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Limited reach of zero-deforestation commitments to Indonesian oil palm smallholders

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Many companies have adopted zero-deforestation commitments (ZDCs) to remove products linked to forest loss from their supply chains. A common concern is that such policies may lead to the supply chain exclusion of smallholder farmers. Here, in this study of the Indonesian palm oil sector, we draw on surveys with 1,541 farm households and 53 interviews with supply chain actors to assess whether and how ZDCs reach non-industrial producers, including effects on market access, prices, training and village-level deforestation. We find that access to ZDC markets depends largely on location within company sourcing areas, while active exclusion appears to be limited. Certification-based engagement reaches some tied smallholders, but ZDC awareness remains low, with weak policy dissemination, limited bottom-up traceability and almost no ZDC-focused capacity building or price differentiation for producers, especially independent smallholders. Deforestation levels in villages within the sourcing areas of ZDC firms are low but similar to patterns elsewhere. These findings highlight effectiveness and equity gaps in current ZDC approaches.

Agriculture is a leading cause of forest loss in the tropics[1–3]. In Indonesia, the largest global producer of palm oil, oil palm development has historically been a primary deforestation driver through large-scale estates and, increasingly, smallholder farming activities[4,5]. In response to civil society pressure, many palm oil firms have adopted zero-deforestation commitments (ZDCs)—that is, voluntary commitments to not source products grown on recently cleared land[6–9]. The growing contribution of small-scale farming to deforestation highlights a potential trade-off between effectiveness and equity in ZDC implementation[10]. To avoid adverse equity outcomes, ZDC companies should ensure deforestation-free supply without excluding small-scale farmers[9–11].

We examine whether ZDC implementation has resulted in smallholder supply chain exclusion, defined here as the inability of smallholders to sell into the supply chains of buyers with ZDCs. Our analysis covers 73 villages in Sumatra, Indonesia, and combines 1,541 surveys of non-industrial oil palm producers with 53 semi-structured interviews with supply chain actors. Indonesia is a particularly important case because it produces 60% of the world's palm oil[9,12]. Between 2000 and

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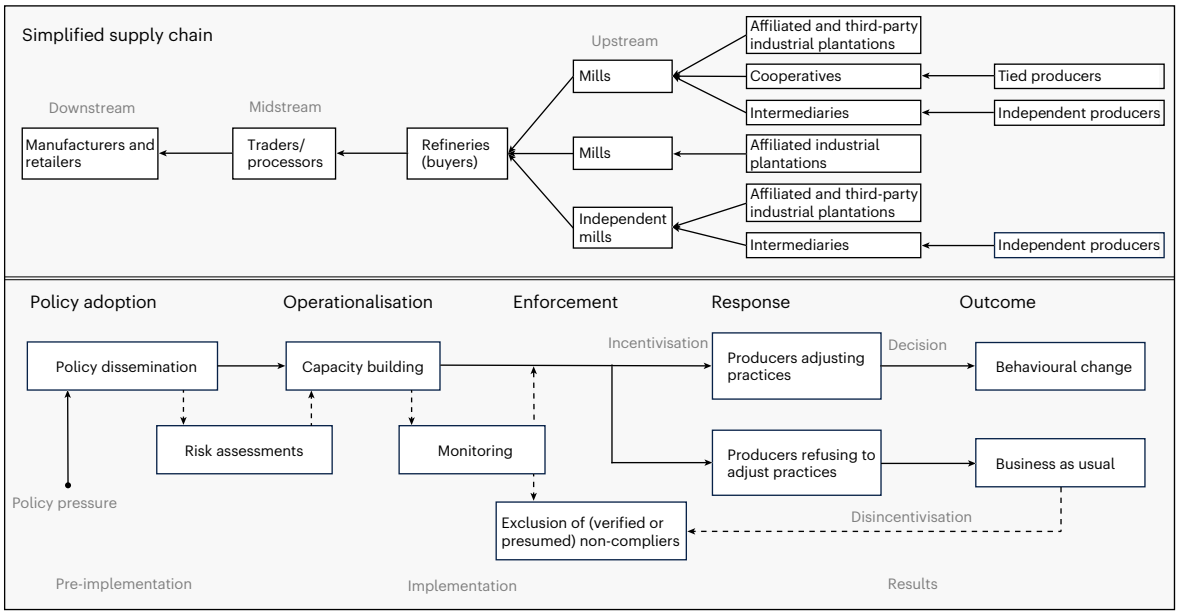

Fig. 1 | Simplified palm oil supply chain and conceptual framework. This figure illustrates key actors in the palm oil supply chain and the process through which policy adoption, operationalisation and enforcement may lead to producer responses and outcomes. Adapted from refs. 10,28.

2019, its oil palm area doubled to 16.24 million hectares, while 11% of its forest cover was lost; 29% of this loss was converted to oil palm in the same year, and another 32% in later years[5].

Non-industrial producers, defined as producers that are not licensed plantation businesses, include both independent smallholders (that is, those who operate independently) and tied smallholders (that is, those who are members of cooperatives affiliated with companies)[9,13]. In 2019, independent smallholders managed 6 million hectares of oil palm in Indonesia, equal to 36% of the national oil palm plantation area[5]. Together, independent and tied smallholders account for one-third of national palm oil production[14]. Yet, their plantations often remain less productive due to factors such as ageing trees and limited access to training, financial and technical assistance[10,15–17]. Smallholders are also often located on marginal lands (for example, peatland), near forest areas or within state forests; a case study in Kalimantan reveals that 70% lack official land titles[13,15,18,19]. Government efforts to sectoral sustainability have centred on the implementation of the Indonesian Sustainable Palm Oil (ISPO) standards[20,21] and land licensing moratoria[22], while tenurial conflicts and inadequate public services remain unresolved[18,23].

Over the past decade, ZDCs in the oil palm sector have largely taken the form of No Deforestation, No Peat and No Exploitation (NDPE) policies, which also include commitments on peatlands, labour and community exploitation. During this period, companies have invested in supply chain traceability, deforestation monitoring and engagement with non-compliant suppliers[11,24,25]. Some also rely on Roundtable on Sustainable Palm Oil (RSPO) certification, although strict deforestation and peat restrictions were introduced there only from late 2019 onwards (the revised RSPO Principles and Criteria were adopted in November 2018, but a 1-year transition period delayed full implementation until November 2019)[6,26]. Here, we focus mainly on deforestation restrictions and refer to 'ZDCs' and 'ZDC policies' in the understanding that the terms encompass NDPE policies with a variety of implementation pathways. We use the terminology 'NDPE-related' requirements or restrictions when referring to provisions beyond deforestation (no peat, no exploitation and no burning).

A persistent challenge for firms with ZDCs is how to integrate non-industrial suppliers into implementation, particularly because these producers often require substantial on-the-ground support to align with NDPE requirements[10,27]. This is especially important because 89% of independent smallholder plantations in Sumatra, Kalimantan and Papua lie within the sourcing areas of companies that have both ZDCs and programmes targeting independent smallholders[28].

Understanding how oil palm smallholders are affected by ZDCs in Indonesia also offers insights for other smallholder-intensive supply chains, including oil palm production in other regions and cocoa, coffee and rubber, which require major adjustments to become deforestation-free[29,30]. This is particularly relevant in light of the European Union (EU) Deforestation Regulation (EUDR), which requires products entering the EU market[31] to be deforestation-free—that is, not sourced from land cleared after 2020. In addition, both the EUDR and UK Deforestation Regulation (UKDR) require production to be compliant with producer-country regulations. Many fear that these requirements might inadvertently exclude non-industrial farmers because of their land legality status and financial barriers[10,11,32–34]. Voluntary ZDC policies share key implementation steps with EUDR, including to establish supply chain traceability, disseminate compliance rules to producers, conduct risk assessments, implement supporting measures (that is, capacity building on rule compliance), encourage behaviour change and exclude non-compliant producers[9,35].

This study advances empirical understanding of ZDC implementation and its conservation and equity implications by addressing gaps in bottom-up traceability, ZDC dissemination, capacity building and economic incentives, while offering lessons for other smallholder-intensive supply chains and future deforestation-free policies.

Conceptual framework

We briefly outline the complexity of the palm oil supply chain, which is crucial for understanding the challenges of implementing ZDCs[24]. Fresh fruit bunches (FFB) are harvested on plantations and transported to mills, the first processing point before refining (Fig. 1). Because FFB must be processed within 48 hours to maintain oil quality, mills are usually located close to plantations[36]. Mills may source FFB from affiliated industrial plantations, third-party industrial plantations or non-industrial producers and are typically owned by a corporate group or an independent company. Non-industrial producers are categorised as 'tied' to a palm oil company (via cooperatives established with company support) or 'independent' producers[9]. Mills purchase FFB from these growers either through cooperatives or through delivery contracts that allow individual producers to sell

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Table 1 | Indicators, theory of change, approach and data corresponding to hypothetical ZDC implementation pathways and outcomes

	Indicator	Theory of change	Approach/analysis	Data	Theory reference
Dissemination (pathway 1)	(1) Non-industrial oil palm producers (henceforth referred to as producers) know which mills they sell to.	Indicator 1 investigates the state of bottom-up traceability in the sector—an important and so far underexplored component of ZDC implementation. While producers typically identify their immediate buyers—be it intermediaries or cooperatives—the final mills processing the FFB can often remain obscure, particularly if producers do not sell directly to the mills or engage with cooperatives that manage sales contracts with specific mills. Producers need to know who they are selling to in order to make informed decisions about their compliance behaviour and associated consequences. ZDCs are implemented at the company level, starting at the mill, where mills and nodes higher up the supply chain are tasked with conducting outreach to smallholders about policy changes. However, if producers are unclear about which supply chain they are part of and which specific ZDC policies apply to them, these outreach efforts can be largely ineffective. This situation underscores the necessity for bottom-up traceability and enhanced market awareness, allowing producers to make well-informed decisions regarding compliance and to align with ZDC policies. Thus, establishing a clear and transparent traceability system becomes essential for informed decision-making and ensuring adherence to environmental commitments.	Supply chain tracing: we linked bottom-up traceability data and top-down traceability data. Producers were asked to identify their mill buyers, which were then manually matched to the top-down mapping. This way, we are able to link producers to broader traceability data and ZDCs.	Household survey: self-reported mill destination for producers' FFB, enhanced top-down traceability data by ref. 28.	25
	(2) Producers within the mill shed of a ZDC mill (henceforth 'ZDC mill sheds') are more aware of NDPE-related restrictions than producers outside of ZDC mill sheds.	Indicator 2 explores whether producers within the ZDC mill sheds, where policy and restriction dissemination are most likely to occur, are more aware of NDPE-related restrictions than producers outside the ZDC mill sheds. Literature suggests that ZDC policies often include rule dissemination and capacity-building activities[10], which are expected to enhance producer awareness and encourage alignment with ZDC practices. While awareness of the policy alone does not guarantee effective dissemination—producers may still lack understanding of the rationale or incentives to comply—knowing a policy exists is a bare minimum for compliance.	Statistical Kruskal–Wallis tests were conducted to compare exposure to NDPE-related restrictions between producers located in high-quality, low-quality and non-ZDC mill sheds. Producers were asked whether their buyers required specific criteria, such as providing land tenure documents, avoiding planting on areas designated as Forest Estate, refraining from burning practices, not cultivating on peatland, adhering to zero-deforestation policies (for example, avoiding planting on HCV/HCS land) and ensuring no exploitation of workers. We also provide additional analysis using qualitative data to support the findings and analysis on awareness of certification, certification status and legal compliance, including the ownership of land tenure documentation (for example, land title and land permit).	Household survey, self-reported exposure to different possible components of NDPE-related restrictions.	10
Training and incentivisation (pathway 1)	(3) Producers within ZDC mill sheds receive greater exposure to capacity-building training about ZDC compliance than producers outside of ZDC mill sheds.	Indicator 3 assesses engagement efforts by palm oil companies with producers aimed at specific capacity gaps to remove barriers to accessing ZDC markets. This indicator posits that producers within the ZDC mills' sourcing bases are more likely to benefit from these targeted capacity-building efforts and more extensive training.	Statistical Kruskal–Wallis tests were conducted to compare exposure to capacity-building training between producers located in high-quality, low-quality and non-ZDC mill sheds. Producers were asked whether they have received capacity-building training.	Household survey, self-reported capacity-building training.	10,25
	(4) Producers who sell to ZDC mills receive higher prices than those who sell to non-ZDC mills.	Indicator 4 explores pricing as a marker of improved market conditions, examining whether there is a price incentive linked to ZDCs. For producers to adopt sustainable practices, incentives are needed to ensure that these adjustments are economically viable. This indicator posits that mills with ZDCs may offer price premiums to incentivise sustainable practices, thereby creating market-based incentives for producers.	Regression analysis assessed whether there was any association between farm gate prices and sales to ZDC mills. Using the data from indicator 1, producers were asked about the average farm gate price they received in 2021. We included control variables as explained in the Methods.	Household survey, self-reported farm gate prices from producers.	7,10

Table 1 (continued) | Indicators, theory of change, approach and data corresponding to hypothetical ZDC implementation pathways and outcomes

	Indicator	Theory of change	Approach/analysis	Data	Theory reference
Exclusion (pathway 2)	(5) Producers within ZDC mill sheds are unable to sell to ZDC mills.	Indicator 5 evaluates the prevalence of exclusion practices, where ZDC companies may avoid sourcing from non-industrial producers within their mill sheds to maintain compliance standards.	Supply chain tracing, qualitative interviews and regression analysis were conducted to assess whether mills with ZDCs source from smallholders, whether exclusion practices are present (based on qualitative interviews with supply chain actors) and whether there is correlation between sales to ZDC mills and being located within ZDC mill sheds.	Household survey, self-reported mill destination for producers' FFB.	7,10,27
Deforestation patterns	(6) Villages within ZDC mill sheds exhibit lower deforestation rates compared with villages outside of ZDC mill sheds.	Indicator 6 examines village-level deforestation patterns within and outside ZDC mill sheds to understand whether the presence of ZDC mills corresponds with differences in forest cover change. While many oil palm plantations may have been established before ZDC implementation, the presence of ZDC mills could still influence producers' land-use decisions and overall forest dynamics within their villages through mechanisms such as monitoring, policy dissemination and engagement. Although deforestation may result from other factors, measuring deforestation rates remains relevant in areas where palm oil is a primary livelihood, particularly given the time lag in detecting palm-driven deforestation.	Geospatial analysis utilised spatial datasets on temporal forest cover and deforestation trends to compare deforestation rates between villages within ZDC mill sheds and those outside.	Forest cover and changes between 2000 and 2022 as well as the extent of oil palm plantation.	6

regularly to a specific mill. Across the supply chain, ZDCs are adopted by downstream companies, refineries and corporate mill groups[9].

Previous studies suggest that ZDCs are most likely to achieve both effective deforestation reduction and equitable producer inclusion when they cover all suppliers and are supported by adequate conservation, traceability and smallholder inclusion efforts[28]. This involves actively tracing their supply chains to their sourcing areas or geographic catchment area from which they source FFB (that is, the 'supply shed'), which typically cover villages within a certain distance of the mills they source from[9,28,37]. Traceability helps firms identify deforestation risks and establish monitoring systems. Second, firms disseminate the rules and restrictions in their ZDC policies to producers in these supply sheds to ensure suppliers are aware of corporate requirements[9,10,38]. They should then build capacity, including ZDC-focused training, in their supply shed to enable producers to adjust their agricultural practices following NDPE requirements to comply with ZDCs[9]. Experience from voluntary sustainability standards also suggests that firms may choose to use financial incentives such as price premiums to attract producers to supply chains with higher environmental standards than the mainstream market[7,39]. Firms should engage with non-compliant producers to explain the rationale for the policy, focusing on the negative impacts of ongoing clearing on the communities themselves[9]. Collectively, these efforts may reduce deforestation rates in non-industrial producer villages within the supply sheds of mills with ZDCs (that is, the area from which mills are most likely to source, as defined by a radius-based approach; henceforth ZDC mill sheds)[9]. A less equitable potential implementation pathway (and less likely to reduce deforestation)[10] would arise if committed companies—in the absence of sufficient resources or initiative to pursue the above-mentioned ideal implementation strategy—simply avoid sourcing from non-industrial producers in ZDC mill sheds, whether due to verified or presumed non-compliance, thereby excluding them from certain markets[9,40].

Following these hypothetical implementation pathways derived from the literature, we formulate the indicators to assess the extent of ZDC implementation in practice[9] presented in Table 1. The more indicators met under pathway 1, the stronger the evidence that ZDCs are successfully targeting, capacitating and incentivising smallholders to achieve deforestation compliance, defined here as not clearing forest or land after a certain cut-off date. Evidence of exclusion (pathway 2) combined with limited evidence for pathway 1 would suggest that companies are prioritising effectiveness outcomes by excluding smallholders. If evidence for both pathways is weak, this would suggest that policies are highly unlikely to be effective (deforestation is ongoing and deforestation rates are not reduced[6]) or equitable (non-industrial producers are not supported in selling to firms with ZDCs[10]).

We used a mixed-methods approach to test these indicators using datasets collected in Sumatra, Indonesia[9]. We traced the supply chains of 1,541 non-industrial producers and assessed their link to ZDCs (indicator 1) and the associated outcomes. We examined the ZDC coverage within the mill sheds of companies that own a mill (henceforth 'mill owners') and refinery companies that source from a mill (henceforth 'buyers'), classifying them based on the quality of their ZDC policies and implementation in line with the six criteria for high-quality ZDCs developed by Chandra et al.[28] (Methods)[9]. Companies were categorised as 'ZDC' or 'non-ZDC', wherein 'non-ZDC' companies lacked a ZDC for all suppliers. 'ZDC' was further divided into 'high-ZDC' for high-quality ZDC companies that committed to zero deforestation across all suppliers and met all six criteria[28], and 'low-ZDC' for low-quality ZDC companies that met only some criteria. As shown by Chandra et al., low-ZDC mills tend to face challenges related to traceability, compliance support for high-risk mills, transparency and smallholder inclusion, which probably shape implementation and outcomes[28]. We used statistical tests to evaluate ZDC awareness among producers (indicators 2 and 3) and regression analyses to explore the correlation of selling to ZDC mills versus non-ZDC mills on prices and revenue (indicator 4) as well as ZDC market access (indicator 5)[9]. We further compared village-level deforestation and land cover characteristics between villages within and outside ZDC mill sheds using geospatial analysis (indicator 6). In addition, we qualitatively analysed 53 semi-structured interviews with supply chain actors[9]. In the next sections, each interviewee is uniquely coded with 'I' and a number (for example, I-1).

Results

ZDC policy coverage and producer characteristics

Nearly 60% of our sampled villages (42/73) were located within ZDC mill sheds in 2020, although only three were in high-ZDC mill sheds[9] (Fig. 5). Similarly, two-thirds of our 1,541 producers were situated within the mill

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Table 2 | Descriptive statistics of household survey dataset by ZDC mill sheds of mill owners

Descriptive statistics	High-ZDC mill sheds (*N*=54)	Low-ZDC mill sheds (*N*=970)	Non-ZDC mill sheds (*N*=517)	*P* value
Year farm was established	2001 (9.4)	2005 (9.8)	2009 (7.6)	1.52×10^{-14}
Total area owned (ha)	6.3 (5.3)	5.3 (15.9)	4.0 (10.8)	4.26×10^{-15}
Area under oil palm (ha)	3.8 (3.2)	3.4 (14.8)	3.4 (10.5)	0.0078
Age of household head (years)	52.2 (10.5)	49.9 (11.9)	46.2 (13.0)	4.08×10^{-8}
Education of household head (years)	8.4 (3.9)	8.5 (4.0)	8.7 (4.4)	0.6041
Number of household members	4.0 (1.2)	4.2 (1.6)	4.4 (1.8)	0.0930
Proportion of household members in productive age range (%)	75.9 (25.4)	68.9 (27.0)	68.8 (25.4)	0.1012
Number of surveyed producers by migration status				$<1\times10^{-22}$
Migrant	43 (79.6%)	446 (46.0%)	84 (16.2%)	
Non-migrant	11 (20.4%)	524 (54.0%)	433 (83.8%)	
Number of surveyed producers by type				$<1\times10^{-22}$
Independent producers	16 (29.6%)	627 (64.6%)	497 (96.1%)	
Tied producers	38 (70.4%)	343 (35.4%)	20 (3.9%)	
Distance to closest mills (km)	6.3 (3.6)	11.5 (15.7)	20.3 (23.4)	3.28×10^{-8}
Farm gate price per kg in 2021 (IDR)	1,980 (425.0)	2,066 (461.8)	2,023 (408)	0.0480
Seedling				0.0018
High-quality seed	42 (77.8%)	604 (62.3%)	289 (55.9%)	
Low-quality seed	12 (22.2%)	366 (37.7%)	228 (44.1%)	
Equipment ownership: truck				0.5210
Own truck	53 (98.1%)	951 (98.0%)	511 (98.8%)	
None	1 (1.9%)	19 (2.0%)	6 (1.2%)	
Revenue per harvest (million IDR)	6.1 (6.4)	5.9 (12.3)	5.5 (19.4)	6.26×10^{-6}

For numerical variables, mean values are shown with standard deviation in parentheses. For categorical variables (that is, migration status and type of producers), producer counts are shown with percentages. The *P* value signifies whether there are statistically significant differences between groups. Comparison between groups reported is based on a Kruskal–Wallis chi-square test. IDR, Indonesian rupiah.

sheds of mill owners with ZDCs, and nearly all (97%) within the sourcing bases of downstream buyers with ZDCs (Supplementary Table 6). We focus on ZDCs by mill owners because their direct market linkages with the producers and the intermediaries provide critical insights into ZDC implementation[28].

Table 2 presents household characteristics of our producer sample by ZDC mill sheds of mill owners, and Table 3 presents forest and land-use characteristics across surveyed villages. Table 2 suggests potential ZDC selection effects in well-established oil palm regions. On average, producers in ZDC mill sheds managed more mature palm trees and larger plantation areas, and were more likely to have migrated to their villages of residence. In 2020, most producers within high-ZDC mill sheds were affiliated with companies (that is, tied smallholders) and were closer to the market (that is, mills). These characteristics are consistent with a mature phase of oil palm development, in which companies initially established plantations and integrated migrant farmers (for example, via a transmigration programme) into their operations. Conversely, those within low- and non-ZDC mill sheds were dominated by independent producers and located farther from the nearest mills. This pattern reflects a more dispersed land use, which is characteristic of areas where oil palm cultivation is expanding. In these areas, local landholders increasingly expand their farms farther from the initially established plantations and mills, indicating a shift from rapid commercial expansion to more fragmented and extensive land use, where smallholders extend farms to dispersed and marginal areas[41].

Limited bottom-up traceability in supply chains

Our supply chain map (Fig. 2a) shows that only 23% of non-industrial producers—either independent producers who, on average, own more than 5 ha and hold delivery contracts, or members of cooperatives—could sell directly to mills. By contrast, 77% lacked such contracts and relied on intermediaries to sell to mills. Those selling via cooperatives were almost entirely tied producers. The category of intermediaries included actors that sourced FFB as well as those that only facilitated the logistics of buying and selling. They accepted FFB regardless of production output, provided loans and engaged in 'contract renting' by leasing delivery contracts to other intermediaries (I-3, I-4, I-5, I-17, I-9, I-11, I-21 and I-50). Because of this high level of intermediation, only 58% of producers were aware of the first processing node of their FFB, leaving 42% unaware of mill destinations and potential buyer requirements. Contract renting could further complicate traceability by shifting FFB handling and oversight away from the official contracting intermediary to other actors.

Out of 73 study villages, the majority of surveyed producers in 61 villages were aware of their mill destinations—28 out of 40 in Aceh and all villages in South Sumatra. Producers accessed up to 9 unique mills, with an average of 3.26 per village. Three-quarters of farmers who knew their FFB mill destinations sold to mills with some form of ZDCs. However, we found potential misalignment in policy implementation across the supply chain: the FFB of over 90% of producers that sold to low-ZDC mills were indirectly linked to supply high-ZDC buyers through the downstream supply chains of those mills. Finally, 47.5% of mills sold to buyers who were not identified in our desk review and data based on the best available supply chain information from Trase[42]. Limited knowledge of both mill destinations and buyer identities underscores a critical traceability problem for research and practice and hinders policy implementation and enforcement[9].

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Table 3 | Forest and land-use characteristics between villages within ZDC and non-ZDC mill sheds

	Non-ZDC mill sheds (*N*=31)	ZDC mill sheds (*N*=42)	*P* value
Share of remaining forest in 2020 (%)	25.53 (30.57)	11.48 (14.80)	0.111
Village area (ha)	991.95 (985.21)	1,518.69 (1,095.19)	0.016
Average deforestation rate between 2001 and 2022	0.04 (0.04)	0.02 (0.02)	0.110
Distance to closest mills (km)	24.37 (32.98)	13.62 (21.21)	0.315
Share of forest areas in 2000 (%)	36.06 (32.41)	18.78 (22.15)	0.011
Share of area under smallholder palm in 2019 (%)	33.89 (33.51)	15.29 (21.45)	0.019
Share of area under industrial palm in 2019 (%)	14.62 (22.64)	32.00 (33.67)	0.014
Share of area under oil palm plantation in 2001 (%)	0.17 (0.44)	0.12 (0.51)	0.400
Share of forest to palm between 2001 and 2019 (%)	4.03 (5.79)	2.10 (5.26)	0.011

For numerical variables, mean values are shown with standard deviation in parentheses. For variables expressed as shares (percentages), values are calculated as total area divided by total village area. The *P* value signifies whether there are statistically significant differences between groups. Comparison between groups reported is based on a Kruskal–Wallis test.

Limited knowledge dissemination in ZDC supply sheds

We found instances where a few companies, linked to large trading firms, stated in their documentation that they had disseminated ZDC information within their sourcing base using flyers (Supplementary Table 4). However, producers on the ground were generally unaware of NDPE-related restrictions, including land-tenure requirements, restrictions on planting in Forest Estate, high conservation value (HCV) and high carbon stock (HCS) areas, no-burning rules, peatland restrictions and no exploitation provisions[9] (Table 1). Awareness of ZDC information was limited to tied producers, with over a quarter located in low- and high-ZDC mill sheds (Fig. 3a), while none of the independent smallholders reported such awareness except on certification (Fig. 3b).

Given this low level of knowledge, we examined potential pathways of dissemination. Because intermediaries play a crucial role in the communication between mills and producers, we would expect that intermediaries are aware of the ZDC policies. However, only 4 of the 38 interviewed intermediaries had even partial knowledge of ZDCs. Although such awareness did not generally imply enforcement, in some cases it was linked to concern or informal restrictions on sourcing from recently cleared land or peat areas; for example, one intermediary noted that "you can't sell to [PT PLB] anymore" (I-20) because the FFB came from peatland. One intermediary was aware of 'no deforestation and no burning' (I-6), two referred to 'no deforestation' as "[products from] forest clearance cannot be accepted by the company" (I-1 and I-2), and one mentioned a 'no peat' policy (I-26). Two additional intermediaries were unfamiliar with ZDCs but knew of the government-enforced 'no burning' rule (I-4 and I-6). Only one intermediary reported receiving information on 'no burning' from companies (I-26); the others learned about it through the media.

By contrast, over half of the cooperatives interviewed had been exposed to expectations around no deforestation and no peat conversion, but only through RSPO certification. This was reflected in the higher share of producers aware of certification—12% of independent producers (135 of 1,140) and 45% of tied producers (180 of 401)—especially in high-ZDC mill sheds. Despite this partial awareness, the share of certified producers (for example, RSPO and ISPO) remained low, with all certified producers being tied producers, nearly all of whom were located within ZDC mill sheds. Overall, the low awareness of NDPE-related restrictions among cooperatives, intermediaries and producers suggests that ZDC information has been poorly disseminated within the sourcing bases of mills with ZDCs.

Absence of ZDC focused training

We found that farmers within ZDC mill sheds received more agricultural training, especially those tied to companies with contractual arrangements (Fig. 3). However, most of the farmers who received training were either certified or in the process of attaining certification. Our qualitative analysis suggests that comprehensive training on ZDC policies was largely absent. Instead, training was typically technical—for example on spraying, planting and pruning—and mainly offered to tied producers during plantation development and certification (I-18, I-41, I-43, I-45 and I-49). We identified only one company-led training on fire awareness (I-51). Concerns were also raised that government extension workers had expertise in food crops but not cash crops and were not involved in company-led training (I-32 and I-47), reinforcing capacity gaps among independent smallholders. These findings suggest that there is almost no ZDC-focused capacity building; and the offered training is largely limited to ongoing certification activities, meaning that independent smallholder farmers are left with little facilitation to enable compliance[9].

Absence of ZDC focused incentivisation

We found no significant relationship between selling to ZDC mills or the proportion of high-ZDC mills within a 40-km radius and improved farm gate prices or revenue per harvest[9] (Fig. 4; see Supplementary Table 8 for full regression results). However, disaggregating by producer type revealed differences. Among tied producers, selling to ZDC mills was modestly associated with higher revenue, whereas among independent producers the relationship was weak and inconsistent across model specifications (Supplementary Table 8). This suggests that the effects of ZDC-linked transactions are context dependent and reflect differences in contractual and pricing arrangements.

Prices were positively correlated with the cultivation of high-quality seeds (accompanied by seed documentation) but negatively associated with larger farm sizes and affiliations with companies via partnership schemes (that is, the plasma programme). Tied producers sold their FFB through cooperatives and received administrative and other deductions, including input and transport costs, resulting in lower farm-gate prices. Revenue was positively associated with high-quality seeds, truck ownership and higher education, but negatively associated with the year of farm establishment. Similar results were observed when regressions included producers who did not know to whom they sold. Overall, these findings indicate an absence of price-based incentives linked to ZDCs that might encourage compliance[9].

Limited exclusion from ZDC supply chains

Producers located within ZDC mill sheds had significantly greater access to ZDC supply chains, and this positive relationship held for both tied and independent producers (Supplementary Table 9). Among farmers who knew their buyers, 54% of those located in ZDC mill sheds sold FFB to ZDC mills, compared with 25% of those located in non-ZDC mill sheds. However, it is clear that producers in both ZDC and non-ZDC mill sheds could sell to ZDC mills.

According to our interviews, companies typically accepted community FFB regardless of location, especially when they did not manage plantations or operate below mill capacity (I-1 and I-19). However,

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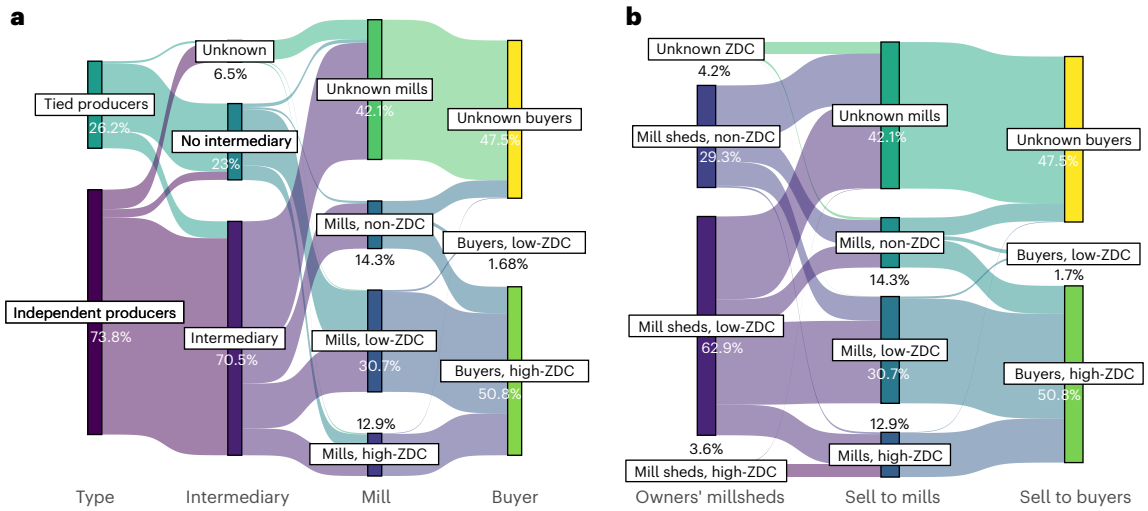

Fig. 2 | Non-industrial producers' supply chains and links to ZDCs. **a**, A simplified overview of non-industrial producers' supply chains and their links to ZDC companies based on household survey data. **b**, The locations of non-industrial producers by ZDC mill sheds, the status of the ZDC mills they sell to, and the ZDC buyers that these mills supply. These panels focus on the household as the unit of analysis. Those who did not know or did not report via whom they sell their FFB are labelled as 'unknown' in the intermediary section; 'unknown mills' refers to the category assigned to data from producers who did not know where their FFB were delivered to; and 'unknown buyers' represents a group of mills' buyers that was not traceable via the Trase platform, which provides information on supply chains and their impacts[42]. Mill sheds are defined by the geographic catchment areas of mills with ZDCs, but, in practice, producers do not always sell to the nearest mill. Some may sell to mills located farther away, meaning that producers classified within a 'non-ZDC' mill shed may in fact supply a ZDC mill, and vice versa.

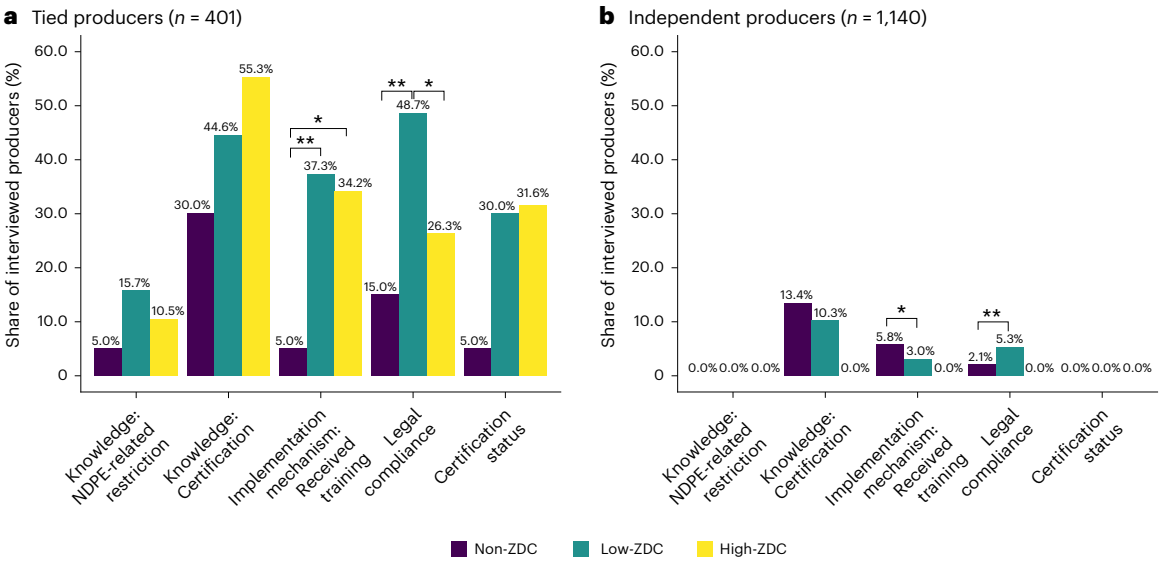

Fig. 3 | Non-industrial producers' self-reported exposure to ZDC policy implementation and other private-led interventions, by ZDC mill sheds. **a**,**b**, Tied smallholders (**a**) and independent smallholders (**b**). 'Knowledge: NDPE-related restriction' represents the share of producers who were knowledgeable on NDPE-related restrictions; 'Knowledge: Certification' refers to knowledge on any certification schemes (for example, RSPO, ISPO and International Sustainability and Carbon Certification (ISCC)); 'Implementation mechanism: Received training' refers to producers' exposure to company-provided agricultural training modules that are commonly delivered as part of bundled agricultural training programmes (for example, good agricultural practices, environmental practices, fire management, record-keeping, gender and so on) and is used here to indicate a potential ZDC implementation mechanism; 'Legal compliance' represents the share of producers who own land title documentation; and 'Certification status' refers to the share of producers that are part of certification scheme(s). Overall group differences were assessed using Kruskal–Wallis tests, followed by post-hoc Dunn's tests with Bonferroni correction for pairwise comparisons. Symbols denote statistically significant pairwise differences based on the adjusted Dunn test *P* values: ***$P \leq 0.001$, **$P \leq 0.01$, *$P \leq 0.05$. Only statistically significant pairwise differences are shown. Exact Kruskal–Wallis and Dunn test results are provided in Supplementary Table 7.

some communities faced supply quotas (I-41 and I-44) or disruptions following changes in mill ownership (I-44). A few mills also implicitly excluded community FFB by offering prices too low to make sales financially viable (I-19, I-27, I-37 and I-51). Most of these mills were committed to the RSPO Identity Preserved scheme, which requires certified products to remain separate from conventional palm oil[43]. While this practice enables mills to control that their supply is not associated with deforestation, without adequate communication, local communities often perceived it as a form of exclusion: "It's just [company name] that doesn't accept it. It was protested by the residents, but that's what the residents protested, [it turned out that the company] set the price below the standard, [causing] outrageous loss." (I-27). Considering the

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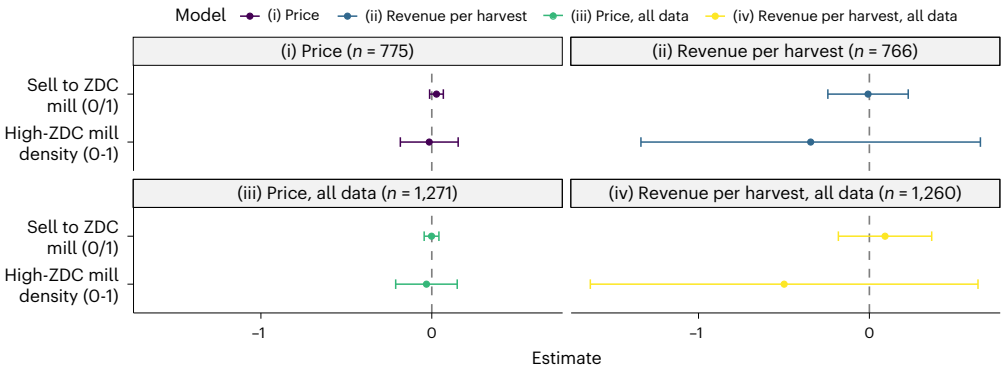

Fig. 4 | Estimates from linear regression models on prices and revenues per harvest. Dependent variables are the logarithmic form of (i) price, (ii) revenue per harvest, (iii) price using all data and (iv) revenue per harvest using all data. The unit of analysis is the interviewed non-industrial producer household. Models (i) and (ii) exclude producers who did not know to whom they sell and use, $n = 775$ and $n = 766$ observations, respectively. Models (iii) and (iv), labelled 'All data', include all producers and use, $n = 1,271$ and $n = 1,260$ observations, respectively, with a separate category for those with unknown sales channels. Points indicate regression coefficient estimates, and horizontal lines indicate 95% confidence intervals around those estimates. Confidence intervals crossing zero indicate that the corresponding predictors are not statistically significant ($P > 0.05$). Full regression tables are provided in Supplementary Table 8.

high competition among mills, producers often retained the option to sell to preferred channels (I-44). In sum, active exclusion within the ZDC supply chain is, if present, very limited[9].

Forest characteristics within and outside ZDC mill sheds

The average deforestation rate at the village level from 2001 to 2020 was 3.5% per year in villages outside ZDC mill sheds, versus 2% in villages within ZDC mill sheds (Fig. 5a). Although villages within ZDC mill sheds (which, as noted above, represented the majority of villages that contain producers selling to ZDC mills) maintained a lower deforestation rate until 2018 (Fig. 5b), a slight increase in deforestation rates in ZDC mill sheds was observed after 2020. Yet, cumulatively, deforestated area between 2001 and 2022 has been lower in ZDC villages than in non-ZDC villages since 2009; by 2022, it was, on average, 15 ha lower.

Villages within ZDC mill sheds were significantly larger in area and had a lower share of forest coverage in 2000 (Fig. 5c) and a greater share of industrial oil palm plantations by 2019. On average, producers within ZDC mill sheds established plantations earlier than those located in non-ZDC mill sheds (see Kruskal–Wallis test results in Table 2). While current deforestation rates across villages are low, these results show ongoing clearing but no statistically significant difference in average deforestation rates between ZDC and non-ZDC villages.

Discussion

To achieve global conservation goals without undermining sustainable livelihoods, forest-focused supply chain policies, such as ZDCs, must be designed and implemented in comprehensive, credible and inclusive ways[6,10,28,44]. ZDCs have demonstrated potential to reduce deforestation in various regions[45–48]. However, the socio-economic implications beyond certification-related outcomes—a common implementation mechanism of ZDCs—remain largely unexplored.

We find very limited evidence that ZDCs are reaching smallholders in ways that support effective or equitable conservation. Over a quarter of tied smallholders reported awareness of NDPE-related restrictions, compared with only around 10% of interviewed intermediaries and none of the independent smallholders. This suggests that some ZDC information reaches tied smallholders, especially those selling through cooperative–mill channels, whereas independent smallholders, who make up most producers, remain largely disconnected from these information flows. We also find no price premium for selling to ZDC mills, almost no ZDC-focused capacity building, and no active exclusion of suppliers, indicating weak enforcement of corporate ZDCs. Deforestation in villages within ZDC mill sheds was lower before 2019, but after 2019 rose slightly above non-ZDC levels while remaining broadly similar in magnitude.

The low reach to independent smallholders, both within and beyond ZDC supply chains, has major implications for avoiding deforestation. This pattern is consistent with evidence from RSPO-certified mill markets[40]. Although most oil palm-related deforestation in Indonesia is driven by industrial plantations (75%), the smallholder sector still contributes a substantial share (25%) that could grow in the future[5]. Consistent with prior studies, our results suggest that current palm ZDCs miss many at-risk forests and lack well-designed approaches to smallholder deforestation[28,49]. Our supply chain mapping further revealed that the FFB of over 90% of producers that sold to low-ZDC mills were indirectly linked to supply high-ZDC buyers through the downstream supply chains of those mills. This suggests that support systems and requirements are much weaker at the local mill level than at the buyer level. These challenges are compounded by systemic mill overcapacity in Indonesia, which intensifies competition among mills and weakens incentives to enforce ZDC requirements[50]. Moreover, less than 10% of Indonesia's palm oil exports go to the EU, while most go to less stringent markets[51].

Our bottom-up evidence of low awareness complements previous studies highlighting that ZDCs lack top-down traceability[11,25,28,32,45]. Our finding that producers are more aware of certifications and legal restrictions than of ZDCs may help explain why certifications have shown stronger evidence of reducing deforestation and fire occurrence[37,52,53], although other factors may also matter. Taken together, these findings suggest that improving ZDC effectiveness and equity will require extending company-level commitments more consistently into mill supply sheds sourcing from independent smallholders, with greater emphasis on dissemination of NDPE-related restrictions, capacity building and reliable implementation, especially as ZDCs shift from voluntary to mandatory policies[10,27,28,54]. Price incentives, if coupled with sufficient monitoring and enforcement, might increase awareness and encourage behavioural change. Existing relationships among producers, intermediaries and mills could also be used more effectively for communication, traceability and policy dissemination[55,56].

Further research and experimentation are needed to identify cost-effective, durable and locally relevant ways to reduce deforestation while improving the well-being and security of Indonesian oil palm communities. At the same time, companies and importing regions must go beyond deforestation control alone and address underlying livelihood needs. This will require coordinated public and private finance, as well as greater attention to supply-shed and jurisdictional approaches[57]. Given the similar challenges faced by smallholders in responding to sustainability policies throughout the world[58], these recommendations are probably relevant for smallholders throughout

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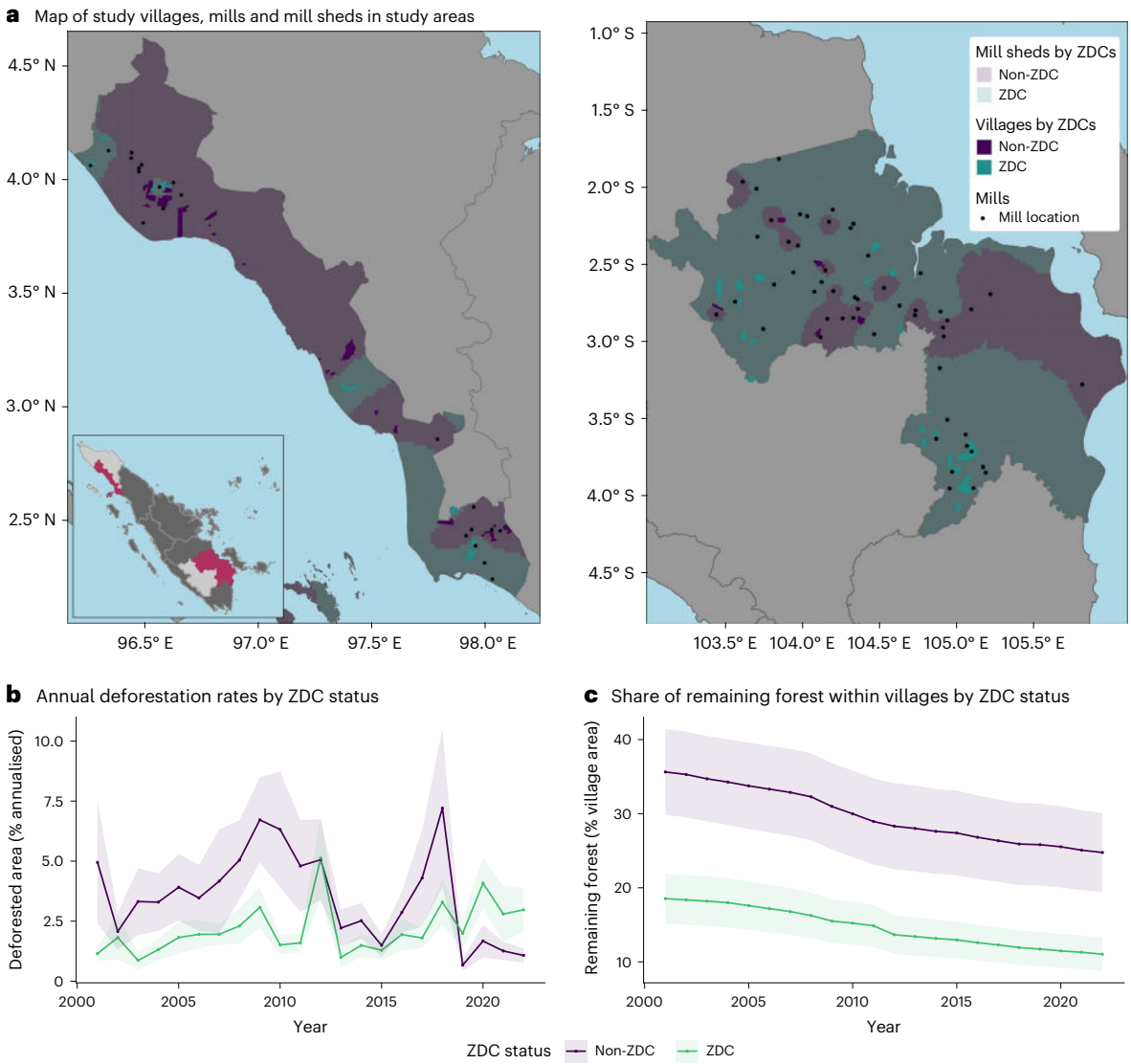

Fig. 5 | Overview of the study area and deforestation rates. a, Maps of village locations, mills[66] and mill sheds[73] in Aceh (left) and South Sumatra (right). **b**, The annual deforestation rates at the village level, categorised by ZDC status, where purple and green indicate non-ZDC and ZDC, respectively. **c**, The share of remaining forest within villages by ZDC status up to 2022. The transparent areas represent 95% confidence intervals for the averages in **b** and **c**. Map administrative boundaries from geoBoundaries[74] under a Creative Commons license CC BY 4.0 and village boundaries from Ina-Geoportal, BIG[75].

the tropics that are producing deforestation-risk commodities. Such policy improvements are especially urgent as zero-deforestation governance shifts from voluntary commitments to mandatory regulation under the EUDR and UKDR.

Our results highlight high supply chain complexity and limited implementation through either engagement or sourcing restrictions, raising concerns about the sector's ability to deliver effective and equitable deforestation control by the EUDR's extended deadline and imminent UKDR implementation. Without stronger support systems tailored to the differentiated needs and contexts of smallholders, more stringent regulation risks having limited effectiveness while further alienating smallholders from higher-standard markets. More broadly, our findings reinforce the need for the 'smart mix' of policy approaches (beyond market exclusion) originally envisaged around EUDR implementation[59], including stronger roles for governments and civil society, as wide-scale smallholder support has lagged behind expectations and the pace of regulatory rollout[60]. Addressing these equity gaps will require greater investment in finance, human resources and experimentation to support alternative production systems and economic pathways.

Limitations

Our study spans 73 villages across two major palm oil-producing provinces, providing a broad snapshot of supply chain conditions and ZDC implementation. However, coronavirus disease 2019 disruptions and limited resources constrained our ability to capture temporal dynamics. Although we improved mill lists and assessed current ZDC practices, we lacked annual data on when mills or companies adopted or revised their ZDCs, limiting our ability to assess temporal dynamics and causal relationships. Household-level data collection also had limitations. Village-based surveys did not fully capture non-resident landholders, migration status was measured only through the household head's relocation, and we could not identify specific ZDC-related price premiums. Instead, we collected farm-gate FFB prices, which reflect multiple factors such as regulation, quality and logistics. Our qualitative data focused on smallholders and intermediaries rather than mill representatives, limiting insight into NDPE/ZDC dissemination and implementation from the mill perspective. In addition, our deforestation analysis relied on publicly available land-cover data on smallholder plantations with limited temporal availability and accuracy, particularly after 2019, restricting our ability to attribute deforestation directly to

palm oil expansion. Finally, because the study focused on Aceh and South Sumatra and only surveyed villages, the findings may not fully generalise to other palm oil-producing regions in Indonesia with different environmental, regulatory and market conditions.

Methods

We studied ZDC implementation in two Indonesian provinces using a mixed-methods approach[61,62] based on survey and regression analysis, qualitative interview analysis, supply chain tracing and geospatial analysis. We chose two study provinces (Aceh and South Sumatra) in Sumatra, as it is the island with the highest proportion of non-industrial producers and palm oil mills. Within these two provinces, we purposively selected seven geographically close regencies that still have remaining forests, and have evidence of ZDC initiatives, including Aceh Singkil, Aceh Selatan, Aceh Barat Daya, Nagan Raya, Musi Banyuasin, Banyuasin and Ogan Komering Ilir. Some areas within these regencies have considerably higher exposure to companies that adopt ZDCs, while the other regencies have less exposure to companies with ZDCs. Given these circumstances, we conducted prematching to identify pairs of villages with the nearest probability of being exposed to ZDCs (see details in the Supplementary Information). We initially sampled 40 villages (that is, 20 village pairs) in each province. However, discussions with local governments and subsequent logistical and political challenges led us to adjust our sample to 36 villages in South Sumatra. Due to additional on-the-ground challenges, our final counts were 40 villages in Aceh and 33 villages in South Sumatra. This article draws in part on the first author's published doctoral dissertation submitted to ETH Zürich (see Chandra[9]).

Ethics approval was obtained from the Social Humanities Research Ethics Committee of IPB University, Indonesia (no. 495/IT3.KEPMSM-IPB/SK/2021), and from the ETH Zürich Ethics Commission, Switzerland (approval no. EK 2019-N-152). Informed consent was obtained from all participants before data collection. Written consent was used where appropriate; however, in villages where requests for signatures were considered sensitive because of prior experiences of land-related disputes, misuse of personal information, or fraud, oral consent was obtained instead.

Cross-sectional survey analysis

We conducted household surveys in 2021/2022 to collect primary data from a total of 1,541 households in seven regencies in Sumatra, following a random selection of villages as mentioned previously. Due to the absence of secondary population data at the village level, we approached the village governments or representatives to compile a list of palm oil producers based on their village registries, categorised by land size—small (less than 2 ha), medium and large (more than 10 ha). This approach was necessary to gather the most representative farmer population in each village. From each category, we randomly selected 20 producers in each village to represent different stages of oil palm development[63], institutional contexts (that is, tied and independent), production scales and land ownership. We then visited the selected producers' houses or farms. If the selected farmers were not present or available at the time of our visit, we substituted them with other producers from the same category on our list. We also attempted to include interviews with managers or caretakers for land owned by non-resident producers, although logistical constraints sometimes limited this reach (Supplementary Information Section 1.1). Overall, managers represented about 0.9% of the total interviewed producers, suggesting that non-resident producers constituted a very small share of our sample.

We asked producers about their understanding of ZDC (that is, NDPE) policies, implementation strategies, their supply chains, socio-economic conditions (such as land ownership, agricultural production and community memberships) and land-use decisions concerning forests, peat and environmental conditions within their properties. We developed a questionnaire to capture data on our variables of interest, available in both English and Bahasa Indonesia (Supplementary Information). The open-data kit application KOBO (https://www.kobotoolbox.org/) facilitated the deployment of these questionnaires, allowing us to digitise data during collection. During the field survey, we trained local enumerators in each province who speak the local language (that is, Acehnese, Minang or Palembang Malay). We pretested the questionnaire and ensured it worked in all contexts/languages.

Quantitative data were analysed using descriptive statistics and regression models in R. To establish statistical differences between groups (that is, ZDC and non-ZDC), we used Kruskall–Wallis tests. We adopted a binary categorisation, following Chandra et al.[28] and Gollnow et al.[46], to ensure consistent scoring and interpretation across various evaluation steps, such as assessing ZDC comprehensiveness and linking scores to supply chains. Although the scoring system by Chandra et al. includes three tiers—0 for no ZDCs, 1 for low-quality ZDCs and 2 for high-quality ZDCs—we simplified it to two categories, ZDC and non-ZDC mills, to address uneven data distribution across provinces. We additionally used OLS regressions to control for potential confounding variables. We used several dependent variable definitions: (1) ZDC market access is defined as the participation in the ZDC supply chain[10], measured by the linkage between producers and mills in supplying FFB; (2) price is determined by the self-reported average farm gate price in 2021; and (3) revenue is defined as the monetary income from selling FFB[64]. Due to price and revenue data skewness when extrapolated on an annual or seasonal basis, we have adapted this definition to reflect revenue gained per harvest. Revenue was then calculated by multiplying the average palm sale price by the total quantity produced per harvest (as reported by each respondent). In regression analysis, we used 'sell to ZDC mill' (0/1) as the independent variable indicating the supply chain linkage between producers with mills with ZDC. Furthermore, we applied a log transformation to both the price and the revenue per harvest variables. We also included other explanatory variables: the year the farm was established, farm size in hectares, use of high-quality seeds (0/1), truck ownership (0/1), type of producers (that is, tied or independent), distance to mills (standardised value), the density of high-ZDC mills within a 40-km radius (0–1), demographic details and regency dummies. Distance to mills was calculated as the distance from each survey location to the nearest mill. Density of high-ZDC mills was determined by the proportion of high-ZDC mills within a 40 km radius of each location, relative to the total number of mills in that radius. This analytical radius differs from the broader 82-km buffer used during presampling to delineate potential mill sheds and ensure coverage of all plausible mill–village linkages before fieldwork.

Qualitative interviews

To gain deeper insights and complement the quantitative data and analysis, we interviewed 53 relevant stakeholders, including intermediaries and cooperatives, who are highly involved in managing the connection between the producers and mill companies and, in many cases, also the buyers. These actors hold strategic positions and play crucial roles in the industry yet are often overlooked and underappreciated[55,56]. We used purposive sampling, aiming to speak to all relevant local supply chain actors in our study regions. Using a topic guide, we conducted semi-structured interviews[65] with 38 intermediaries (locally known as *tauke*, *tengkulak* and *ram* or *ramp*) and 15 cooperatives from 2021 to 2022 in study regencies (Supplementary Table 2). In the main text, each interviewee is uniquely coded with 'I' and a number (for example, I-1). We inquired about their knowledge of private-led supply chain policies and implementations, supply chain complexity, challenges and support needed. The interviews, averaging 21 min and lasting up to 1 h, were transcribed in Bahasa Indonesia, translated into English, and then coded and analysed iteratively[65].

Supply chain tracing

To identify the footprint of mill-level ZDCs and link producers to mills, we combine a top-down mapping of mills and their ZDCs with bottom-up reporting of buyer relationships by producers. Our top-down mapping builds on existing data, including the TRASE dataset[42] sourced from the enhanced Universal Mill List[66] and a mapping of its mills' ZDC coverage[28]. Following Chandra et al.[28], we estimated the coverage of ZDC policy in 2020 within the mill sheds based on the quality of ZDC policy and implementation made by companies that own a mill (referred to as mill owners) and companies that source from a mill at the refinery level (referred to as buyers). ZDC qualities of mills present in the study areas and their buyers were evaluated on the basis of six criteria identified in previous research, including (1) commitment to zero-deforestation policy that is inclusive to all suppliers; (2) full traceability commitment to mills and plantations; (3) smallholder support; (4) compliance support; (5) monitoring mechanism; and (6) transparency (Supplementary Table 3). A company has a high-quality ZDC ('high-ZDC') if it fulfils all criteria; a low-quality ZDC ('low-ZDC') if it meets the first criteria (that is, a commitment to zero deforestation that applies to all suppliers) and some but not all criteria; or zero ('non-ZDC') if it does not satisfy the first criteria.

In the household survey, we used this map to create a list of potential buying mills located in each regency and updated the list on the basis of government data. Respondents were asked to identify their buyers, and we collected the names of companies not listed, which often occurred when FFB travelled outside the regency of residence. After data cleaning, we manually matched the bottom-up and top-down mapping, now going beyond the study regencies. Through this process, we still found that survey respondents reported selling to companies that had not previously been identified. We thus enhanced the top-down dataset by assessing the ZDC quality of missing mills that were identified from our survey data via a desk review of their policies and delineating the mill sheds by spatially interpolating the mill score—that is, assigning each location the ZDC score of nearby mills within a defined buffer (Supplementary Table 4)—using an 82-km radius.

Geospatial analysis

To assess whether ZDCs are associated with lower deforestation rates, we compared the deforestation rate over the period 2001–2022 in villages within ZDC and non-ZDC mill sheds. We used 2018 as a contextual reference point, corresponding to the period when most companies began extending their interventions beyond the mill-level to plantation-level traceability (see further details in Supplementary Table 5).

We estimated forest areas and indirect oil palm-driven deforestation at the village level using the Global Forest Change dataset[67]. We define a forest as having >30% tree cover in 2000[67] as this threshold is inclusive of severely damaged, recuperating and regrowing forests, as well as forested peatland areas that may be high in carbon stocks[68,69]. We excluded areas identified as mixed timber plantations and oil palm plantations in 2000[70] from our forest map. Annual deforestation rates were computed as the decline in forest cover within village boundaries between year t and $t+1$, divided by the forest cover at year t. Due to data limitations, we did not aim to causally assess the impact of ZDCs on deforestation. Instead, we descriptively compared deforestation patterns across ZDC and non-ZDC villages and examined differences in pre-existing characteristics, including forest cover in 2020, deforestation rate, distance to closest mills, and land cover (Table 3).

Data availability

The secondary spatial datasets used in this study are publicly accessible from the references cited. Forest cover data are available via the Global Forest Change viewer at https://glad.earthengine.app/view/global-forest-change, and data on industrial and smallholder oil palm plantations are available via Zenodo at https://doi.org/10.5281/zenodo.6069212 (ref. 71). In addition, mill- and refinery-level ZDC quality scores for 2018–2020 are available via Zenodo at https://doi.org/10.5281/zenodo.10609765 (ref. 28). Due to ethics restrictions, household survey data are not allowed to be published as doing so could risk participant confidentiality and identification, even when identifiers are removed. This is because only certain households will match the comprehensive set of characteristics (size, location, background, land use and so on). As is common with household studies, we provide the village-level mean values for the household data used in the quantitative analysis, together with the questionnaire and other non-sensitive materials, available via Zenodo at https://doi.org/10.5281/zenodo.19616666 (ref. 72).

Code availability

The code used to run the analysis is available via Zenodo at https://doi.org/10.5281/zenodo.19616666 (ref. 72). However, given that the publicly available data are at the village level, we also provide an additional set of code for that layer, which shows village-level mean results.

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Competing interests

The authors declare no competing interests.

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