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Uneven participation of independent and contract smallholders in certified palm oil mill markets in Indonesia

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Sustainability requirements imposed on agricultural producers by downstream supply chain actors risk excluding smallholder farmers from upgraded markets. Here we investigated smallholder participation in sustainably certified palm oil mill markets in Indonesia. We developed and applied a conceptual model to estimate the importance of structural market access, smallholder capacity, and buyer/seller behavior in shaping mill smallholder sourcing. Smallholders who hold exclusive contracts with specific mills were overrepresented at certified mills. Independent smallholders unaffiliated with mills contributed one-third of regional oil palm production but 7% of certified mill supply. We found no evidence that independent smallholders exited markets after mill certification ("active" exclusion). Instead, only 36% of certified mills ever purchased from independent smallholders, and independent smallholder lands were less common around certified (29–38% of palm area) versus noncertified (41–42%) mills. To address such "passive" exclusion, supply chain governance programs should encourage participation of actors well-positioned to source from small-scale producers.

Smallholder farmers are critical producers within the global food system[1–5], supplying >70% of food calories in the tropics[6]. To meet global goals focused on food security and sustainable agriculture[7,8], such farmers—whose livelihoods are often highly vulnerable—must be included in and benefit from food system transformation including sustainable supply chain governance programs[9,10]. These initiatives, which include voluntary certification, corporate no-deforestation pledges, and government-mandated due diligence, require that participating supply chain actors (e.g., farmers, processors, traders) conform with environmental and/or social standards. They are common across tropical agricultural commodity sectors including beef, coffee, cacao, soy, and palm oil[11–18], and promise to accomplish diverse objectives ranging from deforestation reduction to livelihood improvement.

Yet, when such programs are adopted by downstream supply chain actors such as agricultural commodity processing and trading companies[15], they may limit smallholder participation in agricultural commodity supply chains[19,20]. Examples of downstream actor-led programs include zero-deforestation commitments by soy traders in Brazil[21], sustainability certification of palm oil mills in Indonesia[22], and no-deforestation requirements imposed on commodity importing companies by the European Union (EU)[23,24]. In these examples, downstream actors implement minimum

sourcing requirements (e.g., proof of land legality) designed to govern the production practices of primary producers. However, smallholders often struggle to "upgrade" and meet these new, more stringent requirements without outside support[25,26]. If downstream actors implementing these programs help primary agricultural producers, farmers may be able to stay in upgraded supply chains[27,28]. Yet, there is widespread concern that such programs will exclude marginalized farmers, potentially generating trade-offs across social and environmental goals[28,29].

This study defines exclusion as lower-than-expected rates of smallholder participation in markets governed by supply chain initiatives adopted by downstream supply chain actors, relative to overall rates of smallholder market participation. Several factors may influence such exclusion from sustainably governed supply chains. First, if supply chain actors who have adopted these sustainability programs are non-randomly distributed across smallholder producer locations or capacities due to selection or procurement location[30] effects, smallholders may have low *structural market access* to sustainably governed supply chains[31] Second, smallholders might be excluded if they cannot meet minimum sourcing requirements, an issue of *smallholder capacity*[28,32–35]. Third, participating buyers may not purchase from capable smallholders because of costs or risks

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associated with such sourcing behavior[36], or capable smallholders may choose not sell to participating buyers because of additional conditions imposed by these actors (i.e., *buyer and seller behavior*). Together, these mechanisms provide a conceptual foundation for analyses of smallholder access to markets governed by sustainable supply chain initiatives.

Empirical findings on smallholder exit from commodity markets due to smallholder capacity and/or buyer and seller behavior in the face of additional supply chain requirements are mixed. Some researchers have found smallholder exclusion[37,38], while others report relatively neutral[39,40] or even positive[41] smallholder market participation outcomes. Exclusion may vary across small-scale producer attributes including producer size and wealth[38,42]. On the other hand, structural market access has remained largely unexplored in the empirical literature[30,31] in part because data describing the geospatial distribution of smallholders and participating versus non-participating commodity buyers at scales relevant to such analysis is often unavailable. As a result, to our knowledge, interactions between structural market access, smallholder capacity, and buyer and seller behavior in driving smallholder exclusion remain unstudied.

The oil palm industry provides an excellent opportunity to evaluate smallholder participation in upgraded supply chains, across diverse smallholders. Smallholders represent 27–40% of global oil palm area[43,44] and produce the inputs for up to 30% of global crude palm oil[45]. Two broad categories of smallholders—"contract" and "independent"—grow oil palm[19]. Contract smallholders are sometimes known as scheme, plasma, tied, or associated smallholders[19,46]. They have exclusive agreements with a company that runs an industrial palm oil mill where fresh fruit bunches are processed into crude palm oil. The company is required to buy from these contract smallholders, who are in turn required to sell to the company, during the contract period. Decision-making power over land used for contract oil palm farming is held, at least in part, by the company[46]. Independent smallholders do not maintain binding contracts with companies, are not guaranteed mill market access, and retain full control over their oil palm land[46]. Yet most independent smallholders depend on nearby mills to market their produce, often through intermediaries[47]. This is because fresh fruit bunches must be processed to crude palm oil within 24–48 h of harvest[48,49] and, across most oil palm production systems outside of Africa[50], the only option for processing is at industrial mills. Tradeoffs exist between independent and contract farming arrangements. Compared to independence, contracts typically offer lower risks associated with farming and greater access to capital, but may lead to lower profits and a lack of autonomy[51].

The Roundtable on Sustainable Palm Oil (RSPO) is the leader among sustainability certification systems in the palm oil sector, certifying >450 palm oil mills in 2021[52]. Certified mills are associated with industrial oil palm plantations, and both mills and plantations are evaluated against the RSPO's certification standard for oil palm growing companies[53–56]. The RSPO also recognizes smallholder producers, defined as farmers who manage <50 hectares of oil palm[57]. Contract smallholders, which the RSPO refers to as "scheme" smallholders, are certified through the support of their associated certified mills[58], and 6% of RSPO certified land is attributed to contract smallholders[43]. Independent smallholders may also participate in RSPO certification[26], and account for <3% of global RSPO certified area[43].

RSPO certified mills choose from several physical RSPO supply chain certification model options that allow traceability of certified palm oil and derivatives from the mill along supply chains[59]. The supply chain model type dictates whether a certified mill is able to accept fruits from noncertified producers, including smallholders. Two supply chain models—"segregated" and "identity preserved"—require that all fruits processed by the mill are from certified sources[60], and therefore exclude any noncertified smallholder supply. The "mass balance" supply chain model allows mixing of certified and noncertified product[61,62], meaning that noncertified smallholders can sell to mills using this supply chain model.

Since 2018, the RSPO's company certification standard has emphasized supporting all smallholders—via smallholder inclusion in RSPO supply chains and improvement of smallholder livelihoods through partnerships—as one of its core principles[55,56]. This principle partly responds to research documenting the multiple barriers that independent farmers face in becoming certified[25,26,32,34,63–66]. Yet, to our knowledge, no studies have looked more broadly at inclusion of all smallholders, including those who are not certified, at certified mill markets. Santika et al.[67] asked whether certification of large-scale oil palm plantations in Indonesia reduced poverty, but did not include sourcing from noncertified smallholders as an analytical factor. Chandra et al.[20] assessed the coverage of corporate zero-deforestation commitments in the Indonesian oil palm sector that addressed independent smallholder inclusion, but did not link this to smallholder sourcing. The lack of research in this area may be due to a paucity of accessible data on palm oil mill sourcing disaggregated by actor. For instance, the RSPO does not publish fresh fruit bunch volumes that certified mills purchase from noncertified sources, including smallholders, in its annual reports. The degree and drivers of smallholder inclusion at certified palm oil mill markets have thus been unknown[19,28].

Given the prevalence of supply chain governance initiatives adopted by downstream actors in tropical agricultural commodity sectors with substantial smallholder presence, systematic evaluation of the magnitude and determinants of small farmer participation in these markets is critically needed. Here, we investigate how and why implementation of supply chain governance initiatives adopted by large corporate actors influences smallholder market participation. By developing regional geospatial data on the locations of supplier-specific commodity production and participating and non-participating supply chain actors, and combining this with a database of supplier-specific annual commodity sourcing information, we provide empirical evidence regarding the general mechanisms that underpin smallholder exclusion in the oil palm sector. Our research advances understanding of how governance initiatives undertaken by supply chain actors downstream of primary agricultural producers condition market participation across diverse smallholders. By exploring smallholder ability to sell to downstream certified supply chain actors, our study complements existing scholarship on barriers to smallholder adoption of sustainability certification[25,26,32,34,63–66] in the palm oil sector. Our findings inform the broader implications of sustainability certification for smallholder market participation, including the risk of widespread exclusion of vulnerable farmers in the tropics from upgraded markets. In doing so, we address concerns around the equity of supply chain governance interventions.

Our evaluation focused on palm oil mills in Indonesia[68] (Fig. 1), which produced 58% of global palm oil supply in 2021[69]. We developed and applied a conceptual model of smallholder market participation (Fig. 2) to estimate the importance of structural market access, smallholder capacity, and behavior of buyers and sellers in explaining oil palm fruit sourcing patterns at these mills. Our empirical evaluation combined multiple datasets to enable application of this model. First, we combined data describing circa 2020 land cover[70] and administrative zone (Fig. S1) and oil palm yields and production for industrial growers and independent smallholders (Figs. S2, S3) in "supply sheds" around all RSPO certified (*n* = 250 mills) and noncertified palm oil mills (*n* = 917 mills) across major palm oil producing regions of Kalimantan and Sumatra (Fig. S4). Second, we compiled annual information about fresh fruit bunches supplied to a subset of 87 randomly selected certified mills (Fig. 1) as reported in their RSPO audit reports by supplier type (i.e., industrial growers, contract smallholders, independent smallholders; Table S1). From these sampled mills, we created a "balanced panel" of 360 mill-years (i.e., the number of mills times the number of years of sourcing for each mill) which spanned the five years after a mill's initial certification and which included 72 sampled mills. We used these data to quantify and compare the contribution of each supplier type to land cover and oil palm production in supply sheds, and fresh fruit bunch supply to mills. We incorporated uncertainty by analyzing supply sheds defined by 10, 20, 40 and 80 km radii around each mill (Fig. 3). The Methods section contains a full explanation of our approach.
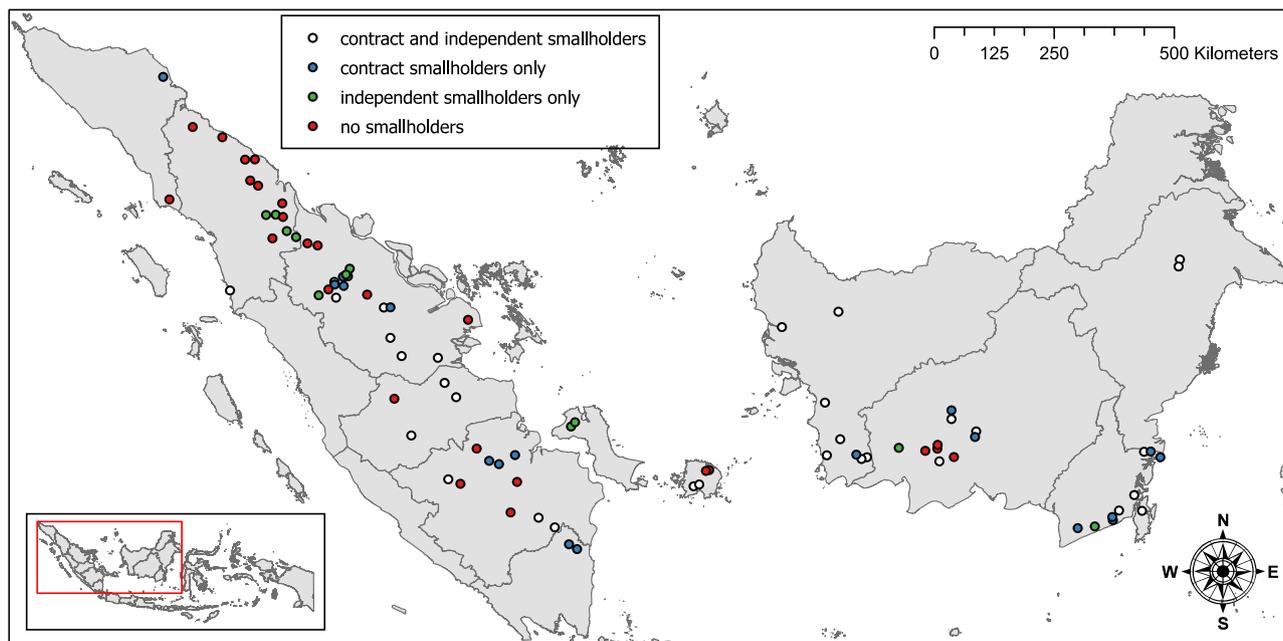
Fig. 1 | Sampled Roundtable on Sustainable Palm Oil (RSPO) certified palm oil mills in Indonesia. These sampled mills ($n = 87$) were distributed across Sumatra (64%) and Kalimantan (36%). This is approximately representative of the overall distribution of palm oil mills in Indonesia (63% Sumatra, 32% Kalimantan, 3% Sulawesi, 1% Papua)[68]. Mills are coded by observed fresh fruit bunch sourcing from smallholders derived from the full panel of annual RSPO audit reports. Some mills never sourced fresh fruit bunches from smallholders ("no smallholders"). Others sourced at least some fruits only from contract smallholders who hold exclusive agreements with a mill, only from independent smallholders with no relationship to a mill, and some sourced from both categories of smallholders.
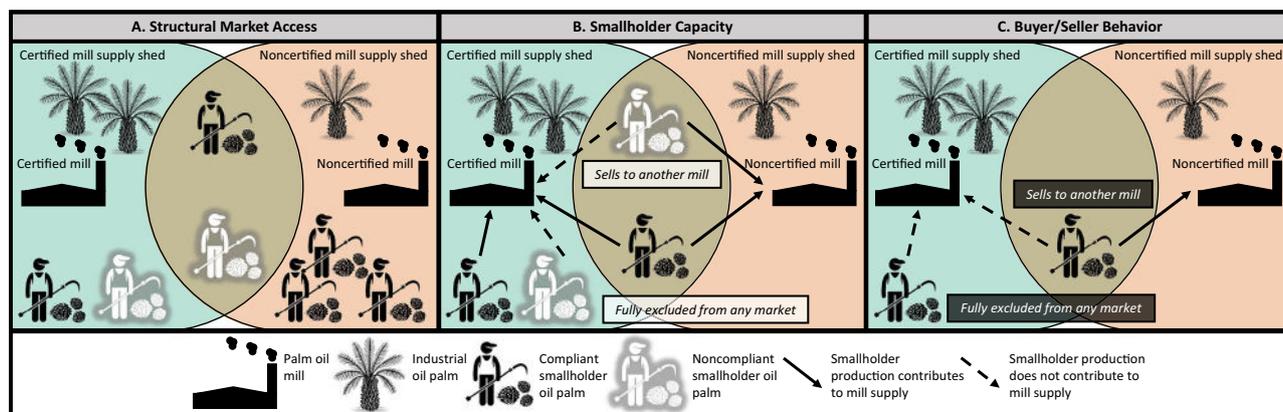
Fig. 2 | Conceptual model of smallholder participation at Roundtable on Sustainable Palm Oil (RSPO) certified palm oil mill markets in Indonesia. This model illustrates the potentially interacting factors that influence the degree of smallholder participation in these markets. **A** Structural market access is represented by the spatial distribution of certified mills across smallholder producers and capacities. If this distribution is skewed, (capable) smallholders may have skewed access to certified mills. **B** Smallholder capacity describes the ability of smallholders near certified mills to comply with standards needed to sell to these mills. **C** Buyer/seller behavior represents the combined decisions of: (1) certified mills to purchase from capable suppliers and (2) capable suppliers or their intermediaries to sell to certified mills. Smallholders excluded from certified mills may have the opportunity to market their produce to another mill, or may be fully excluded from any market because they are located far from other mills that would accept their fruit. Industrial oil palm (Artist: Kullawat Kanjanasoontree) and smallholder (Artist: Leremy) images used under license from Shutterstock.com.

Results

Conceptual model: Smallholder market participation at RSPO certified palm oil mills in Indonesia

Here, we present a conceptual model of the interacting factors—i.e., structural market access, smallholder capacity, and buyer/seller behavior—that potentially influence the degree of smallholder market participation at RSPO certified palm oil mill markets in Indonesia (Fig. 2).

Both independent and contract smallholders may experience biases in certified mill access if the spatial distribution of certified mills differs from the spatial distribution of smallholder lands (i.e., structural market access; Fig. 2A). Because contract smallholders hold exclusive legally-binding agreements with mills, we expect no influence of smallholder capacity (Fig. 2B) and by extension the spatial distribution of such capacity (Fig. 2A) or buyer/seller behavior (Fig. 2C) on certified mill sourcing from contract smallholders. However, independent smallholder sales to nearby mills may be shaped by mill certification in two additional ways.

First, the RSPO's requirements for third-party suppliers to certified mills might affect smallholder ability to sell or interest in selling to these mills. Third-party suppliers are external entities that sell fresh fruit bunches to mills. They include independent smallholders and unaffiliated industrial
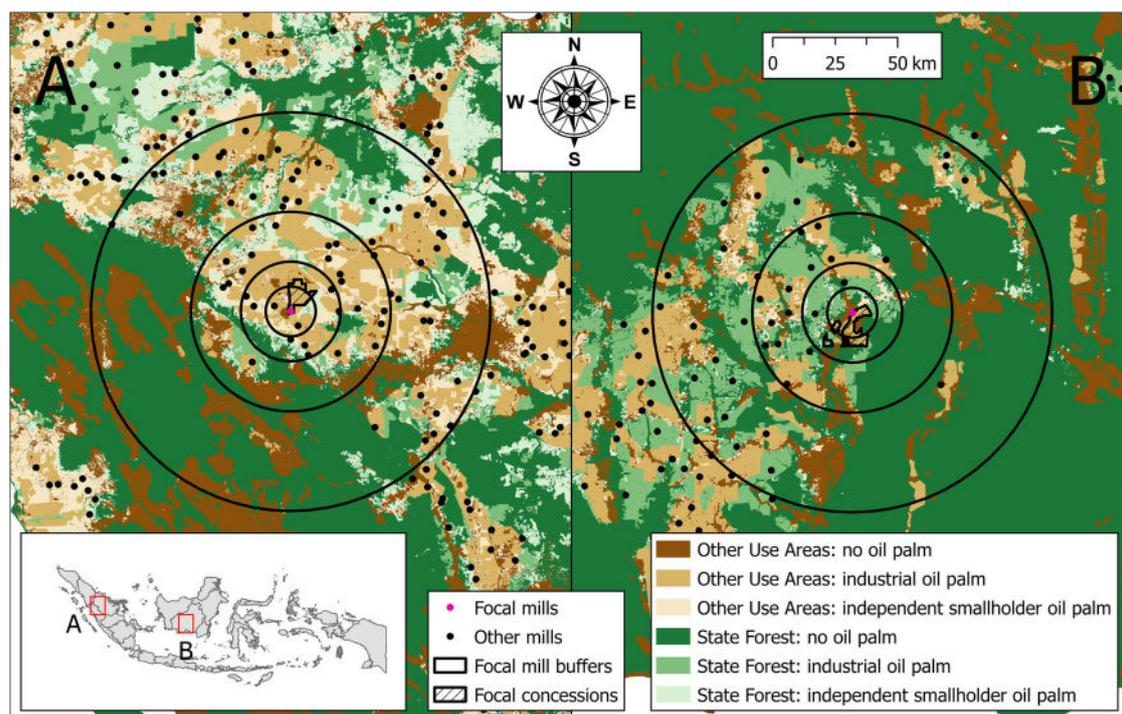
Fig. 3 | Buffers around two Roundtable on Sustainable Palm Oil (RSPO) certified mills in Indonesia overlaid on oil palm producer and administrative land zoning categories. Circles with radii of 10, 20, 40, and 80 km illustrate the effect of different assumptions on land cover included in the buffer. In both (**A**; province of Riau, Sumatra) and (**B**; province of Central Kalimantan, Kalimantan), the concession boundary associated with the certified mill falls between the 10 and 20 km buffers, and dozens of other mills fall within the 80 km buffer. Administrative land zones are *Kawasan Hutan* (KH; State Forest), where oil palm plantations are generally illegal, and *Areal Penggunaan Lain* (APL; Other Use Areas), where plantations can be legally established[121]. These are intersected with remotely sensed industrial and independent smallholder oil palm plantation lands[70].

plantations. RSPO certification has always compelled certified companies to comply with all applicable laws and regulations[53], and its certification standard has included increasingly explicit third-party supplier sourcing requirements over time. The original RSPO standard in 2007 had no specific constraints related to certified mill sourcing from third-party suppliers[53]. The preamble of the 2013 standard suggested that mills should buy from "identified, legal, and responsible" sources[54]. The 2018 standard mandated that mills provide evidence that fruits come from legal sources, in the form of geo-location of origins, proof of land tenure, and legal permission to sell. Proof of land tenure is a key issue for Indonesian smallholders, because around a quarter of all smallholder oil palm area in Indonesia falls within the State Forest[71] (*Kawasan Hutan*), where farmers typically cannot receive nationally recognized land title. Upon designation in 1967, State Forest covered about 70% of Indonesian land area including already-farmed customary community lands[72]. Actors ranging from customary community members to companies have since developed State Forest land to oil palm[72]. The RSPO's third-party supplier legality requirement came into force in November 2021[55] at the tail end of our study. It could lead certified palm oil mills to drop past independent smallholder suppliers and/or decline to purchase from new suppliers either because of noncompliance (i.e., smallholder capacity; Fig. 2B) or because of costs associated with verifying and/or supporting compliance (i.e., buyer behavior; Fig. 2C)[36]. If they have a choice regarding where to sell, independent smallholders or their intermediaries may also choose to avoid certified mills due to these additional requirements (i.e., seller behavior; Fig. 2C).

Second, certified mills' choice of physical supply chain certification model affects market access of noncertified independent smallholders. Mills may select the RSPO's mass balance supply chain model, which accommodates noncertified supply from independent smallholders. Alternatively, to achieve greater price premia and/or market access[73], mills can adopt the RSPO's segregated or identity preserved supply chain certification models. These models exclude all noncertified suppliers, including noncertified

independent smallholders who otherwise comply with the RSPO's requirements for third-party suppliers[39,60] (i.e., buyer behavior; Fig. 2C). In the following sections, we empirically appraise the relationship between the factors in our conceptual model and smallholder supply to RSPO certified palm oil mills in Indonesia.

Structural market access: Distribution of independent and contract smallholder producers across certified and noncertified supply sheds

We first evaluated structural market access in terms of the distribution of independent and contract smallholder oil palm lands across certified and noncertified mill markets (Fig. 2A). This analysis provides relatively more insight into independent smallholder market access, because we lacked maps of contract smallholder oil palm plantings, and could only infer these areas around sampled certified mills.

Relative to noncertified palm oil mills, certified mills were more commonly found in landscapes with lower proportions of independent smallholder oil palm area compared to total palm area (Fig. 4A; Table S2). Across mill buffer sizes (indicated by ranges here and below), independent smallholder oil palm area accounted for a mean of 29–38% of total oil palm area in certified supply sheds, and 41–42% of total palm area in noncertified supply sheds. This difference was significant ($p < 0.05$) across all buffer sizes. Independent smallholders also produced a lesser proportion of estimated 2020 fresh fruit bunch weight in certified mill supply sheds (per-mill mean of 25–32% of total supply shed fresh fruit bunch production) compared to noncertified mills (35–36%; significant across all buffer sizes; Fig. 5A; Table S2). Relative production was lower than relative area because independent smallholders have lower yields than industrial producers[74,75] (Fig. S2). These findings were consistent across Kalimantan and Sumatra. This bias was driven by the prevalence of industrial oil palm plantation in certified compared to noncertified supply sheds (Fig. 4B; Table S2). Indeed, independent smallholder oil palm area occupied a similar or significantly
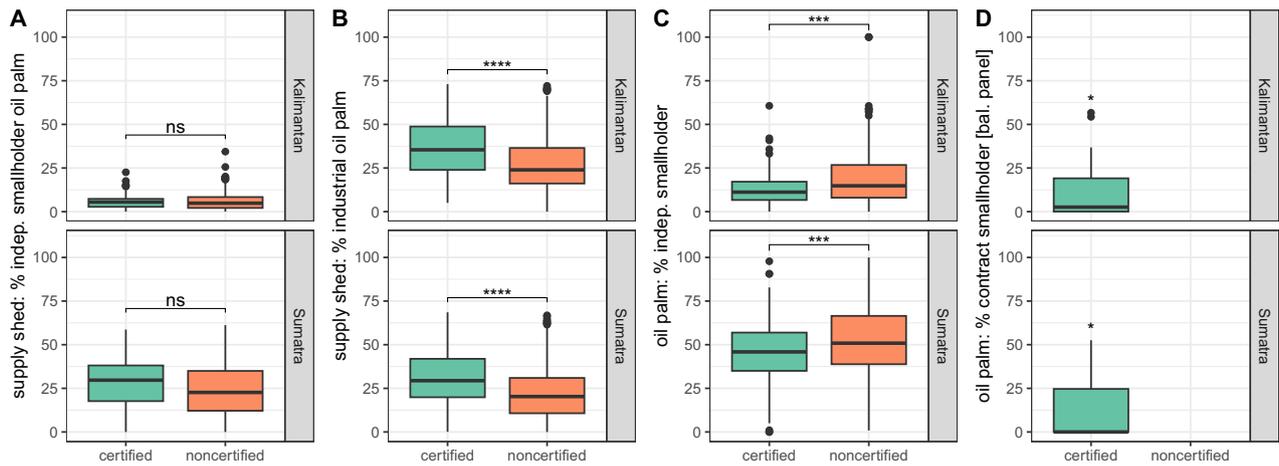
Fig. 4 | Comparisons of fractional circa 2020 areas within supply sheds of Roundtable on Sustainable Palm Oil (RSPO) certified and noncertified palm oil mills across Kalimantan and Sumatra, Indonesia. We show the percentage of: supply shed area under independent smallholders (**A**) and industrial producers (**B**); and oil palm area under independent smallholders (**C**) and contract smallholders (**D**). Data represent certified ($n = 250$) or noncertified ($n = 917$) mills, except (**D**) which uses the balanced panel of 72 mills. We use a 20 km radius to define the supply shed. The lower and upper hinges represent the first and third quartiles, the upper (lower) whisker extends to the largest (smallest) value no further than 1.5 times the inter-quartile range, the bar represents the median, and the symbol above the bracket or box denotes the significance level of the p-value (ns = $0.05 \leq p$, * = $0.01 \leq p < 0.05$, ** = $0.001 \leq p < 0.01$, *** = $0.0001 \leq p < 0.001$, **** $p < 0.0001$) derived from t-tests.
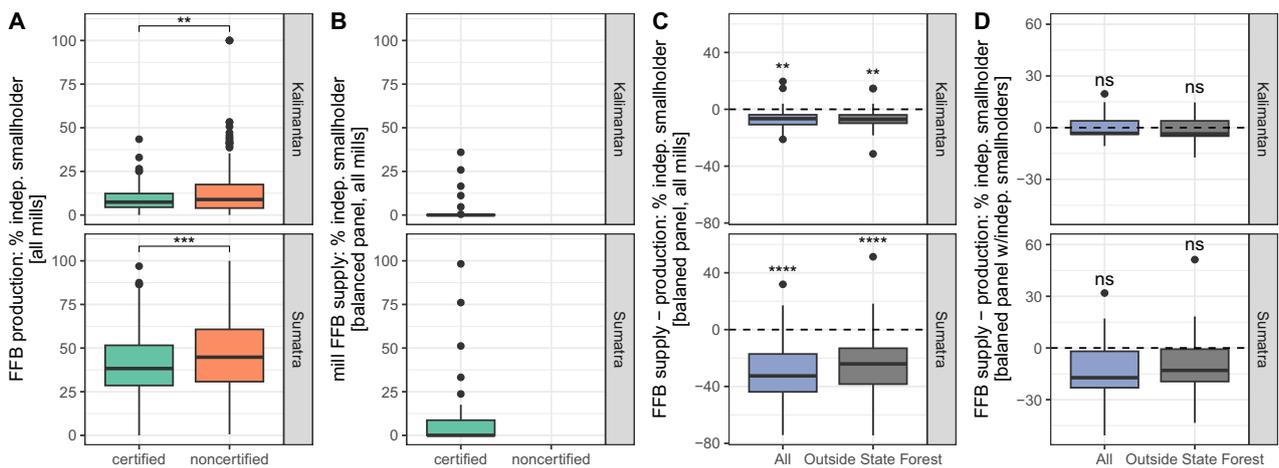
Fig. 5 | Comparisons of fractional circa 2020 independent smallholder supply shed fresh fruit bunch (FFB) production and reported supply received by palm oil mills across Kalimantan and Sumatra, Indonesia. These include (**A**) the esti- mated proportional contribution of independent smallholders to total supply shed FFB production across Roundtable on Sustainable Palm Oil (RSPO) certified ($n = 250$) or noncertified ($n = 917$) mills, (**B**) the proportional contribution of independent smallholders to total FFB supply to the balanced panel of sampled RSPO certified mills ($n = 72$ mills) as reported in RSPO audit reports, and the difference between **A** and **B** for the balanced panel of sampled certified mills (**C**) or just those mills that sourced from independent smallholders (**D**), where negative values indicate more production than reported supply. For **C**, **D** we present results under scenarios assuming that mills sourced from all smallholders or only small- holders outside of the State Forest, and compare the group mean to zero [dashed line] rather than the means of the groups to one another. We use a 20 km radius to define the supply shed. The lower and upper hinges represent the first and third quartiles, the upper (lower) whisker extends to the largest (smallest) value no further than 1.5 times the inter-quartile range, the bar represents the median, and the symbol above the bracket or box denotes the significance level of the p-value (ns = $0.05 \leq p$, * = $0.01 \leq p < 0.05$, ** = $0.001 \leq p < 0.01$, *** = $0.0001 \leq p < 0.001$, **** $p < 0.0001$) derived from t-tests.

greater fraction of *supply shed* area (rather than oil palm area within the supply shed, as reported above) around certified compared to noncertified mills (Fig. 4C; Table S2). Across the region, 13–20% of certified versus 11–22% of noncertified supply sheds were under independent smallholders.

In contrast, we found significantly more contract smallholder oil palm around sampled balanced panel certified mills than expected based on contract smallholder prevalence in Indonesia (Fig. 4D; Table S3). Contract smallholder oil palm occupied about 12-13% of balanced panel certified supply shed oil palm area in 2020, more than double the reported percentage of contract smallholder oil palm across Indonesia (~5% of total oil palm

plantation area)[64]. Contract smallholder area in certified supply sheds was slightly less common in Sumatra (11-12% of total oil palm plantation area) than Kalimantan (13-14%).

Structural market access: Distribution of independent smallholder land legality across certified and noncertified supply sheds

Next, we assessed structural market access from the standpoint of inde- pendent smallholder capacity to meet RSPO legality requirements (Fig. 2A). Third-party supplier requirements at certified mills might disadvantage
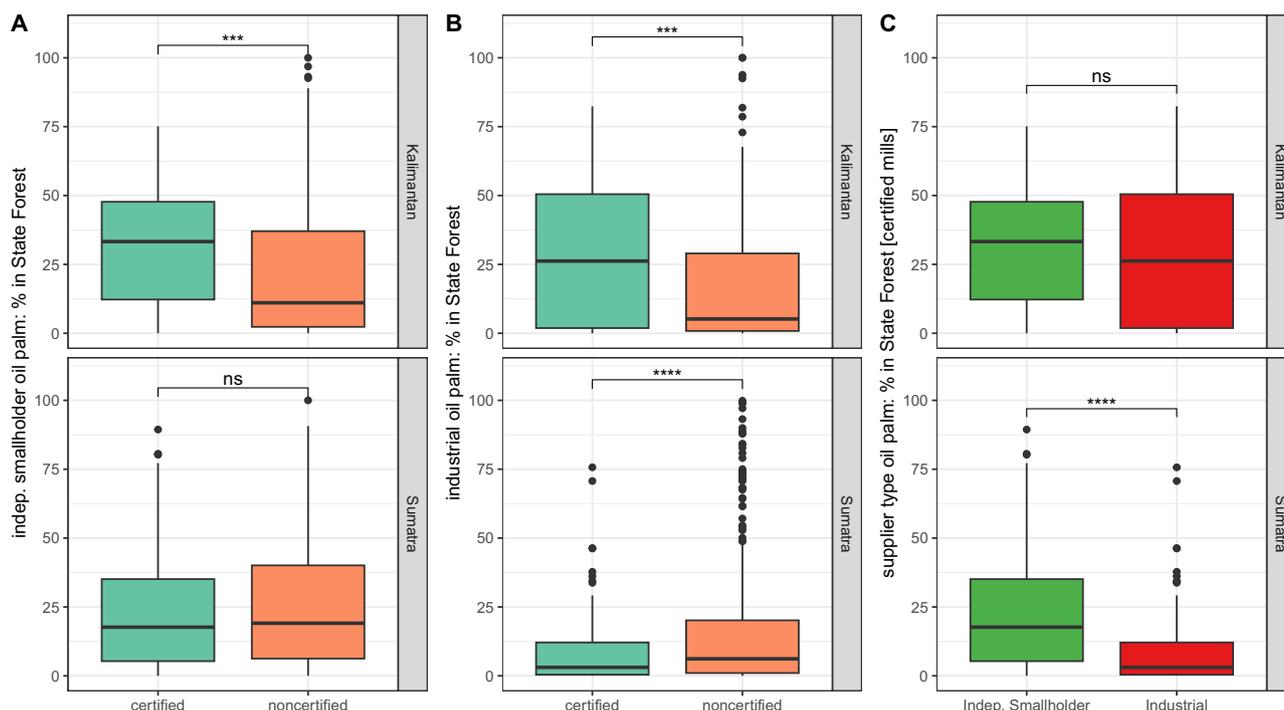
Fig. 6 | Comparisons of State Forest overlap with circa 2020 oil palm areas within supply sheds of Roundtable on Sustainable Palm Oil (RSPO) certified and noncertified palm oil mills across Kalimantan and Sumatra, Indonesia. We show the percentage of: Independent smallholder (**A**) and industrial (**B**) oil palm overlap with State Forest across certified ($n = 250$) versus noncertified ($n = 917$) mill supply sheds, and (**C**) independent smallholder versus industrial oil palm overlap with State Forest within certified mill supply sheds. We use a 20 km radius to define the supply shed. The lower and upper hinges represent the first and third quartiles, the upper (lower) whisker extends to the largest (smallest) value no further than 1.5 times the inter-quartile range, the bar represents the median, and the symbol above the bracket denotes the significance level of the p-value (ns = $0.05 \leq p$, * = $0.01 \leq p < 0.05$, ** = $0.001 \leq p < 0.01$, *** = $0.0001 \leq p < 0.001$, **** $p < 0.0001$) derived from t-tests.

independent smallholders located within the State Forest, where land title is typically unavailable to farmers.

In Kalimantan, more independent smallholder lands around certified mills were exposed to legal barriers to accessing certified mill markets, compared to such lands around noncertified mills (Fig. 6A; Table S2). Specifically, a mean of 28–31% of independent smallholder oil palm area in certified mill supply sheds overlapped with State Forest, significantly greater than the 18–20% overlap in noncertified supply sheds. This may be due to the prevalence of certified mills in the province of Central Kalimantan, where a large portion of oil palm is zoned as State Forest[76]. In Sumatra, certified and noncertified independent smallholdings had similar overlap with State Forest at larger (20–80 km) buffer sizes (per-mill mean of 23–28% of independent smallholdings for certified; 26–28% for noncertified; Fig. 6A; Table S2). For the smallest (10 km) buffer size in Sumatra, supply sheds of noncertified mills had significantly more (21%) smallholder oil palm overlapping with State Forest compared to certified mill supply sheds (15%; Table S2). The bias of certified mill supply sheds in Kalimantan toward independent smallholder oil palm lands in the State Forest may exacerbate the structural market access bias in terms of overall independent producer locations reported in Results "**Structural market access: Distribution of independent and contract smallholder producers across certified and noncertified supply sheds**". The opposite may be true in Sumatra especially near certified mills.

Smallholder capacity: Independent smallholder compliance with land legality requirements at certified mills

We then appraised independent smallholder capacity to sell to certified mills (Fig. 2B). To do so, we compared the degree to which industrial versus independent smallholder oil palm within each RSPO certified supply shed overlapped with State Forest (Fig. 6C; Table S4). This serves as proxy for equal opportunity of smallholders and industrial producers to meet minimum criteria for access to certified mills[28].

In Kalimantan, independent smallholder and industrial oil palm grower lands in certified supply sheds had similar levels of overlap with State Forest (pairwise two-sample t-tests; p > 0.05). In Sumatra, independent smallholder oil palm lands around certified mills overlapped significantly more State Forest (per-mill mean of 16–28% of total supply shed smallholder area was within State Forest) than industrial oil palm lands in the same supply sheds (4.3–13%). Compared to industrial oil palm growers, independent smallholders in Sumatra but not Kalimantan may face outsized legal barriers to certified mill markets.

Buyer and seller behavior: Independent smallholder participation in certified mill markets

To explore the influence of buyer and seller behavior on independent smallholder participation in RSPO certified mill markets (Fig. 2C), we narrowed our focus to the balanced panel of sampled certified mills for which we had annual fresh fruit bunch supply weight by supplier type. Since this random sample encompassed 35% of all RSPO certified mills in Indonesia and had supply shed characteristics similar to non-sampled certified mills, patterns that characterize this sample likely reflect broader trends across all certified mills.

Within our balanced panel sample, 32% of certified mills never sourced from any smallholders, 57% of mills incorporated contract smallholders, and 36% purchased from independent smallholders (Fig. 1). Accordingly, most fresh fruit bunches handled by certified mills came from industrial actors (71 ± 30% of per-mill total supply in the balanced panel; mean ± standard deviation), followed by contract smallholders (15 ± 23%), independent smallholders (5.9 ± 15%), and unknown sources (8.1 ± 16%; Fig. 7A). Smallholder contributions to mill supply were more prevalent in Sumatra than Kalimantan. Contract and independent smallholders respectively accounted for 17 ± 26% and 7.5 ± 18% of per-mill total supply in Sumatra and 13 ± 18% and 3.2 ± 7.9% of per-mill total supply in Kalimantan.
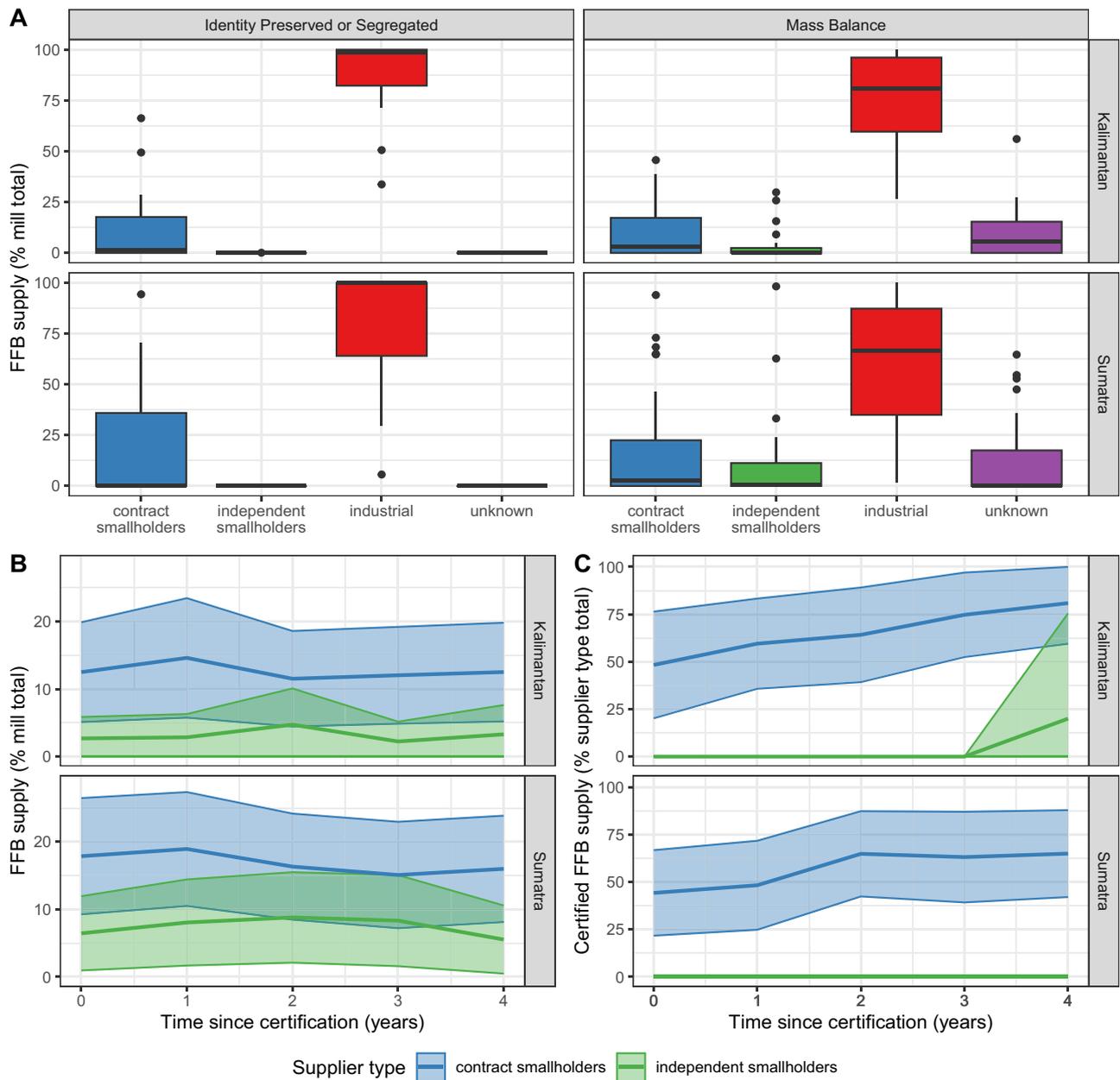
Fig. 7 | Oil palm fresh fruit bunch (FFB) supply and Roundtable on Sustainable Palm Oil (RSPO) certification rates for the balanced panel of certified palm oil mills across Sumatra and Kalimantan, Indonesia. A FFB supply for all balanced panel mill-years with a known supply chain certification model (i.e., Identify Preserved or Segregated; Mass Balance) displayed by supplier type (i.e., industrial producers, contract smallholders, independent smallholders, supplier type unknown). For contract and independent smallholders from initial certification (year 0) to year 4, **B** percentage of annual per-mill total FFB supply by supplier type and **C** percentage of annual per-mill supplier FFB certified. Further details on certification can be found in Supplementary Note 1. In A, the lower and upper hinges represent the first and third quartiles, the upper (lower) whisker extends to the largest (smallest) value no further than 1.5 times the inter-quartile range, the bar represents the median. In **B**, **C**, the center line represents the mean value, while shaded areas represent 95% confidence intervals.

Certified balanced panel mills purchased relatively less oil palm fruit from independent smallholders (per-mill mean of 6.8 ± 17% of total supply, after allocating unknown sources according to the proportion of known sources of supply; Fig. 5B) than the estimated fraction of fruit that independent smallholders produced within these supply sheds (per-mill mean of 24-29% of total supply shed production; Fig. 5A). Although the magnitude of differences was greater across Sumatra (per-mill difference of 25–31 percentage points) than Kalimantan (5.7–7.6 percentage points), differences were significant in all cases (Fig. 5C, Table S3). If we assumed that certified mills did not purchase fresh fruit bunches produced within the State Forest, we found

similarly significant differences between independent smallholder production and supply (Table S3).

This finding was driven by the 64% of mills in the balanced panel that never sourced from independent smallholders (Fig. 5D). After eliminating these mills from the analysis, we found non-significant differences between independent smallholder production and supply under assumptions of purchase from any supplier and only from those outside State Forest (Table S3). These results indicate that certified mills in Indonesia purchased proportionally less supply from independent smallholders than expected based on supply shed production. This is because most certified mills never sourced from independent smallholders.

Table 1 | Regression models of fractional smallholder supply to certified palm oil mills over time since initial certification

Dependent Variable	Region	# mills	# mill-years	Model Type	Time Since Certification			Model Fit	
					β	odds ratio	*p*-value	adjusted R²	Hosmer-Lemeshow *p*-value
FFB supply sourced from independent smallholders (proportion)	All	26	130	Linear	−0.002	—	0.827	0.639	—
				Logistic	−0.117	0.890	0.496	—	0.797
	Sumatra	17	85	Linear	−0.004	—	0.752	0.656	—
				Logistic	−0.084	0.920	0.683	—	0.494
	Kalimantan	9	45	Linear	0.002	—	0.887	0.409	—
				Logistic	−0.195	0.823	0.538	—	0.952
FFB supply sourced from contract smallholders (proportion)	All	41	205	Linear	−0.010	—	0.037*	0.871	—
				Logistic	0.072	1.074	0.706	—	0.958
	Sumatra	22	110	Linear	−0.016	—	0.018*	0.895	—
				Logistic	−0.089	0.914	0.765	—	0.987
	Kalimantan	19	95	Linear	−0.004	—	0.609	0.771	—
				Logistic	0.180	1.198	0.467	—	0.713

We report the relationship between dependent variables (i.e., proportion of mill fresh fruit bunch [FFB] supply from independent smallholders or contract smallholders) and time since initial palm oil mill Roundtable on Sustainable Palm Oil (RSPO) certification (years) using the balanced panel for the entire dataset and by island (Sumatra and Kalimantan). For logistic models, we report both the coefficient (β) and the odds ratio, a measure of association between the predictor variable and the outcome, by exponentiating the beta coefficient (e^{β}). Models are fully described in Methods. * = $0.01 \leq p < 0.05$.

Buyer behavior: Mill supply chain certification model and sourcing from independent smallholders

We next examined temporal trends in the relationship between independent smallholder sourcing and a mill's choice of supply chain certification model, a buyer behavior (Fig. 2C).

Within one year of a supply chain certification model upgrade (i.e., from mass balance, which can accommodate noncertified supply, to identity preserved/segregated, which only allows certified supply) or downgrade (i.e., from identity preserved/segregated to mass balance), a handful of mills dropped or added independent smallholders (Supplementary Note 2). However, more often, mills that added or dropped independent smallholders made no corresponding change to their supply chain model. Many of these mills continued sourcing from other noncertified suppliers (e.g., third-party industrial producers), and thus needed to maintain the mass balance model even if they stopped buying from independent smallholders. Mill sourcing from independent smallholders was often unrelated to the mill's selection of supply chain model.

Smallholder capacity and buyer/seller behavior: Temporal trends in contract and independent smallholder supply to certified mills

Finally, we evaluated whether and how the fraction of smallholder fruit supply to certified sampled mills changed over time using regression models. Although our findings potentially provide insight into the interaction between smallholder capacity to meet increasingly stringent third-party sourcing requirements (Fig. 2B) and buyer/seller behavior (Fig. 2C), other time-linked dynamics (e.g., palm maturity, which drives fresh fruit bunch yields) may affect the distribution of mill supply across supplier types. Therefore, we stop short of drawing causal conclusions from this analysis.

For both contract and independent smallholders, we found few significant trends (Fig. 7B, Table 1). For contract smallholders, supply share in Sumatra *decreased* from 18 ± 29% of per-mill fresh fruit supply at initial certification to 16 ± 26% by year four, a significant change only according to our linear model. In Kalimantan, contract smallholder supply *remained stable*, from 12 ± 19% at initial certification to 13 ± 18% by year four. For independent smallholders in both Sumatra and Kalimantan, we found *no significant change* in supply share from year zero to year four.

Discussion

Our analysis of RSPO certified palm oil mill supply shed attributes and sourcing patterns across major Indonesian oil palm producing regions informs the equity implications of corporate supply chain sustainability efforts[28] while considering the heterogeneity of smallholders[64]. We found that independent smallholders accounted for a larger fraction of fresh fruit bunch production (34% of total circa 2020 supply shed production across Sumatra and Kalimantan across all mill buffer sizes) than their overall contribution to certified mill fresh fruit bunch supply (6.8% of total supply to balanced panel mills). This difference was especially large in Sumatra, where about 8.5% of balanced panel mill supply was attributed to independent smallholders, but where 45–46% of total production was from these farmers. Just as independent smallholders have faced difficulties participating in group certification[39], this imbalance indicates that they are underrepresented in certified mills' supply chains. In contrast, contract smallholders comprised about 12% of oil palm area around certified mills (Table S3), double the ~5% of Indonesian oil palm land area they occupied[64].

The low reliance of certified mills on independent smallholder supply occurred mainly at extensive (i.e., the choice of whether to source from independent smallholders) rather than intensive (i.e., how much product to source from independent smallholders) margins. Why did 64% of certified mills in the balanced panel never purchase oil palm fruit from independent smallholders? This decision may have evolved in anticipation of certification, a buyer behavior. For instance, mills may have dropped independent smallholders, who are typically not certified, before their initial RSPO audit to achieve identity preserved or segregated supply chain models. Since only about half of the mills that never sourced from independent smallholders maintained these stringent supply chain models throughout time (Supplementary Note 2), other factors likely contributed to this choice by mills. As our mill sourcing dataset was limited to post-certification behavior, we cannot directly test such hypotheses. Alternatively, mills that seek certification may be less likely to source from independent smallholders than mills that never become certified, a pre-certification buyer behavior. Self-selection into voluntary certification programs is frequently biased toward certain producer types (e.g., highly capable ones)[22,77,78]. Indeed, we found lower prevalence of independent smallholder plantation compared to overall oil palm plantation area around certified versus noncertified mills (Fig. 4A). Since this effect was driven by the dominance of industrial oil palm near certified mills (Fig. 4B), rather than a lack of oil palm development by smallholders in these regions (Fig. 4C), it seems unlikely that sourcing decisions by mills that select into certification influenced independent smallholder oil palm development decisions. Instead, greater industrial areas within certified supply sheds may be driven by the previously

documented older age of certified relative to noncertified mills[22], generating a structural market access bias of certified mills toward areas with less proportional supply shed production by independent smallholders.

For certified mills that did source from independent producers, we found that fractional sourcing from these suppliers was close to expected based on estimated independent smallholder supply shed production (Fig. 5D). We also found no evidence that fractional independent smallholder purchases changed over time (Table 1). This is corroborated by our result that mills infrequently switch supply chain model when adding or dropping independent smallholders, which suggests that mills rarely exclude independent smallholders with whom they already have relationships to achieve greater price premia or market access. Taken together, these findings suggest that neither shortcomings in smallholder capacity nor buyer/seller behavior drove exclusion of independent smallholders from certified supply chains through 2020. We caution that this may change under more restrictive third-party sourcing requirements for RSPO certified mills starting in 2021. In Sumatra, certified mills may find purchasing from industrial suppliers less risky, relative to independent smallholders, given lower rates of industrial supplier overlap with State Forest (Fig. 6C). Moreover, there is an inherent tradeoff between noncertified smallholder market access via the RSPO's mass balance supply chain model and the current highest standards for traceability and claims of fully sustainable content via the identity preserved and segregated models (Fig. 7A).

In contrast to our independent smallholder finding, our analysis indicates that certified mills are located in places with more contract smallholders than the estimated overall contribution of these producers to Indonesian oil palm area. This structural market access bias favors contract smallholders. Yet, this comparison is uncertain because we lack high-quality information about contract smallholder contributions to Indonesian palm oil production. The central Indonesian government does not provide data differentiating contract smallholder area or production from independent smallholders—who dominate these statistics—in their annual reports. Remote sensing cannot reliably discern contract smallholder lands from industrial plantations. Despite these uncertainties, because certified mills ensure that many of their contract smallholders also achieve certification (Fig. 7C; Supplementary Note 1), the bias of certified mill locations toward contract smallholders likely means that adoption of supply chain measures by industrial actors also has outsized positive benefits for these farmers. When contract smallholders participate in certification, they can achieve higher profits especially if they do not bear certification costs[79]. Indeed, smallholder RSPO certification via mill certification is currently far more expansive than direct certification of independent smallholders. By 2021, industrial palm oil mills had certified almost eight times more contract smallholder oil palm area (208,707 ha) than the RSPO's group certification option for independent smallholders (26,839 ha)[52].

Our finding of a significant decline in proportional contract smallholder supply to certified mills was limited to our linear model in Sumatra and across the study region (Table 1). This decrease cannot be causally attributed to certification because we lack detailed data on fruit supply patterns at noncertified mills, and pre-certification supply at certified mills, from which to develop robust counterfactuals. We cannot rule out the possibility that certification itself differentially influenced smallholder and industrial yields or fruit quality[80], which could affect the relative contribution of smallholders to mill supply without changing smallholder ability to sell to mills. Nevertheless, we argue that certification is unlikely to *reduce* contract smallholder contributions to overall supply since certification has been found to have neutral or positive effects on smallholder yields[81–83]. A more likely cause is that time since certification is correlated with another variable outside our analysis that drove the observed decline (e.g., contract smallholders completing exclusive agreements with mills and becoming independent suppliers[26]).

Conclusion

Smallholder exclusion has immense consequences for global food system equity and sustainability[84]. We explored the implications of sustainable supply chain governance initiative implementation by downstream actors for smallholder producer participation in tropical agricultural commodity markets using the case of oil palm sustainability certification. To guide this analysis, we developed and applied a conceptual model of three interacting factors—structural market access, smallholder capacity, and buyer and seller behavior—to explain smallholder market participation at Roundtable on Sustainable Palm Oil certified mills. We found that, relative to their overall contribution to oil palm production in Indonesia's major oil palm cultivation regions of Kalimantan and Sumatra, contract smallholders were overrepresented and independent smallholders underrepresented in certified mill supply chains. Structural market access bias—certified oil mills surrounded by relatively more industrial oil palm and less independent smallholder oil palm compared to noncertified mills—contributed to these differences. Buyer behavior, where most certified mills never sourced from independent smallholders after certification, furthered aggregate independent smallholder underrepresentation in certified supply chains. Yet, this behavior was not clearly linked to the use of more stringent supply chain models that exclude noncertified producers. Critically, when certified mills sourced from independent smallholders at least once post-certification, we found no empirical evidence for exclusion. This was true even in Sumatra, where independent smallholders were located on State Forest lands at higher rates than industrial growers in the same certified mill supply sheds.

We conclude that exclusion at RSPO certified mills is largely "passive", created through selection bias. Passive exclusion generates limited farmer access to the positive benefits of certification implemented by downstream actors (e.g., price transparency). Certified mills with no sourcing from independent smallholders may fall short of achieving the RSPO criterion about smallholder inclusion in spirit[55,56], especially if they are not supporting nearby independent smallholders to pursue certification. We recommend research into the spatial distribution and fruit sales of RSPO certified independent smallholder groups—is there evidence that these groups are actively supported by nearby mills who are RSPO members? Passive exclusion contrasts with "active" exclusion where smallholders invest their resources in oil palm cultivation with the expectation that they will be able to sell their production to a nearby mill and are excluded due to changing supply chain requirements. In the case of active exclusion, farmers may suffer reduced profits and associated livelihood impacts[24]. We found no evidence for active smallholder exclusion in Indonesia due to RSPO certification through 2020. Tracking how more stringent sourcing requirements at RSPO certified mills starting in 2021 have influenced active smallholder exclusion is now needed[55].

In particular, the RSPO's requirement for third-party supplier legality might affect independent smallholder access to certified mills. While legality is a basic requirement of many supply chain governance initiatives, when combined with complex land tenure situations common in the tropics, it potentially creates a major barrier for smallholder inclusion in upgraded supply chains[28,65]. For instance, in Sumatra and Kalimantan, 20–26% of all independent smallholder land in palm oil mill supply sheds fell within State Forest, where oil palm cultivation is typically not legal. To avoid disadvantaging smallholders farming legally noncompliant commodities, collaboration with producing country governments to redefine what is legal may be one pathway forward. In Indonesia, accelerating land titling and agrarian reform[85] efforts will support smallholder legality outside of the State Forest. Re-zoning of the State Forest through Indonesia's amnesty program, which has thus far focused on legalizing industrial-scale oil palm plantations[86], may also be necessary to ensure smallholder inclusion.

Our findings inform potential impacts of the EU's 2023 regulation on deforestation-free products (EUDR), which has also raised fears of smallholder exclusion[26]. The EUDR requires that products entering the EU market are deforestation free, legally compliant, and traceable to production site by the end of 2025[87–90]. Many smallholder producers are already deforestation-free[91]. In 2020, about 90% of palm oil imports to the EU were RSPO certified, and this volume accounted for half of all certified palm oil globally[92]. However, mixing of EUDR compliant and non-compliant supply —a mass balance approach—will be unacceptable[93]. To make EUDR

compliance easier and cheaper, traders may choose to exclusively source oil palm products destined for the EU oil via mills with RSPO certified identity preserved supply chain models, which are limited to certified producers. This approach is possible because the percentage of palm oil consumed in the EU totaled only 8.2% of global palm oil in 2020 and has been declining in recent years[94], meaning that fully traceable RSPO certified supply can likely fill current demand. Yet, such segregation will definitively exclude non-certified independent smallholders from EU-bound supply chains: Independent smallholders contributed <0.01% of overall supply under identity preserved or segregated supply chain models compared to 8.2% of under mass balance (Fig. 7A; Supplementary Note 2). Studies are needed evaluating how multiple supply chain governance programs with distinct requirements might influence the wellbeing of vulnerable farmers through exclusion or other means.

We urge powerful supply chain actors such as palm oil traders[47] and organizations that define supply chain governance program requirements (e.g., the RSPO, the EU) to develop new approaches or improve existing policies[95,96] that encourage inclusion of diverse small farmers and provide these producers with support to ensure compliance with market demands[19,20,28,97,98]. Jurisdictional certification[99] and other similar collaborations between actors from civil society or the private sector and governments that support all producers within a policy-relevant area are one potential remedy to prevent or reduce smallholder exclusion[100]. Directly addressing passive exclusion by encouraging adoption of supply chain governance policies by buyers already engaging with or located near smallholder producers may be another effective approach which may have substantial benefits in terms of additionality[20,73]. Such large-scale deployment of inclusive, proactive approaches holds the potential to jointly benefit vulnerable rural people and the natural environment.

Methods
Study system
In Indonesia, smallholders often have no control over their status as "independent" or "contract" farmers. This is because oil palm development has been driven by large-scale plantation companies that have typically been required to offer smallholder contracts to nearby communities or government-sponsored in-migrants, but not to independent producers that have already planted their own oil palm. These arrangements with mills vary across Indonesia, in part driven by the timing of government smallholder program implementation[101]. Starting in the 1970s the national government started various nucleus estate and smallholder (NES) programs. Under these arrangements oil palm companies provided support and assistance for smallholders to develop their oil palm plantings, known as *plasma*[64]. Giving their early timing, these programs are especially common in Sumatra[102]. More recently, the *Kredit Koperasi Primer Anggota* (KKPA) programs, which are typically organized under a cooperative unit such as *Koperasi Unit Desa* (KUD—Village Unit Cooperative)[103], support contract smallholders, including by providing access to credit[104]. In contrast, independent farmers who choose to develop oil palm apart from these schemes typically have no contract with an industrial mill.

Nevertheless, the area of oil palm in Indonesia managed by independent smallholders exceeds that managed by contract smallholders. Independent smallholder area comprised 3.8–6.0 million hectares or 33–41% of total Indonesian oil palm area in 2019[70]. An additional 0.7–0.9 million hectares of oil palm (4–6% of total oil palm area) was managed by contract smallholders circa 2016[64], and contract farmers constituted ~14% of all oil palm smallholders in Indonesia in 2020[105]. Because independent smallholder yields tend to be much lower than those achieved by industrial growers[74,75], the contribution of independent smallholders to fresh fruit bunch supply is relatively lower than the oil palm area under independent smallholder management.

In 2021, 26,839 hectares or 0.4–0.7% of total Indonesian independent smallholder area was RSPO certified[52]. In contrast, RSPO-certified contract smallholder area in Indonesia totaled 208,707 hectares[52], 23–30% of total estimated contract oil palm smallholder area in the country[64,70]. At the same

time, the RSPO had certified 2,240,554 hectares under industrial "grower" certifications, totaling 22% of Indonesia's industrial oil palm area[52].

Sumatra and Kalimantan are key regions for palm oil production in Indonesia. Sumatra has an oil palm cultivation history dating back to the early 20th century[106]. By 2019, remotely sensed estimates indicate that Sumatra had a total of 9.5 million hectares of oil palm or 58% of total oil palm in Indonesia, with 4.8 million hectares (51%) cultivated by independent smallholders, contributing 81% of total Indonesian independent oil palm smallholder area[70]. Large-scale oil palm development in Kalimantan began in the 1990s with rapid expansion through the early 2010s[107]. In 2019, Kalimantan had around 6 million hectares of oil palm (37% of oil palm in Indonesia), with 0.94 million hectares (16%) managed by independent smallholders (15% of Indonesian independent smallholder area)[70]. We report findings across Kalimantan and Sumatra as well as within these major oil palm producing regions of Indonesia.

Conceptual model of smallholder market participation at RSPO certified palm oil mills in Indonesia
Here, we present a conceptual model of factors that potentially influence the degree of smallholder market participation at RSPO certified palm oil mills in Indonesia. We define market participation as the sale of smallholder-grown fresh fruit bunches to RSPO certified palm oil mills, which is distinct from the certification of smallholders under an RSPO standard. Our conceptual model, illustrated in Fig. 2, assumes that smallholder participation in markets regulated by sustainability initiatives adopted by downstream actors is partly a function of the interaction between: (1) the spatial distribution of these initiatives across smallholder producers and capacities, which affects *structural market access* to markets; (2) the ability of smallholders to meet standards needed to sell to a supply chain governed by a sustainability initiative (i.e., *smallholder capacity*); (3) decisions of participating buyers to purchase (or not) from smallholders or their intermediaries who meet program requirements (i.e., *buyer behavior*); and (4) decisions by smallholder farmers or their intermediaries who meet program requirements about whether to sell to participating buyers (i.e., *seller behavior*).

Structural market access refers to the possibility that, if participating corporate supply chain actors are non-randomly distributed across smallholder producer locations or capacities, capable producers may have skewed structural market access to such supply chains[31]. Selection bias is prevalent in voluntary supply chain initiatives[22]. If corporations select into supply chain governance initiatives based on the prevalence or capacity of smallholder suppliers, or some other variable correlated with this prevalence or capacity, selection bias may affect the access that smallholders have to sustainably governed supply chains[31]. In the palm oil sector, independent smallholders can only sell to certified mills if they are located near those mills. Fresh fruit bunches must be supplied to a mill within about 24 to 48 h after harvest before quality deteriorates[48,49]. Furthermore, independent smallholders may face barriers to selling to certified mills if their supply does not meet certain standards for sale (e.g., legal production) to these mills. Contract smallholders must sell to mills with which they have contracts, and mills are required to buy from these smallholders. Therefore, if the distribution of certified mills is not representative of the distribution of independent and contract smallholder producers, or independent smallholder capacities, this will enhance or diminish the overall potential of smallholders to access discerning markets via large-scale mills.

Regarding **smallholder capacity**, if smallholder attributes do not align with the requirements of the supply chain governance program at the point of sale (e.g., proof of land legality), these farmers may be excluded from selling to buyers that check performance against these requirements[19]. Since requirements vary across supply chain programs, smallholder capacity to meet standards may also vary. In the case of the RSPO, minimum standards have become more stringent over time. From 2007 to 2013, there was no explicit requirement for certified mills related to third-party supplier sourcing[53]. The 2013 RSPO standard suggested that certified mills should buy from "identified, legal, and responsible" sources[54], but mills were not required to abide by this suggestion. The 2018 RSPO standard imposed

requirements on certified mills for the first time. For third-party supplier sourcing, mills needed to provide evidence that fresh fruit bunches came from legal sources, in the form of geo-location of origins, proof of land tenure, and legal permission to sell. This legality mandate came into force in November 2021[55]. Regarding proof of land tenure, in Indonesia, oil palm cannot typically be legally grown within lands zoned as *Kawasan Hutan* (State Forest)[108], even though 19% of 2019 oil palm was planted in this zone[71]. Oil palm lands within the State Forest are thus unlikely to be eligible for a land deed (i.e., *Sertifikat Hak Milik*) issued by the national government. Nevertheless, the National Interpretation of the 2018 RSPO standard for Indonesia indicates that proof of land tenure issued at the local level (e.g., *Surat Keterangan Tanah* / Land Certificate) is acceptable[109]. Research in Kalimantan indicated that 14% of oil palm smallholders have no proof of land tenure at all[25]. Regarding legal permission to sell oil palm, the Indonesian national interpretation of the 2018 RSPO standard[109] does not list proof of legal permission to sell for farmers with <25 hectares of oil palm, a *Surat Tanda Daftar Budidaya* / Cultivation Registration Letter, as a requirement for legality. Yet, many farmers hold >25 hectares of oil palm[25], and thus may be required to present legal permission to sell their oil palm fruits to mills.

Considering **buyer behavior**, buyers may choose not to purchase from smallholders who meet sustainability program requirements because of costs or risks associated with such sourcing behavior[36]. Palm oil mills are required to source from their contract smallholders but have a choice regarding whether to purchase fresh fruit bunches from independent smallholders and their intermediaries. Sourcing from such third-party suppliers may benefit a mill with unmet capacity when the price of palm oil is sufficiently high, but when a mill can fulfill its capacity without sourcing from outside growers or when the price of palm oil is too low, there may be no incentive for a mill to purchase from these third-party suppliers[87,110]. Since mills participating in supply chain governance initiatives may face additional supplier verification and monitoring costs when sourcing from independent smallholders[36], the benefit of purchasing from these actors may be more often outweighed by costs than for a non-participating mill. Similarly, if a mill wishes to achieve the improved market access and price premia often associated with identity preserved or segregated supply chain models offered by the RSPO[61,62], it likely needs to exclude independent smallholders since few such smallholders are certified and those who are typically sell their certified supply through credit systems[26].

Several factors may influence **seller behavior**. Capable independent smallholders and intermediaries (i.e., those that meet the minimum requirements to sell to mills) may prefer (not) to sell fresh fruit bunches to nearby certified mills[39]. These preferences may be shaped by factors correlated with certification such as past relationships with mills[111], mill-gate fruit price, and/or documentation (e.g., land title) required by the mill[32]. For instance, even if a smallholder has land title, the intermediary that the smallholder sells to may only transact with mills that do not require such documentation. The density of mills surrounding a smallholder farm is likely to shape market options for smallholders, since a smallholder may have more choices about where to sell when there are more nearby mills.

Roundtable on Sustainable Palm Oil (RSPO) certified mill audit database

We developed a certified palm oil mill audit database from information in publicly available annual RSPO audit reports, certificates, and certification announcements[112]. First, we generated a list of all palm oil mills in Indonesia ever certified by the RSPO through June 2021 (251 mills) from the RSPO website[112] and an existing database of RSPO certified mills[22]. From this list, because of the significant workload needed to extract data from each mill's audit reports, we randomly sampled 87 mills located in Kalimantan or Sumatra that were certified through 2020, 35% of the 251 total certified mills in Indonesia (Fig. 1). Mills that reported the same fresh fruit bunch supply across all certified years (3 mills) were replaced with alternate selections, because this supply pattern indicates that the company did not report actual

supply for one year or more. For each sampled mill, we recorded the island where the mill was located.

We then recorded reported fresh fruit bunch weight supplied to each sampled certified mill from these audit reports, for all years for which audit reports were available starting in the year of initial certification through 2022. We labeled supply with supplier type (Table S1), supplier relation (i.e., supply base, RSPO member, third party, unknown), and certification status (i.e., certified, noncertified, unknown) based on interpretation of audit reports and certificates. In some cases, audit reports described supply from "outgrowers", "third-party suppliers", "outside suppliers", "independent outgrowers", and other similar terms. If we could not identify these suppliers as industrial, contract smallholder, or independent smallholder after checking the remainder of the audit report for additional information about these suppliers, we assigned them to the "unknown" supplier type. When possible, we used the weight of fresh fruit bunches received by a mill to represent supply. If this information was not available, we used the weight of fresh fruit bunches harvested (i.e., production). These metrics may not be equivalent because some fresh fruit bunches may be lost during transport to the mill, not all fresh fruit bunches are accepted by the mill due to requirements for size and quality, and fresh fruit bunches may be measured differently between large-scale growers and smallholders[113].

Audit reports frequently detailed supply that did not align with a single calendar year (e.g., from July to June), and sometimes sequential reports provided supply across overlapping periods or with gaps in time. Reported fresh fruit bunch supply was not always a full year. To ensure comparable supply across mills and years, we scaled reported fresh fruit bunch supply to annual supply (i.e., 12 months) based on the start and ends date of the supply period in the audit report. In cases when the report did not include supply dates, we assumed a supply period of 12 months. Then, we assigned a single year label to each reported supply record. When available, we used the start date of the reported supply period as the year label (e.g., if supply was reported from 2020-07-01 to 2021-06-30, we assigned 2020 as the year), otherwise we used the end date to label the year. When this procedure produced duplicate mill-years (e.g., 2020-01-01 to 2020-12-31 and 2020-07-01 to 2021-06-30 are both labeled as 2020 for a single mill), we re-labeled the second record with the end date year for that record. When the audit report did not include supply dates, we labeled the record with the year before the audit year. When this approach produced duplicate mill-years, we re-labeled the mill-year with the audit year instead of the year before the audit year. When audit reports included two years of supply data, we divided supply between years: If the report included year-specific supply variations and dates, we divided supply according to that information, otherwise we divided supply and start/end dates by two. When there was a gap in the annual fresh fruit bunch timeseries, we linearly interpolated to fill the gap for each combination of supplier type, supplier relation, and certification status. To check whether annual fresh fruit weights supplied to each mill were realistic (i.e., did not exceed mill capacity), we compared this annual supply with estimated annual mill capacity (Figs. S5 S6). To do so, we multiplied reported annual mill capacity (tonnes fresh fruit bunches per hour) by the number of annual palm oil mill operating hours reported for a representative mill in Riau province, Sumatra (5700 hours per year = 20 hours per day * 285 days per year)[114].

For each mill-year, we assigned a supply chain model (i.e., mass balance and/or segregated/identity preserved, or unknown) based on the model reported on the certificate for that year. The identify preserved and segregated supply chain models both require that mills source only from RSPO certified growers. In contrast, the mass balance model allows for blending certified and noncertified fresh fruit bunches. In cases where there was no information about the supply chain model used in a given mill-year, we interpolated the model using the following logic. If the mill used the same model throughout known mill-years, we applied that model to the unknown years. If the supply chain model was missing during the initial year of certification, we assigned model the mill used for their second year of

certification to the initial year record. In cases of one or two missing consecutive supply chain labels, and equivalent supply chain labels before and after those missing labels, we applied the label from before/after the missing mill-years. After applying these changes, 24 mill-years (4% of all mill-years in the full panel) had unclassified supply chain models.

The RSPO certified mill audit database fresh fruit bunch supply data allow us to observe all sampled certified mills through approximately 2020. Yet, variation in the date of initial certification means that our complete panel dataset tracking outcomes as a function of time since initial certification is unbalanced. For example, although 85 sampled certified mills provided supply for the first year of certification, only 16 sampled mills had time to report on their practices after 10 years of certification. To ensure that these changes in the certified mill sample did not confuse our interpretation of supply changes occurring within certified mills, we developed two panel datasets for analysis: a "full" panel and a "balanced" panel. The full panel consists of all sampled certified mills and all years of supply data available for each of these mills. The balanced panel includes only certified sampled mills with five years of data starting from the initial certification year (0), and only those five years (0-4) of supply data for selected mills. This balanced panel includes information from 83% of the mills in our full, random sample of certified mills. The full sampled certified mill panel dataset is summarized in Fig. S7.

Spatially-explicit fresh fruit bunch production by producer type across Indonesia

We mapped spatially-explicit oil palm fruit production in year 2020 at 30-meter spatial resolution by producer type (i.e., industrial producers and independent smallholders) across Sumatra and Kalimantan. To our knowledge such spatially-explicit production data are not available from other sources. To do so, we combined oil palm area and production data provided by the Indonesian government with spatially explicit locations of oil palm producer types derived from remote sensing. We did not map contract smallholder production because there are no available high-quality data on contract smallholder area and production, or spatially-explicit locations, across the study region.

We collated annual 2019 to 2021 oil palm area and crude oil palm oil production from the Indonesian Ministry of Agriculture[115]. These data were available at the provincial level for private and government producers, and at the district level for *perkebunan rakyat* or smallholders. We grouped private and government producer categories together as industrial producers because both categories are corporate entities that use large-scale production practices. The Indonesian government includes both independent and contract smallholders in the smallholder producer category[116], which masks potentially important differences between contract and independent smallholder production systems. Contract smallholder oil palm is often developed and fully or partially managed by a corporate plantation, and contract smallholders that manage their own lands often receive benefits (e.g., loans, inputs) from companies. As a result, contract smallholders tend to have higher yields than independent smallholders[117]. Given the relative prevalence of independent over contract smallholder oil palm land in Indonesia, this smallholder category is most representative of independent rather than contract smallholders. Therefore, we assumed that this dataset represented independent but not contract smallholders. We discuss the uncertainties associated with this choice in Methods "**Uncertainties and Limitations**" below.

To generate crude palm oil yield, we divided government reported provincial (industrial producers) or district (independent smallholder producers) total crude palm oil production by total oil palm area to get industrial (province level) or independent smallholder (district level) crude palm oil yield for 2019, 2020, and 2021. We converted these values to fresh fruit bunch yields by dividing them by a recent estimate of Indonesia's palm oil extraction rate (*OER*; 0.23)[118]. Equation 1, with producer type represented by t, province or district represented by i, Y indicating fresh fruit bunch yield (tonnes fresh fruit bunches per hectare per year), A indicating oil palm area (hectares), and P representing total crude palm oil production

(tonnes crude palm oil), formally describes our approach.

$$Y_{t,i} = \frac{P_{t,i}}{A_{t,i}} \times \frac{1}{OER} \qquad (1)$$

There were spatial and temporal gaps in these yield data (e.g., provinces or districts that did not report oil palm area for 2021), which we filled using the following approach which accounted for nesting of districts within provinces. For industrial yields (province level), we calculated mean 2019-2021 yield by province, omitting years with no data from calculations. For provinces with no reported yields across 2019-2021, we applied the median industrial oil palm yield from all provinces (12.4 tonnes fresh fruit bunches per hectare per year). For independent smallholder yields (district level), we took a two-step approach. To fill in values for districts missing yields, we applied the provincial-level smallholder mean yield across all district yields in that province for that year, where available. Then, we calculated the mean smallholder yield by district across 2019-2021, omitting years with no data from calculations. We then filled remaining missing smallholder yields at the district level with the median smallholder oil palm fresh fruit bunch average yield from all districts (5.7 tonnes fresh fruit bunches per hectare per year). We spatialized these gap-filled yield data by mapping them onto vectors of provincial boundaries (industrial producers; Fig. S2A) and district-level boundaries (smallholder producers; Fig. S2B)[119].

To estimate oil palm fruit production (tonnes fresh fruit bunches per raster grid cell per year) by producer type (i.e., industrial and independent smallholder), we multiplied these spatialized yields (Fig. S2) by oil palm area of independent smallholders or industrial growers in year 2020 derived from remote sensing[70] at 30-meter spatial resolution (Fig. S1). We note that in this remote sensing derived dataset, industrial plantation area is likely to include contract smallholder plantings because these plantings are developed by the contracting company and often have attributes indiscernible from industrial plantations based on interpretation of remote sensing data[70]. The resulting map represents fresh fruit production from industrial oil palm growers and independent smallholders in Sumatra and Kalimantan, Indonesia, around the year 2020 at a 30-meter spatial resolution (Fig. S3).

Palm oil mill supply sheds

To identify the geospatial locations of both certified and noncertified mills, we used an industrial palm oil mill dataset that represents all mills in Indonesia established through 2022[68] (Fig. S4). These mills are typically operated by the same oil palm companies that develop industrial plantations[120], and are established within or near industrial concessions (Fig. 3) because fresh fruit bunches should reach a mill within 24 to 48 hours upon harvesting to preserve quality[48,49]. From this mill dataset we identified sampled certified, non-sampled certified, and noncertified mills using string matching with company names in the RSPO certified mill database.

We then defined areas where each of these palm oil mills is likely to source its fresh fruit bunches. Such palm oil mill supply bases have been calculated in diverse ways, including using buffers around mills with between 5 and 84 km radii[48]. Since each mill has a unique supply base, which varies widely in size and shape across mills[48], we used 10, 20, 40, and 80 km radius buffers, the latter of which captures approximately the 99th percentile of RSPO supply base distance from mill[121]. These buffers may include industrial, contract smallholder, and independent smallholder oil palm plantation, as well as non-oil palm land cover. In the main text figures and table, we report results for the 20 km buffer, chosen to minimize overlap between mill buffers while typically including some lands outside of the industrial concession associated with the mill which is likely concentrated in the area nearest the mill (Fig. 3).

We converted each buffer to the 30-meter resolution spatial grid used to represent industrial and smallholder oil palm producer locations. In grid cells covered by only one mill buffer, we assumed that any fresh fruit production was supplied to the mill associated with that single buffer. The scarcity of artisanal (i.e., non-industrial) mills Indonesia[50], increasing travel costs to more distant mills[122], and the need to quickly process fresh fruit

bunches to crude palm oil[48,123] all suggest that this is a reasonable assumption. In grid cells where buffers overlapped, we ensured that no land or associated production was double-counted across mills. To do so, we divided land area in each grid cell according to the number of individual mill buffers occupying that grid cell (e.g., if a grid cell had 10 overlapping buffers, each mill was allocated 1/10 of land in that grid cell). We refer to these independent areas as each mill's "supply shed".

Several factors (e.g., long-standing relationships between independent smallholders and preferred mills; the location of concession boundaries within supply sheds linked to different mills) spatially pattern these supply relationships[48]. Therefore, these supply sheds do not represent the real land-to-mill supply of oil palm fresh fruit bunches. While such detailed supply data would be useful, they are not necessary to our analysis, which evaluates whether RSPO-certified supply sheds are different from noncertified supply sheds (e.g., in terms of the proportion of independent smallholders in these supply sheds), and whether certified mills source from producer types at rates similar to the distribution of these producers in their supply sheds.

Palm oil mill supply shed land use and land control

We extracted metrics of land use, land control, and oil palm fruit production in these palm oil mill supply sheds. First, for each supply shed, we quantified the area under industrial and independent smallholder operated oil palm plantings[70], as well as estimated fresh fruit production from these plantings. To evaluate whether oil palm lands potentially met RSPO certified mill requirements for land legality, we coded oil palm land use and fruit production as being inside (i.e., potentially does not meet legality requirements) or outside (i.e., potentially meets legality requirements) of State Forest (Fig. 3, Fig. S1).

For sampled certified mills, we further inferred the area of supply shed contract smallholder oil palm from sourcing records for each mill. Specifically, we assumed that the division of fresh fruit bunch sourcing reported by certified mills across industrial and contract smallholders represented the proportion of planted area across these sources in the supply shed. This is because industrial plantation area in the remote sensing dataset that we used to map the locations of different producer types likely includes contract smallholder lands[70]. For this calculation, we first allocated fresh fruit bunch weight from unknown suppliers according to the proportion of known supply sources (i.e., industrial, contract smallholder, and independent smallholder). Then, we multiplied the proportion of industrial oil palm in the supply shed with the proportion of mill sourcing from contract smallholders aggregated across all mill-years for each mill. This approach assumes that contract smallholders have yields equivalent to industrial plantations.

For each supply shed, we then estimated proportions of the supply shed land area, oil palm area, and fresh fruit bunch production under various categories (e.g., planted with oil palm, under independent smallholder production, within year-2020 State Forest lands[121]). All proportional calculations respected the division of land area or production across mills in overlapping mill buffers.

Certified mill fresh fruit bunch sourcing analysis

For both balanced and full panels from the RSPO certified mill audit database, we assessed the degree to which certified mills sourced from each supply source (Table S1) by aggregating fresh fruit bunch mass across all mill-years for all sources, and then computing the fraction of overall supply attributed to each source. To assess sourcing across supply chain models, we calculated supply by mill-year for each supply chain model (mass balance or segregated/identity preserved). We also quantified the fraction of fresh fruit bunch supply that was certified across all mill-years for each source.

Smallholder exclusion assessment

We developed an evaluation of the role that structural market access, smallholder capacity, and behavior of buyers and sellers—as described in our conceptual model (Fig. 2)—play in driving observed fresh fruit bunch sourcing patterns from contract and independent smallholders at RSPO certified mills. Where possible, we used the full population of certified mills (i.e., all certified mills in the palm oil mill location dataset), but for assessments that required information on fresh fruit bunch supply we used only sampled certified or balanced panel mills, since we have supply data only for these mills. Our assessment relied on a combination of several approaches. Statistical comparisons using t-tests relied on the R package rstatix[124], and we report p-values adjusted for multiple comparisons across the four mill buffer sizes for each comparison using the Benjamini and Hochberg adjustment method[125].

We evaluated **structural market access** (Fig. 2A) by comparing the distribution of smallholder locations and capacities to meet the RSPO's requirements to sell to certified mills across all certified (i.e., sampled and non-sampled) and noncertified palm oil mills in the palm oil mill location dataset. For independent smallholders, we compared the mean proportion of total supply shed oil palm land area (i.e., independent smallholder + industrial) classified as independent smallholder area across certified and noncertified mills. We also evaluated whether certified mill locations were skewed toward independent smallholder lands that might not meet minimum requirements to sell to these mills, relative to noncertified mills. Specifically, we quantified the proportion of supply shed independent smallholder oil palm lands within the State Forest, where smallholders cannot typically have land title. We note that being located in the State Forest would likely only affect decision-making by certified mills, since during our study period, noncertified mills were unlikely to have traceability measures or third-party supplier legality sourcing requirements in place. These comparisons used two-sample t-tests. For contract smallholders, we compared the mean proportion of total supply shed oil palm land area under contract smallholders across all sampled certified mills to the estimated contribution of contract smallholders to oil palm plantation area in Indonesia (i.e., 5% of total oil palm under contract smallholders)[64]. This comparison used one sided t-tests, with μ = 0.05 as the null hypothesis.

To assess **smallholder capacity** to sell to certified mills (Fig. 2B), we compared the degree to which circa 2020 industrial versus independent smallholder oil palm within each supply shed for all certified mills in the palm oil mill location dataset overlapped with State Forest. We recognize that smallholders may hold proof of land tenure within the State Forest that is acceptable at certified mills according to the Indonesian interpretation of the 2018 RSPO standard[109]. Nevertheless, this comparison provides insight into whether smallholders potentially face greater barriers than industrial growers in marketing their fruit production to nearby certified mills, all else equal. Our comparisons used two-sample t-tests.

We developed insight into **behavior of both buyers and sellers** (Fig. 2C) of fresh fruit bunches grown by smallholders at sampled certified mills. To do so, we compared estimated supply shed production by independent smallholders to reported supply to mills by these independent smallholders to understand whether mills were sourcing from independent smallholders at a rate that reflected their importance in the supply shed. We also evaluated temporal trends in the relative importance of independent and contract smallholder supply to mills, to ascertain if the contribution of smallholders to supply changes after certification. Finally, we examined connections between one potential driver of mill behavior (i.e., choice of supply chain certification model) and smallholder sourcing.

For the independent smallholder production-supply comparison, we calculated the proportion of total mill fresh fruit bunch sourcing from independent smallholders across all mill-years. For this calculation, we allocated unknown sourcing according to the proportion of known sources (i.e., industrial, contract smallholder, and independent smallholder). We subtracted the mill-reported independent smallholder supply proportion from the proportion of estimated supply shed fruit production. Then, we compared this difference to zero (i.e., no difference in proportions; μ = 0) using a one-sided t-test. We developed two versions of this analysis. The first assumed that mills only purchased from suppliers who potentially conform to RSPO rules (i.e., whose lands fall outside of the State Forest) and used only smallholder and industrial area from outside of the State Forest to calculate

fresh fruit bunch production. The second assumed that the mill did not differentiate between suppliers with lands within and outside of the State Forest and used all oil palm area in the supply shed to assess production.

For the temporal trend analysis, we used fixed effects models to assess the presence and direction of any relationship at certified sampled palm oil mills between time since certification and the annual proportion of total fresh fruit bunch supply from smallholders. We developed different models for independent and contract smallholders. Like Schuster and Maertens[126] our response variable was the annual proportion of independent or contract smallholder supply to a mill. Because this quantity ranges from 0 to 1, and linear regression will assess values beyond that range, we developed both linear and logistic models. For logistic models, we converted the annual proportion to a binary metric which denoted sourcing from independent or contract smallholders (1) or not (0). We did not include calendar year in our models because it was strongly correlated with time since certification. We excluded mills that never sourced from the model's focal smallholder type (i.e., independent or contract) for each analysis. Our models were specified as follows:

$$S = \beta_0 + \beta_1 T + \beta_2 M_1 + \cdots + \beta_m M_n \qquad (2)$$

Here, S is the proportion of overall supply or a binary metric indicating some or no supply from independent or contract smallholders for a given mill-year, T is the number of years since initial mill certification for a given mill-year, M indicates dummy variables representing individual mills 1 to n, and β are coefficients 0 to m. We used the *lm* function to develop linear models and *glm* function for logistic models, both in R[127], and report the significance of statistical correlations using the p-value. We report model fit using adjusted R^2 for linear models and Hosmer-Lemeshow goodness-of-fit test p-values for logistic models. We ran each regression using the balanced panel.

Finally, we evaluated the degree to which a mill's chosen supply chain model (Fig. 7A) was related to independent smallholder sourcing. The less stringent mass balance model allows a mill to handle noncertified fresh fruit bunches, while the more stringent segregated and identity preserved models require that mills handle only RSPO certified oil palm fruits. We hypothesized that greater market access and/or higher price premia offered by more stringent supply chain model types[61,62] might incentivize mills to stop buying from independent smallholders, so that they could upgrade from mass balance to identity preserved or segregated models.

We identified cases when mills switched between less and more stringent supply chain model types (e.g., a mill reported an identity preserved model in 2017 and mass balance model in 2018). We also identified cases when mills added or dropped independent smallholders from their supply mix across years (e.g., a mill reported sourcing from independent smallholders in 2017 but not in 2018). Then, we assessed the degree to which adding or dropping smallholders happened concurrently with changes in supply chain model. We also quantified the degree to which mills that never sourced from smallholders versus those that sourced from smallholders at least once maintained supply chain model stringency throughout time since certification. For this analysis, we examined the full panel of mills ($n = 87$) and mill-years ($n = 712$) because supply chain certification model changes were relatively uncommon.

Uncertainties and limitations
There are some uncertainties and limitations in our research. First, the number of randomly sampled mills (87 mills) represents 35% of all RSPO certified mills in Indonesia, potentially generating a sample not reflecting the population of certified mills. To understand whether our sample of certified mills represented the population of certified mills, we used two-sample t-tests to compare each supply shed metric derived from sampled certified mills to non-sampled certified mills. We detected only one significant difference in land cover and administrative zone across all buffer sizes for the full pool of sampled or non-sampled mills, not unexpected given the

number of comparisons undertaken (Table S5). This suggests that our sample represents the population of certified mills for metrics of interest.

Although we applied several error-checks to ensure that the information obtained from RSPO audit reports and certificates was as complete and accurate as possible, any remaining inaccuracies in these data were propagated into our analysis. We also validated our supply data by comparing it to mill capacity. Like a previous comparison of mill capacity and supply shed production in Central Kalimantan[48] our validation suggests that many certified mills were operating under capacity. We detected just 34 exceedances of capacity across the 526 mill-years in the full panel with mill capacity data (6.5% of mill-years; Figs. S5, S6), and we also note that supply was relatively stable across most mills over time. Most of our supply data therefore pass basic quality checks.

The proportion of unknown supply to mills (8.1 ± 16% in the balanced panel) exceeded the degree of known independent smallholder supply (5.9 ± 15% in the balanced panel). Audit reports frequently grouped third-party industrial supply with independent smallholder supply, meaning that some but not all unknown supply was from independent smallholders. To explore this uncertainty, we developed a bookend scenario by classifying all unknown supply as independent smallholder supply. We found that for mills in the balanced panel that sourced from independent smallholders and/or unknown suppliers ($n = 38$ mills, 53% of 72 total mills), just as with the independent smallholder-only analysis, there were no significant differences in estimated fractional production and supply (Fig. S8D). In Kalimantan, for all mills (i.e., those that source from independent smallholders and those that do not) there were no significant differences between fractional production and supply to mills by independent smallholders (Fig. S8C). This differs from the independent smallholder-only analysis (Fig. 5C). Assessing change in aggregate independent smallholder + unknown sourcing over time since certification, several regression models suggest significant positive trends in sourcing from independent smallholders (Table S6), which contrasts with our results of no change in the independent smallholder-only regression analysis (Table 1). These findings add weight to the argument that certified mills have not actively excluded independent smallholders.

Our analysis assumed that contract smallholders had yields equivalent to industrial plantations. If this assumption of equivalent contract smallholder and industrial yields is incorrect, we may have misestimated the contribution of contract smallholder lands to production. Similarly, if the ratio of independent to industrial smallholder yields was not representative of the actual yield ratio, then we may have under- or over-estimated the contribution of independent smallholder production to supply shed fresh fruit bunch production.

Regarding smallholder capacity to meet requirements at certified mills, we lacked information about the distribution of land titles and production permits across smallholder oil palm lands, which would have provided a more definitive assessment of smallholder land conformance with recent RSPO mill legality criteria. It is also possible that smallholder producers within the State Forest have proof of land tenure (e.g., issued by a Village Head or *Kepala Desa*) that RSPO auditing teams would deem acceptable for supplying to certified mills. Our analysis also did not consider other potential attributes of smallholder lands (e.g., recent deforestation) that might make purchasing smallholder fresh fruit bunch supply risky for companies participating in other supply chain governance initiatives focused on forest conservation (e.g., zero-deforestation commitments)[19,28].

More broadly, we lacked annual fresh fruit bunch sourcing data from noncertified palm oil mills, as well as sourcing data prior to certification for most certified mills. This prevented us from developing a robust counterfactual analysis (e.g., difference-in-differences) to understand the causal impact of certification on smallholder inclusion in certified mill markets. Such information would also help us check whether observed sourcing patterns are representative of mills within our study region, a further evaluation of selection bias.

Finally, the 2018 RSPO requirements for third-party supplier legality came into force in November 2021[55], while the bulk of our data are from

2020 and before. Moreover, Indonesia's own oil palm certification system – Indonesia Sustainable Palm Oil (ISPO) – is designed to ensure that mills and all producers including smallholders and large-scale plantations operate legally and sustainably, and has expanded substantially since its creation in 2011[128]. Future analyses will be needed to capture the effects of new RSPO requirements on independent smallholder fresh fruit bunch supply to certified mills, as well as ISPO's influence on smallholder legality and sales to mills.

Data availability

Code availability

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Author contributions

Competing interests

The authors declare no competing interests.

Additional information