Environmental Research Letters

PAPER • OPEN ACCESS

Deforestation spillovers from oil palm sustainability certification

To cite this article: Robert Heilmayr *et al* 2020 *Environ. Res. Lett.* **15** 075002

Environmental Research Letters

OPEN ACCESS

RECEIVED
1 August 2019

REVISED
4 March 2020

ACCEPTED FOR PUBLICATION
11 March 2020

PUBLISHED
18 June 2020

PAPER

Deforestation spillovers from oil palm sustainability certification

Robert Heilmayr[1,2], Kimberly M Carlson[3,4] and Jason Jon Benedict[1]

1 Environmental Studies Program, University of California, Santa Barbara, CA, United States of America
2 Bren School of Environmental Science and Management, University of California, Santa Barbara, CA, United States of America
3 Department of Natural Resources and Environmental Management, University of Hawai'i, at Mānoa, Honolulu HI, United States of America
4 Department of Environmental Studies, New York University, New York, NY, United States of America

E-mail: rheilmayr@es.ucsb.edu

Keywords: forests, leakage, oil palm, indonesia, supply chains, impact evaluation

Supplementary material for this article is available online

Abstract

Environmental policies that impose restrictions within one location may be undermined or reinforced by 'spillover effects,' the movement of actors, processes, or knowledge to other locations. Such spillovers are an important consideration in the design of interventions seeking to reduce commodity driven deforestation. In these settings, global markets and mobile actors can move deforestation and conservation behaviors over large distances, complicating efforts to measure and manage spillovers. Here we quantify forest loss and conservation spillovers from the Roundtable on Sustainable Palm Oil (RSPO) certification system in Indonesian Borneo (Kalimantan). We examine whether spillovers from certification are transmitted through corporate groups (i.e. to non-certified, RSPO member-held plantations) or local agricultural markets (i.e. to lands near certified mills). We find that, from 2009 to 2016, spillovers from RSPO certification reduced deforestation within Indonesia's forest estate, but increased deforestation in areas zoned for agricultural use. The private RSPO certification system has complemented public conservation by aligning de facto land cover with central government land zoning policy. Despite these benefits, aggregate avoided deforestation attributed to direct and spillover effects was statistically and substantively insignificant when compared to the total deforestation occurring inside all of Kalimantan's oil palm concessions. While certification has reduced illegal deforestation, stronger sector-wide action appears necessary to ensure that oil palm production is no longer a driver of forest loss.

1. Introduction

In a tightly interconnected global market, environmental policies that impose restrictions in one locality can be undermined or reinforced by the movement of actors, processes, and knowledge to other locations, effects known as 'spillovers' [1]. Such spillovers impact the effectiveness of a broad array of policies such as carbon taxes [2], fishery catch shares [3], and protected areas [4]. Policy spillovers are a particularly important consideration in the design of forest conservation initiatives. Protected areas [5], payments for ecosystem services [6], and corporate zero-deforestation commitments [7] may underperform their objectives if they displace the activities (e.g. logging) that they are designed to prevent. On the other hand, conservation policies may yield unexpected benefits if they change societal norms to promote conservation or transmit knowledge about more sustainable practices [8]. Quantifying the direction, magnitude and drivers of such spillovers is critical for ensuring the effectiveness of conservation policies [9].

From 2001 to 2015, production of highly traded, undifferentiated commodities drove around one quarter of global deforestation, and most such commodity-linked forest loss occurred in the tropics [10]. Since tropical commodities are often substitutable and are grown by thousands of diverse producers, policies targeting commodity-driven deforestation are thought to be particularly exposed to spillover effects [11, 12]. This is especially true of nonstate, market-driven policies such as voluntary sustainability certification and market exclusion mechanisms. Because these policies are often adopted heterogeneously across a landscape, they tend to affect only a portion of producers and therefore provide multiple opportunities for spillovers [7, 13–15]. Yet, much prior research on certification programs documented only their direct impacts on deforestation within the policy boundary or immediate surroundings [16, 17], while investigations into spillover effects have primarily focused on state-led programs such as protected areas and payments for ecosystem services [5, 9, 18, 19] (supplement section 3 (stacks.iop.org/ERL/15/075002/mmedia)). Here we seek to address this gap by providing a rigorous quantification of the spillovers emerging from certification by the Roundtable on Sustainable Palm Oil (RSPO).

Oil palm is the world's leading edible oil and an important cause of deforestation in Southeast Asia [20]. Third-party sustainability certification has been widely adopted by companies along oil palm supply chains and in 2019, around 20% of all palm oil was certified by the RSPO [21]. Certification signals to customers, importers, and investors that the oil palm products they handle meet environmental and social sustainability criteria [22] and may provide producers with monetary benefits in the form of price premia [23, 24].

To become certified, an oil palm mill and its associated 'supply base'—including planted oil palm managed by the company or smallholders with contractual ties to that company, and other lands claimed by the oil palm company—are audited against the RSPO's Principles and Criteria (P&C). The P&C include several criteria that confer forest protection. For example, certified producers should maintain riparian buffers and may not clear primary or High Conservation Value (HCV) forests. In Indonesia, such protections have reduced deforestation within certified supply bases [17]. However, no evaluations have estimated the effects of oil palm certification on land cover outside of certified supply bases. As a result, it remains unclear whether reductions in deforestation associated with certification were offset or enhanced by spillovers to other regions, actors, or commodities.

Here we aim to identify forest loss spillovers onto lands outside of RSPO certified supply bases that result from RSPO certification. Specifically, we ask: (1) What spillover effects on forests are most likely to occur under oil palm certification in Indonesia, and what are the potential mechanisms leading to these effects?; and (2) What is the direction and magnitude of spillovers near oil palm mills and within corporate groups that participate in certification?

We first develop logic around the plausible mechanisms of spillovers from RSPO certification in Indonesia based on the framework proposed by Pfaff and Robalino [8]. We then test for potential spillovers from RSPO certification in Kalimantan, Indonesian Borneo. To do so, we measure the exposure of non-certified forests to certification, either within corporate groups or local markets for fresh fruit bunches (FFB). Next, we quantify deforestation trends within these non-certified forests as a function of this exposure. By evaluating spatial patterns of empirically observed spillovers, we seek to link them to plausible causal mechanisms.

2. Deforestation spillovers in the oil palm sector

Previous assessments of the RSPO's impact on deforestation have measured the program's direct effects within certified supply bases [17, 25, 26]. In addition to this direct effect, the RSPO certification system may lead to 'intended' and 'unintended' spillovers that change deforestation rates outside of certified supply bases (figure 1, table 1). Intended spillovers emerge from requirements of the program that relate to changes in deforestation outside the policy footprint (here, RSPO-certified supply bases). In contrast, unintended spillovers are the secondary effects of the certification program. The expected spatial distribution and direction of these effects are summarized in table 1 and figure 1, while a full description of these mechanisms is provided in the supplement.

Intended spillovers may arise in two ways (table 1). First, RSPO member companies are required to follow rules that may reduce deforestation within their non-certified operations (figure 1(b)). Second, the RSPO's requirements for certified mills' FFB purchases from non-certified producers could reduce forest loss within the supply shed of a certified mill (figure 1(c)).

Five channels may drive unintended spillovers from certification [8] (figure 1(b)–(d)). First, under the 'input reallocation' channel, implementation of a conservation policy by an actor with limited access to capital can free up inputs that enable the actor to undertake additional deforestation or conservation outside the policy footprint [18, 27–29]. Such behavior could be enabled by the resources freed up through not cultivating areas set aside for conservation ('restriction-induced') or by the additional revenues generated from selling certified products at a price premium or higher yields due to improved management practices ('resource transfer-induced'). These spillovers would likely occur within non-certified, RSPO member-held oil palm concessions. Second, the 'market price' channel occurs when conservation policies change commodity production within the policy footprint and alter prices for the commodity, and/or the inputs of production. These price changes could either incentivize or disincentivize deforestation at global to local scales [30]. Third, in the 'learning' channel, actors learn new conservation practices or technologies from conservation programs, which may

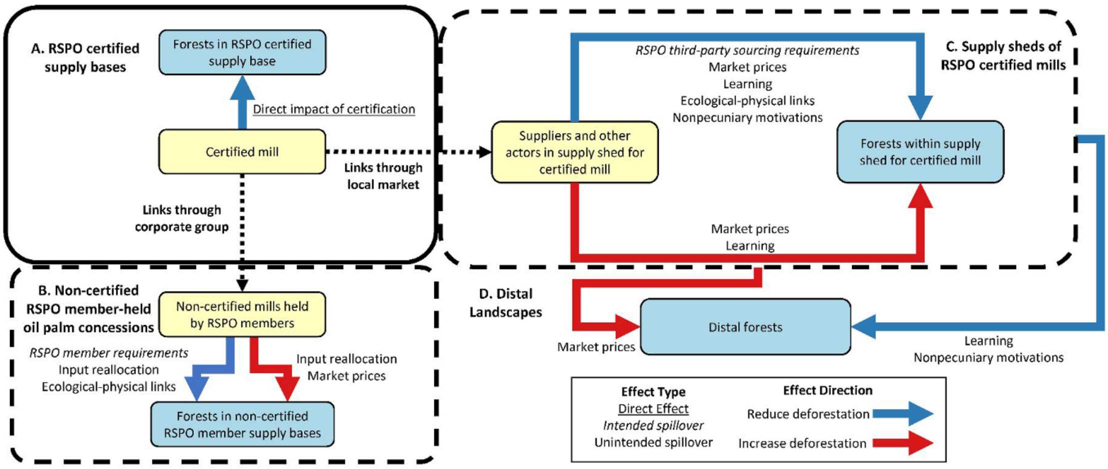

Figure 1. Conceptual diagram of the spatial distribution and direction of possible spillover channels from RSPO certification. See Supplement section 1 for full explanation of spillover dynamics and terms, and table 1 for a synthesis of these effects. Direct effects of certification (a) occur because certified mills must conform with the Roundtable on Sustainable Palm Oil (RSPO) certification standard, which requires protection of forests within RSPO certified supply bases. Certification also leads to intended and unintended effects outside of the certified supply base through changes in social system (e.g. the documentation third-party oil palm growers must provide to sell oil palm fruits to an RSPO certified mill) and natural system (e.g. reduced fire risk from protecting peatlands through certification) processes transmitted to local markets and/or corporate groups. Intended spillover effects are likely to occur because the certification system asks RSPO member corporate groups to move toward compliance with the standard for their non-certified concessions (b), and to source legal and responsible oil palm fruits from third-party growers from within the supply shed of RSPO certified mills (c). Unintended spillovers are potentially transmitted to distal landscapes far from certified mills (d), as well as non-certified supply bases held by RSPO member corporate groups (b) and supply sheds of certified mills (c) via spillover channels including input reallocation, market prices, learning, non-pecuniary motivations, and ecological-physical links. Spillovers can either increase (red arrow) or reduce (blue arrow) deforestation.

lead to additional forest conservation or loss [8]. Depending on the learning mechanism, this spillover could happen within certified mill supply sheds, in non-RSPO member concessions neighboring RSPO member company plantations, or in regions of oil palm expansion that include RSPO member companies. Fourth, 'nonpecuniary motivations,' including a program's alignment with social norms and perceptions of program equity, may influence an actor's decision to implement one or more components of the program and thereby enhance forest conservation [8]. If the program is considered inequitable or does not align with social norms, deforestation could also increase. This spillover is hypothesized to occur in lands controlled by actors within social networks that include RSPO-certified companies. Finally, 'ecological-physical links' occur when an intervention changes the trajectory of a natural system, such as fire risk (e.g. [31]), which then leads to changes in deforestation rates. These ecological effects may be concentrated in supply sheds of RSPO certified mills and/or in non-certified RSPO member-held oil palm concessions near RSPO certified plantations

3. Methods

3.1. Study area and sample

We focused on oil palm producing landscapes in Kalimantan, Indonesian Borneo. In 2018, Kalimantan produced about 15% [32, 33] of global palm oil and accounted for 55% of the RSPO-certified area in Indonesia [34]. Although parts of Kalimantan are still experiencing oil palm expansion into forests [30, 35], previous analyses suggest that RSPO certification significantly reduced deforestation in Kalimantan's certified supply bases [17].

We limited our analysis to oil palm producing landscapes to improve the comparability of our treatment and control points. We defined oil palm producing landscapes as locations within oil palm mill 'supply sheds.' To delineate these supply sheds, we developed a novel dataset of oil palm mills within Kalimantan (supplement section 4), and then estimated the area over which mills source FFB each year. Our mill database included annual (2004–2016) information on mill location, operational status, installed capacity (tonnes FFB hour^{-1}), and ownership. Then, we used previously digitized RSPO audit reports [17] to evaluate relationships between the distance to the mill and the share of a supply base area captured within that distance (supplement section 4.1.3). Based on this analysis, we define the 'supply shed' over which a mill sources FFB as a circle with a radius of 82 km.

We drew an evenly spaced, 2×2 km grid across the supply shed of all Kalimantan oil palm mills and sampled individual points at the intersection points of this grid (10889 points, representing 427556 km^2). To enable measurement of spillovers outside of industrial oil palm concession boundaries, we sampled across the broader landscape (i.e. within and outside of concession boundaries).

Table 1. Channels of Roundtable on Sustainable Palm Oil (RSPO) certification system impacts on deforestation. These include direct effects of certification within RSPO certified supply bases and spillovers outside of the policy footprint, including to areas within supply sheds of certified mills, to non-certified RSPO member-held oil palm concessions, and to other areas more distant from RSPO certification. Spillovers include both intended and unintended impacts of the RSPO certification system. Based on our knowledge of the certification system and literature review of spillover effects, we hypothesize the likely spatial distribution and direction of the effect. Empirical field-based research is required to test whether and how these proposed mechanisms lead to spillover effects. A full description of the mechanisms leading to these channels is provided in supplement section 1, and a visualization of these effects is available in figure 1.

Effect type	Category	Sub-category	Likely direction of effect	Likely distribution of effect	Description
Direct effect	n/a	n/a	Reduced deforestation	RSPO certified supply bases	To gain and maintain certification, oil palm companies must comply with the RSPO P&C, which during the study period required identification and protection of High Conservation Value (HCV) and primary forests within RSPO certified supply bases
Intended spillovers	RSPO member requirements	n/a	Reduced deforestation	Non-certified RSPO member-held oil palm concessions	The RSPO requires that all members conform with the Code of Conduct and the New Planting Procedure, which prohibit clearance of HCV areas and primary forests in non-certified RSPO member-held concessions
	RSPO third-party sourcing requirements	n/a	Reduced deforestation	Due to localized FFB markets, supply sheds of RSPO certified mills	The preamble to the 2013 RSPO certification standard asks certified mills to source from legal and responsible sources, which may change incentives for third party FFB suppliers (e.g. smallholders) to establish oil palm in forest estate lands where they are unlikely to be able to gain land title
Unintended spillovers	Input Reallocation	Restriction-induced	Reduced or increased deforestation	Non-certified RSPO member-held oil palm concessions: within non-HCV non-primary forest lands (clearance) or within HCV and/or primary forest lands (protection)	After conserving or avoiding forests due to certification, a producer with limited access to capital reallocates inputs that would have been used to clear these forests to convert other forests not protected by certification or to better protect forests already conserved
		Resource transfer-induced	Reduced or increased deforestation	Non-certified RSPO member-held oil palm concessions: within non-HCV non-primary forest lands (clearance) or within HCV and/or primary forest lands (protection)	Premiums for certified palm oil or higher yields due to best management practices increase revenues for certified producers; credit-constrained certified producers use this capital to invest in additional clearing or enhance forest protection
	Market Prices	Global price effects	Increased deforestation	Global frontiers of vegetable oil crop expansion	Reduced oil palm production due to restrictions on forest clearing by producers pursuing certification elevates global vegetable oil prices, and reduces prices for inputs to production
		Local price effects: fresh fruit bunch (FFB) prices	Reduced deforestation	Due to localized FFB markets, supply sheds of RSPO certified mills	Inability to sell non-certified or illegal FFB to certified mills reduces the farm-gate price of non-certified FFB near that mill and reduces profits from non-certified or illegal oil palm development
		Local price effects: mill overcapacity	Increased deforestation	Due to localized FFB markets, supply sheds of RSPO certified mills	Certified company supply base is smaller than planned due to RSPO-imposed land clearing restrictions, and associated certified mill pays higher prices to third-party FFB suppliers to meet capacity goals, incentivizing oil palm development

Table 1. (Continued.)

Effect type	Category	sub-category	Likely direction of effect	Likely distribution of effect	Description
Unintended spillovers	Market Prices	Local price effects: land prices	Increased deforestation	Due to localized FFB markets, supply sheds of RSPO certified mills	Companies that pursue certification preferentially convert non-forest lands, increasing the price of non-forest lands relative to forest lands
		Inputs to forest conversion: labor	Reduced deforestation	Because labor force lives on or near oil palm plantations, concentrated in supply sheds of RSPO certified mills	Reduction in labor demand for forest clearing reduces worker investment of earnings in development of land around plantation
		Inputs to forest conversion: equipment	Increased deforestation	Due to regional contractor markets, concentrated in regions of oil palm expansion that include RSPO member companies	Reduction in forest-clearing equipment demand reduces price of forest-clearing contract work
	Learning	Oil palm company to oil palm smallholder	Reduced or increased deforestation	Due to localized FFB markets, supply sheds of RSPO certified mills	Oil palm smallholders are trained on the RSPO standard by RSPO certified plantation companies; this training could lead to implementation of conservation practices (e.g. riparian buffer conservation) and/or increases in profits which could lead to additional land clearing by smallholders
		Oil palm company to company	Reduced deforestation	Within non-RSPO member plantations near RSPO member company plantations	Non-RSPO member oil palm grower companies located near RSPO member growers copy sustainability initiatives
		Oil palm company to third-party contractor	Reduced deforestation	Due to regionalized contractor markets, concentrated in regions of oil palm expansion that include RSPO member companies	Third-party contractors that work for RSPO certified companies learn about and implement legal requirements for forest conservation
	Nonpecuniary motivations	n/a	Reduced deforestation	Concentrated in lands controlled by actors within social networks that include RSPO-certified companies	Social norms and perceptions regarding the certification system lead to broader adoption of more 'sustainable' management practices
	Ecological-physical links	Fire	Reduced deforestation	Due to local effects of conservation on fire, supply sheds of RSPO certified mills	Improved peatland conservation and fire management generate greater forest resilience within the RSPO certified areas or in neighboring areas during droughts
		Rare, threatened, or endangered species	Reduced deforestation	Non-certified RSPO member-held oil palm concessions near RSPO certified plantations	Conservation actions by a certified company may lead to protection of a species, which can lead to greater forest conservation by an adjacent company undergoing certification due to the presence of the protected species

3.2. Deforestation

Our outcome metric is a binary variable indicating whether each forested point was deforested in a specific year from 2004 to 2016. We chose this time frame because it represents the temporal overlap between available deforestation (2000–2016) and oil palm mill capacity (2004–2016) data. We used Google Earth Engine [36] to extract year 2000 percent tree cover and a binary measure of annual tree cover loss from 2001 to 2016 [37]. We defined year 2004 forested pixels as locations with >90% tree cover in 2000, which were not planted with industrial scale oil palm, pulp, or rubber in 2000 [38], and which were not deforested between 2000 and 2004. We then created a variable to indicate deforestation of point i at time t ($defor_{i,t}$) that takes the value of 0 prior to deforestation and 1 in the year when a forested pixel was cleared. We dropped points from the dataset after they were deforested because we assumed no forest regrowth in previously deforested areas. Our deforestation metric does not differentiate between causes of forest loss (e.g. unintentional fire, or industry or small farmer clearance), or between land use/cover after clearance (e.g. oil palm, grassland, rubber). Because we lack maps of non-industrial high canopy cover land uses (e.g. smallholder rubber, fruit gardens, and oil palm) in year 2000, we were not able to exclude these from our forest layer. Thus, some observed 'deforestation' may be replanting or management of non-industrial tree crops.

3.3. Land use zones

Indonesia's land base can be broadly divided into forest estate (*kawasan hutan*, 66% of total land in Indonesia in 2018) and other use lands (APL; *areal pengunaan lain*) [39] (figure 2). To understand how RSPO certification's effects on deforestation vary with these political designations, we identified whether each sample was designated as forest estate or other use lands in 2008 [40]. Although we use this designation in our primary model specification, we explore an alternate specification using a 2018 map of the forest estate [41] in supplement section 2.

3.4. Management units

We controlled for time-invariant differences in land management and local attributes (e.g. topography, soil suitability, accessibility) through the inclusion of management unit fixed effects. We sought to define management units at the scale at which decisions were made by actors who control and use these lands. The management unit for each point was assigned through the following process. For the 11261 points that fell within one of 890 oil palm concessions [17], we assigned the oil palm concession as the management unit. For the remaining 22301 points that fell within one of 396 timber and pulp concessions [44, 45], we assigned the timber or pulp concession as the management unit. For the final 25951 points located outside of any concession, we assigned the local village (*Desa*) [46] as the management unit. Importantly, while concession maps indicate allocation of land by the Indonesian government to a specific company, other actors including smallholder farmers and companies often have competing claims to these lands [47, 48].

3.5. Intensity of exposure to certification

Certified oil palm supply bases and mills, and the year in which certification was initiated, were sourced from Carlson *et al* [17]. We used the date of a company's letter announcing its intent to certify as the start of certification. Using this information, we created a binary variable $D_{i,t}$ indicating whether each point i was located inside a certified concession in a given year t.

We measured spillovers by contrasting deforestation in non-certified locations with different levels of exposure to certified oil palm production. Specifically, we quantified the relationship between the intensity of exposure to certification on non-certified lands and the likelihood of deforestation on these lands. We measured the intensity of exposure to certification via the degree of certification of oil palm concessions held by a single RSPO member 'corporate group', and the degree of certification around a forested location ('local markets'), as described in equations (1) and (2).

- Corporate group: Some hypothesized spillover channels involve the transfer of knowledge or resources within a company (i.e. RSPO member requirements, input reallocation; figure 1, table 1). To capture exposure to certification through corporate group holdings, we calculated the proportion of each corporate group's Indonesian holdings $\left(G_{g,t}\right)$ that were certified in each year using equation (1). For every corporate group (g), we identified the concessions (s) under their control $\left(s \in S_g\right)$ in our dataset of all Indonesian oil palm concessions. We then used the area of each concession (A_s), and whether that concession was certified $\left(I_{cert_{p,t}=1}\right)$ in year t to calculate $G_{g,t}$.

$$G_{g,t} = \frac{\sum_{s=1}^{S_g} I_{cert_{s,t}=1} A_s}{\sum_{s=1}^{S_g} A_s} \tag{1}$$

- Local markets: A second set of channels is hypothesized to emerge within supply sheds of certified mills (i.e. RSPO third-party sourcing requirements, local price effects, inputs to forest conversion, oil palm company to smallholder learning, ecological physical links; figure 1, table 1). To capture these dynamics, we quantified the share of a point i's potential FFB market that was certified

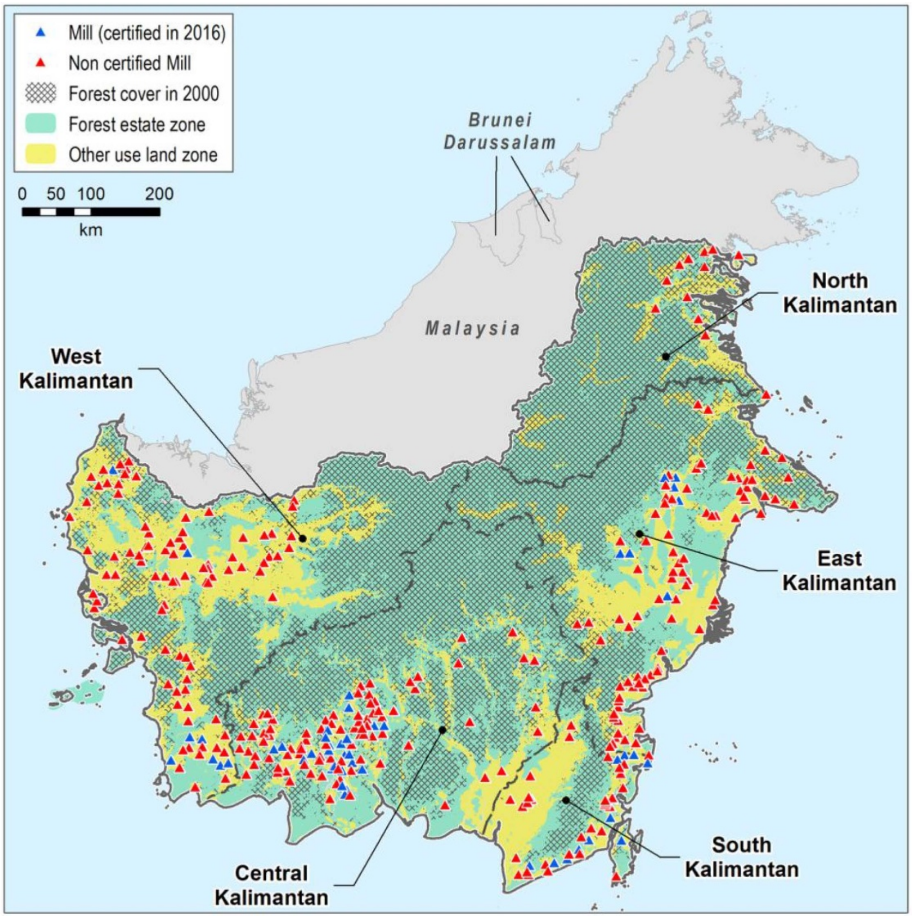

Figure 2. Roundtable on Sustainable Palm Oil (RSPO)-certified and non-certified oil palm mills in Kalimantan, Indonesian Borneo in 2016. Mills are overlaid on year 2000 forest cover and 2018 land zones. Oil palm can be legally grown on lands zoned as 'other use lands' (APL, areal pengunaan lain), but is largely illegal in the forest estate [42, 43].

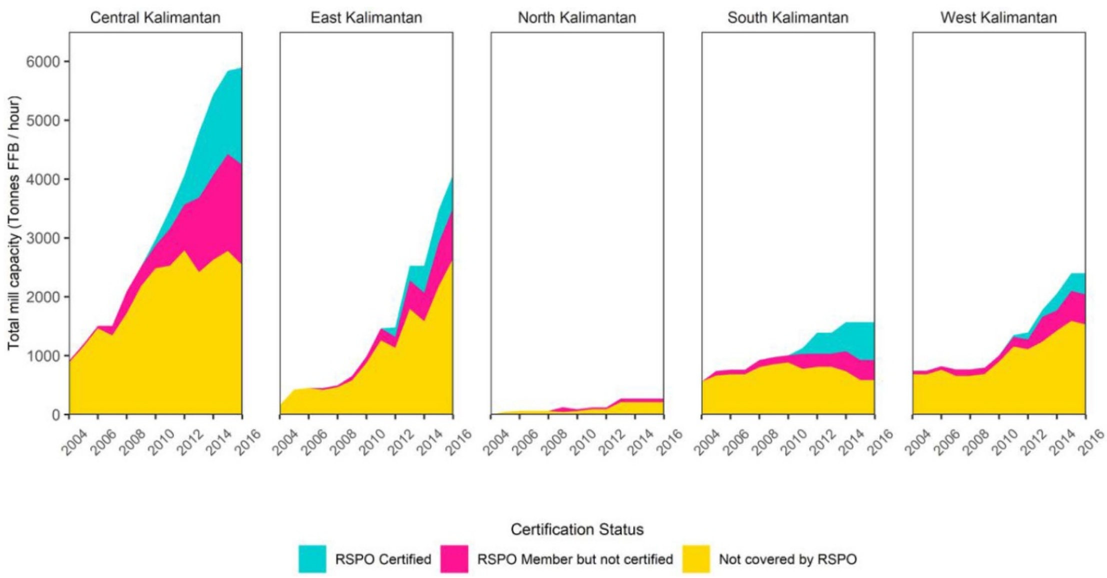

Figure 3. Trends in annual total installed oil palm mill capacity across five provinces in Kalimantan, Indonesian Borneo from 2004 to 2016. These include mills certified by the Roundtable on Sustainable Palm Oil (RSPO), non-certified mills held by RSPO member companies, and mills held by companies that were not RSPO members. FFB = fresh fruit bunches.

in year t. For each point in our sample, we identified each mill (m) within the point's supply shed ($m \in M_{i,t}$). For each of these mills, we determined the annual capacity of the mill ($C_{m,t}$) and whether the mill was certified $\left(I_{cert_{m,t}=1}\right)$. We then calculated the certified proportion of the point's local market ($L_{i,t}$) using equation (2).

$$L_{i,t} = \frac{\sum_{m=1}^{M_{i,t}} I_{cert_{m,t}=1} C_{m,t}}{\sum_{m=1}^{M_{i,t}} C_{m,t}} \tag{2}$$

3.6. Empirical model

We estimated a model of the likelihood that any point i, in corporate group g and management unit u, will be deforested in year t. We included management unit fixed effects (μ_u) to control for time-invariant, observable and unobservable characteristics of each unit (e.g. local suitability for oil palm production, corporate management). We included year fixed effects (γ_t) to control for time-varying characteristics such as changes in market conditions.

The full model specification (table 2, column 8) includes our measure of direct exposure to certification ($D_{i,t}$), as well as measures of indirect exposure to certification through certification intensity for corporate groups $\left(G_{g,t}\right)$ and local markets ($L_{i,t}$). To evaluate heterogeneity in spillover impacts based on land zoning, we included dummy variables indicating whether a point was designated as part of the forest estate (F_i). In alternate specifications, we explored the robustness of our full model results by including a single metric of certification exposure and removing land use zone interactions (table 2, columns 1–7).

Due to the low likelihood of deforestation events in our sample and our desire to simulate deforestation outcomes, we determined that a logit model would be more appropriate than a linear probability model. Using the binary variable of deforestation events ($defor_{i,t}$), we define $P_{i,u,t,g}$ as the probability that a location i will be deforested at time t. Thus, our primary logit model can be specified in terms of log odds using equation (3):

$$ln\left(\frac{P_{i,u,t,g}}{1-P_{i,u,t,g}}\right) = \alpha F_i D_{i,t} + \beta F_i L_{i,t} + \delta F_i G_{g,t} + \lambda F_i + \mu_u + \gamma_t \tag{3}$$

The vectors of coefficients β and δ estimate spillover effects occurring within and outside the forest estate (F_i). One challenge with the logit model is that the large number of unit-level fixed effects would yield biased coefficient estimates due to the incidental parameters problem. To address this concern, we estimated our model using a pseudo-demeaning algorithm [49] coupled with an analytical bias-correction [50] as implemented in the 'bife' package in R [51].

3.7. Simulations

To more clearly interpret our non-linear model, we predicted deforestation under two scenarios and quantified the aggregate impact of estimated direct and spillover effects. Our 'historical baseline' scenario modeled deforestation using observed patterns of certification. Our 'no certification' scenario explores a counterfactual world in which no mills or concessions received certification. In this latter scenario, we set variables representing direct exposure to certification ($D_{i,t}$), indirect exposure through a corporate group $\left(G_{i,g,t}\right)$, and indirect exposure through a local market ($L_{i,t}$) equal to zero for all points in all years. We interpret the difference between these two scenarios as a measure of the deforestation avoided or induced by certification and its spillovers.

For each scenario, we used the model presented in equation (3) to predict each observation's likelihood of deforestation $\hat{P}_{i,t}$. We then aggregated these predictions to estimate the total area of forests remaining in 2016 in each land use category (F_C) using equation (4).

$$F_C = \sum_{i \in C} \prod_{t=2004}^{2016} \left(1 - \hat{P}_{i,t}\right) \tag{4}$$

To quantify uncertainty in our simulated forest areas, we repeated this process using a Monte Carlo simulation. For each of 1000 repetitions, we took an independent draw from the coefficient estimates and covariance matrix generated through estimation of equation (3). We then compared the forest area remaining in different land use zones under the no certification counterfactual to the forests remaining in the baseline scenario.

4. Results

4.1. Exposure to certification over time

Total Kalimantan palm oil mill capacity increased 496% from 2373 to 1145 tonnes of FFB hour^{-1} between 2004 and 2016 (figure 3). Mill investments were particularly pronounced in Central and East Kalimantan, where installed capacity increased 548% and 2450%, respectively. The first letter of intent to RSPO-certify a Kalimantan oil palm mill was issued on 12 March 2009. Subsequently, certification rates increased in all provinces except North Kalimantan. By 2016, 23% of total mill capacity in Kalimantan was certified, with an additional 25% attributed to non-certified mills held by RSPO member companies. The RSPO has also expanded its influence over plantations—by 2016, 8% of oil palm concession area had been certified and companies pursuing RSPO certification controlled an additional 13% of concessions.

4.2. Spillovers within corporate groups

As companies expanded certification into more of their operations, they did not significantly alter deforestation patterns across all their non-certified holdings (table 2—column 3). However, where their non-certified concessions overlapped with the forest

Table 2. Average partial effects of direct (i.e. certified supply bases) and indirect (i.e. non-certified supply bases held by RSPO members, and non-certified lands around certified mills) exposure to Roundtable on Sustainable Palm Oil (RSPO) certification in Kalimantan, Indonesian Borneo, from 2004 to 2016. Standard errors are given in parentheses. All models are identical except for differences in the included explanatory variables (rows).

	Model 1	Model 2	Model 3	Model 4	Model 5	Model 6	Model 7	Model 8
Certified	−0.0167[a] (0.0016)		−0.0159[a] (0.0018)		−0.0167[a] (0.0016)		−0.0160[a] (0.0018)	
Certified x Not forest estate		−0.0158[a] (0.0022)		−0.0158[a] (0.0023)		−0.0170[a] (0.0020)		−0.0166[a] (0.0021)
Certified x Forest estate		−0.0172[a] (0.0019)		−0.0157[a] (0.0023)		−0.0169[a] (0.0020)		−0.0153[a] (0.0024)
Certified share of parent company's holdings			−0.0061 (0.0038)				−0.0062 (0.0038)	
Certified share of parent company's holdings x Not forest estate				−0.0004 (0.0047)				−0.0037 (0.0048)
Certified share of parent company's holdings x Forest estate				−0.0144[b] (0.0057)				−0.0134[b] (0.0057)
Certified share of local mill capacity					0.0014 (0.0021)		0.0015 (0.0021)	
Certified share of local mill capacity x Not forest estate						0.0146[a] (0.0035)		0.0148[a] (0.0035)
Certified share of local mill capacity x Forest estate						−0.0049[b] (0.0024)		−0.0047 [c] (0.0024)
N. observations	553 019	553 019	553 019	553 019	553 019	553 019	553 019	553 019
N. points	48 157	48 157	48 157	48 157	48 157	48 157	48 157	48 157

[a]$p < 0.01$; [b]$p < 0.05$; [c]$p < 0.1$

estate, greater exposure to within-company certification was associated with reduced deforestation (table 2—column 4). The average partial effect of increasing the share of a company's certified holdings by 1 percentage point (pp) was a 0.0144 pp reduction ($p = 0.01$) in the likelihood of deforestation on forest estate portions of non-certified RSPO member-held concessions.

4.3. Local market spillovers

Elevated oil palm mill certification rates had no significant impact on the aggregate likelihood of deforestation in surrounding non-certified supply sheds (table 2—column 5). However, this null result masks heterogeneity in impacts across land use zones (table 2—column 6). The likelihood of deforestation on lands outside the forest estate increased

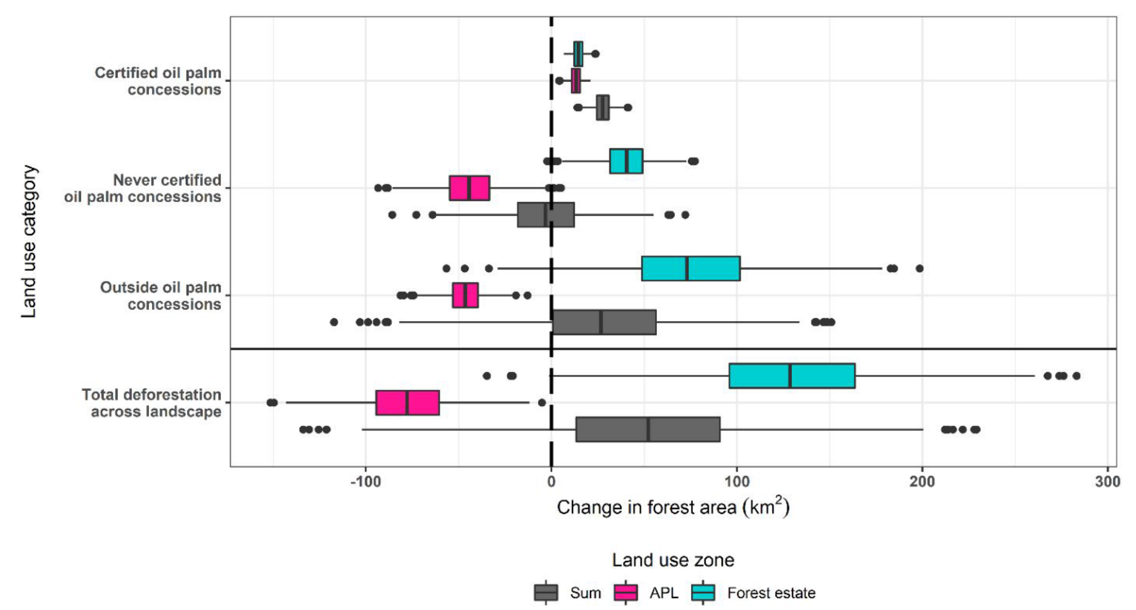

Figure 4. Simulated distribution of differences in forest area under historical baseline scenario including Roundtable on Sustainable Palm Oil (RSPO) certification in Kalimantan (Indonesian Borneo) and no-certification counterfactual scenario through 2016 (n = 1000 repetitions). Impacts are disaggregated by land use zone (colors) and concession types (rows). Box plot depicts the mean, simulated change in forest area (center line), the interquartile range of simulated changes (box edge), the last observations within ± 1.5×interquartile range (whisker edge) and outliers (points outside whisker).

with the local market's rate of certification, while deforestation in the forest estate was inversely related to certification intensity. Holding all else constant, the average partial effect of increasing the share of local market certification by 1 pp was a 0.0146 pp increase ($p < 0.01$) in deforestation outside the forest estate, and a 0.0049 pp decrease ($p = 0.05$) within the forest estate.

4.4. Aggregate impact of certification

Compared to the no-certification counterfactual, corporate group and local supply chain spillovers generated a statistically insignificant increase in total 2016 forest area outside of certified oil palm supply bases (median simulation = + 7 km^2, 0.025–0.975 quantile range = − 51 to + 97 km^2) (figures 4 and 5). However, these effects differed across land use zones. Spillovers had a clear conservation benefit within the forest estate (median simulation = + 49 km^2, 0.025–0.975 quantile range = + 7 to + 141 km^2), but induced deforestation in APL lands (median simulation = − 46 km^2, 0.025–0.975 quantile range = − 72 to − 18 km^2). The median simulation indicates that aggregate avoided deforestation from certification's direct and spillover effects in Kalimantan was 52 km^2. However, due to the large variance in simulated spillover effects, only 81% of simulations estimated a net increase in total Kalimantan forest area. This contrasts with the precisely estimated, positive direct impacts of certification in certified supply bases (median simulation = + 28 km^2, 0.025–0.975 quantile range = + 19 to + 37 km^2).

5. Discussion

5.1. Multiple spillover channels

Heterogeneity in the location, magnitude, and direction of spillovers (figure 4) suggests that RSPO certification affected deforestation on non-certified lands through multiple spillover channels. Since many of these channels may simultaneously affect deforestation dynamics, we are unable to isolate the individual effect of each channel. Instead, we compare observed spillovers (table 2) to the theoretically consistent directionality and spatial pattern of each spillover channel (table 1) to reflect on each channel's importance in this system.

We found no evidence that corporate groups with some already-certified plantations shifted deforestation towards not-yet-certified assets in Kalimantan. This result is unsurprising given that RSPO member growers are well-capitalized companies with access to credit, and certification is unlikely to increase company access to capital resources needed for additional oil palm development [18]. If input reallocation did support deforestation on non-certified holdings, it was offset by positive spillovers that reduced deforestation on these holdings. Indeed, forest loss within RSPO members' non-certified holdings zoned as forest estate decreased with increasing group certification rates. This pattern is consistent with the RSPO membership requirement that any forest estate land within member-held concessions be approved for release to APL before the company can begin the New Planting Procedure, a prerequisite for any new oil palm development [52]. RSPO members

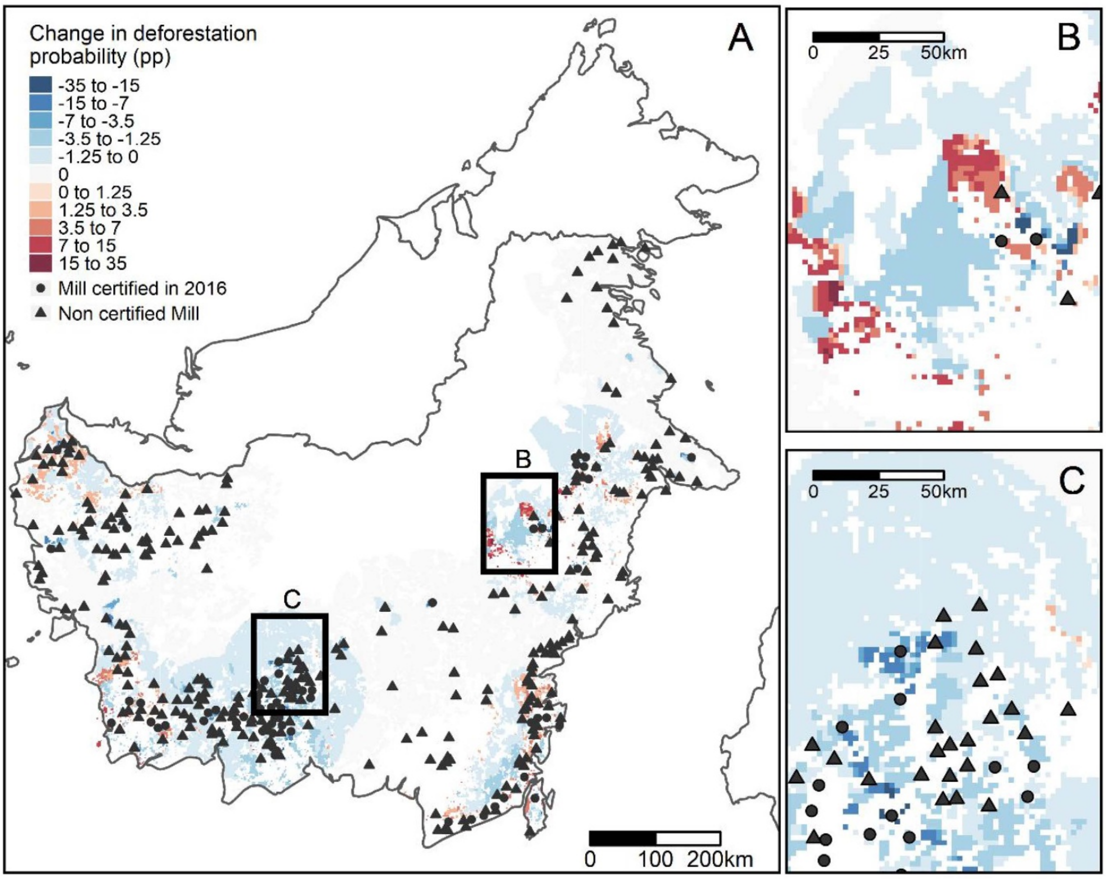

Figure 5. Spatial distribution of change in the cumulative likelihood of deforestation in Kalimantan, Indonesian Borneo from 2004 to 2016 resulting from Roundtable on Sustainable Palm Oil (RSPO) certification's direct and spillover effects (a). Values represent the median change (percentage points) in a pixel's mean probability of deforestation based on 1000 simulations. Effects occur in the supply sheds of RSPO-certified mills and those held by RSPO members where forest was present in 2004. Detailed insets depict a landscape with relatively few mills in East Kalimantan (B) and a landscape with many mills in Central Kalimantan (C). White areas represent locations that are not included in our study because they fall outside of Indonesian Borneo, fall outside the supply shed of all mills, and/or started the study period as deforested.

with more certified properties appear to be more effective at conserving forest estate forests on their non-certified properties, an effect potentially mediated by input reallocation or RSPO requirements for members.

Local market effects on forests outside of certified concessions differed according to a forest's land use zone. Elevated exposure to RSPO certification through local markets appeared to slow deforestation inside the forest estate, while promoting deforestation in APL lands. Most spillover channels with the potential to alter deforestation in areas near certified mills—including learning, ecological-physical links, and non-pecuniary motivations—are unlikely to differentially affect the forest estate and APL lands. Instead, this result is consistent with a scenario in which certified mills exerted pressure on their suppliers to meet the RSPO's legal and responsible aspirations in the preamble of the 2013 P&C (i.e. an intended spillover from RSPO third-party sourcing requirements). Specifically, certified mills may have required suppliers to present proof (e.g. land certificates, geographic coordinates) that their FFB were legally sourced from lands outside the forest estate. Such requirements may have induced market price effects (e.g. reduction in FFB prices from forest estate land) which are likely to enhance the conservation impact of certification in the forest estate. As a result, land clearing for oil palm that would have otherwise occurred in the forest estate may have instead happened on APL lands. Because third-party industrial scale growers are more likely to operate their own mills and/or have proof that their land claims are legal, we suspect this effect was mediated by smallholder farmer decision-making. Notably, requirements for legal sourcing from third-party FFB suppliers were made mandatory in the 2018 update to the RSPO P&C [53], which may lead to larger future spillover effects.

5.2. Public and private policy interactions

Our finding of heterogenous impacts across Indonesian land zones provides evidence that voluntary non-state certification systems can influence the effectiveness of public efforts to govern forests [54]. In Indonesia, deforestation within the forest estate is commonly undertaken by actors that range from large capitalized companies to small farmers [55], even though regulations require protection and/or sustainable management of these lands [56]. Although APL lands are zoned for non-forest uses such as agricultural and urban development and are considered political 'non-forests' [57], they contain extensive biophysical forests [56]. Our findings suggest that intended spillover effects from certification may enhance compliance with these central government policies. To assess the release of forest estate lands to APL between 2008 and 2018 and the relative rates of deforestation on these lands, we conducted further analyses presented in supplement section 2. This analysis provides additional evidence that actors within certified supply sheds may be sensitive to legal restrictions on the production of oil palm within the forest estate.

Such interactive private-public effects can be interpreted through a lens of state control. In Indonesia, where forests have long served as capital-generators for political elites [58], government officials have accused the RSPO of infringing on government sovereignty [59]. By changing economic conditions across land zones, RSPO certification systems have apparently introduced new economic incentives to actors in regions of oil palm production. The Indonesian government must now consider these novel dynamics in land use planning and policy implementation.

5.3. Implications for assessing certification's impact on forests

Although sustainability certification is primarily used to signal a high level of social and ecological responsibility of the products and producers that have been certified, there is also hope that certification will improve the environmental performance of the entire oil palm sector [60]. However, if certification induces significant displacement of deforestation outside of its policy boundaries, it is unlikely to reduce total deforestation associated with palm oil production [14]. Our analysis suggests that, rather than undermining public policy objectives, secondary effects of RSPO certification may reduce illegal deforestation outside of certified supply bases. However, any net benefit of RSPO certification for forest protection is extremely small in comparison to the scale of the deforestation challenge. We estimate that, since the first RSPO certificate was issued in 2009, Kalimantan's certified and non-certified oil palm concessions experienced 14432 km^2 of forest loss. Our maximum estimate of avoided deforestation from the RSPO's direct and indirect impacts is <2% of this clearing. It remains to be seen whether new requirements outlined in the 2018 P&C, including third-party sourcing restrictions and conservation of High Carbon Stock forests, will support the RSPO's efforts to achieve meaningful forest conservation.

By quantifying spillovers from certification, we are also able to increase confidence in estimates of the direct impacts of certification. Spillovers can violate assumptions underpinning the econometric models used to estimate the direct effects of certification. Panel models often used to assess the impact of conservation policies rely upon the Stable Unit Treatment Value Assumption (SUTVA) that the assignment of treatment to one set of units does not affect the outcomes observed in other units [61]. For example, if non-certified forests experienced increased rates of deforestation in response to certification of nearby mills, the direct impact of certification would be overestimated. By comparing the estimated impact of certification from a naïve model that does not account for spillovers (table 2—columns 1–2) to more complete models with spillovers (table 2—columns 7–8), we can assess the bias that might emerge from a SUTVA violation. We find that naïve and spillover model estimates are not substantively different, likely due to the existence of counteracting positive and negative spillovers in this specific certification system, landscape, and spatial extent.

5.4. Limitations and opportunities for future research

While our analysis provides one of the first assessments of deforestation spillovers generated from a sustainability certification system, several limitations highlight opportunities for future research. First, additional information on the actors (e.g. oil palm smallholder versus company) who clear forests and how certification changes the incentives that these actors face would help to disentangle the diverse spillover channels that are aggregated in this study's empirical estimates. Second, future studies could use a broader geographical scope to assess more distant and diffuse spillovers to other regions, both Indonesian (e.g. Papua, which is heavily forested and considered to be a new frontier of expansion) and global (e.g. oil palm development frontiers in Africa and South America). Third, certain market forces (e.g. diffusion of agricultural technologies, intensification responses) and ecological feedbacks (e.g. edge effects that lead to gradual forest cover loss in small patches) operate over long time scales and are unlikely to be captured in the first eight years of RSPO certification in Indonesia that we study. Researchers should continue to monitor the RSPO's impacts to assess these slower or lagged processes. Fourth, data on temporal dynamics in plantation ownership and sourcing would enable researchers to document resource shuffling, which refers to efforts to comply with policy requirements through asset swaps [62, 63]. Specifically, RSPO member companies could shift their portfolio of properties toward low-forest lands, which may simply reorganize ownership without reducing regional deforestation. Similarly, increasingly stringent RSPO regulations with respect to Indonesian law have led to revision of certified supply bases over time, and our oil palm concession database does not incorporate such dynamic certification boundaries. Fifth, while most of our datasets are annual time series, we only had access to maps reflecting 2008 and 2018 land zones. In Kalimantan during the study period, lands tended to be removed from, rather than added to, the forest estate [64]. We explored the sensitivity of our results to aggregate changes in the forest estate (supplement section 2), but future research using more frequent maps of the forest estate could provide a more nuanced assessment of how land zone designation interacts with the RSPO certification system to facilitate or prevent deforestation. Finally, we do not account for the functional characteristics of different types of forest, including their carbon stocks, biodiversity, or connectivity to other forests. Future work should directly assess the impact of RSPO certification on climate regulation, conservation of biodiversity, and support of local community livelihoods via impacts on land cover.

6. Conclusions

Supply chain interventions have inspired hope for tropical forest conservation, but they may be undermined by spillovers. To explore this concern, we quantified the deforestation impact of exposure to oil palm sustainability certification through corporate ownership and local markets. Within Kalimantan, Indonesian Borneo, we found that spillovers from certification reduced the likelihood of forest clearing within the government designated forest estate. These conservation benefits were offset by deforestation-inducing spillovers to APL lands. Like previous studies, our analysis indicates that RSPO certification reduced the likelihood of forest clearing within certified supply bases. In aggregate, the total direct and indirect impact of RSPO certification on deforestation has been insignificant in comparison to overall deforestation from oil palm expansion in Kalimantan. To substantially affect forest conservation, the RSPO could require that member companies conserve more forest, work to increase industry certification rates, or promote changes to overall industry practices that accentuate conservation spillovers. One potential route to increased forest protection is via interactions between private and public governance. In locations where public agencies do not have the resources or political will to enforce land use regulations designed to protect forests, private initiatives can serve as an important complement by monitoring and enforcing legality. This impact can occur within certified concessions, but also via spillover effects to lands and actors who do not directly participate in the certification program. Finally, our research emphasizes that areas outside of certified oil palm concessions contain nearly all of Kalimantan's remaining forests, suggesting that meaningful conservation initiatives should focus on these areas rather than on already-developed oil palm plantations. Certification programs like the RSPO have an opportunity to leverage supply chains and corporate ownership networks to maximize conservation spillovers throughout oil palm producing landscapes.

Acknowledgments

Thanks to the RSPO Secretariat, as well as five anonymous reviewers, for feedback that substantially improved this manuscript. We acknowledge support for this research from the University of California Santa Barbara's Academic Senate Faculty Research Grant Program, the NASA New (Early Career) Investigator Program in Earth Science (NNX16AI20G), a Google Earth Engine Research Award, and the US Department of Agriculture's National Institute of Food and Agriculture, including Hatch Project HAW01136-H and McIntire Stennis Project HAW01146-M, managed by the College of Tropical Agriculture and Human Resources. Funders had no role in study design, data collection and analysis, decision to publish, or preparation of the manuscript.

Data availability statement

The data, code and specification of the computing environment used for our study are available at https://github.com/jasonjb82/rspo_leakage.

ORCID iDs

Robert Heilmayr https://orcid.org/0000-0001-8980-9639
Kimberly M Carlson https://orcid.org/0000-0003-2162-1378
Jason Jon Benedict https://orcid.org/0000-0003-1760-3994

References

[1] Liu J Q, Hull V, Batistella M, DeFries R, Dietz T Fu F *et al* 2013 Framing sustainability in a telecoupled world *Ecol. Soc.* **18** 26
[2] Barker T, Junankar S, Pollitt H and Summerton P 2007 Carbon leakage from unilateral environmental tax reforms in europe, 1995–2005 *Energy Policy* **35** 6281–92
[3] Cunningham S, Bennear L S and Smith M D 2016 Spillovers in regional fisheries management: do catch shares cause leakage? *Land Econ.* **92** 344–62
[4] Armsworth P R, Daily G C, Kareiva P and Sanchirico J N 2006 Land market feedbacks can undermine biodiversity conservation *Proc. Natl Acad. Sci.* **103** 5403–8
[5] Andam K S, Ferraro P J, Pfaff A, Sanchez-Azofeifa G A and Robalino J A 2008 Measuring the effectiveness of protected area networks in reducing deforestation *Proc. Natl Acad. Sci.* **105** 16089
[6] Jayachandran S, Laat de J, Lambin E F, Stanton C Y, Audy R and Thomas N E 2017 Cash for carbon: a randomized trial of payments for ecosystem services to reduce deforestation *Science* **357** 267–73

[7] Alix-Garcia J M and Gibbs H K 2017 Forest conservation effects of Brazil's zero deforestation cattle agreements undermined by leakage *Glob. Environ. Change* **1** 201–17

[8] Pfaff A and Robalino J 2017 Spillovers from conservation programs *Annu. Rev. Resour. Econ.* **9** 299–315

[9] Fuller C, Ondei S, Brook B W and Buettel J C 2019 First, do no harm: a systematic review of deforestation spillovers from protected areas *Glob. Ecol. Conserv.* **1** e00591

[10] Curtis P G, Slay C M, Harris N L, Tyukavina A and Hansen M C 2018 Classifying drivers of global forest loss *Science* **361** 1108–11

[11] Hertel T W 2018 Economic perspectives on land use change and leakage *Environ. Res. Lett.* **13** 075012

[12] Lima M G B, Persson U M and Meyfroidt P 2019 Leakage and boosting effects in environmental governance: a framework for analysis *Environ. Res. Lett.* **14** 105006

[13] Lambin E F, Gibbs H K, Heilmayr R, Carlson K M, Fleck L C Garrett R D *et al* 2018 The role of supply-chain initiatives in reducing deforestation *Nat. Clim. Change* **8** 109

[14] Garrett R D, Levy S, Carlson K M, Gardner T A, Godar J Clapp J *et al* 2019 Criteria for effective zero-deforestation commitments *Glob. Environ. Change* **1** 135–47

[15] Moffette F and Gibbs H 2019 Agricultural displacement and deforestation leakage in the Brazilian Legal Amazon. *Working Paper*

[16] Heilmayr R and Lambin E F 2016 Impacts of nonstate, market-driven governance on Chilean forests *Proc. Natl Acad. Sci.* **113** 2910–15

[17] Carlson K M, Heilmayr R, Gibbs H K, Noojipady P, Burns D N Morton D C *et al* 2018 Effect of oil palm sustainability certification on deforestation and fire in Indonesia *Proc. Natl Acad. Sci.* 2 **115** 121–6

[18] Alix-Garcia J M, Shapiro E N and Sims K R E 2012 Forest conservation and slippage: evidence from mexico's national payments for ecosystem services program *Land Econ.* **88** 613–38

[19] Robalino J, Pfaff A and Villalobos L 2017 Heterogeneous local spillovers from protected areas in costa rica *J. Assoc. Environ. Resour. Econ.* 15 **4** 795–820

[20] Meijaard E, Garcia-Ulloa J, Sheil D, Carlson K M, Wich S A Juffe-Bignoli D, ed, *et al* 2018 Oil palm and biodiversity: a situation analysis by the IUCN Oil Palm Task Force [Internet]. IUCN, International Union for Conservation of Nature (*Accessed* 24 August 2018). (*available at*: https://portals.iucn.org/library/node/47753)

[21] RSPO 2019 Impact [Internet] (*Accessed* 7 November 2019). (*available at*: https://rspo.org/impact)

[22] Nesadurai H E S 2018 New constellations of social power: states and transnational private governance of palm oil sustainability in southeast asia *J. Contemp. Asia* **48** 204–29

[23] Levin J, Ng G, Fortes D, Garcia S, Lacey S and Grubba D 2012 Profitability and sustainability in palm oil production: analysis of incremental financial costs and benefits of RSPO compliance. WWF, FMO and CDC

[24] RSPO 2019 Sales and Premiums [Internet] (*Accessed* 7 November 2019). (*available at*: https://rspo.org/rspo-credits/i-am-a-seller/sales-and-premiums)

[25] Noojipady P, Morton D C, Schroeder W, Carlson K M, Huang C Gibbs H K *et al* 2017 Managing fire risk during drought: the influence of certification and El Niño on fire-driven forest conversion for oil palm in Southeast Asia *Earth Syst. Dyn Discuss.* **9** 1–23

[26] Cazzolla Gatti R, Liang J, Velichevskaya A and Zhou M 2019 Sustainable palm oil may not be so sustainable *Sci. Total Environ.* **20** 48–51

[27] Wu J 2000 Slippage effects of the conservation reserve program *Am. J. Agric. Econ.* **82** 979–92

[28] Aukland L, Costa P M and Brown S 2003 A Conceptual framework and its application for addressing leakage: the case of avoided deforestation *Clim. Policy* **3** 123–36

[29] Atmadja S and Verchot L 2012 A review of the state of research, policies and strategies in addressing leakage from reducing emissions from deforestation and forest degradation (REDD+) *Mitig. Adapt. Strateg. Glob. Change* **17** 311–36

[30] Gaveau D L A, Locatelli B, Salim M A, Yaen H, Pacheco P and Sheil D 2019 Rise and fall of forest loss and industrial plantations in Borneo (2000–2017) *Conserv. Lett.* **12** e12622

[31] Cattau M E, Marlier M E and DeFries R 2016 Effectiveness of Roundtable on Sustainable Palm Oil (RSPO) for reducing fires on oil palm concessions in Indonesia from 2012 to 2015 *Environ. Res. Lett.* **11** 105007

[32] Directorate General of Estate Crops 2016 Tree Crop Estate Statistics Of Indonesia, Oil Palm 2015–2017 [Internet].Indonesia Ministry of Agriculture. (*available at*: http://ditjenbun.pertanian.go.id/?publikasi=buku-publikasi-statistik-2015-2017)

[33] United States Department of Agriculture 2018 USDA Foreign Agriculture Service PSD (Production, Supply and Distribution) [Internet]. (*available at*: https://apps.fas.usda.gov/psdonline/app/index.html#/app/downloads)

[34] Roundtable on Sustainable Palm Oil 2018 RSPO Impacts [Internet]. (*Accessed* 30 November 2018). (*available at*: https://www.arcgis.com/home/item.html?id=17421c0ad7a54fc3bc0b4a71b399e96e)

[35] Austin K G, Schwantes A, Gu Y and Kasibhatla P S 2019 What causes deforestation in Indonesia? *Environ. Res. Lett.* **14** 024007

[36] Gorelick N, Hancher M, Dixon M, Ilyushchenko S, Thau D and Moore R 2017 Google earth engine: planetary-scale geospatial analysis for everyone *Remote Sens. Environ.* **1** 18–27

[37] Hansen M C, Potapov P V, Moore R, Hancher M, Turubanova S A Tyukavina A *et al* 2013 High-resolution global maps of 21st-century forest cover change *Science* 15 **342** 850–3

[38] Gunarso P, Hartoyo M E, Agus F and Killeen T J 2013 Oil palm and land use change in Indonesia, Malaysia and Papua New Guinea. p36

[39] Menteri Kehutanan Republik Indonesia 2009 Peraturan Menteri Kehutanan Republik Indonesia, Nomor : P. 50/Menhut-II/2009 [Internet]. (*available at*: http://landspatial.bappenas.go.id/komponen/peraturan/the_file/P50_09.pdf)

[40] Minnemeyer S, Boisrobert L, Stolle F, Muliastra Y I K, Hansen M Arunarwati B *et al* 2009 Interactive Atlas of Indonesia's Forests. World Resources Institute

[41] Kementerian Lingkungan Hidup dan Kehutanan (KLHK) 2019 Forest Area [Internet]. (*available at*: http://geoportal.menlhk.go.id/arcgis/rest/services/KLHK_EN/Forest_Area_mei2019/MapServer/0)

[42] KEHATI (Indonesian Biodiversity Conservation Trust Fund) 2019 Hutan Kita Bersawit [Internet]. Yayasan KEHATI, p 113 (*available at*: http://revampingispo.com/publikasi/DownloadFile/2036/hutan-kita-bersawit-(buku))

[43] The House of Representatives of The Republic of Indonesia 2014 Undang-undang Republik Indonesia Nomor 6 Tahun 2014 tentang Desa (UU Desa) [Internet]. (*available at*: https://www.dpr.go.id/dokjdih/document/uu/UU_2014_6.pdf)

[44] Global Forest Watch 2018 Managed Forest Concessions [Internet]. (*Accessed* 28 November 2018). (*available at*: http://data.globalforestwatch.org/datasets/33451575fd3e440db27952ea456abb46_10)

[45] Global Forest Watch 2018 Indonesia wood fiber concessions [Internet]. (*Accessed* 28 November 2018). (*available at*: http://data.globalforestwatch.org/datasets/indonesia-wood-fiber-concessions)

[46] Database of Global Administrative Areas (GADM) [Internet]. (*Accessed* 28 November 2018). (available from: https://gadm.org/about.html)

[47] Gaveau D L A, Pirard R, Salim M A, Tonoto P, Yaen H Parks S A *et al* 2017 Overlapping land claims limit the use of satellites to monitor no-deforestation commitments and no-burning compliance *Conserv. Lett.* **10** 257–64
[48] Prabowo D, Maryudi A and Senawi Imron M A 2017 Conversion of forests into oil palm plantations in West Kalimantan, Indonesia: insights from actors' power and its dynamics *For. Policy Econ.* **1** 32–39
[49] Stammann A, Heiß F and McFadden D 2016 Estimating fixed effects logit models with large panel data. In Kiel und Hamburg: ZBW - Deutsche Zentralbibliothek für Wirtschaftswissenschaften, Leibniz-Informationszentrum Wirtschaft (*Accessed* 4 April 2019). (*available at*: https://www.econstor.eu/handle/10419/145837)
[50] Hahn J and Newey W 2004 Jackknife and analytical bias reduction for nonlinear panel models *Econometrica* **72** 1295–319
[51] Stamman A, Czarnowske D, Heiss F and McFadden D 2019 bife [Internet]. (*Accessed* 12 November 2019). (*available at*: https://cran.r-project.org/web/packages/bife/bife.pdf)
[52] RSPO 2015 RSPO New Planting Procedure
[53] Roundtable on Sustainable Palm Oil 2018 RSPO Principles and Criteria for the Production of Sustainable Palm Oil 2018 [Internet]. (*available at*: https://www.rspo.org/library/lib_files/preview/842)
[54] Lambin E F, Meyfroidt P, Rueda X, Blackman A, Börner J Cerutti P O *et al* 2014 Effectiveness and synergies of policy instruments for land use governance in tropical regions *Glob. Environ. Change* **28** 129–40
[55] Setiawan E N, Maryudi A, Purwanto R H and Lele G 2016 Opposing interests in the legalization of non-procedural forest conversion to oil palm in Central Kalimantan, Indonesia *Land Policy* **15** 472–81
[56] Brockhaus M, Obidzinski K, Dermawan A, Laumonier Y and Luttrell C 2012 An overview of forest and land allocation policies in Indonesia: is the current framework sufficient to meet the needs of REDD+? *For. Policy Econ.* **1** 30–37
[57] Peluso N L and Vandergeest P 2001 Genealogies of the political forest and customary rights in indonesia, malaysia, and thailand *J. Asian Stud.* **60** 761–812
[58] Obidzinski K and Kusters K 2015 Formalizing the logging sector in indonesia: historical dynamics and lessons for current policy initiatives *Soc. Nat. Resour.* **28** 530–42
[59] Schouten G and Hospes O 2018 Public and private governance in interaction: changing interpretations of sovereignty in the field of sustainable palm oil *Sustainability* **10** 4811
[60] Roundtable on Sustainable Palm Oil. Theory of Change [Internet]. (*Accessed* 8 November 2019). (*available at*: https://rspo.org/impact/theory-of-change)
[61] Lechner M 2010 The estimation of causal effects by difference-in-difference methodsestimation of spatial panels *Found Trends® Econom.* **4** 165–224
[62] Gibbs H K, Munger J, L'Roe J, Barreto P, Pereira R Christie M *et al* 2016 Did ranchers and slaughterhouses respond to zero-deforestation agreements in the brazilian amazon?: brazil's zero-deforestation pacts *Conserv. Lett.* **9** 32–42
[63] Cullenward D and Coghlan A Structural oversupply and credibility in California's carbon market *Electr. J.* **29** 7–14
[64] Gaveau D L A, Kshatriya M, Sheil D, Sloan S, Molidena E Wijaya A *et al* 2013 Reconciling forest conservation and logging in indonesian borneo *PLoS One* 14 **8** e69887