World Development 174 (2024) 106441

Contents lists available at ScienceDirect

World Development

journal homepage: www.elsevier.com/locate/worlddev

Overlapping extractive land use rights increases deforestation and forest degradation in managed natural production forests

Bingcai Liu [a,*], Anand Roopsind [b,c], Brent Sohngen [d]

[a] Data Analytics Program, Denison University, Granville, OH 43023, USA
[b] Center for Natural Climate Solutions, Conservation International, 2011 Crystal Drive, Suite 600, Arlington, VA 22202, USA
[c] Department of Biological Sciences, Boise State University, Boise, ID 83725, USA
[d] Department of Agricultural, Environmental and Development Economics, The Ohio State University, Columbus, OH 43210, USA

ARTICLE INFO

Keywords:
Sustainable forest management
Impact evaluation
Logging
Overlapping property rights
Deforestation and forest degradation

ABSTRACT

Guyana manages an estimated 5.3 million hectares of old-growth tropical forests, 29% of its total forest area, for timber extraction. Individuals and companies can apply for time-limited leases that allocate access, management, and extraction rights for timber through a concession system. In many tropical regions, including Guyana, a lack of integrated land use planning often leads to overlapping extractive and forest use rights for logging and mining. Overlapping land rights in turn create uncertainty and limit investments toward sustainable forest management, affecting deforestation and forest degradation rates. In this study, we use matched fixed-effect and difference-in-differences panel data models to quantify the impact of establishing logging tenure on deforestation and forest degradation. We assess the impact of different tenure use allocations for Guyana, a high forest cover low deforestation country, utilizing a 31-year (1990–2020) remotely sensed annual time series dataset on deforestation and forest degradation. The rate of forest loss (deforestation plus degradation) in public forests managed by the State with no authorized use allocation activities were 0.062% per year. The issuance of timber concessions increases the probability of deforestation by 33.5% and forest degradation by 8.9% compared to unallocated state forests. Forests with overlapping use rights for timber and mining had a 156% and 19.1% higher probability of deforestation and degradation relative to unallocated public forests and forests where only timber harvesting was authorized, respectively. We conclude that overlapping land use allocations result in conflicting resource use strategies that ultimately will limit sustainability and climate goals related to reducing deforestation and degradation.

1. Introduction

At the 14th Conference of Parties (COP) in Poznan, the role of forest conservation, sustainable forest management, and the enhancement of forest carbon stocks was officially integrated into global climate mitigation policies (Agrawal et al., 2011). This initial recognition of the importance of reducing emissions from deforestation and forest degradation (REDD) has further been solidified by analyses demonstrating the role of forests as natural climate solutions to limit global temperature increase to 1.5 degrees Celsius (Angelsen et al., 2009; Griscom et al., 2017, Griscom et al., 2020). In order to better align and achieve these global climate ambitions, we need a more robust understanding of the relationship between forest tenure and tropical forest outcomes (Robinson et al., 2014).

One dominant forest tenure allocation that could impact forest conservation and climate goals is the establishment of logging concessions, with an estimated 437 million hectares of natural tropical forests allocated towards timber production (Blaser et al., 2011; FSC International Center, 2021). These timber-producing forests are generally state owned, with government issued leases to individuals and companies to access, manage, and extract timber (Tegegne et al., 2019; UNEP & FAO, 2020). Researchers have hypothesized that forests managed for timber production incentivize the maintenance of forests by generating revenue from timber sales and provide the largest conservation potential outside of protected areas (Runting et al., 2019). Adoption of improved forest management and reduced-impact logging practices in these timber concessions could also deliver on important biodiversity and climate mitigation goals (Edwards et al., 2014; Putz et al., 2012).

* Corresponding author.
E-mail addresses: liub@denison.edu (B. Liu), aroopsind@conservation.org (A. Roopsind), sohngen.1@osu.edu (B. Sohngen).

https://doi.org/10.1016/j.worlddev.2023.106441

Available online 27 October 2023

Table 1
Land tenure disaggregated by IPCC land cover classes for Guyana in 2018.

Tenure	Forests ('000 ha)	Non-Forest ('000 ha)					Total Area ('000 ha)
		Grassland	Cropland	Settlements	Wetlands	Other Lands	
State Forest Area	12,142	194	19	12	121	106	12,594
Titled Amerindian Lands	2298	637	7	7	26	331	3306
State Lands	2469	910	344	48	125	178	4074
Protected Areas	1092	30	0	0	12	4	1138
Total Area (ha)	18,001	1771	370	67	284	619	21,112

Source: Guyana REDD+ Monitoring Reporting & Verification System (MRVS) Report – Assessment Year 2020.

However, research results on the level of forest protection gained with the establishment of tenure rights to access, manage, and extract timber have been mixed. In a review of spatially explicit econometric studies that control for confounding variables, timber activity was not consistently associated with higher or lower deforestation (Busch & Ferretti-Gallon, 2017). Studies applying quasi-experimental analytical methods have found lower rates of forest loss in logging concessions in Guatemala (Fortmann et al., 2017) and Kalimantan, Indonesia (Gaveau et al., 2013) relative to matched control forests. Panlasigui et al. (2018) also found that logging concessions in Cameroon have a 1% lower rate of forest loss relative to their matched control forests outside of timber concessions. In contrast, Blackman & Villalobos (2021) found that the issuance of timber extraction permits to Mexican communal land-holding organizations (*ejidos*) did not result in a statistical effect of lower rates of tree cover loss.

These mixed forest protection outcomes have been attributed to local biophysical conditions, governance, market factors, and the level of economic returns from timber (Busch & Ferretti-Gallon, 2017). Establishing logging concessions reduces forest loss in areas with pre-existing high deforestation pressure (Panlasigui et al., 2018) and when logging tenure is maintained over time (Gaveau et al., 2013). In contrast, logging concessions are less effective at stemming forest loss in areas where opportunity costs of maintaining forest cover are moderately high (Blackman & Villalobos, 2021) and law enforcement is limited (Chervier et al., 2024). Continued understanding of national tenure contexts and associated forest outcomes is necessary to fully validate theories of change associated with the hypothesis that forests managed for timber production can extend conservation and climate gains (Mohren, 2019; Romero & Putz, 2018).

Potentially compounding these findings on deforestation outcomes is when land tenure and land-use claims are often unclear, overlapping, and contested, a common phenomenon in many tropical countries (Meyfroidt et al., 2022). Under existing land governance systems, land use or access rights are often allocated to different people, and claims apply to different aspects, such as ownership versus use rights (Giller et al., 2008; Larson et al., 2013; Peters, 2009). These overlapping tenure rights can result in conflicts that drive higher rates of forest loss as different actors aim to capture benefits from intensified forest exploitation caused by competition with other authorized forest users. For example, overlapping tenure rights are associated with higher deforestation rates in Uganda (Walker et al., 2023). However, studies have also found lower rates of forest loss in indigenous areas overlapping with patrimony or protected forests (restricted-use, public and private lands) than single tenure forms (De Los Rios, 2022; Hänggli et al., 2023; Holland et al., 2014). In these instances, the overlapping tenure and management systems are more favorable for maintain forest cover (Anderson et al., 2018).

Guyana provides an interesting policy context to assess the impact of establishing logging rights on forest loss and how overlapping tenure impacts deforestation outcomes. The majority of Guyana's forests are publicly owned (87%) with forests leased under a concession system for timber production and gold mining that can overlap spatially (Guyana Office for Investment, 2021). In addition, Guyana has had historically low rates of annual deforestation (0.06%; 2010–2020) and is the first country to be issued jurisdictional REDD+ credits for emissions reductions under the ART (Architecture for REDD+ Transactions) TREES (The REDD+ Environmental Excellence Standard) for high forest low deforestation (HFLD) countries (Architecture for REDD+ Transactions, 2022). Under these forest use allocation and policy contexts, our study aims to answer three questions: (1) Does establishing logging concessions with rights to access, manage, and extract timber reduce forest loss rates relative to unallocated public forests? (2) Does concession characteristics related to concession size and duration of timber concession leases influence forest loss? and (3) Does overlapping tenure associated with timber and gold mining increase the rate of forest loss? To answer these questions, we use a 30-year annual time series of remotely sensed data from 1990 to 2020 on forest loss and degradation with matched fixed-effect and difference-in-difference (DID) panel data models to identify the impact of establishing logging concessions. We apply spatial multinomial logistic models to accommodate the expectation that a pixel can be classified as intact, deforested, or degraded.

The remainder of the paper is organized as follows. Section 2 of the paper provides a background on drivers of forest loss and forest tenure in Guyana, including the issue of overlapping land tenure allocation for timber and gold mining. Section three presents our theory of change on hypothesized causal pathways between the establishment of logging rights and forest loss. The fourth section describes our empirical modeling approach, including covariates, matching, and robustness checks. Section five presents the results from our empirical analysis, and section six discusses our results based on our hypothesized causal pathways that impact forest loss.

2. Background

2.1. Forests tenure allocation in Guyana

Guyana's current land property regime emerged from British colonial rule, where ownership and use rights were vested in the government (Bulkan, 2014). The majority of the forest estate (15.7 million hectares; 87 %) falls under state ownership, including the categories of State Forests, State Lands, and Protected Areas (Table 1). State forests and State lands are managed by the government with a structure of licenses for extraction and use rights to generate revenue. State forests are allocated primarily to two land uses, timber extraction, and mining, by separate ministerial departments, the Guyana Forestry Commission (GFC) and the Guyana Geological and Mines Commission (GGMC), respectively. Protected Areas are forests that have been set aside for the explicit purpose of conservation (Singh, 2021). Forests outside of state ownership are communally owned by indigenous and local communities, representing 2.3 million hectares (13 %), and are governed by rules set by elected members of the communities (Table 1).

2.2. Forest management and policy context

Guyana's forests are classified as slow dynamic forests that sit outside of the impact of natural disturbances such as hurricanes (Bovolo et al., 2018; Hammond, 2015; ter Steege & Hammond, 2001). From 2001 to 2021, Guyana lost 38.2kha of tree cover from fires and 192kha

Table 2
Forests designated and allocated for timber production under different timber harvesting licenses in 2021.

Forest Production Lands	Description	Number of Leases	Total Area (ha)
Logging concession leases			
- State Forest Permits (SFP)	Non-exclusive permit allowing the holder to remove a certain quota of timber from an area, valid for two years and less than 8,047 ha	536	2,271,091
- State Forest Exploratory Permits (SFEP)	Issued for undertaking exploratory operations such as forest inventories, environmental and social impact assessments, and the preparation of management plans. They do not include full commercial harvesting rights, although limited harvesting is allowed.	6	821,472
- Timber Sales Agreement (TSA)	concession with a duration of 25 years and a total area ≥ 24,281 ha	17	2,125,976
Total concession leases		559	5,218,539
Unallocated State Forests			7,320,361

Source: Forestry – Goinvest.

from all other drivers of loss that included mining and forestry (Tyukavina et al., 2022).

Timber production is conducted mainly in State Forests through a concession system, where individuals, communities, and companies can be issued timber harvesting licenses for varying sizes of forests and lease time with varying forest management requirements (Table 2). These government-owned production forests are managed under a forest management system that relies on natural regeneration to replenish timber stocks between harvest cycles. Under national forest management guidelines, timber harvest extraction is restricted to 0.33 m^3/ha/yr and is capped at 20 m^3/ha in any harvest cycle (Guyana Forestry Commission, 2018), with logging done based on a selective harvest system focused on high-value species (Arets, 2005; United Nations, 1997). At the end of 2021, 5.23 million hectares were allocated for timber production across the three main categories of licenses, which are Timber Sales Agreement (TSA), State Forest Permits (SFP), and State Forest Exploratory Permits (SFEP) (Table 2). Timber production from these areas totaled 340,000 m^3, with the forestry sector contributing 3 % of Guyana's GDP in 2021 (Guyana Office for Investment, 2021). The Guyana Forestry Commission has also developed a robust wood tracking and verification system to distinguish between legally and illegally produced forest products (Guyana Forestry Commission, 2013). The level of illegal logging is estimated to be at low levels in Guyana relative to other tropical countries (Arsenault, 2021).

Similar to the issuance of forest licenses through a concession system for logging, other state agencies, such as the Guyana Geology & Mines Commission, can issue land use rights based on the purview of their agency. However, poor inter-agency coordination related to data sharing and coordination of land use allocations results in overlapping legally approved land use activities and is especially prevalent for logging and gold mining concessions (Humphrey, 2018).

In addition to being a high forest cover low deforestation country, Guyana has been implementing a REDD+ program over the last decade based on a low carbon development strategy. This reducing emissions from deforestation and degradation program (REDD) was initiated through a bilateral agreement between the Kingdom of Norway and Guyana in 2010 (Guyana & Norway, 2011). More recently Guyana's REDD+ program was validated under the ART Trees standard (Architecture for REDD+ Transactions, 2022). Analysis of Guyana's REDD + jurisdictional program has shown that performance based payments was effective at reducing forest loss (Roopsind et al., 2019).

2.3. *Theory of Change: Hypothesized causal pathways*

Baseline deforestation and forest degradation rates in unallocated public forests overseen by the government are predicted to be low due to national conditions related to Guyana being a historically high forest cover, low deforestation country, low levels of reported illegal deforestation, low population pressure, and a national REDD+ program that has resulted in Guyana receiving payments for demonstrated reductions in deforestation (Arsenault, 2021; Roopsind et al., 2019). Establishing logging concessions is expected to increase deforestation and forest degradation relative to unallocated public forests in Guyana, where no legally approved authorization exists for forest utilization. These higher expected deforestation and degradation outcomes in timber concessions relative to unallocated public forests would be expected as a result of

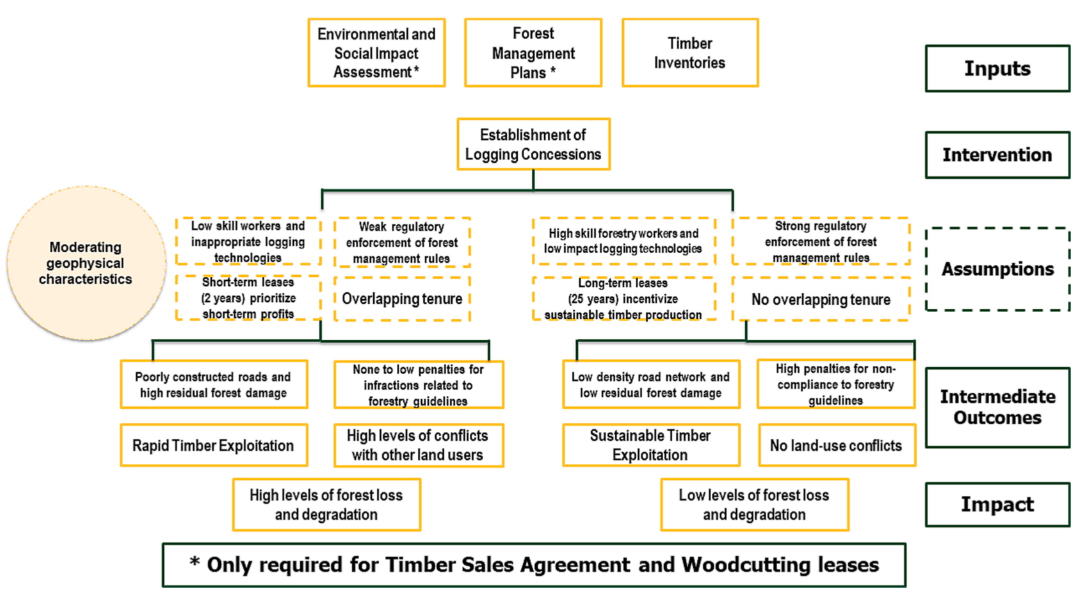

Fig. 1. Hypothesized causal pathway guiding analysis on the impact of establishing timber concessions and overlapping tenure.

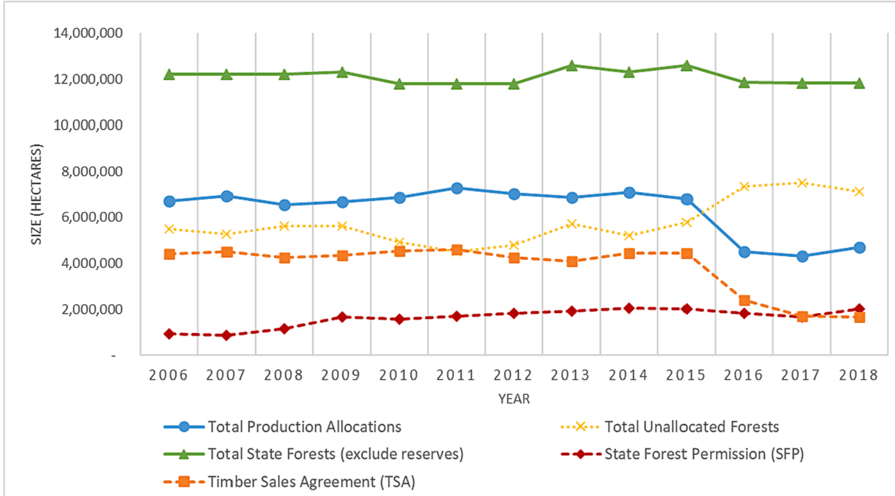

Fig. 2. Publicly owned forest allocation in Guyana (2006–2018). *Total production allocation is the total area of TSAs, SFPs, and SEFPs.

deforestation associated with logging infrastructure (roads and log storage sites) and forest degradation (collateral damage to the residual forest stand).

We use these underlying Guyana-specific contexts to build a theory of change that describes our hypothesized causal pathways between establishing tenure rights for logging and observed deforestation and forest degradation levels. We disaggregate our theory of change to capture the prerequisite inputs for the establishment of a logging concession, assumptions, and intermediary outcomes associated with either high or low levels of deforestation and forest degradation (Fig. 1). Prior to the issuance of timber concessions, forest inventories are conducted to assess commercial stocking and financial viability of establishing a logging enterprise. Concessionaires must also prepare forest management plans and conduct environmental and social impact assessments depending on the type of timber concession lease.

The magnitude of deforestation and forest degradation observed in logging concessions could be mediated by moderating biophysical conditions (e.g., accessibility and topographic complexity - see empirical approach for a complete list of biophysical covariates), infrastructure building, existence and level of compliance to forest management guidelines, and magnitude of penalties for non-compliance meted out by responsible Government agencies, forestry workers' skill level and logging technologies (e.g., reduced-impact logging), length of tenure for timber harvesting, and overlapping legally approved land uses such as mining which is a common phenomenon in Guyana. We would expect that weak forest regulations and enforcement, shorter-term timber harvesting leases that disincentivize long-term investments and prioritize immediate profits, low-skill workers, inappropriate logging technologies, and competing land uses would result in higher deforestation and forest degradation levels. In contrast, strong enforcement of forest management guidelines and high penalties for non-compliance, skilled forestry workers, long-term timber harvesting leases, and no overlapping land uses will result in lower deforestation and forest degradation levels.

3. Methods

3.1. Data inputs and processing

Deforestation and degradation annual time series data: We utilize the tropical moist forest (TMF) dataset, which tracks annual forest cover from 1990 to 2021 (30 years) to assess the impact of establishing timber concessions on deforestation and forest degradation (Vancutsem et al., 2021). The TMF data are produced at a spatial resolution of 30 m utilizing the Landsat archive, with a forested pixel in any year classified as undisturbed forest, degraded forest, deforested, or regrowth. An undisturbed forest pixel is defined as a closed evergreen or semi-evergreen forest without any disturbance (deforestation or forest degradation) detected throughout the Landsat time series. A deforested forest pixel refers to a longer-term conversion of forest into non-forested land with no vegetative regrowth detected over the past 3 years. A degraded forest pixel is defined as a closed evergreen or semi-evergreen forest that has been temporarily disturbed during a period of maximum 2.5 years caused by selective logging, fires, and natural disturbances (e.g., hurricanes, drought, blowdown). For our analysis we do not include pixels experiencing regrowth after deforestation. We choose not to model regrowth outcomes because it is such a rare phenomenon on our dataset that does not give us statistical power to estimate these outcomes with high confidence.

Timber concession data: The allocation of land to TSAs, SFPs and mining concessions in Guyana changes every year because some leases end without renewal, and new leases are written elsewhere. SFP's for instance, only have a two-year time length. TSAs are longer, but over the long time period of our dataset, a number of TSAs were added, and later not renewed. For example, a number of TSAs were added in 1990 and not renewed in 2015 (Fig. 2). Our data do not provide information on why either SFPs or TSAs were not renewed. Fig. 2 shows the size of two main types of timber concessions (TSA and SFP), unallocated state forests, total production allocations, and total state forests excluding the national reserved areas (reserves) from 2006 to 2018. Eighteen percent of the forest estates in Guyana are owned by indigenous people (Rainforest Foundation US, 2022), and exclude theses community owned areas from our control sample pool which is restricted to state owned and managed forests. The concession data in this research is the Guyana land allocation information in 2016. The data is collected by the Guyana Forestry Commission, and it includes the size and position of each active concession and its issuance year.

We overlay the locations of timber concessions in Guyana onto the TMF annual forest layers, and track pixel level forest and concession changes for 31 years (1990–2021). Our spatial data of timber concessions, produced in 2018, includes the concession type of lease and date of issuance/renewal (Table 3). Lowland tropical moist forests are typically found at lower elevations, usually below 1,000 m (3,280 feet) above sea level. Most of Guyana's forests are spread at elevations under 1000 m above sea level., and most timber and mining concessions occur primarily in lowland forests. As a result, we restrict our analysis to Guyana lowland moist tropical forests. We also incorporate data for other geophysical characteristics that might affect the status of a forest

Table 3
Data inputs in our analysis to quantify the impact of establishing tenure on deforestation and forest degradation.

Data Inputs	Description	Spatial Resolution	Analytical Use	Source
Tropical Moist Forest Land Cover	Annual pixel level land cover classes from 1990 to 2020 that depicts the sequential dynamics of changes that include: (1) Undisturbed tropical moist forest, (2) Degraded tropical moist forest and (3) Deforested land	30 *m*	Response variable	Vancustem et al. (2021)
Shuttle Radar Topography Mission Digital Elevation Model	Pixel level elevation (m)	30 *m*	Matching algorithm	NASA SRTM
	Pixel level slope (degrees)	30 *m*		
Climate	30 Year average of monthly mean temperature (Kelvin)	27830 *m*	Matching algorithm	ERA5-Land
	30 Year average of monthly total precipitation (m)	27830 *m*		
	Annual average of monthly temperature for 1990—2020 (Kelvin)	27830 *m*	Explanatory variable	
	Annual average of monthly temperature for 1990—2020 (m)	27830 *m*		
Rivers (Guyana specific layer)	Distance to main rivers (m)		Matching algorithm and Explanatory variable	GuyNode Spatial Data Portal
Main Roads (Guyana specific layer)	Distance to main roads (m)		Matching algorithm and Explanatory variable	GuyNode Spatial Data Portal
Settlements (Guyana specific layer)	Distance to nearest settlement (m)		Matching algorithm and Explanatory variable	GuyNode Spatial Data Portal
Ports (Guyana specific layer)	Distance to nearest Port (m)		Matching algorithm and Explanatory variable	GuyNode Spatial Data Portal
Annual Lumber FOB prices (Guyana $) for 1990–2020	Export prices of non-coniferous - adjusted to real Guyana dollars		Explanatory variable	FAOSTAT
Annual gold prices (Guyana $)	Annual gold prices - adjusted to real Guyana dollars		Explanatory variable	World Gold Council
Labor force	Number of employed workers and people who are seeking jobs – by thousand people		Explanatory variable	World Bank Open Data

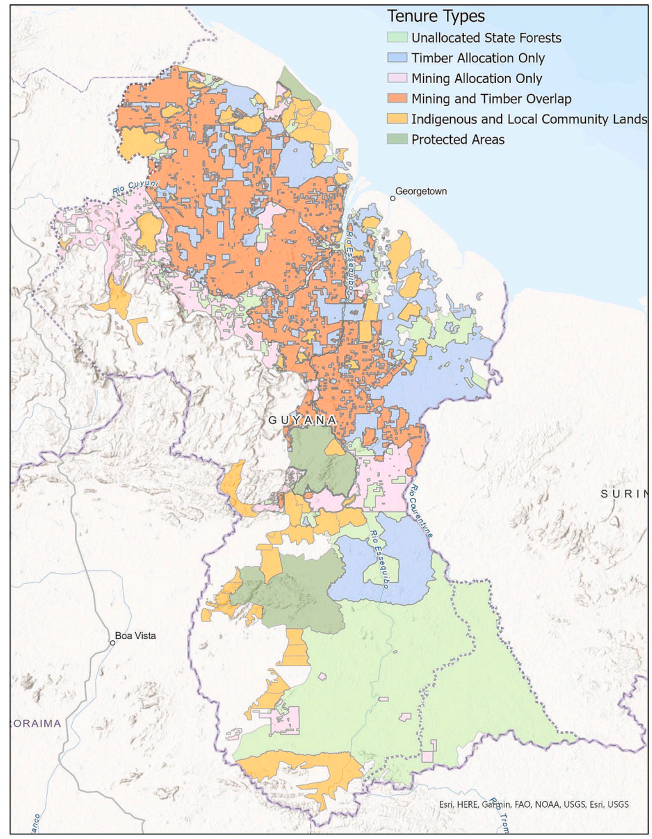

Fig. 3. Forest tenure in Guyana and forest use allocations of State-owned forests restricted to Guyana moist forests in 2016.

Table 4
Sample size (number of 30 × 30 m pixels) after matching for treatment and comparison groups based on land tenure designation.

Models Implemented for Different Tenure Categories	Control Group	Sample Size (# of matched pixels)	Treatment Group	Sample Size (# of matched pixels)
Timber Only vs Unallocated State Forests	Unallocated State Forest	6776	Timber Concession Only	76,509
Mining Only vs Unallocated State Forests	Unallocated State Forest	5689	Mining Concession Only	75,269
Timber & Mining Overlap vs Unallocated State Forests	Unallocated State Forest	3565	Timber & Mining Overlap	79,300
Timber Only vs Timber & Mining Overlap	Timber Concession Only	17,028	Timber & Mining Overlap	79,300

pixel, including elevation (m), slope (degrees), rainfall (m), temperature (Kelvin), distance (meters) from major roads, navigable rivers, ports, and settlements (see Table 3 for additional details on datasets and analytical use). The change of road density is a driver of forest cover change (Pfaff, 1999), however, we do not have road construction data, so we use distance to major roads, which has not changed over the 31-year time period. Non-spatial data also could influence the observed status of pixels, including for example, the price of gold (GUY $), price of lumber (GUY $) and labor availability, so we include these variables as well (Table 3). We also calculated each point's distance to the forest edge, as an indicator of deforestation likelihood. However, initial model implementations with distance to forest edge included as a covariate

Table 5
Point level fixed effect results from the multinomial logistic model. Dependent variable is the deforestation status on sample plot i in year t, timber concession is TSA and SFP combined, time period is from 1990 to 2020.

	Timber vs Control		Overlap vs Control		Timber vs Overlap		Mining vs Control	
Degraded								
Concession type.Timber	0.0852	*						
Concession type.Overlap			0.1703		0.1750	***		
Concession type.Mining							0.3478	***
temperature (K)	0.9709	***	−0.0102		0.0512		0.2547	***
annual rainfall (m)	0.4509	***	−0.6485	***	−0.7726	***	−0.1385	***
roundwood price (k GYD)	0.0123	***	−0.0069	***	−0.0073	***	−0.0035	*
gold price (k GYD)	0.0034	***	0.0013	***	0.0010	**	0.0028	***
labor force (k people)	0.0188	***	0.0163	***	0.0179	***	0.0118	***
distance to nearest harbor (km)	−0.0067	***	0.0022	***	0.0016	***	0.0016	***
distance to nearest major road (km)	0.0017	**	−0.0241	***	−0.0234	***	−0.0390	***
distance to nearest river (km)	−0.0459	***	−0.0157	***	−0.0116	***	−0.0060	***
distance to nearest settlement (km)	−0.0096	***	−0.0090	***	−0.0101	***	−0.0024	***
Time Stage								
1995–1999	1.7120	***	2.1062	***	2.1199	***	1.1118	***
2000–2004	3.3378	***	3.9977	***	3.9841	***	2.3429	***
2005–2009	3.2313	***	4.6936	***	4.6850	***	2.6265	***
2010–2014	2.6620	***	4.8170	***	4.8547	***	2.4325	***
2015–2020	2.5611	***	5.4211	***	5.3892	***	2.9847	***
Deforested								
Concession type.Timber	0.2891	***						
Concession type.Overlap			0.9392	***	0.0874			
Concession type.Mining							1.3952	***
temperature (K)	1.3882	***	−0.2058	***	−0.1252	**	0.2693	***
annual rainfall (m)	0.1798	***	−0.9787	***	−0.9658	***	−0.0813	*
roundwood price (k GYD)	0.0151	***	−0.0082	***	−0.0085	**	0.0046	
gold price (k GYD)	0.0014	***	−0.0018	***	−0.0018	***	0.0001	
labor force (k people)	0.0224	***	0.0276	***	0.0268	***	0.0215	***
distance to nearest harbor (km)	−0.0067	***	0.0077	***	0.0078	***	0.0018	***
distance to nearest major road (km)	−0.0001		−0.0259	***	−0.0289	***	−0.0404	***
distance to nearest river (km)	−0.0142	***	−0.0487	***	−0.0454	***	−0.0218	***
distance to nearest settlement (km)	−0.0142	***	−0.0109	***	−0.0103	***	0.0042	***
Time Stage								
1995–1999	3.0311	***	2.6473	***	3.2398	***	2.1393	***
2000–2004	4.8355	***	4.1282	***	4.6571	***	3.9626	***
2005–2009	4.8531	***	5.2921	***	5.7460	***	4.3810	***
2010–2014	4.4522	***	5.9572	***	6.4002	***	4.4806	***
2015–2020	3.9943	***	6.5384	***	6.9637	***	4.7487	***
$p < 0.1$ *, $p < 0.05$ **, $p < 0.01$ ***								

indicated that this variable had strong collinearity with the dependent variable due to the low rates of observed deforestation and the small size of deforestation patches in Guyana (Alin, 2010). Thus, we did not include this variable in our final regressions.

We overlay the timber concession layer onto mining concessions (allocated primarily for gold mining) to identify areas of competing land use, and areas with only timber harvesting and mining allocation. To identify public forests managed by the government with no forest use allocation, we overlay the timber and mining concessions onto state forests, excluding protected areas and indigenous and local community lands (Fig. 3). This resulted in four categories of forest tenure included in our analysis, (1) unallocated public forests managed by government agencies (2) timber concessions only (no overlapping land use), (3) overlapping timber and mining allocations and (4) mining allocations only (Table 4).

3.2. Matching on observations

To create a time-series data structure for the four categories of land use allocations in state-owned forests (no allocation, timber only, timber and mining overlap, and mining only), we randomly sampled 80,000 pre-matching pixels from each group. The pixels are selected from each tenured and non-tenured area. The selection is completely random. Since the samples will be evaluated and trimmed in a matching process, the samples are not spatially balanced or stratified.

We filter these samples to remove pixels classified as water, and other land cover classes, keeping only pixels that were classified as undisturbed forests in the first year (1990) of the TMF dataset. We then track the annual status (undisturbed, deforested, or degraded) for each pixel for 30 years using the TMF dataset.

Our analysis is based on observational data. To help reduce bias in covariates, we trim the data using matching methods (Ho et al., 2007). We implement matching using Mahalanobis distance (MD) based on observable covariates for each pixel for the different pairwise combinations of the tenure categories (Table 4). We use eight time-invariant geophysical and climatological characteristics for matching: elevation, slope, 30-year average annual rainfall and temperature, distance from the nearest major roads, rivers, ports and settlements.

The MD matching represents the distance between two points in multivariate space and is specified as:

$$d(x, y) = \sqrt{(x - y)^T S^{-1} (x - y)} \quad (1)$$

where x and y are two vectors representing points from the control and comparison group, and S is the covariance matrix. Our MD matching is implemented based on nearest-neighbor matching with replacement, which means in the control group, some points can be matched with multiple points from the treatment group, and some points will not be matched with any point from the treatment group. The MD matching with replacement can help to identify the best matches for each concession group (De Maesschalck et al., 2000). In our analysis, the MD matching with replacement process improved balance in samples (Fig. A1.a–A1.d).

Table 6
Point level difference-in-differences multinomial logistic result, Dependent variable is the deforestation status on sample plot i in year t, timber concession is TSA and SFP combined, time period is from 1990 to 2016.

	Timber vs Control				Overlap vs Control			
	Degraded		Deforested		Degraded		Deforested	
Concession type.Timber	0.2161	***	0.1999	***				
Concession type.Overlap					0.3720	***	0.7864	***
Post Issuance × Concession	−0.1595	***	−0.0216		−0.1005	***	0.3032	***
temperature (K)	1.1421	***	1.4970	***	0.2370	***	0.1474	**
annual rainfall (m)	0.4579	***	0.0207		−0.5401	***	−0.7467	***
roundwood price (k GYD)	0.0281	***	0.0231	***	0.0068	*	0.0063	
gold price (k GYD)	−0.0003		−0.0001		0.0009	**	0.0005	
labor force (k people)	0.0315	***	0.0305	***	0.0201	***	0.0363	***
distance to nearest harbor (km)	−0.0069	***	−0.0078	***	0.0015	***	0.0090	***
distance to nearest major road (km)	0.0045	***	0.0086	***	−0.0289	***	−0.0262	***
distance to nearest river (km)	−0.0521	***	−0.0142	***	−0.0157	***	−0.0459	***
distance to nearest settlement (km)	−0.0135	***	−0.0214	***	−0.0091	***	−0.0135	***
Time Stage								
1995–1999	1.6008	***	2.9631	***	1.9861	***	2.4667	***
2000–2004	3.4370	***	4.9179	***	3.9656	***	4.1433	***
2005–2009	3.4663	***	4.9915	***	4.5699	***	4.9365	***
2010–2014	3.1233	***	4.6566	***	4.6526	***	5.1759	***
2015–2016	2.1635	***	3.7188	***	4.7649	***	5.3281	***

* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

3.3. Model specification

The goal of our analysis is to estimate the impact of concessions on deforestation, which is the average treatment effect on the treated (ATT). We implement a multinomial logistic model (MLM) to accommodate pixel status that can transition between undisturbed, deforested, and degraded. The regression is weighted by matching weights. For the ATT, each treated unit has a weight of 1. Each control unit is weighted as the sum of the inverse of the number of control units matched to the same treated unit across its matches (Ho et al., 2011). The multinomial logistic model can accommodate multiclass problems like ours, where there are multiple possible outcomes at time of disturbance, in this case, forest degradation or deforestation. Other strategies that eliminate observations or combine categories could lead to less efficient estimates (Kwak & Clayton-Matthews, 2002), and are subject to concerns about whether the IIA (Independence of Irrelevant Alternatives) assumption is satisfied.

The multinomial logistic model is specified as:

$$log\frac{Pr(Y_{it}=k)}{Pr(Y_{it}=K)} = \beta_0 + \beta_1 \cdot ConcessionLand_i + \beta_2 \cdot X_{it} + \beta_3 \cdot TimeStage_t + \varepsilon_{it} \tag{2}$$

where K is the base outcome (undisturbed forest), k stands for other outcomes (degraded, deforested).Y_{it} is the land status on sample point i in year t. $ConcessionLand_i$ is the fixed-effect variable equal to 1 if the observation (sample point) lies in the treatment group, which includes State Forest Permits (SFPs) that were active in 2016, and TSAs that were issued earlier but expired in 2016. TSAs that expired in 2016 are coded 0 after 2016. X_{it} is a vector of other covariates (Table 3). $TimeStage_t$ is a time stage indicator variable, which equals to 0, 1, 2, 3, 4, 5 if t is in 1990–1994, 1995–1999, 2000–2004, 2005–2009, 2010–2014, 2015–2020. ε_{it} is an error term which is assumed to be independent of all covariates.

The timber concession information dataset also includes the year each concession was issued and the expiration year for some TSAs, allowing us to estimate a difference-in-differences (DID) model that assesses whether the time of issuance influences the results. However, the data collection year is 2016 and the concession issuance information in Guyana after 2016 is not included, so we remove the 2017–2020 data for this DID model. With the 1990–2016 data, we estimate a staggered difference-in-differences (DID) model to assess the impact of timber concessions before and after the concession issuance time (Athey & Imbens, 2022).

The staggered DID model is specified as:

$$log\frac{Pr(Y_{it}=k)}{Pr(Y_{it}=K)} = \beta_0 + \beta_1 \cdot ConcessionLand_i + \beta_2 \cdot PostIssuance_{it} \times ConcessionLand_i + \beta_3 \cdot X_{it} + \beta_4 \cdot TimeStage_t + \varepsilon_{it} \tag{3}$$

where $PostIssuance_{it} \times ConcessionLand_i$ is the DID term that captures the treatment effect on the treated (ATT).

4. Results

In logistic regression models, the coefficients represent how independent variables impact the odds, or probabilities, associated with the outcome relative to the undisturbed forest (degraded or deforested). A positive coefficient indicates the variable is positively related to the odds of forest degradation or deforestation. With the fixed-effect multinomial logit model, all concession types are predicted to increase deforestation and forest degradation (Table 5; see odd rations in Table A8). Mining concessions status is the strongest predictor of both deforestation and forest degradation. For pixels extracted from mining concessions, deforestation probability is 303 % higher than pixels from unallocated forests, and the probability of forest degradation is 41.6 % higher. Pixels from timber concessions have a 33.5 % higher deforestation probability and an 8.9 % higher forest degradation probability than unallocated state-owned forests. Overlapping concessions have a 156 % higher deforestation probability than pixels from unallocated forests and a 19.1 % higher forest degradation probability than pixels from timber-only concessions.

Timber and gold price changes also influence deforestation and forest degradation. In timber concessions, roundwood price positively affects both deforestation and forest degradation, as expected. However, a higher roundwood price in overlapping concession areas has a negative effect on deforestation and forest degradation probability. Gold price is positively related to forest degradation in all concession areas, but sometimes negatively related to deforestation. We suspect this has to do with the typical type of mining that occurs in Guyana, where the majority of mineral extractions are from small or medium scale operators (Laing, 2019; planetGOLD, 2022), combined with the definition of deforested land in the TMF dataset. In the TMF dataset, a deforested forest pixel is counted as deforested after long-term conversion of forest

Table 7
Point level, sub-group fixed effect multinomial logistic result, Dependent variable is the deforestation status on sample plot i in year t.

Timber Sales Agreement (TSA)	Timber vs Control		Overlap vs Control		Overlap vs Timber	
Degraded						
Concession type.Timber	−0.5173	***				
Concession type.Overlap			0.0444		0.2724	***
Deforested						
Concession type.Timber	−0.3178	***				
Concession type.Overlap			0.8346	***	0.0609	
State Forest Permits (SFP)	Timber vs Control		Overlap vs Control		Overlap vs Timber	
Degraded						
Concession type.Timber	0.2658	***				
Concession type.Overlap			0.4326	***	0.0144	
Deforested						
Concession type.Timber	0.4885	***				
Concession type.Overlap			0.9285	***	0.1088	
* p < 0.1, ** p < 0.05, *** p < 0.01						

Table 8
Point level, sub-group staggered DID multinomial logistic result, Dependent variable is the deforestation status on sample plot i in year t.

Timber Sales Agreement (TSA)	Timber vs Control		Overlap vs Control	
Degraded				
Concession type.Timber	−0.8753	***		
Concession type.Overlap			−0.1888	
Post Issuance × Concession	0.3860	***	0.4046	***
Deforested				
Concession type.Timber	−1.8830	***		
Concession type.Overlap			0.2018	
Post Issuance × Concession	1.7594	***	0.8445	***
State Forest Permits (SFP)	Timber vs Control		Overlap vs Control	
Degraded				
Concession type.Timber	0.4284	***		
Concession type.Overlap			0.7582	***
Post Issuance × Concession	−0.1688	***	−0.2147	***
Deforested				
Concession type.Timber	0.5610	***		
Concession type.Overlap			0.8886	***
Post Issuance × Concession	−0.3601	***	0.2234	***
* p < 0.1, ** p < 0.05, *** p < 0.01				

into non-forested land with no vegetative regrowth detected over the past 2 years. While in most cases, the severity of forest impacts related to small-scale mining is limited (World Bank Group, 2019), the forest change caused by small-scale mining in Guyana could be categorized as forest degradation in the TMF data. To test if there is a categorization lag in the TMF data, we rerun the regressions with lagged gold and timber prices. If the tree cover loss caused by mining and timber logging is categorized as deforestation after two years, we expect to see a positive relationship between two types of tree cover loss (deforestation, forest degradation) and 2-year lagged prices (gold price and timber price). The results are shown in Table A6 and A7 and indicate that the increase of gold and timber prices will lead to more deforestation and forest degradation.

Distances to major roads or rivers also significantly impact deforestation probabilities. The areas closer to major roads or rivers are more likely to be deforested by 1.4 % to 4.8 % for every one kilometer closer. The time stage fixed-effects control for unobservable that is correlated with time but have the same effect on each pixel over time. In timber concession areas, the probability of deforestation increased from 1990 to 2009, then declined after 2010, while the probability of deforestation increased throughout the analysis period in mining concessions and overlap concessions. The decline of deforestation on timber concession areas after 2010 could be related to the Norway-Guyana REDD + Program, which was in effect from 2010 to 2015. This program which significantly reduced Guyana's tree cover loss during the program effective time (Roopsind et al., 2019). We would also have expected the program to reduce deforestation rates in mining areas, but deforestation kept increasing after 2010 both in mining only areas and overlap areas. The rate of increase in deforestation in mining concessions, however, slowed for the 2010–2014 period compared to the 2005–2009 period, although the rate increased again after the program REDD + program ended in 2015.

The multinomial logit model with DID structure, measuring the impact of timber-related concession (timber only, overlap) before and after the issuance year results are present in Table 6 with the odds ratios presented in Table A9. The issuance year is the year when a timber concession (on timber-only concession or on overlapped concession) becomes Government approved. The concession fixed effects are the same in direction as the effects in the fixed-effect model. The scales are different because the DID is capturing some of the effects for example the parameter on post-issuance (DID estimator) captures the effect of the issuance of timber concessions on forest degradation or deforestation. For the overlapped concessions, issuance of concessions is estimated to decrease the probability of forest degradation and increase the probability of deforestation, both significantly. The main effects both are positive, so the overlap concession areas have a higher probability of deforestation than unallocated public forests, but establishment of the concession lowers the probability of forest degradation, while it increases the probability of deforestation. For the timber only concession, lands that are timber concessions have higher probability of deforestation and forest degradation relative to unallocated public forests, but issuance of the concession agreement lowers the probability of forest degradation, while it has no statistically significant effect on the probability of deforestation.

4.1. Subgroup impacts

We estimate our multinomial logit models using subsamples that include only SFPs or TSAs to test if the concession impact is different under different forest management leases (Tables 7 and 8; odds ratios are shown in Table A10 and A11). The coefficients of the concession variable indicate that when timber concessions have no overlap with mining concessions, compared to unallocated state forests, SFPs have higher probability of forest degradation and deforestation and TSAs are less likely to be degraded and deforested. This result makes sense in Guyana, given that TSAs represent long-term, 25 years, commitments by companies to manage a larger area of land for timber production. In contrast, SFPs represent short-term harvesting leases, lasting for only two years.

When timber concessions overlap with mining concessions, compared to unallocated state forests, SFPs are also more likely to be degraded and deforested than unallocated land. TSAs have a higher probability of deforestation compared to unallocated land, but the impact on forest degradation is insignificant. When comparing timber-only concessions and overlapping concessions, overlapped concessions have a 31.3 % higher probability of forest degradation on TSAs. And there is no significant difference in the probability of forest degradation and deforestation on SFPs.

On TSAs, the probabilities of forest degradation and deforestation are lower on timber-only concession lands than the control, however, the probabilities of forest degradation and deforestation on TSAs overlapped with mining are insignificantly different from zero when compared to unallocated public forests (see Table 8 DID model results). The issuance of TSA concessions is estimated to significantly increase the forest degradation and deforestation probability both for timber-only and overlapped concessions. On SFPs, both timber-only and overlapping concessions have higher probabilities of forest degradation and deforestation than unallocated public forests. The issuance of concessions is estimated to decrease the forest degradation probability on timber-only and overlapping concessions and decrease the deforestation probability on timber-only concessions. Issuance is estimated to have a

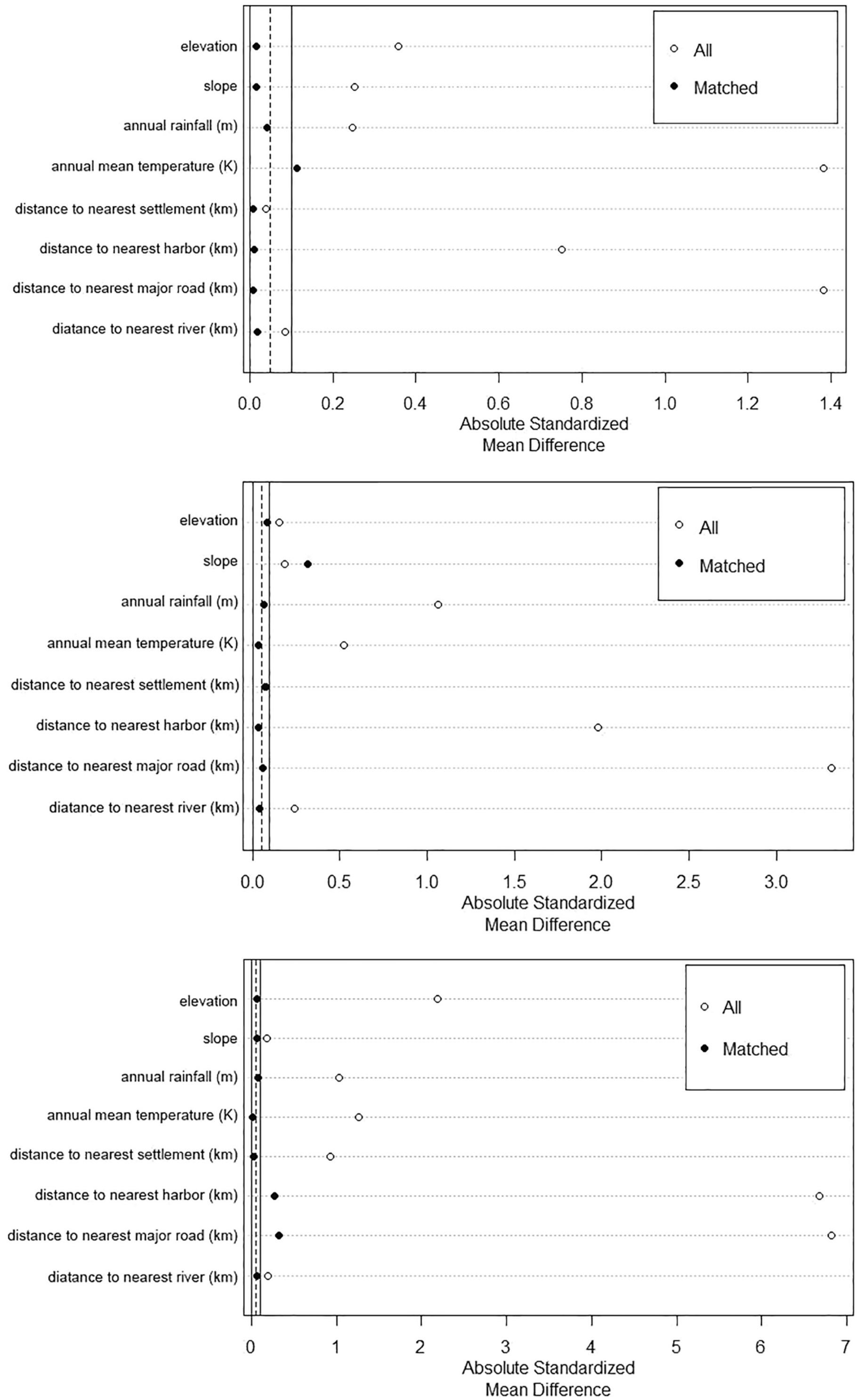

Fig. A1. Absolute Standardized Difference before and after matching. (a) Overlap vs Timber Only. (b) Control vs Mining. (c) Control vs Overlap. (d) Control vs Timber Only. Absolute Standardized Difference before and after matching.

positive impact on deforestation on overlapping SFP concessions.

5. Robustness checks

We test the robustness of the results from multinomial models by estimating a logistic model with the same dataset. The logit approach is implemented so we can more closely compare our results to those analytical outcomes using a different, more widely used, tropical forest land use change dataset, the Global Land Analysis and Discovery (GLAD) laboratory data (Hansen et al., 2013). In that data, forest cover reduction is defined as a stand-replacement disturbance, or a change from a forest to non-forest state. In the logit model in our analysis, we modify the TMF data to make it closer to Hansen data. If a point in the TMF data is classified as degraded, we reclassify it as forested in the robustness test.

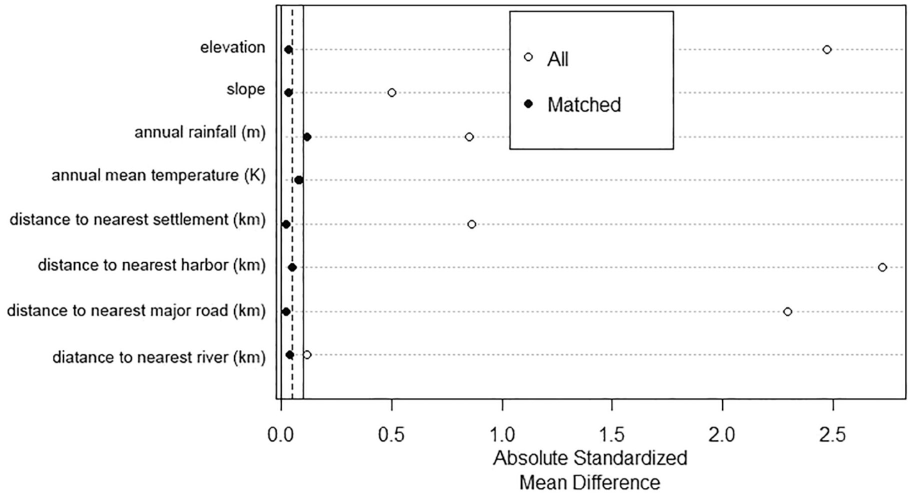

Fig. A1. (*continued*).

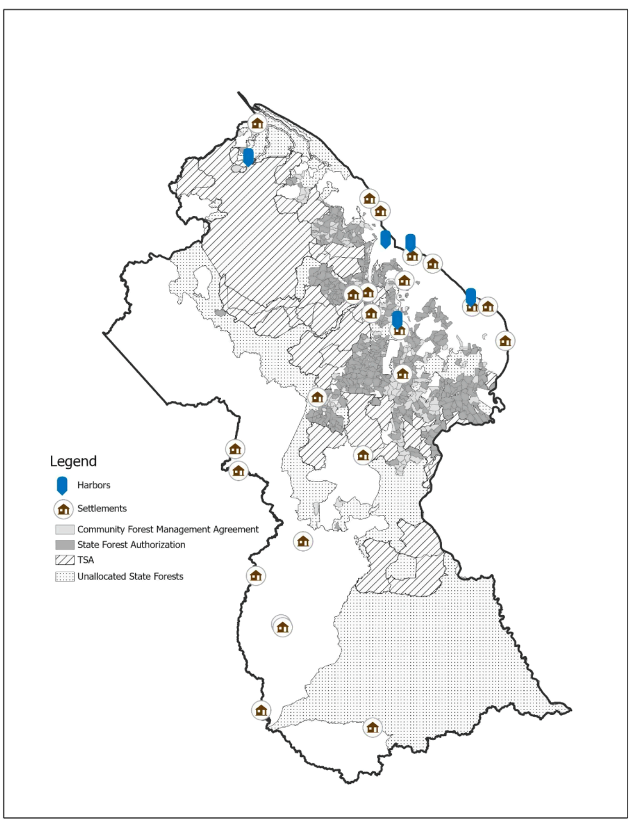

Fig. A2. The position of harbors and settlements in Guyana.

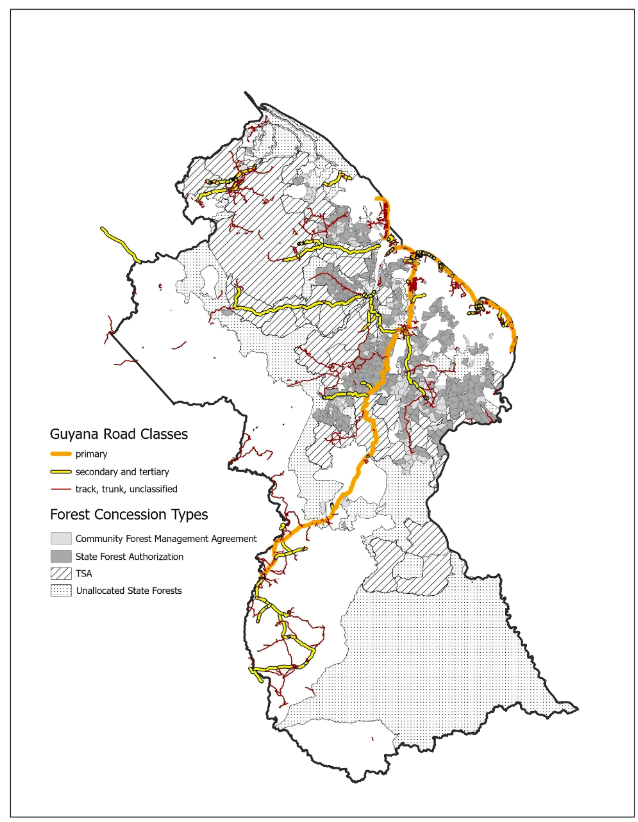

Fig. A3. The distribution of major and minor roads in Guyana in 2010.

With the logit, we estimate both fixed effect and staggered DID models.

The logistic regression model and staggered DID model are specified as:

$$Y_{it} = \beta_0 + \beta_1 \cdot ConcessionLand_i + \beta_2 \cdot X_{it} + \beta_3 \cdot TimeStage_t + \varepsilon_{it} \tag{4}$$

$$Y_{it} = \beta_0 + \beta_1 \cdot ConcessionLand_i + \beta_2 \cdot PostIssuance_{it} \times ConcessionLand_i + \beta_3 \cdot X_{it} + \beta_4 \cdot TimeStage_t + \varepsilon_{it} \tag{5}$$

where Y_{it} is the deforestation outcome (0 or 1) which indicates if a sample plot is deforested or not.

The results are shown in Table A1 and A2. The coefficients for each type of concession land and the issuance of concession have the same signs and similar magnitudes as those in the multinomial logistic models. The coefficients for climatology, geophysical, and socioeconomic variables also show similar signs and magnitudes.

Since we don't have access to the detailed land allocation and concession issuance data after 2016, some early SFPs which are not recorded in the 2016 data may influence the robustness of the results. We know that from 2006 to 2015, the total SFP and TSA areas did not have major changes (Fig. 2). Thus, we run the three multinomial logistic models (fixed effect, staggered DID, and sub-group DID) using data from 2006 to 2015. Our results are shown in Table A3-A5, and these results are qualitatively identical to results in the original model.

Table A1
Point level, fixed effect logistic model result, Dependent variable is the deforestation status on sample plot i in year t.

	Timber vs Control		Overlap vs Control		Overlap vs Timber		Mining vs Control	
Concession type.Timber	0.2873	***						
Concession type.Overlap			0.9364	***	0.0849	*		
Concession type.Mining							1.3905	***
temperature (K)	1.3649	***	−0.2090	***	−0.1265	***	0.2671	***
annual rainfall (m)	0.1653	***	−0.9722	***	−0.9550	***	−0.0763	
roundwood price (k GYD)	0.0148	***	−0.0082	**	−0.0083	***	0.0047	
gold price (k GYD)	0.0014	***	−0.0018	**	−0.0019	***	0.00002	
labor force (k people)	0.0219	***	0.0273	***	0.0266	***	0.0214	***
distance to nearest harbor (km)	−0.0066	***	0.0077	***	0.0077	***	0.0018	***
distance to nearest major road (km)	−0.0001		−0.0255	***	−0.0286	***	−0.0400	***
distance to nearest river (km)	−0.0134	***	−0.0486	***	−0.0453	***	−0.0219	***
distance to nearest settlement (km)	−0.0141	***	−0.0108	***	−0.0102	***	0.0043	***
Time Stage								
1995–1999	3.0376	***	3.1577	***	3.2393	***	2.1384	***
2000–2004	4.8238	***	4.6296	***	4.6495	***	3.9556	***
2005–2009	4.8477	***	5.7932	***	5.7349	***	4.3725	***
2010–2014	4.4621	***	6.4641	***	6.3902	***	4.4753	***
2015–2020	4.0087	***	7.0402	***	6.9455	***	4.7319	***

* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

Table A2
Point level, staggered DID logistic model result, Dependent variable is the deforestation status on sample plot i in year t.

	Timber vs Control		Overlap vs Control	
Concession type.Timber	0.3459	***		
Concession type.Overlap			0.8532	***
Post Issuance × Concession	−0.0872	***	0.0942	*
temperature (K)	1.3614	***	−0.2098	***
annual rainfall (m)	0.1606	***	−0.9696	***
roundwood price (k GYD)	0.0147	***	−0.0082	**
gold price (k GYD)	0.0014	***	−0.0019	***
labor force (k people)	0.0225	***	0.0266	***
distance to nearest harbor (km)	−0.0067	***	0.0077	***
distance to nearest major road (km)	−0.0002		−0.0256	***
distance to nearest river (km)	−0.0137	***	−0.0486	***
distance to nearest settlement (km)	−0.0139	***	−0.0109	***
Time Stage				
1995–1999	3.0454	***	3.1426	***
2000–2004	4.8481	***	4.6031	***
2005–2009	4.8784	***	5.7630	***
2010–2014	4.5021	***	6.4331	***
2015–2020	4.0670	***	7.0021	***

* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

Table A3
Point level, fixed effect logistic model result, Dependent variable is the deforestation status on sample plot i in year t, using 2006–2015 data.

	Timber vs Control		Overlap vs Control		Overlap vs Timber	
Degraded						
Concession type.Timber	0.1047	*				
Concession type. Overlap			0.3413	**	0.1754	***
temperature (K)	1.1408	***	−0.1989	***	−0.0686	
annual rainfall (m)	0.6179	***	−0.5639	***	−0.6878	***
roundwood price (k GYD)	−0.0079	***	0.0081	***	0.0066	***
gold price (k GYD)	−0.0009	**	−0.0005		−0.0003	
labor force (k people)	0.0464	***	0.0183	***	0.0211	***
distance to nearest harbor (km)	−0.0060	***	0.0007	*	0.0004	
distance to nearest major road (km)	0.0003		−0.0279	***	−0.0266	***
distance to nearest river (km)	−0.0560	***	−0.0164	***	−0.0123	***
distance to nearest settlement (km)	−0.0105	***	−0.0092	***	−0.0103	***
Post 2009	−0.6400	***	0.2635	***	0.2204	***
Deforested						
Concession type.Timber	0.3097	***				
Concession type. Overlap			0.9642	***	0.0964	
temperature (K)	1.6699	***	−0.1024		0.0157	
annual rainfall (m)	0.2626	***	−0.6811	***	−0.6312	***
roundwood price (k GYD)	−0.0126	***	0.0087	***	0.0079	**
gold price (k GYD)	−0.0015	**	−0.0001		−0.0004	
labor force (k people)	0.0487	***	0.0452	***	0.0437	***
distance to nearest harbor (km)	−0.0060	***	0.0075	***	0.0078	***
distance to nearest major road (km)	−0.0027		−0.0239	***	−0.0262	***
distance to nearest river (km)	−0.0060	*	−0.0450	***	−0.0432	***
distance to nearest settlement (km)	−0.0152	***	−0.0113	***	−0.0107	***
Post 2009	−0.6408	***	0.2007		0.2043	

* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

6. Discussion and conclusions

Governments use a variety of mechanisms to manage resources in publicly owned forests. These forests may hold valuable timber or minerals or be converted to grazing or cropland. With growing concern over climate change and recognition that deforestation and forest degradation lead to significant CO2 emissions, efforts have been made to understand better how various approaches to managing tropical forests influence deforestation and forest degradation. In particular, timber and mining leases have been widely used throughout the tropics and can influence forest degradation and deforestation rates. Perhaps more importantly, in some countries, different agencies sometimes compete to control the same government-owned forest, resulting in overlapping leases for timber and mining. It is unclear in the literature whether these overlap forest use leases influence deforestation and degradation.

We deployed a novel dataset that allows us to account not only for deforestation but also forest degradation. We focus on Guyana because of its unique forest context (high forest cover low deforestation rates) and a long history of forestry and mining uses of forestland and overlapping legally approved tenure. For the analysis, we use spatial multinomial logistic regression models to measure the impact of logging

Table A4
The results of staggered multinomial logistic DID model.

	Timber vs Control				Overlap vs Control			
	Degraded		Deforested		Degraded		Deforested	
Concession type.Timber	0.1564	**	0.2847	***				
Concession type.Overlap					0.3550	**	0.6800	***
Post Issuance × Concession	−0.0856	***	0.0411		−0.0189		0.3676	***
temperature (K)	1.1407	***	1.6696	***	−0.1939	***	−0.1862	**
annual rainfall (m)	0.6064	***	0.2679	***	−0.5673	***	−0.6217	***
roundwood price (k GYD)	−0.0078	***	−0.0126	***	0.0081	***	0.0090	***
gold price (k GYD)	−0.0009	**	−0.0015	**	−0.0005		−0.0001	
labor force (k people)	0.0473	***	0.0482	***	0.0185	***	0.0425	***
distance to nearest harbor (km)	−0.0062	***	−0.0060	***	0.0007	*	0.0073	***
distance to nearest major road (km)	0.0001		−0.0026		−0.0279	***	−0.0239	***
distance to nearest river (km)	−0.0565	***	−0.0058	*	−0.0165	***	−0.0439	***
distance to nearest settlement (km)	−0.0102	***	−0.0153	***	−0.0091	***	−0.0122	***
Post-2009	−0.6302	***	−0.6454	***	0.2624	***	0.2142	
* p < 0.1, ** p < 0.05, *** p < 0.01								

Table A5
The results of sub-group staggered multinomial logistic DID model.

Timber Sales Agreement (TSA)	Timber vs Control		Overlap vs Control	
Degraded				
Concession type.Timber	−0.8788	***		
Concession type.Overlap			−0.0942	
Post Issuance × Concession	0.4050	***	0.3843	***
Deforested				
Concession type.Timber	−1.8734	***		
Concession type.Overlap			0.0355	
Post Issuance × Concession	1.8735	***	0.9445	***
State Forest Permits (SFP)	Timber vs Control		Overlap vs Control	
Degraded				
Concession type.Timber	0.3535	***		
Concession type.Overlap			0.7469	***
Post Issuance × Concession	−0.1068	***	−0.0810	
Deforested				
Concession type.Timber	0.6094	***		
Concession type.Overlap			0.8781	***
Post Issuance × Concession	−0.2620	***	0.3905	***
* p < 0.1, ** p < 0.05, *** p < 0.01				

and mineral concession rights on deforestation and forest degradation in Guyana from 1990 to 2020. Compared to our control, state-owned unallocated forest, we find most concessions have a significant positive impact on forest degradation and deforestation on average, but the impact varies in different types of forest concessions, depending on the length of their lease. In Guyana, a timber concession in state-owned forest increases the deforestation probability by 33.5 % compared to unallocated forest, and a mining concession will increase the deforestation probability by three times.

Though we would expect higher deforestation from the compounded effect higher probability of deforestation associated with logging and mining leases, we find overlap concession areas have a higher probability of deforestation and forest degradation compared to timber-only concession areas, but lower than areas that are mining-only concessions. The result confirms that overlapping land allocation could disincentivize sustainable forest management and increase deforestation. We recommend further studies to disentangle the indirect drivers of deforestation in overlapping areas.

Our results suggest that the likelihood of deforestation varies in different concession types. However, unlike the suggestion by Gray (2002), we find that large concessions with longer length of authorization (TSAs) have lower deforestation probability than small concessions with shorter length of authorization (SFPs). There are some possible reasons for this result. First, SFPs are closer to settlements and harbors compared to TSAs (Fig. A2) and have more access to major and minor roads (Fig. A3). Thus, it is easier for landowners to harvest and transport timber logs from SFPs. Second, since Guyana has strict harvest restrictions, concession owners with short authorization length could tend to reach the upper limit of harvest to maximize their profits.

Due to the limitation of the available data, our study does not have access to the complete information for each timber concession. We only have access to the issue time of currently valid timber concessions, however, if other concessions were valid on the same area before the current concession, we don't have access to the time that previous concessions were issued. In our analysis, we assume the issue time of currently valid timber concessions are the first issuance, then apply the staggered DID analysis. The results indicate that, in most cases, the probability of forest degradation and deforestation can change significantly before and after the concession issuance year. Our results could be more convincing if we could get more detailed issuance information for each timber concession.

Our study provides useful policy implications related to forest management in tropical countries. Unlike some countries where regulated timber extraction can help preserve tropical forests (Gaveau et al.,

Table A6
The results of multinomial logistic fixed-effect and sub-group staggered DID model, with 2-year lagged gold price.

	Mining vs Control		Overlap vs Control		Overlap vs Timber		Overlap vs Control (DID)	
Degraded								
Concession type.Mining	0.3449	***						
Concession type.Overlap			0.1921	*	0.1689	***	0.2891	***
Post Issuance × Concession							−0.1572	***
2-year lagged gold price (k GYD)	0.0006		0.0015	***	0.0017	***	0.0018	***
Deforested								
Concession type.Mining	1.3981	***						
Concession type.Overlap			0.9396	***	0.0940	**	0.9090	***
Post Issuance × Concession							0.0482	
2-year lagged gold price (k GYD)	0.0022	***	0.0024	***	0.0023	***	0.0023	***
p < 0.1 *, p < 0.05 **, p < 0.01 ***								

Table A7
The results of multinomial logistic fixed-effect and sub-group staggered DID model, with 2-year lagged timber price.

	Timber vs Control		Overlap vs Control		Overlap vs Timber		Overlap vs Control (DID)	
Degraded								
Concession type.Timber	0.0953	**						
Concession type.Overlap			0.1958	*	0.1717	***	0.2873	***
Post Issuance × Concession							−0.1494	***
2-year lagged timber price (k GYD)	0.0092	***	0.0088	***	0.0097	***	0.0075	***
Deforested								
Concession type.Timber	0.2928	***						
Concession type.Overlap			0.9415	***	0.0957	**	0.9111	***
Post Issuance × Concession							0.0481	
2-year lagged timber price (k GYD)	0.0082	***	0.0049	***	0.0052	***	0.0054	***
$p < 0.1$ *, $p < 0.05$ **, $p < 0.01$ ***								

Table A8
Point level fixed effect multinomial logistic result, Dependent variable i 1 s the deforestation status on sample plot i in year t, timber concession is TSA and SFP combined, time period is from 1990 to 2020. Coefficients represent odds ratio.

	Timber vs Control		Overlap vs Control		Timber vs Overlap		Mining vs Control	
Degraded								
Concession type.Timber	1.0889	*						
Concession type.Overlap			1.1856		1.1912	***		
Concession type.Mining							1.4160	***
temperature (K)	2.6402	***	0.9898		1.0525		1.2901	***
annual rainfall (m)	1.5697	***	0.5228	***	0.4618	***	0.8706	***
roundwood price (k GYD)	1.0123	***	0.9931	***	0.9927	***	0.9965	*
gold price (k GYD)	1.0034	***	1.0013	***	1.0010	**	1.0028	***
labor force (k people)	1.0190	***	1.0164	***	1.0181	***	1.0119	***
distance to nearest harbor (km)	0.9933	***	1.0022	***	1.0016	***	1.0016	***
distance to nearest major road (km)	1.0017	**	0.9762	***	0.9768	***	0.9617	***
distance to nearest river (km)	0.9551	***	0.9844	***	0.9885	***	0.9940	***
distance to nearest settlement (km)	0.9904	***	0.9910	***	0.9900	***	0.9976	***
Deforested								
Concession type.Timber	1.3352	***						
Concession type.Overlap			2.5578	***	1.0913			
Concession type.Mining							4.0359	***
temperature (K)	4.0077	***	0.8140	***	0.8823	**	1.3090	***
annual rainfall (m)	1.1970	***	0.3758	***	0.3807	***	0.9219	*
roundwood price (k GYD)	1.0152	***	0.9918	***	0.9916	**	1.0046	
gold price (k GYD)	1.0014	***	0.9982	***	0.9982	***	1.0001	
labor force (k people)	1.0227	***	1.0280	***	1.0272	***	1.0217	***
distance to nearest harbor (km)	0.9933	***	1.0077	***	1.0078	***	1.0018	***
distance to nearest major road (km)	0.9999		0.9745	***	0.9715	***	0.9604	***
distance to nearest river (km)	0.9859	***	0.9524	***	0.9556	***	0.9784	***
distance to nearest settlement (km)	0.9859	***	0.9892	***	0.9898	***	1.0043	***
$p < 0.1$ *, $p < 0.05$ **, $p < 0.01$ ***								

Table A9
Point level difference-in-differences multinomial logistic 1 result, Dependent variable is the deforestation status on sample plot i in year t, timber concession is TSA and SFP combined, time period is from 1990 to 2016. Coefficients represent odds ratio.

	Timber vs Control				Overlap vs Control			
	Degraded		Deforested		Degraded		Deforested	
Concession type.Timber	1.2412	***	1.2213	***				
Concession type.Overlap					1.4507	***	2.1954	***
Post Issuance × Concession	0.8526	***	0.9786		0.9044	***	1.3542	***
temperature (K)	3.1333	***	4.4683	***	1.2674	***	1.1588	**
annual rainfall (m)	1.5807	***	1.0209		0.5827	***	0.4739	***
roundwood price (k GYD)	1.0285	***	1.0234	***	1.0068	*	1.0063	
gold price (k GYD)	0.9997		0.9999		1.0009	**	1.0005	
labor force (k people)	1.0320	***	1.0310	***	1.0204	***	1.0369	***
distance to nearest harbor (km)	0.9931	***	0.9922	***	1.0015	***	1.0090	***
distance to nearest major road (km)	1.0045	***	1.0086	***	0.9715	***	0.9741	***
distance to nearest river (km)	0.9492	***	0.9859	***	0.9844	***	0.9551	***
distance to nearest settlement (km)	0.9866	***	0.9788	***	0.9909	***	0.9866	***
* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$								

2013; Panlasigui et al., 2018; Tritsch et al., 2020), the positive impacts of all types of concessions on deforestation suggest that all kinds of production activities in Guyana can cause forest degradation and deforestation. On one hand, this study offers insights from an under-studied location that differs from previous work because of the low deforestation pressure in unallocated forests. The results reflect the fact

Table A10
Point level, sub-group fixed effect multinomial logistic result, 1 Dependent variable is the deforestation status on sample plot i in year t. Coefficients represent odds ratio.

Timber Sales Agreement (TSA)	Timber vs Control		Overlap vs Control		Overlap vs Timber	
Degraded						
Concession type.Timber	0.5961	***				
Concession type.Overlap			1.0454		1.3131	***
Deforested						
Concession type.Timber	0.7277	***				
Concession type.Overlap			2.3040	***	1.0628	
State Forest Permits (SFP)	Timber vs Control		Overlap vs Control		Overlap vs Timber	
Degraded						
Concession type.Timber	1.3044	***				
Concession type.Overlap			1.5413	***	1.0145	
Deforested						
Concession type.Timber	1.6299	***				
Concession type.Overlap			2.5307	***	1.1149	

* p < 0.1, ** p < 0.05, *** p < 0.01

Table A11
Point level, sub-group staggered DID multinomial logistic result, Dependent variable is the deforestation status on sample plot i in year t. Coefficients represent odds ratio.

Timber Sales Agreement (TSA)	Timber vs Control		Overlap vs Control	
Degraded				
Concession type.Timber	0.4167	***		
Concession type.Overlap			0.8280	
Post Issuance × Concession	1.4710	***	1.4988	***
Deforested				
Concession type.Timber	0.1521	***		
Concession type.Overlap			1.2236	
Post Issuance × Concession	5.8088	***	2.3268	***
State Forest Permits (SFP)	Timber vs Control		Overlap vs Control	
Degraded				
Concession type.Timber	1.5348	***		
Concession type.Overlap			2.1345	***
Post Issuance × Concession	0.8447	***	0.8068	***
Deforested				
Concession type.Timber	1.7524	***		
Concession type.Overlap			2.4318	***
Post Issuance × Concession	0.6976	***	1.2503	***

* p < 0.1, ** p < 0.05, *** p < 0.01

that the Guyana government successfully preserved the forest resources on state owned lands, as a result, even well-regulated selective harvest activities in timber concessions can cause more deforestation than unallocated state-owned forest. It is also important to clarify the land allocation on the overlapping concession areas. The contrasting nature of the two activities, one focused on maintaining productive forests for timber extraction, and the other requiring the clearing of forests to access precious minerals are incompatible land uses. On overlapping concession areas, separating forests allocated for timber and forests allocated for mining concessions can help create clear management duties and remove obstacles towards forest conservation and restoration.

We certify that the article is the Authors' original work. The article has not received prior publication and is not under consideration for publication elsewhere. On behalf of all Co-Authors, the corresponding Author shall bear full responsibility for the submission. This research has not been submitted for publication, nor has it been published in whole or in part elsewhere. We attest to the fact that all Authors listed on the title page have contributed significantly to the work, have read the manuscript, attest to the validity and legitimacy of the data and its interpretation, and agree to its submission to Word Development.

CRediT authorship contribution statement

Bingcai Liu: Methodology, Formal analysis, Visualization, Project administration, Data curation, Software, Writing – original draft, Writing – review & editing. **Anand Roopsind:** Conceptualization, Software, Visualization, Supervision, Data curation, Formal analysis, Writing – original draft, Writing – review & editing. **Brent Sohngen:** Conceptualization, Methodology, Formal analysis, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Acknowledgements

We thank Daniela Miteva for providing comments on preliminary drafts of the manuscript and FORAD consortium for the assistance and comments. And we appreciate two reviewers for their constructive comments on the paper. We also express our gratitude to the researchers and data analysts who have compiled the multiple global datasets and statistics that we employed in our analysis. Anand Roopsind acknowledges financial support from NASA (grant number: 80NSSC20K1491).

Appendix

References

Agrawal, A., Nepstad, D., & Chhatre, A. (2011). Reducing emissions from deforestation and forest degradation. *Annual Review of Environment and Resources, 36*(1), 373–396. https://doi.org/10.1146/annurev-environ-042009-094508
Alin, A. (2010). Multicollinearity. *WIREs Computational Statistics, 2*(3), 370–374. https://doi.org/10.1002/wics.84
Anderson, C. M., Asner, G. P., Llactayo, W., & Lambin, E. F. (2018). Overlapping land allocations reduce deforestation in Peru. *Land Use Policy, 79*, 174–178. https://doi.org/10.1016/j.landusepol.2018.08.002
Angelsen, A., Brockhaus, M., Sunderlin, W. D., & Verchot, L. (2009). *Realising REDD+: National Strategy and Policy Options*. CIFOR.
Architecture for REDD+ Transactions. (2022). *ART Issues World's First Jurisdictional Forestry TREES Carbon Credits to Guyana*. https://www.artredd.org/art-issues-worlds-first-jurisdictional-forestry-carbon-credits-to-guyana/.
Arets, E. J. M. M. (2005). Long-term responses of populations and communities of trees to selective logging in tropical rain forests in Guyana. *Utrecht University*. https://dspace.library.uu.nl/handle/1874/1274.
Arsenault, C. (2021, December 15). *Amazon Deforestation Is Rising. Guyana Offers a Rare Bright Spot*. Pulitzer Center. https://pulitzercenter.org/stories/amazon-deforestation-rising-guyana-offers-rare-bright-spot.
Athey, S., & Imbens, G. W. (2022). Design-based analysis in Difference-In-Differences settings with staggered adoption. *Journal of Econometrics, 226*(1), 62–79. https://doi.org/10.1016/j.jeconom.2020.10.012
Blackman, A., & Villalobos, L. (2021). Use Forests or Lose Them? Regulated Timber Extraction and Tree Cover Loss in Mexico. *Journal of the Association of Environmental and Resource Economists, 8*(1), 125–163. https://doi.org/10.1086/710837
Blaser, J., Sarre, A., Poore, D., & Johnson, S. (2011). *Status of Tropical Forest Management 2010, No 38.)*. International Tropical Timber Organization. ITTO Technical Series.
Bovolo, C. I., Wagner, T., Parkin, G., Hein-Griggs, D., Pereira, R., & Jones, R. (2018). The Guiana Shield rainforests—Overlooked guardians of South American climate. *Environmental Research Letters, 13*(7), Article 074029. https://doi.org/10.1088/1748-9326/aacf60
Bulkan, J. (2014). Forest grabbing through forest concession practices: The case of Guyana. *Journal of Sustainable Forestry, 33*(4), 407–434. https://doi.org/10.1080/10549811.2014.899502

Busch, J., & Ferretti-Gallon, K. (2017). What drives deforestation and what stops it? A meta-analysis. *Review of Environmental Economics and Policy, 11*(1), 3–23. https://doi.org/10.1093/reep/rew013

Chervier, C., Ximenes, A. C., Mihigo, B.-P.-N., & Doumenge, C. (2024). Impact of industrial logging concession on deforestation and forest degradation in the DRC. *World Development, 173*, Article 106393. https://doi.org/10.1016/j.worlddev.2023.106393

De Los Rios, C. (2022). The double fence: Overlapping institutions and deforestation in the Colombian Amazon. *Ecological Economics, 193*, Article 107274. https://doi.org/10.1016/j.ecolecon.2021.107274

De Maesschalck, R., Jouan-Rimbaud, D., & Massart, D. L. (2000). The Mahalanobis distance. *Chemometrics and Intelligent Laboratory Systems, 50*(1), 1–18. https://doi.org/10.1016/S0169-7439(99)00047-7

Edwards, F. A., Edwards, D. P., Larsen, T. H., Hsu, W. W., Benedick, S., Chung, A., Vun Khen, C., Wilcove, D. S., & Hamer, K. C. (2014). Does logging and forest conversion to oil palm agriculture alter functional diversity in a biodiversity hotspot? *Animal Conservation, 17*(2), 163–173. https://doi.org/10.1111/acv.12074

Fortmann, L., Sohngen, B., & Southgate, D. (2017). Assessing the Role of Group Heterogeneity in Community Forest Concessions in Guatemala's Maya Biosphere Reserve. *Land Economics, 93*(3), 503–526. https://doi.org/10.3368/le.93.3.503

FSC International Center Guidance for Demonstrating Ecosystem Services Impacts 2021 https://open.fsc.org/handle/resource/336.

Gaveau, D. L. A., Kshatriya, M., Sheil, D., Sloan, S., Molidena, E., Wijaya, A., Wich, S., Ancrenaz, M., Hansen, M., Broich, M., Guariguata, M. R., Pacheco, P., Potapov, P., Turubanova, S., & Meijaard, E. (2013). Reconciling Forest Conservation and Logging in Indonesian Borneo. *PLoS One1, 8*(8), e69887.

Giller, K. E., Leeuwis, C., Andersson, J. A., Andriesse, W., Brouwer, A., Frost, P., Hebinck, P., Heitkönig, I., van Ittersum, M. K., Koning, N., Ruben, R., Slingerland, M., Udo, H., Veldkamp, T., van de Vijver, C., van Wijk, M. T., & Windmeijer, P. (2008). Competing Claims on Natural Resources: What Role for Science? *Ecology and Society, 13*(2). https://www.jstor.org/stable/26267992.

Gray, J. A. (2002). *Forest concession policies and revenue systems: country experience and policy changes for sustainable tropical forestry*. World Bank Publications.

Griscom, B. W., Adams, J., Ellis, P. W., Houghton, R. A., Lomax, G., Miteva, D. A., … Fargione, J. (2017). Natural climate solutions. *Proceedings of the National Academy of Sciences, 114*(44), 11645–11650. https://doi.org/10.1073/pnas.1710465114

Griscom, B. W., Busch, J., Cook-Patton, S. C., Ellis, P. W., Funk, J., Leavitt, S. M., … Worthington, T. (2020). National mitigation potential from natural climate solutions in the tropics. *Philosophical Transactions of the Royal Society B: Biological Sciences, 375* (1794), 20190126. https://doi.org/10.1098/rstb.2019.0126

Guyana Forestry Commission National Wood Tracking System 2013 http://www.unece.lsu.edu/ebusiness/documents/2015Mar/sc14-04.pdf.

Guyana Forestry Commission. (2018). *Guidelines for Forest Operations For State Forest Authorizations- Timber Sales Agreements, Wood Cutting License Holders, State Forest Exploratory Permits*. WCLs, SFEPs: SFA-TSAs. https://forestry.gov.gy/.

Guyana, & Norway. (2011). *Joint Concept Note on REDD+ cooperation between Guyana and Norway*. https://www.regjeringen.no/globalassets/upload/md/2011/vedlegg/klima/klima_skogprosjektet/guyana/jointconceptnote_31mars2011.pdf.

Guyana Office for Investment Forestry: Lumber for All Applications 2021 https://goinvest.gov.gy/portfolio/forestry-products/.

Hammond, D. S. (2015). Tropical forests of the Guiana shield: Ancient forests in a modern world. *CABI publishing.* https://www.cabidigitallibrary.org/doi/abs/10.1079/9780851995366.0000.

Hänggli, A., Levy, S. A., Armenteras, D., Bovolo, C. I., Brandão, J., Rueda, X., & Garrett, R. D. (2023). A systematic comparison of deforestation drivers and policy effectiveness across the Amazon biome. *Environmental Research Letters, 18*(7), Article 073001. https://doi.org/10.1088/1748-9326/acd408

Hansen, M. C., Potapov, P. V., Moore, R., Hancher, M., Turubanova, S. A., Tyukavina, A., Thau, D., Stehman, S. V., Goetz, S. J., Loveland, T. R., Kommareddy, A., Egorov, A., Chini, L., Justice, C. O., & Townshend, J. R. G. (2013). High-Resolution global maps of 21st-century forest cover change. *Science, 342*(6160), 850–853. https://doi.org/10.1126/science.1244693

Ho, D., Imai, K., King, G., & Stuart, E. A. (2007). Matching as nonparametric preprocessing for reducing model dependence in parametric causal inference. *Political Analysis, 15*(3), 199–236. https://doi.org/10.1093/pan/mpl013

Ho, D., Imai, K., King, G., & Stuart, E. A. (2011). MatchIt: Nonparametric Preprocessing for Parametric Causal Inference. *Journal of Statistical Software, 42*, 1–28. https://doi.org/10.18637/jss.v042.i08

Holland, M. B., de Koning, F., Morales, M., Naughton-Treves, L., Robinson, B. E., & Suárez, L. (2014). Complex Tenure and Deforestation: Implications for Conservation Incentives in the Ecuadorian Amazon. *World Development, 55*, 21–36. https://doi.org/10.1016/j.worlddev.2013.01.012

Humphrey, D. (2018). *Effective land administration—land administration in Guyana*. Deqing, Zhejiang, China: Deqing International Seminar on United Nations Global Geospatial Information Management.

Kwak, C., & Clayton-Matthews, A. (2002). Multinomial logistic regression. *Nursing Research, 51*(6), 404–410.

Laing, T. (2019). Small man goes where the large fears to tread: Mining in Guyana: 1990–2018. *Resources Policy, 63*, Article 101426. https://doi.org/10.1016/j.resourpol.2019.101426

Larson, A. M., Brockhaus, M., Sunderlin, W. D., Duchelle, A., Babon, A., Dokken, T., Pham, T. T., Resosudarmo, I. A. P., Selaya, G., Awono, A., & Huynh, T.-B. (2013). Land tenure and REDD+: The good, the bad and the ugly. *Global Environmental Change, 23*(3), 678–689. https://doi.org/10.1016/j.gloenvcha.2013.02.014

Meyfroidt, P., de Bremond, A., Ryan, C. M., Archer, E., Aspinall, R., Chhabra, A., zu, E. K. H. J., & Ermgassen. (2022). Ten facts about land systems for sustainability. *Proceedings of the National Academy of Sciences, 119*(7). https://doi.org/10.1073/pnas.2109217118

Mohren, F. (2019). Use tropical forests or lose them. *Nature Sustainability, 2*(1), Article 1. https://doi.org/10.1038/s41893-018-0211-0

Panlasigui, S., Rico-Straffon, J., Pfaff, A., Swenson, J., & Loucks, C. (2018). Impacts of certification, uncertified concessions, and protected areas on forest loss in Cameroon, 2000 to 2013. *Biological Conservation, 227*, 160–166. https://doi.org/10.1016/j.biocon.2018.09.013

Peters, P. E. (2009). Challenges in land tenure and land reform in africa: anthropological contributions. *World Development, 37*(8), 1317–1325. https://doi.org/10.1016/j.worlddev.2008.08.021

Pfaff, A. S. P. (1999). What drives deforestation in the Brazilian Amazon?: Evidence from satellite and socioeconomic data. *Journal of Environmental Economics and Management, 37*(1), 26–43. https://doi.org/10.1006/jeem.1998.1056

planetGOLD. (2022). *Converting to mercury free by 2025*. https://www.planetgold.org/guyana.

Putz, F. E., Zuidema, P. A., Synnott, T., Peña-Claros, M., Pinard, M. A., Sheil, D., Vanclay, J. K., Sist, P., Gourlet-Fleury, S., Griscom, B., Palmer, J., & Zagt, R. (2012). Sustaining conservation values in selectively logged tropical forests: The attained and the attainable. *Conservation Letters, 5*(4), 296–303. https://doi.org/10.1111/j.1755-263X.2012.00242.x

Rainforest Foundation US. (2022). *Guyana*. Rainforest Foundation US. https://rainforestfoundation.org/our-work/where-we-work/guyana/.

Romero, C., & Putz, F. E. (2018). Theory-of-Change Development for the Evaluation of Forest Stewardship Council Certification of Sustained Timber Yields from Natural Forests in Indonesia. *Forests, 9*(9), Article 9. https://doi.org/10.3390/f9090547

Roopsind, A., Sohngen, B., & Brandt, J. (2019). Evidence that a national REDD+ program reduces tree cover loss and carbon emissions in a high forest cover, low deforestation country. *Proceedings of the National Academy of Sciences, 116*(49), 24492–24499. https://doi.org/10.1073/pnas.1904027116

Runting, R. K., Ruslandi, Griscom, B. W., Struebig, M. J., Satar, M., Meijaard, E., Burivalova, Z., Cheyne, S. M., Deere, N. J., Game, E. T., Putz, F. E., Wells, J. A., Wilting, A., Ancrenaz, M., Ellis, P., Khan, F. A. A., Leavitt, S. M., Marshall, A. J., Possingham, H. P., … Venter, O. (2019). Larger gains from improved management over sparing–sharing for tropical forests. *Nature Sustainability*, *2*(1), Article 1. https://doi.org/10.1038/s41893-018-0203-0.

Singh, J. (2021). Guyana REDD+ Monitoring Reporting & Verification System (MRVS) MRVS Report – Assessment Year 2020. *Guyana Forestry Comission.* https://forestry.gov.gy/wp-content/uploads/2021/10/Guyana-MRVS-Assessment-Year-2020-Report-Final-September-2021.pdf.

Tegegne, Y. T., Cramm, M., Van Brusselen, J., & Linhares-Juvenal, T. (2019). Forest concessions and the united nations sustainable development goals: Potentials, challenges and ways forward. *Forests, 10*(1), Article 1. https://doi.org/10.3390/f10010045

ter Steege, H., & Hammond, D. S. (2001). Character convergence, diversity, and disturbance in tropical rain forest in Guyana. *Ecology, 82*(11), 3197–3212. https://doi.org/10.1890/0012-9658(2001)082[3197:CCDADI]2.0.CO;2

Tritsch, I., Le Velly, G., Mertens, B., Meyfroidt, P., Sannier, C., Makak, J.-S., & Houngbedji, K. (2020). Do forest-management plans and FSC certification help avoid deforestation in the Congo Basin? *Ecological Economics, 175*, Article 106660. https://doi.org/10.1016/j.ecolecon.2020.106660

Tyukavina, A., Potapov, P., Hansen, M. C., Pickens, A. H., Stehman, S. V., Turubanova, S., Parker, D., Zalles, V., Lima, A., Kommareddy, I., Song, X.-P., Wang, L., & Harris, N. (2022). Global Trends of Forest Loss Due to Fire From 2001 to 2019. *Frontiers in Remote Sensing, 3*. https://www.frontiersin.org/articles/10.3389/frsen.2022.825190.

UNEP, & FAO. (2020, May 21). *The State of the World's Forests: Forests, Biodiversity and People*. UNEP - UN Environment Programme. http://www.unep.org/resources/state-worlds-forests-forests-biodiversity-and-people.

United Nations, D. for P. C. and S. D. (1997). *Guyana Country Profile—Implementation of Agenda 21: Review of Progress Made Since the United Nations Conference on Environment and Development, 1992*. https://www.un.org/esa/earthsummit/guyan-cp.htm.

Vancutsem, C., Achard, F., Pekel, J.-F., Vieilledent, G., Carboni, S., Simonetti, D., Gallego, J., Aragão, L. E. O. C., & Nasi, R. (2021). Long-term (1990–2019) monitoring of forest cover changes in the humid tropics. *Science Advances*, *7*(10), eabe1603. https://doi.org/10.1126/sciadv.abe1603.

Walker, S., Alix-Garcia, J., Bartlett, A., Van Den Hoek, J., Friedrich, H. K., Murillo-Sandoval, P. J., & Isoto, R. (2023). Overlapping land rights and deforestation in Uganda: 20 years of evidence. *Global Environmental Change, 82*, Article 102701. https://doi.org/10.1016/j.gloenvcha.2023.102701

World Bank Group. (2019). Forest-Smart Mining: Identifying Good and Bad Practices and Policy Responses for Artisanal and Small-Scale Mining in Forest Landscapes. *World Bank*. https://doi.org/10.1596/32026