estate-crop expansion at a time of interest. The Cox proportional hazard model takes the following form:

$$h_i\ (t) = \lambda_0\ (t) \exp\left(\beta_1 Protect_i + \beta_2 x_{i1} + \cdots + \beta_k x_{ik}\right),$$
$$(1)$$

where we use the occurrence of estate-crop expansion transition as the dependent variable $h_i(t)$. The term λ_0 is the baseline hazard. $Protect_i$ represents the protection status in the starting year of each period, and $x_{i1} \cdots x_{ik}$ are a set of biophysical and socioeconomic variables selected to proxy the pressure of converting NF to estate-crop plantation (Note S1.4).

The Cox model assumes explanatory variables exert constant effects on hazards over time, which might be violated
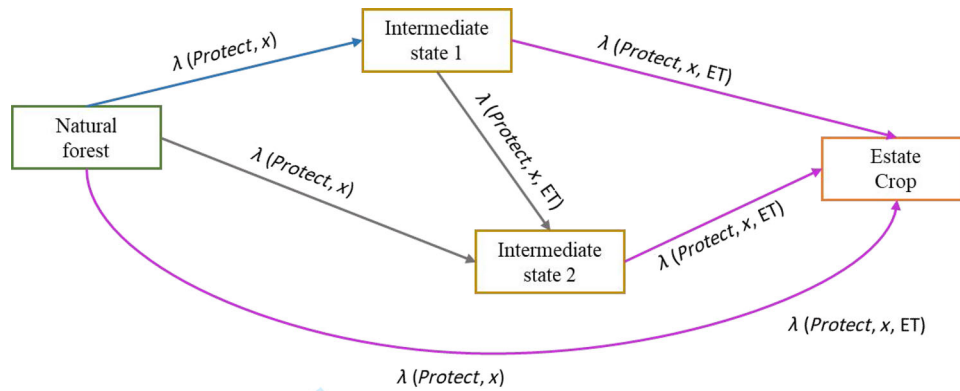
FIGURE 2 Graphical representation of the multistate model. Nodes represent possible states and links represent possible conversions between states, where parameters that influence the hazard are indicated. The possible trajectories include (1) direct transition from natural forest to estate crop; (2) natural forest → Intermediate State 1 → estate crop; (3) natural forest → Intermediate State 2 → estate crop; and (4) natural forest → Intermediate State 1 → Intermediate State 2 → estate crop. Six direct conservations are modeled: (1) natural forest → Intermediate State 1; (2) natural forest → Intermediate State 2; (3) natural forest → estate crop; (4) Intermediate State 1 → Intermediate State 2; (5) Intermediate State 1 → estate crop; and (6) Intermediate State 2 → estate crop. $Protect$, the ratio of protected area (PA) (or two binary variables representing establishment time and location of PA in the models on PAs); x, the biophysical and socioeconomic variables; ET, the establishment time of the intermediate state, calculated as (established year – 1996). λ () is the hazard function.

in the process of rapid LCLUC. Therefore, we extend the model with time-dependent effects (Note S1.5), following Chen et al. (2016). We further check whether the time-dependent effects have been addressed by the extended models successfully; if not, we apply strata models to these variables to see their effects in each period (Note S1.6).

We used multistate models to reveal the different risks of direct conversion from NF to estate crop and conversions with hopping to different intermediates, conditioned on the characteristics (e.g., $Protect_i$, x_{ik}) of each grid cell. We use a semi-Markov chain with estate-crop plantation as the final states, as shown schematically in Figure 2 (Notes S1.7 and S1.8).

3 | RESULTS

3.1 | LCLUC trajectories in Indonesia

Estate-crop plantation in Indonesia expanded from 56,900 km^2 in 1996 to 127,300 km^2 in 2015, with approximately half occurring at the expense of NF in 1996. Conversions from NF to estate crop could either occur directly within one observation period (3–4 years) or take a longer process with hopping to degraded land, especially shrub and BG, as intermediates (Figure S1; Note S2.1). A total of 55.50% of estate-crop expansion occurred as direct outcome of deforestation and 39.94% as indirect outcome of trajectory hopping via shrub or/and BG (Figures 3 and S1). Four major trajectories that together account for over 95% of all estate-crop expansion into NF are (1) direct transition from NF to

estate crop, and three processes with trajectory hopping: (2) NF → shrub → estate crop, (3) NF → BG → estate crop, and (4) NF → shrub → BG → estate crop (Figure 3).

3.2 | Estate-crop expansion into protected NF

In 1996–2015, appropriately 13,660 km^2 NF was lost in Indonesian PAs, with 6772 km^2 in Sumatra and 2432 km^2 in Kalimantan. Around 922 km^2 estate-crop expansion occurred in Sumatra PAs in 1996–2015, 71% of which were at the expense of NF in 1996. More than 90% of the direct conversion occurred in 1996–2000 (Figure 4c). Estate-crop expansion into protected NF in Kalimantan was limited (around 87 km^2), with around 70% of the expansion occurring in 2012–2015 (Figure 4d). In both Sumatra and Kalimantan, shrub was the largest sink of NF loss in PAs before 2012, while BG became the largest sink in 2012–2015 (Figure 4c,d). Once hopped to shrub, the risks of further conversion to estate crop increased by about 12 times (~ 0.008 to ~ 0.1) in Sumatra. The majority of BG established after 1996 was further converted to estate crop in the following period in both islands (Figure S3).

3.3 | Effectiveness of PAs

The results of Cox proportional hazard models demonstrate that estate-crop expansion into NF tended to occur at lowland forest with high oil palm attainable yield but low annual average temperature, at gentle slope, as well
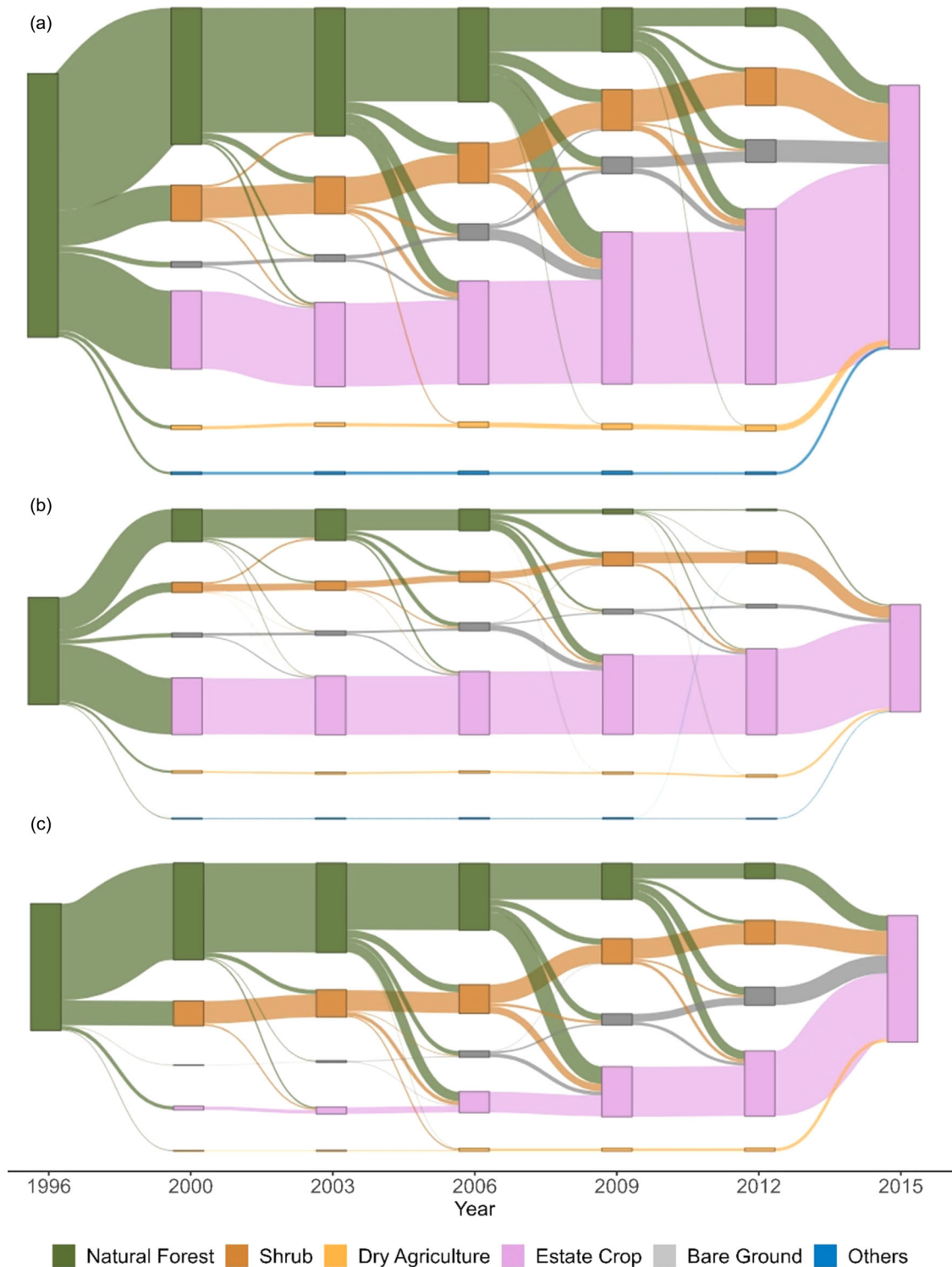
FIGURE 3 Land-cover and land-use change trajectories of estate-crop expansion into natural forest in Indonesia (a), Sumatra (b), and Kalimantan (c). Time is used as the *x*-axis; from left to right, the figures show the land-cover and land-use change (LCLUC) in each 3(or 4)-year period from 1996–2000 to 2012–2015. Nodes represent the six LCLU classes (natural forest, shrub, bare ground, dry agriculture, estate crop, and others), and links represent the direct conversions (conversions occurred within 3 [or 4] years intervals) among the LCLU classes. The height of each node represents the area that was under such LCLU class at the time. The height of each link represents the amount of direct conversion. All nodes and links in all figures are comparable to each other. The sum of inflows from natural forest to an LCLU class represents the direct conversion of natural forest to the LCLU class; the sum of inflows from LCLU classes other than natural forest and the LCLU itself represents the conversion to the LCLU class with intermediate states. The units are km^2. Links smaller than 100 km^2 for the whole country and 50 km^2 for the Islands were not shown in the figure.

(a)

(b)

(c)

(d)
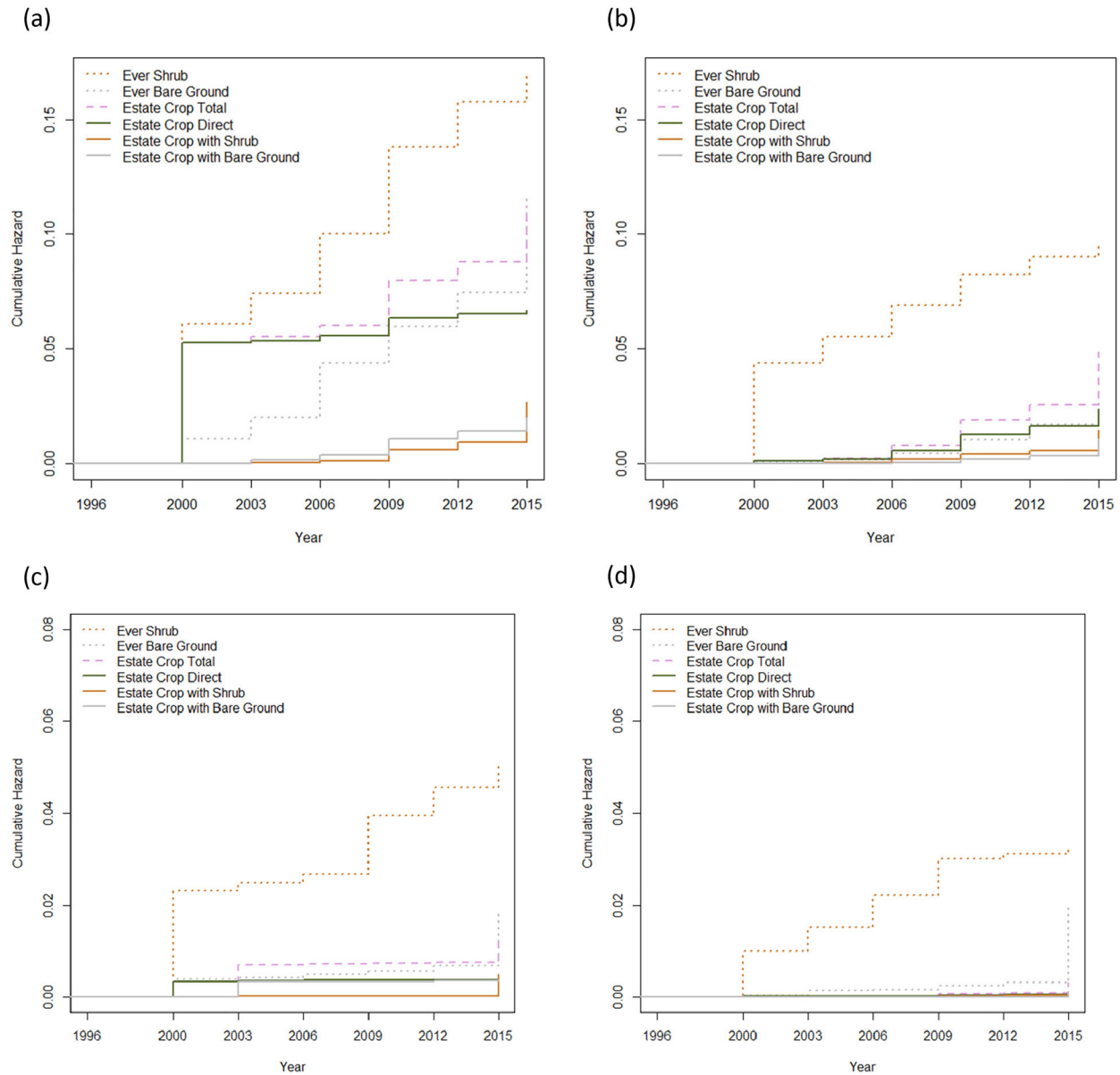
FIGURE 4 Cumulative hazard of deforestation to shrub, bare ground, and estate crop across Sumatra (a), Kalimantan (b), Sumatra protected areas (PAs) (c), and Kalimantan PAs (d). The cumulative hazard tells the total amount of hazard that has been accumulated up to a time. The gradient of the cumulative hazard indicates the hazard being subject to in a period. Ever Shrub and Ever Bare Ground indicate all deforestation trajectories that involved shrub or bare ground for at least one period in 1996–2015. For example, the hazard value of Ever Shrub equals 0.1 in the year 2006 represents the probability that we would expect to observe shrub on deforested land over 1996–2006 is 0.1; the hazard value of Estate Crop with Bare Ground equals 0.02 in the year 2015 represents the probability that we would expect to observe bare ground and estate crop in sequence on deforested land over 1996–2006 is 0.02.

as close to old plantation and palm oil processing mills (Table 1, Base model). The extended models reveal that the effects of infrastructure accessibility (e.g., accessibility to old plantations and processing mills) decreased over time and/or even changed directions in 2012–2015, while the effects of biophysical suitability (e.g., elevation, slope, attainable yield) were not time variant (Table 1, Model with time-variant effects; Note S2.2).

As trajectory hopping to shrub and/or BG before estate-crop expansion is prevalently observed, we use shrub and BG as the intermediate states of the multistate models (Figure 2). With the multistate analysis, we find that 8-year shrub (8 years since deforestation to shrub) had the highest risks of further conversion to estate crop in Sumatra, and 3-year shrub and BG had the highest risks of further conversion to estate crop in Kalimantan (Figure S2). Although

TABLE 1 Results of Cox proportional hazard models and the models extended by time-dependent effects $x_{ik} \times t$ on estate-crop expansion into natural forest in Sumatra and Kalimantan.

	Sumatra								Kalimantan							
	Base model				Model with time-variant effects				Base model				Model with time-variant effects			
	Coef.	Hazard	z	Sig.	Coef.	Hazard	z	Sig.	Coef.	Hazard	z	Sig.	Coef.	Hazard	z	Sig.
Log(Oil palm attainable yield)	0.135	1.144	3.647	****	0.146	1.157	3.172	***	0.441	1.555	3.243	***	-0.721	0.486	-12.941	****
Log(Distance to 1990 plantation)	-0.266	0.767	-8.431	****	-0.362	0.696	-8.853	****	-0.168	0.845	-5.076	****	-1.434	0.238	-12.367	****
Log(Distance to oil palm mills)	-0.954	0.385	-27.785	****	-0.935	0.393	-27.343	****	-1.197	0.302	-27.056	****	0.100	1.105	1.616	
Access time	-0.861	0.423	-7.063	****	-0.886	0.412	-7.408	****	0.099	1.104	1.601		-0.623	0.537	-2.995	***
Temperature	-0.093	0.911	-1.627		-0.116	0.890	-2.066	**	-0.193	0.824	-2.358	**	0.028	1.028	2.111	**
Shortwave radiation	-0.014	0.986	-3.796	****					0.007	1.007	2.058	**	0.717	2.049	8.397	****
Annual precipitation	0.215	1.240	7.257	****	0.194	1.215	6.890	****	-0.037	0.964	-1.071		0.200	1.222	7.501	****
Driest month precipitation	-0.339	0.712	-8.795	****	-0.748	0.473	-9.280	****	0.146	1.157	5.787	****	-0.195	0.823	-5.962	****
Slope	-0.291	0.748	-10.027	****	-0.284	0.753	-9.498	****	-0.208	0.812	-6.059	****				
Elevation	-0.053	0.948	-1.176		-0.088	0.916	-1.847	*	-0.565	0.568	-6.436	****	-0.591	0.554	-6.946	****
Population density	0.169	1.185	0.948						-0.571	0.565	-1.665	*				
Protected ratio	-1.121	0.326	-6.345	****	-4.809	0.008	-3.737	****	-2.474	0.084	-6.382	****	-2.602	0.074	-6.629	****
Peatland ratio	0.077	1.080	1.300		-0.549	0.578	-5.912	****	0.073	1.075	0.907		-2.213	0.109	-7.118	****
Log(Oil palm attainable yield) × t													0.086	1.090	3.276	***
Log(Distance to 1990 plantation × t)					0.039	1.040	3.190	***					0.133	1.142	10.153	****
Log(Distance to oil palm mills × t)													0.045	1.046	2.191	**
Access time × t																
Temperature × t													0.096	1.100	2.324	**
Shortwave radiation × t					-0.006	0.994	-6.543	****					-0.004	0.996	-1.822	*
Annual precipitation × t													-0.173	0.841	-9.594	****
Driest month precipitation × t					0.139	1.149	6.857	****								
Slope × t																
Elevation × t																
Population density × t																

(Continues)

TABLE 1 (Continued)

| | Sumatra | | | | | | | | Kalimantan | | | | | | | |
| | Base model | | | | Model with time-variant effects | | | | Base model | | | | Model with time-variant effects | | | |
	Coef.	Hazard	z	Sig.	Coef.	Hazard	z	Sig.	Coef.	Hazard	z	Sig.	Coef.	Hazard	z	Sig.
Protected ratio × t					0.800	2.226	3.446	****								
Peatland ratio × t T					0.226	1.253	8.432	****					0.456	1.577	7.977	****
Concordance	0.914				0.916				0.947				0.950			
AIC	28,236.45				28,047.43				24,322.73				24,020.15			
LogLik	−14,105.20				−14,007.72				−12,148.36				−11,992.07			
Number of grids	17,661								31,833							
Number of events	1117								677							

*Note: t refers to time. *, **, ***, and **** stand for the significant level of 10%, 5%, 1%, and 0.1%, respectively.*

conversion with intermediates made more share in recent years (Figure 4a,b), the effects of biophysical and socioeconomic drivers (except PA) did not vary much between the total and the direct estate-crop expansion into NF (Note S2.3). The patterns of estate-crop expansion into NF in PAs (Table S8), as well as deforestation to shrub and BG (Tables S9.3 and S9.4), generally mirror those across the whole islands (Note S2.4).

The risks of estate-crop expansion into NF in both Sumatra and Kalimantan were significantly lower in PAs than outside PAs (Table 1, Base model); however, the extent of differences in Sumatra decreased after 2000 and became insignificant in 2012–2015 (Figure 5). In Sumatra, PAs were highly effective in preventing direct deforestation to estate crop as the hazard level of PAs was only 2%−13% of that in non-PAs at the 95% confidence level and had no significant temporal trend (Figure 5). The decreasing trend of PA effectiveness was present with hopping to shrub as an intermediate state (Figure 5). After 2000, the hazard levels of estate-crop expansion into shrub (established after 1996) became higher in PAs as time went by and became significantly higher than that in non-PAs in 2012–2015. Although the hazard levels of deforestation to shrub were significantly lower in PAs (48%−64% of the hazard levels in non-PAs), the differences were much smaller than direct deforestation to estate crop (2%−13% of the hazard levels in non-PAs). In Kalimantan, although PA effectiveness was significant in preventing the total estate-crop expansion into NF and showed no significant temporal trend, the effectiveness in preventing deforestation to shrub and BG was remarkably smaller than in preventing direct deforestation to estate crop (Figure 5). The high risks of BG establishment inside PAs, especially in 2012–2015 (Figures 4d and 5), substantially contributed to forest loss in Kalimantan PAs. As PAs were not effective in preventing conversion from BG to estate crop, the land may eventually be utilized for estate-crop production.

PA effectiveness is significantly influenced by the edges (Figure S4). NF at the boundaries of PAs had significantly higher risks of conversion to estate crop than NF completely inside PAs, although the extent of differences became insignificant in 2012–2015 in Sumatra. The decreasing trend in Sumatra was mainly due to the conversions with hopping to shrub as an intermediate state (Note S2.5).

4 | DISCUSSION

Estate-crop expansion into PAs has been observed in many countries, especially in tropical regions critical for biodiversity conservation and climate mitigation (Castellanos-Navarrete, 2021; Riggio et al., 2019). Our study is the first
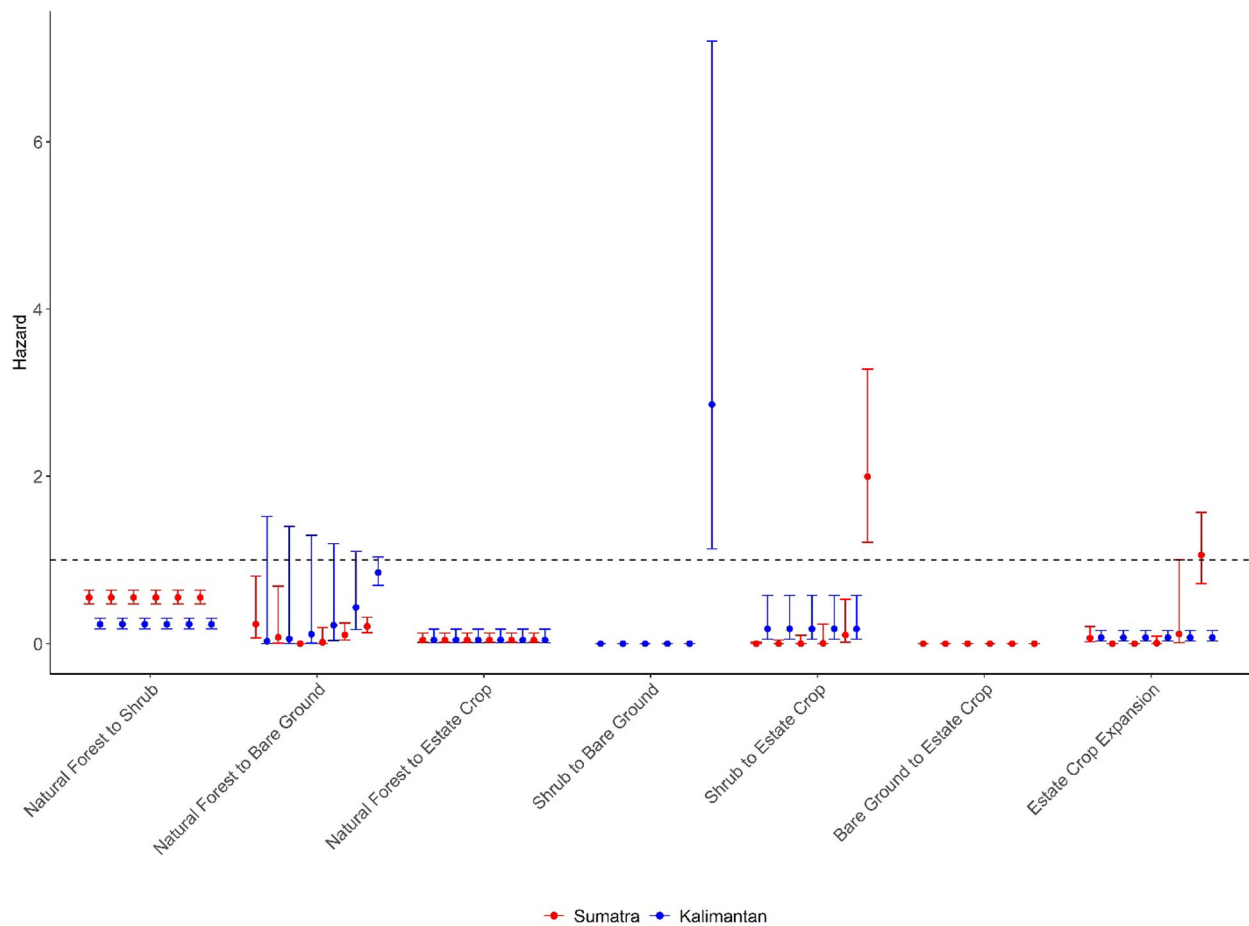
FIGURE 5 Effectiveness of protected areas (PAs) on estate-crop expansion into natural forest as revealed by the multistate regressions. The vertical axis is the exponent of the PA coefficient, $\exp(\beta_1)$, indicating the hazard a grid would be subject to because of PAs in each 3(or 4)-year period. The horizontal axis shows different land-cover and land-use change (LCLUC) types. The first six represent the six direct conversions in the multistate process, and the seventh, Estate-Crop Expansion, represents the total estate-crop expansion into natural forest. Vertical bars correspond to 95% confidential intervals. For each transition type on each island, the vertical bars from left to right represent time period 1996–2000, 2000–2003, 2003–2006, 2006–2009, 2009–2012, and 2012–2015, respectively. Only transition types that PAs are significantly effective in at least one period are shown in the figure. The effectiveness of PAs in conversion from shrub to bare ground in Sumatra and conversion from bare ground to estate crop in Kalimantan was insignificant during the whole study period ($p > 0.3$ and $p > 0.6$); therefore, they are not shown in the figure. The dashed horizontal line is Hazard = 1. If the vertical bars fall completely under the dashed horizontal line, the grids inside PAs have significantly lower risks of experiencing the LCLUC than those out of PAs; if the vertical bars fall completely above the dashed horizontal line, the grids inside PAs have significantly higher risks of LCLUC than those out of PAs; if the vertical bars intersect with the horizontal line, the effects of PAs are not statistically significant.

to examine the effectiveness of PAs in curbing estate-crop expansion into NF across Sumatra and Kalimantan, the epicenter of palm oil production, contributing over 50% of the global supply (Xin et al., 2021). Unlike previous research that relies on snapshot data and does not account for temporal details (Brun et al., 2015; Graham et al., 2021), we employ a longitudinal study with survival analysis and multistate models to capture temporal aspects of PA effectiveness and LCLUC hopping. Our findings highlight the role of the trajectory-hopping mechanism, which involves degraded land as intermediates, in facilitating estate-crop expansion into NF and decreasing PA effectiveness.

Our research shows that estate-crop expansion risks in Indonesia are significantly lower inside PAs and away from boundaries, confirming that PAs effectively prevented deforestation (Gaveau et al., 2012; Graham et al., 2021), especially in core areas (Poor et al., 2019; Watson et al., 2014). However, the time-variant survival analysis reveals decreasing PA effectiveness over time, with this trend more pronounced in Sumatra than in Kalimantan because Kalimantan is a latecomer with relatively abundant land resources (Austin et al., 2017; Xin et al., 2021). As land resources become scarcer, estate-crop expansion encroaches further into PAs and goes deeper into

the central area. Our results align with existing literature, demonstrating that estate-crop expansion tends to occur at lowland forest areas, which are biophysically and socioeconomically suitable for estate-crop plantation (Pirker et al., 2016; Xin et al., 2021). Unfortunately, these areas are also known for their high levels of biodiversity richness (Kinnaird et al., 2003; Poor et al., 2019). Accessibility to infrastructure becomes less constraining over time, allowing estate-crop expansion into more remote area. This growing incursion into protected NF not only results in habitat loss but also isolates forest patches (Kinnaird et al., 2003) and introduces anthropogenic disturbances (e.g., infrastructure construction, use of fertilizer and pesticides), adversely affecting biodiversity (Barlow et al., 2016). Therefore, it should be a main concern of conservation activities. To maximize conservation benefits with limited management resources, it is vital to prioritize PAs in regions with scarce land resources but suitable for estate-crop plantation.

The multistate models show that the risk of direct conversion from NF to estate crop remains minimal in PAs; however, the effectiveness of PAs is significantly reduced by the LCLUC trajectory-hopping tactic. Forest loss to shrub and BG inside PAs closely resembles that outside of PAs (Laurance et al., 2012) and is a key driver of deforestation (Austin et al., 2019). PA effectiveness is notably smaller in preventing deforestation to shrub and BG compared to direct deforestation to estate-crop plantations. Once NF is transformed into shrub and/or BG, the risk of conversion to estate-crop multiplies, especially in recent years (Geldmann et al., 2019). Over half of the degraded lands established in Indonesia since 1990 are due to deliberate clearing (Parker, 2022), and this share would be higher if intentional fire were included (Harrison et al., 2009). The rapid conversion of degraded land to estate-crop plantation (risk is highest with 8 years for shrub and 3 years for BG) and limited natural regeneration (e.g., BG to shrub, shrub to NF; Figure S5) suggest a considerable proportion of the degraded land is being actively used as a land banking to facilitate estate-crop expansion into NF, especially in illegal areas (Xin et al., 2021).

Forest loss to degraded land is often seen as a natural process, while estate crop replacing degraded land is frequently overlooked in monitoring and evaluation, particularly in Indonesia's complex policy landscape (Astuti et al., 2022; Parker, 2022). Mobilizing different stakeholders in PA management and identifying trajectory-hopping mechanism are vital for forest conservation. The recent "One-Map Policy" is a promising start, as it clarifies land boundaries, establishes unified geospatial information data, and promotes interinstitutional collaborations (Astuti et al., 2022). However, given the economic focus of government policies (Astuti et al., 2022) and limited local involvement in PA management (Myers et al., 2017), nongovernmental organization-led conservation coalitions that aggregate stakeholders from local to international level can play a key role in managing PAs and mitigating deforestation (Ruysschaert & Hufty, 2020). To limit forest loss to estate crop via degraded land, policies and enforcement measures should aim to prevent clearing and intentional burning of NF and prohibit sales of land and estate-crop products on recently established degraded land. In this connection, a near-real-time and open-access monitoring system can help detect the LCLUC timely, disseminate the knowledge, facilitate broad cooperation among stakeholders, and strengthen public oversight by visualizing the PA effectiveness (Tacconi et al., 2019; Taheripour et al., 2019).

Trajectory hopping not only reduces PA effectiveness but also contributes to estate-crop expansion into NF outside PAs in Indonesia. Although many producers commit to sustainable requirements (e.g., zero deforestation, RSPO, ISPO), deforestation to nonproductive land is sometimes used as a land-banking mechanism prior to certification and creates a "blind spot" in sustainable palm oil production (Astuti et al., 2022; Xin et al., 2021). Recent remote-sensing data indicate a decline in estate-crop plantation and deforestation after 2016, but this may be due to dropping palm oil prices rather than effective policies (Parker, 2022). The 2020 deforestation increase in Kalimantan, alongside palm oil price recovery, underscores the need for effective regulations to prevent forest loss, especially through LCLUC trajectory hopping.

DATA AVAILABILITY STATEMENT
The sources of data that support the findings of this study are provided in Table S2.

ORCID
Yu Xin https://orcid.org/0000-0002-7173-6707
Laixiang Sun https://orcid.org/0000-0002-7784-7942

REFERENCES
Andam, K. S., Ferraro, P. J., Pfaff, A., Sanchez-Azofeifa, G. A., & Robalino, J. A. (2008). Measuring the effectiveness of protected area networks in reducing deforestation. *Proceedings of*

the National Academy of Sciences of the United States of America, 105(42), 16089–16094. https://doi.org/10.1073/pnas.0800437105

Astuti, R., Miller, M. A., McGregor, A., Sukmara, M. D. P., Saputra, W., & Taylor, D. (2022). Making illegality visible: The governance dilemmas created by visualising illegal palm oil plantations in Central Kalimantan, Indonesia. Land Use Policy, 114, 105942. https://doi.org/10.1016/j.landusepol.2021.105942

Austin, K. G., Mosnier, A., Pirker, J., McCallum, I., Fritz, S., & Kasibhatla, P. S. (2017). Shifting patterns of oil palm driven deforestation in Indonesia and implications for zero-deforestation commitments. Land Use Policy, 69, 41–48. https://doi.org/10.1016/J.LANDUSEPOL.2017.08.036

Austin, K. G., Schwantes, A., Gu, Y., & Kasibhatla, P. S. (2019). What causes deforestation in Indonesia? Environmental Research Letters, 14(2), 024007. https://doi.org/10.1088/1748-9326/AAF6DB

Bailey, K. M., McCleery, R. A., Binford, M. W., & Zweig, C. (2016). Land-cover change within and around protected areas in a biodiversity hotspot. Journal of Land Use Science, 11(2), 154–176. https://doi.org/10.1080/1747423X.2015.1086905

Barlow, J., Lennox, G. D., Ferreira, J., Berenguer, E., Lees, A. C., Nally, R. M., Thomson, J. R., de Barros Ferraz, S. F., Louzada, J., Fonseca Oliveira, V. H., Parry, L., de Castro Solar, R. R., Vieira, I. C. G., Aragão, L. E. O. C., Begotti, R. A., Braga, R. F., Cardoso, T. M., de Oliveira, R. C., Jr., Souza, C. M., Jr., … Gardner, T. A. (2016). Anthropogenic disturbance in tropical forests can double biodiversity loss from deforestation. Nature, 535(7610), 144–147. https://doi.org/10.1038/nature18326

Brun, C., Cook, A. R., Lee, J. S. H., Wich, S. A., Koh, L. P., & Carrasco, L. R. (2015). Analysis of deforestation and protected area effectiveness in Indonesia: A comparison of Bayesian spatial models. Global Environmental Change, 31, 285–295. https://doi.org/10.1016/J.GLOENVCHA.2015.02.004

Carlson, K. M., Curran, L. M., Ratnasari, D., Pittman, A. M., Soares-Filho, B. S., Asner, G. P., Trigg, S. N., Gaveau, D. A., Lawrence, D., & Rodrigues, H. O. (2012). Committed carbon emissions, deforestation, and community land conversion from oil palm plantation expansion in West Kalimantan, Indonesia. Proceedings of the National Academy of Sciences of the United States of America, 109(19), 7559–7564. https://doi.org/10.1073/PNAS.1200452109

Caro, T., Rowe, Z., Berger, J., Wholey, P., & Dobson, A. (2022). An inconvenient misconception: Climate change is not the principal driver of biodiversity loss. Conservation Letters, 15(3), e12868. https://doi.org/10.1111/conl.12868

Castellanos-Navarrete, A. (2021). Oil palm dispersal into protected wetlands: Human–environment dichotomies and the limits to governance in southern Mexico. Land Use Policy, 103, 105304. https://doi.org/10.1016/j.landusepol.2021.105304

Chen, Y., Li, X., Liu, X., Ai, B., & Li, S. (2016). Capturing the varying effects of driving forces over time for the simulation of urban growth by using survival analysis and cellular automata. Landscape and Urban Planning, 152, 59–71. https://doi.org/10.1016/J.LANDURBPLAN.2016.03.011

Curran, L. M., Trigg, S. N., McDonald, A. K., Astiani, D., Hardiono, Y. M., Siregar, P., Caniago, I., & Kasischke, E. (2004). Lowland forest loss in protected areas of Indonesian Borneo. Science, 303(5660), 1000–1003. https://doi.org/10.1126/SCIENCE.1091714

Food and Agriculture Organization (FAO). (2016). Global Forest Resources Assessment 2015: How are the world's forests changing? https://www.fao.org/3/i4793e/i4793e.pdf

Gaveau, D. L., Wandono, H., & Setiabudi, F. (2007). Three decades of deforestation in southwest Sumatra: Have protected areas halted forest loss and logging, and promoted re-growth? Biological Conservation, 134(4), 495–504. https://doi.org/10.1016/j.biocon.2006.08.035

Gaveau, D. L. A., Curran, L. M., Paoli, G. D., Carlson, K. M., Wells, P., Besse-Rimba, A., Ratnasari, D., & Leader-Williams, N. (2012). Examining protected area effectiveness in Sumatra: Importance of regulations governing unprotected lands. Conservation Letters, 5(2), 142–148. https://doi.org/10.1111/J.1755-263X.2011.00220.X

Geldmann, J., Barnes, M., Coad, L., Craigie, I. D., Hockings, M., & Burgess, N. D. (2013). Effectiveness of terrestrial protected areas in reducing habitat loss and population declines. Biological Conservation, 161, 230–238. https://doi.org/10.1016/j.biocon.2013.02.018

Geldmann, J., Coad, L., Barnes, M., Craigie, I. D., Hockings, M., Knights, K., Leverington, F., Cuadros, I. C., Zamora, C., Woodley, S., & Burgess, N. D. (2015). Changes in protected area management effectiveness over time: A global analysis. Biological Conservation, 191, 692–699. https://doi.org/10.1016/j.biocon.2015.08.029

Geldmann, J., Manica, A., Burgess, N. D., Coad, L., & Balmford, A. (2019). A global-level assessment of the effectiveness of protected areas at resisting anthropogenic pressures. Proceedings of the National Academy of Sciences of the United States of America, 116(46), 23209–23215. https://doi.org/10.1073/PNAS.1908221116

Graham, V., Geldmann, J., Adams, V. M., Negret, P. J., Sinovas, P., & Chang, H. C. (2021). Southeast Asian protected areas are effective in conserving forest cover and forest carbon stocks compared to unprotected areas. Scientific Reports, 11, 23760. https://doi.org/10.1038/s41598-021-03188-w

Harrison, M. E., Page, S. E., & Limin, S. H. (2009). The global impact of Indonesian forest fires. Biologist, 56(3), 156–163.

Jamaludin, J., De Alban, J. D. T., Carrasco, L. R., & Webb, E. L. (2022). Spatiotemporal analysis of deforestation patterns and drivers reveals emergent threats to tropical forest landscapes. Environmental Research Letters, 17(5), 054046. https://doi.org/10.1088/1748-9326/ac68fa

Jones, K. R., Venter, O., Fuller, R. A., Allan, J. R., Maxwell, S. L., Negret, P. J., & Watson, J. E. (2018). One-third of global protected land is under intense human pressure. Science, 360(6390), 788–791. https://doi.org/10.1126/SCIENCE.AAP9565

Kinnaird, M. F., Sanderson, E. W., O'Brien, T. G., Wibisono, H. T., & Woolmer, G. (2003). Deforestation trends in a tropical landscape and implications for endangered large mammals. Conservation Biology, 17(1), 245–257. https://doi.org/10.1046/J.1523-1739.2003.02040.X

Laurance, W. F., Carolina Useche, D., Rendeiro, J., Kalka, M., Bradshaw, C. J., Sloan, S. P., Laurance, S. G., Campbell, M., Abernethy, K., Alvarez, P., Arroyo-Rodriguez, V., Ashton, P., Benítez-Malvido, J., Blom, A., Bobo, K. S., Cannon, C. H., Cao, M., Carroll, R., Chapman, C., … Scott McGraw, W. (2012). Averting biodiversity collapse in tropical forest protected areas. Nature, 489(7415), 290–294. https://doi.org/10.1038/nature11318

Myers, R., Intarini, D., Sirait, M. T., & Maryudi, A. (2017). Claiming the forest: Inclusions and exclusions under Indonesia's 'new' forest policies on customary forests. Land Use Policy, 66, 205–213. https://doi.org/10.1016/j.landusepol.2017.04.039

Parker, D. (2022). Forest loss trajectories and palm oil extent in Indonesia (Doctoral dissertation). University of Maryland. https://doi.org/10.13016/jqxy-5exn

Pirker, J., Mosnier, A., Kraxner, F., Havlík, P., & Obersteiner, M. (2016). What are the limits to oil palm expansion? *Global Environmental Change*, *40*, 73–81. https://doi.org/10.1016/j.gloenvcha.2016.06.007

Poor, E. E., Frimpong, E., Imron, M. A., & Kelly, M. J. (2019). Protected area effectiveness in a sea of palm oil: A Sumatran case study. *Biological Conservation*, *234*, 123–130. https://doi.org/10.1016/J.BIOCON.2019.03.018

Pouzols, F. M., Toivonen, T., Di Minin, E., Kukkala, A. S., Kullberg, P., Kuusterä, J., Lehtomäki, J., Tenkanen, H., Verburg, P. H., & Moilanen, A. (2014). Global protected area expansion is compromised by projected land-use and parochialism. *Nature*, *516*(7531), 383–386. https://doi.org/10.1038/nature14032

Purnomo, H., Okarda, B., Dermawan, A., Ilham, Q. P., Pacheco, P., Nurfatriani, F., & Suhendang, E. (2020). Reconciling oil palm economic development and environmental conservation in Indonesia: A value chain dynamic approach. *Forest Policy and Economics*, *111*, 102089. https://doi.org/10.1016/J.FORPOL.2020.102089

Riggio, J., Jacobson, A. P., Hijmans, R. J., & Caro, T. (2019). How effective are the protected areas of East Africa? *Global Ecology and Conservation*, *17*, e00573. https://doi.org/10.1016/j.gecco.2019.e00573

Ruysschaert, D., & Hufty, M. (2020). Building an effective coalition to improve forest policy: Lessons from the coastal Tripa peat swamp rainforest, Sumatra, Indonesia. *Land Use Policy*, *99*, 103359. https://doi.org/10.1016/j.landusepol.2018.04.034

Shah, P., & Baylis, K. (2015). Evaluating heterogeneous conservation effects of forest protection in Indonesia. *PLoS ONE*, *10*(6), e0124872. https://doi.org/10.1371/JOURNAL.PONE.0124872

Tacconi, L., Rodrigues, R. J., & Maryudi, A. (2019). Law enforcement and deforestation: Lessons for Indonesia from Brazil. *Forest Policy and Economics*, *108*, 101943. https://doi.org/10.1016/j.forpol.2019.05.029

Taheripour, F., Hertel, T. W., & Ramankutty, N. (2019). Market-mediated responses confound policies to limit deforestation from oil palm expansion in Malaysia and Indonesia. *Proceedings of the National Academy of Sciences of the United States of America*, *116*(38), 19193–19199. https://doi.org/10.1073/PNAS.1903476116

Wang, N., Brown, D. G., An, L., Yang, S., & Ligmann-Zielinska, A. (2013). Comparative performance of logistic regression and survival analysis for detecting spatial predictors of land-use change. *International Journal of Geographical Information Science*, *27*(10), 1960–1982. https://doi.org/10.1080/13658816.2013.779377

Watson, J. E., Dudley, N., Segan, D. B., & Hockings, M. (2014). The performance and potential of protected areas. *Nature*, *515*(7525), 67–73. https://doi.org/10.1038/nature13947

Wilcove, D. S., Giam, X., Edwards, D. P., Fisher, B., & Koh, L. P. (2013). Navjot's nightmare revisited: Logging, agriculture, and biodiversity in Southeast Asia. *Trends in Ecology & Evolution*, *28*(9), 531–540. https://doi.org/10.1016/J.TREE.2013.04.0051

Xin, Y., Sun, L., & Hansen, M. C. (2021). Biophysical and socioeconomic drivers of oil palm expansion in Indonesia. *Environmental Research Letters*, *16*(3), 034048. https://doi.org/10.1088/1748-9326/ABCE83

SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

How to cite this article: Xin, Y., Sun, L., & Hansen, M. C. (2023). Land-cover and land-use change trajectory hopping facilitates estate-crop expansion into protected forests in Indonesia. *Conservation Letters*, e12957. https://doi.org/10.1111/conl.12957