# Voluntary sustainability standards can mitigate deforestation-export trade-offs

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# Voluntary sustainability standards can mitigate deforestation-export trade-offs

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## Abstract

**Agrifood trade is key for food security and climate change adaptation[1–3], but contributes to significant environmental impacts, including deforestation[4,5]. The governance of sustainability in global food systems is shifting from the public to the private sector[6], with Voluntary Sustainability Standards (VSS) as the most widespread private governance instrument promoting sustainability through trade[7,8]. However, their effectiveness in reducing deforestation at scale remains poorly understood as studies predominantly focus on farm-level analyses[9–12] and overlook indirect land use change, spillovers, and broader trade-offs[12–14]. Here, we provide novel large-scale evidence by combining country-level analyses with innovative commodity-attributed deforestation data for seven major forest-risk commodities, 12 leading VSS, and 125 producing countries (2012 to 2020). We examine the relation between VSS coverage and deforestation, as well as potential trade-offs with export growth in forest-risk commodities[12,14], and further assess the role of VSS design[15,16]. Overall, contrary to farm-level evidence, VSS coverage is not significantly linked with reduced country-wide commodity-driven deforestation, but is associated with mitigating deforestation-export trade-offs. Associations vary across commodities—VSS coverage is linked with reduced deforestation in the palm oil sector but with increased deforestation in the cocoa and coffee sectors—and across VSS, which is explained by differences in design, with stronger enforcement, rather than stricter criteria alone, enhancing effectiveness. Results indicate that VSS can help reconcile export growth with forest protection, pointing to relative rather than absolute decoupling. This study provides evidence that private governance through VSS has the potential to reduce commodity-driven deforestation at scale, contingent on standard design, and that with certification, less forest is lost per dollar or ton exported, signaling progress toward more sustainable agricultural trade. Increasing VSS effectiveness in mitigating deforestation-export growth trade-offs requires prioritizing enforcement, addressing broader land-use dynamics, and stimulating uptake of certified commodities.**

## Main

Deforestation continues at a rate of 11 Mha per year—equivalent to a football pitch every two seconds—driving greenhouse gas emissions, biodiversity loss, and the decline of ecosystem services and forest-dependent livelihoods[4,17,18]. Agricultural expansion emerges as the primary driver, fuelling 61% of deforestation, with a quarter linked to international trade in forest-risk commodities such as beef, soy, palm oil, cocoa, and coffee[4]. As trade in forest-risk commodities increases[4,19], a tension arises between expanding agricultural export growth in low- and middle-income countries (SDG 17) and halting global deforestation (SDG 15)—both key objectives of Agenda 2030—posing a key challenge for governing sustainability in the agrifood sector.

In response to growing sustainability concerns in global agrifood trade, a myriad of initiatives emerged, with a shift in governance from mandatory government regulations to voluntary private initiatives, such as Voluntary Sustainability Standards (VSS)[6,20]. VSS—like Rainforest Alliance (RA) and the Roundtable on Sustainable Palm Oil (RSPO)—are the most prevalent private governance instrument to promote sustainability in global agrifood trade[7,8]. VSS set criteria that suppliers voluntarily adopt, ensure compliance through third-party certification, and communicate credence attributes to consumers via product labeling[21]. By leveraging trade as a mechanism for sustainability, VSS incentivize producers to adopt more sustainable and ethical practices through premium prices and market access, driven by consumer demand for certified products. VSS predominantly certify tropical forest-risk commodities and are widespread, covering at least 10% of global cropland for banana, cocoa, coffee, oil palm, soy, sugarcane and tea[22]. Recognizing the critical ecological value of tropical forests[17], most VSS have over the past decades integrated explicit deforestation-related criteria[23].

Although VSS are designed to help align export growth with forest protection, their effective contribution to deforestation reduction at scale remains an empirical question. Conceptually, by setting requirements to prevent forest conversion, VSS may contribute to a reduction in the absolute deforestation area, leading to absolute decoupling of commodity production and trade from deforestation. However, meaningful effects at scale may be limited due to low VSS coverage, lack of adoption in deforestation-prone regions, or weak criteria and poor enforcement[24]. Deforestation may even increase with VSS, due to displacement to non-certified producers, other crops, or less-regulated forest types[13] or through rebound effects—for example, when price premiums and improved market access incentivize land expansion and further forest conversion[16]. In such cases, VSS may still mitigate trade-offs between deforestation and export growth by reducing deforestation per unit of export volume or value, thereby contributing to relative decoupling. This implies that, with VSS, forest loss increases more slowly than exports, or remains stable despite export growth. The literature often assumes that VSS are trade-enhancing[14,25,26], so that VSS may support relative decoupling by enabling export growth with a smaller deforestation burden. However, VSS might also amplify this trade-off when they increase deforestation area and/or reduce exports. A better understanding of how VSS affect both deforestation levels and trade-offs with export growth requires investigation at large spatial scales to capture wider land use dynamics.

Empirical evidence on the broader land use effects of VSS remains limited. Most studies provide context-specific and farm-level evidence for a single commodity and single VSS, and report mixed results, pointing to modest on-farm deforestation reductions[9–12]. Given the heterogeneity in VSS effects across commodities and contexts[24], findings may not generalize to other settings. Few studies examine off-site landscape- or national-level dynamics, capturing both direct and indirect land use change and potential spillovers. An exception are studies on RSPO in Indonesia, which observe reduced deforestation within certified plantations and mills, and the forest estate, but increased deforestation in adjacent agricultural lands[27,28]. Another study reveals weak and heterogenous associations with overall tropical forest loss for seven VSS, with Fairtrade International (FI) certification being associated with lower primary forest loss, and UTZ, RSPO, and the International Federation of Organic Agriculture Movements (IFOAM) with larger primary forest loss[29]. Evidence on commodity-driven deforestation is lacking, primarily due to limited availability of systematic data and the complex measurement of cascading effects of different land uses and time-lags between deforestation and crop production. Additionally, how VSS design—including requirements, criteria, and enforcement procedures—shapes their effectiveness is unclear, yet such insights are essential to understand private sustainability governance[15,16]. Meanwhile, studies on the trade implications of VSS report increased export values, mainly through increased export volumes, although with variation across commodities and VSS[25,26]. Yet, the potential trade-offs between deforestation mitigation and export growth remain largely unexplored[10], representing a notable gap in the current understanding of VSS as private governance tool for sustainability.

This study quantifies the relation between certification to VSS and deforestation attributed to commodities, as well as deforestation per unit of export value and volume, at the country level, and how VSS design shapes this relation. We rely on deforestation attribution data from the Deforestation Driver and Carbon Emission (DeDuCE) model—currently the most comprehensive source of commodity-level deforestation attribution data globally—spanning the past two decades and all producing countries[4]. The model integrates high-resolution satellite data on tree cover loss, land-use, and forest management with national agricultural statistics to attribute deforestation to specific commodities using either spatial crop maps or land-balance approaches. This enables the analysis of broader land use dynamics, including potential spillover effects across commodities, regions, and time. To understand how VSS design shapes outcomes, we explore the moderating role of deforestation-related and enforcement stringency of VSS. The analysis covers seven major forest-risk commodities, 12 VSS representing the majority of certified areas in these sectors[22], and 125 producing countries from 2012 to 2020. We employ Pseudo-Poisson Maximum Likelihood (PPML) estimators with multiple fixed effects, alongside an instrumental variable (IV) PPML estimator with machine learning-based instrument selection. Our findings provide the first global, multi-commodity evidence on VSS effectiveness in reconciling SDG 15 and 17, offering insights on private sustainability governance in the agrifood sector.

## Results

**Certified area and export volumes grow while commodity-driven deforestation and export values decline**

Between 2012-2020, global VSS coverage (i.e., absolute certified area) for the seven most-certified commodities expanded substantially from 10.2 Mha to 16.8 Mha (Figures 1a-b, Tables A4-5). Cocoa (+2.7 Mha), oil palm (+1.6 Mha), UTZ (+1.8 Mh), and RSPO (+1.5 Mha) experienced the largest absolute increases, whereas VSS coverage declined for sugarcane (-0.3 Mha), ProTerra (-1.0 Mha), and GlobalGAP (-0.003 Mha). The share of total production area certified increased across all commodities and most VSS (except FI and GlobalGAP). The largest relative increases occurred for tea (+9.9 percentage points (pp)), oil palm (+6.1pp), RSPO (+4.6pp), and Bonsucro (+2.0pp). Some VSS certify multiple commodities, with IFOAM and RA certifying all seven commodities assessed here, while others, including GlobalGAP, RSPO, 4C, Bonsucro, the Round Table on Responsible Soy (RTRS), Alliance for Water Stewardship (AWS), and Cocoa Trace, target a single commodity (Figure 1c). VSS coverage in the studied sectors is geographically widespread, with the largest VSS coverage found in Brazil (soy; ProTerra and RTRS), Indonesia (oil palm; RSPO), and Côte d'Ivoire (cocoa; UTZ, FI, and RA) (Figures 1d and A1-2). Of the 125 producing countries in the study, 90 had certified production under at least one VSS, while 35 had none.

Over the same period, commodity-driven deforestation associated with the seven studied commodities declined at the country-level at an average annual rate of 7.3% (Figure 2a). This decline was largely driven by reductions in deforestation for oil palm in Indonesia and Malaysia and soy in Argentina, Brazil, and Bolivia (Figures 2b and A3). Still, Indonesia and Malaysia (oil palm) and Brazil (soy) remain deforestation hotspots, next to Côte d'Ivoire (cocoa). Export values for the seven commodities decreased by 1.9% annually, particularly due to declines in sugarcane, coffee, and palm oil (Figure 2c), while export volumes increased by 2.5% annually, driven largely by soy and sugarcane (Figure 2e). Major export hubs are centered in Brazil (soy and sugarcane) and Indonesia and Malaysia (palm oil and sugarcane) (Figures 2d-f and A4-5).

Taken together, these trends raise several questions about the linkages between VSS and deforestation. First, does the simultaneous expansion of VSS coverage and decline in deforestation at the country level indicate a possible association between VSS and commodity-driven deforestation mitigation? Second, does the concurrent drop in export values suggest an influence of VSS in the apparent trade-off between forest protection and export growth? Third, does the simultaneous increase in export volumes reflect a relative or absolute decoupling of the trade-off between deforestation and export growth under certification? To address these questions, we assess these linkages more rigorously through econometric analyses that estimate conditional associations. Specifically, we estimate how changes in VSS coverage relate to changes in deforestation and deforestation per unit of export value and volume, and analyze how VSS design moderates these effects. We control for a suite of covariates that are known to affect the outcomes in three ways: fixed effects to capture time-constant commodity-country level characteristics, and time-varying year- and country-year level characteristics; control variables for observed time-varying confounding factors; and an IV estimator with machine learning-based instrument selection to reduce remaining sources of endogeneity to the extent possible.

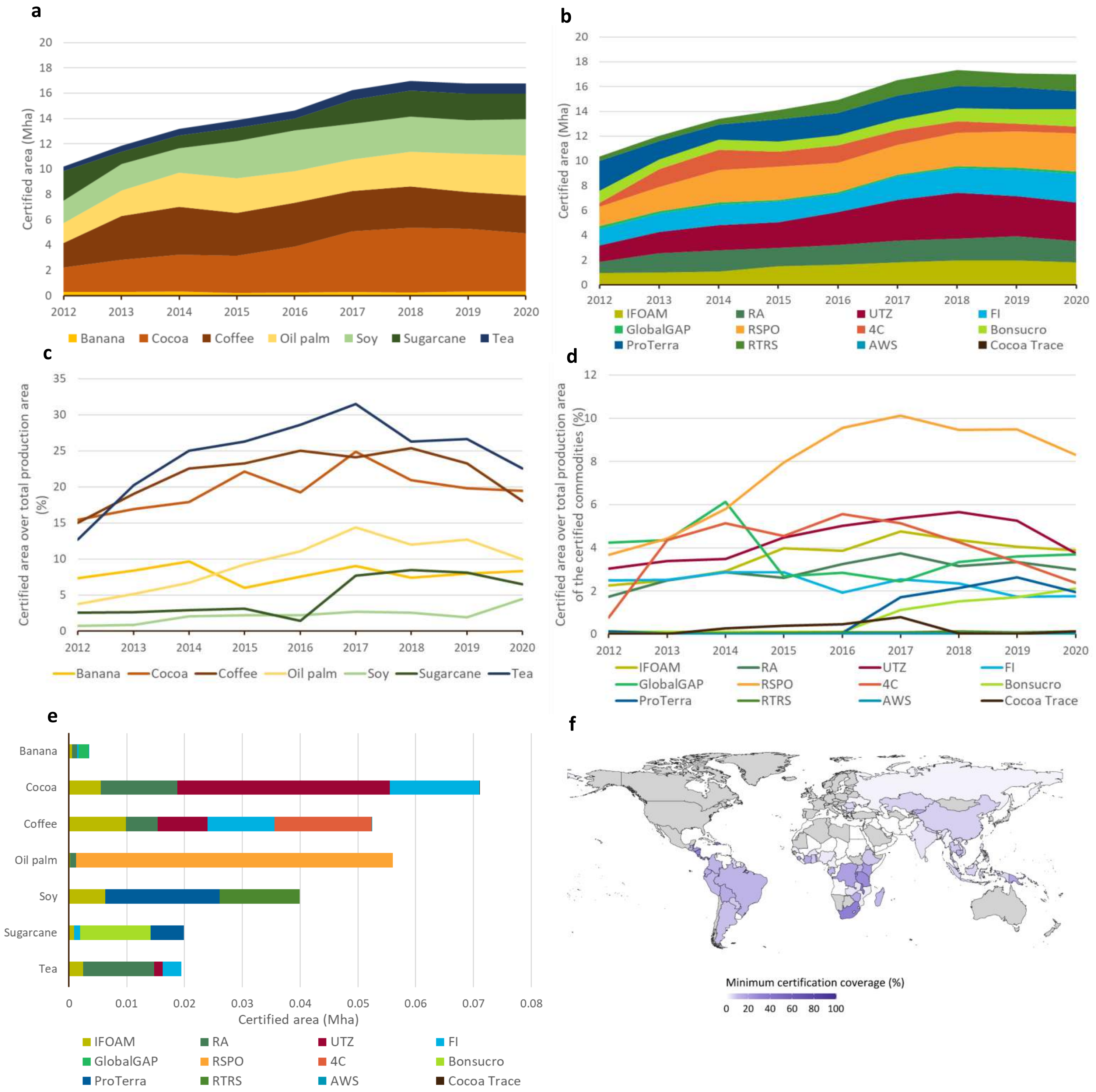


**Figure 1 | Temporal and geographical trends in certification.** Temporal trends over 2012-2020 in (**a**) certified area (Mha) by commodity, (**b**) certified area (Mha) by VSS, (**c**) share of certified production area by commodity, (**d**) share of certified production area by VSS. (**e**) Certified area by commodity and VSS averaged over 2012-2020. (**f**) Geographical certification coverage, expressed as the average share of certified production area across countries over 2012-2020. *Notes*: Figures are for seven commodities, and based on maximum certified area, assuming no overlap between VSS (panel a, b, e) or minimum share of certified area, assuming full overlap between VSS (panel c, d, f). The sample includes all non-OECD producer countries with a minimum area threshold of 500 ha and 0.05% of national cropland devoted to the commodity (N=3,929 commodity-country observations). Abbreviations: IFOAM – International Federation of Organic Agriculture Movements; RA – Rainforest Alliance; FI – Fairtrade International; RSPO – Roundtable on Sustainable Palm Oil; RTRS – Round Table on Responsible Soy; AWS – Alliance for Water Stewardship.

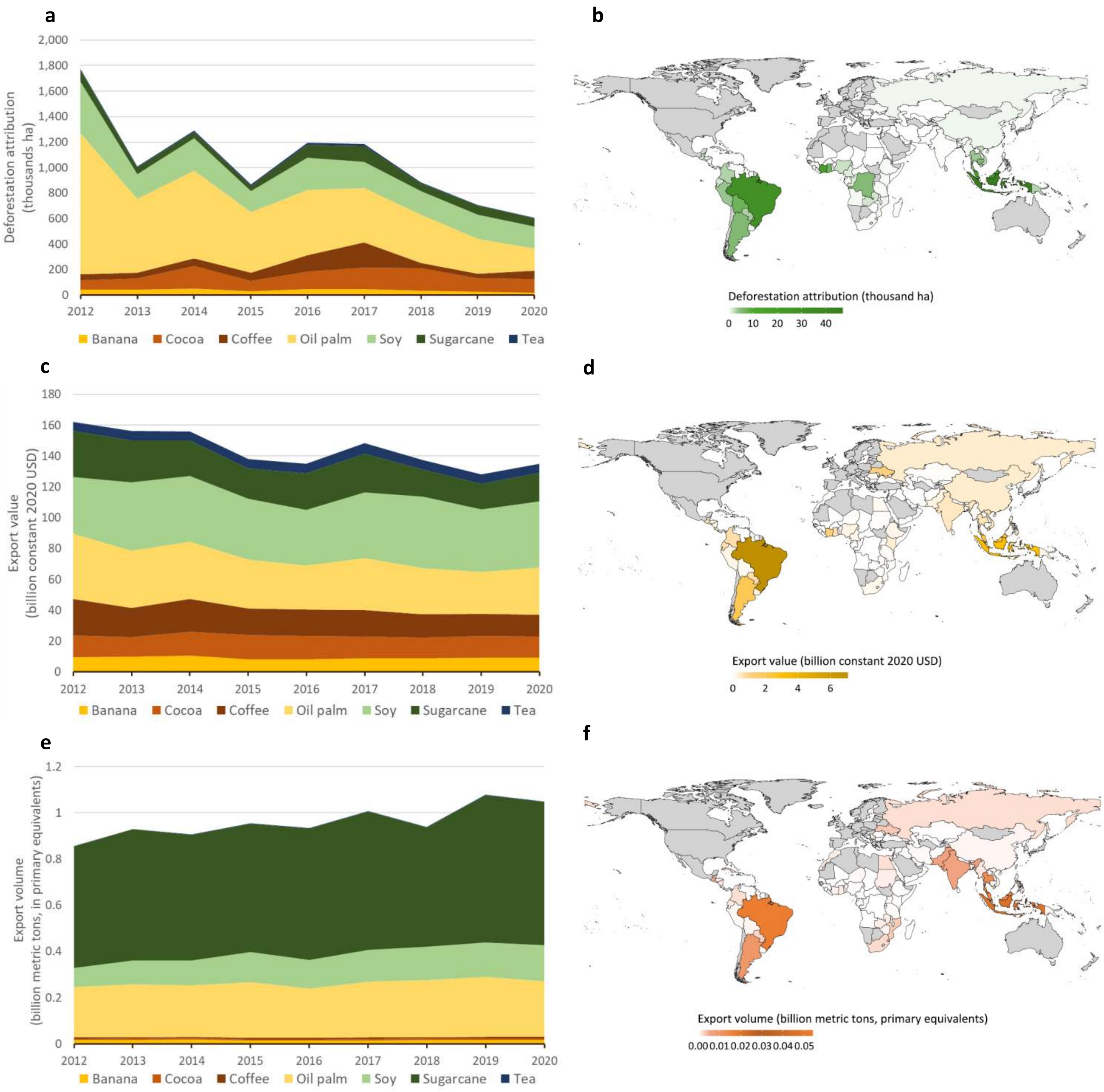


**Figure 2 | Temporal and geographical trends in deforestation attribution, export value, and volume.** Temporal trends by commodity over 2012-2020 in (**a**) total deforestation attribution (thousand ha), (**c**) export value (billion constant 2020 USD), and (**e**) export volume (billion metric tons in primary equivalents). Geographical distribution, averaged over 2012-2020, of (**b**) total deforestation attribution (thousand ha), (**d**) export value (billion constant 2020 USD), and (**f**) export volume (billion metric tons in primary equivalents). *Notes*: Figures are for seven commodities. The sample includes all non-OECD producer countries with a minimum area threshold of 500 ha and 0.05% of national cropland devoted to the commodity (N=3,929 commodity-country observations). Export volumes of agricultural products are represented in primary equivalents to connect secondary (processed, e.g., soybean oil) with their primary (harvested, e.g., soybeans) products.

**No consistent association between VSS and commodity-driven deforestation but variations across commodities and VSS**

Econometric results show no significant overall association between expanding VSS coverage and deforestation attribution at the country level over 2012-2020 (Figure 3a; Table A10), which is corroborated by robustness checks (Table A15). However, heterogeneity in estimated effects emerges across commodities and VSS. Specifically, a 1% increase in certified area is associated with increased deforestation for banana (0.12%), cocoa (0.14-0.24%), and coffee (0.08-0.09%), and with decreased deforestation for oil palm (0.05-0.10%), rather consistently across different model specifications (Figure 3a; Table A11). These are modest but environmentally meaningful effects, especially in countries with high deforestation pressures or where VSS coverage is expanding rapidly. For example, using cumulative values in the full sample, model 1 estimates imply that over 2012-2020, a 0.03Mha increase in certified banana area was associated with 456ha of additional commodity-driven deforestation, a 1.56Mha increase in certified cocoa area with 15,966–25,723ha, and a 0.29Mha increase in certified coffee area with about 1,194–1,208ha. In contrast, a 1.52Mha expansion of certified oil palm corresponded to an avoided deforestation of 50,873–101,746ha. No consistent estimates are found for soy and no significant estimates for other commodities. Estimated deforestation attribution effects are also heterogenous across VSS and rather consistent across estimates, with an increase in deforestation associated with IFOAM (0.02-0.04%), UTZ (0.06-0.08%), and FI (0.05-0.09%), and a decrease for RA (0.02-0.03%), and RSPO (0.05-0.06%) (Figure 3b; Tables A12-13). No significant associations are found for other VSS, and no consistent estimates are identified for GlobalGAP.

To assess variation across forest types, we use alternative tree cover density thresholds (Figures 3c-d, Tables A10-12). A 10% threshold captures more open woodlands and sparse tree cover compared to the main analysis (25% threshold), while a 75% threshold focuses on dense, closed-canopy forests. The results show that the estimated deforestation-increasing effect for banana, cocoa, coffee, IFOAM, UTZ, and FI is similar using a 10% threshold, while the association weakens (cocoa), vanishes (coffee, UTZ, FI), or remains (IFOAM) using a 75% threshold. This suggests that the estimated deforestation-increasing effect of VSS for these commodities and VSS mainly occurs in more degraded or fragmented forests, rather than in dense forests. Apart from RSPO, where the estimated conservation effect is more pronounced in less dense forests, the estimated deforestation-reducing effects of oil palm certification and RA hold across forest types.

Certain VSS set their own forest definitions with specific tree cover density thresholds (Table A14). Aligning with these thresholds, the results show that the estimated deforestation-reducing effect of RA remains significant using its 10% threshold (2020 standard), whereas RSPO's reduction effect disappears at its higher 60-80% threshold (2018 standard). Similarly, the positive association between deforestation and UTZ vanishes at its 10% threshold (2014 standard). We find no significant associations for 4C (10% threshold, 2020 standard) and Bonsucro (10–30% threshold, 2011 standard).

We expect certification to mainly reduce direct deforestation for the certified commodity, potentially resulting in more indirect land-use change to non-certified and all other commodities (i.e., expansion instead occurring on already cleared forestland). To test this hypothesis, we use deforestation attribution data with an extended lag period for attributing forest loss to subsequent land-uses (from 3 to 5 years) capturing *temporal spillovers* (Figures 3e-f, Tables A16-18). We see a strengthened positive association between deforestation and VSS coverage for IFOAM and an emerging positive association for banana, supporting the hypothesis of indirect deforestation effects. In line with this, the estimated deforestation-reducing effects for oil palm, RA, and RSPO disappear as we include more indirect land-use dynamics, while the estimated deforestation-increasing effect of cocoa persists. The previously observed positive associations for coffee, UTZ, and FI vanish, suggesting it is driven by shorter-term or more direct land-use dynamics. Estimated effects for other commodities and VSS, as well as the overall estimated effect of expanding VSS coverage, are weakened and remain non-significant.

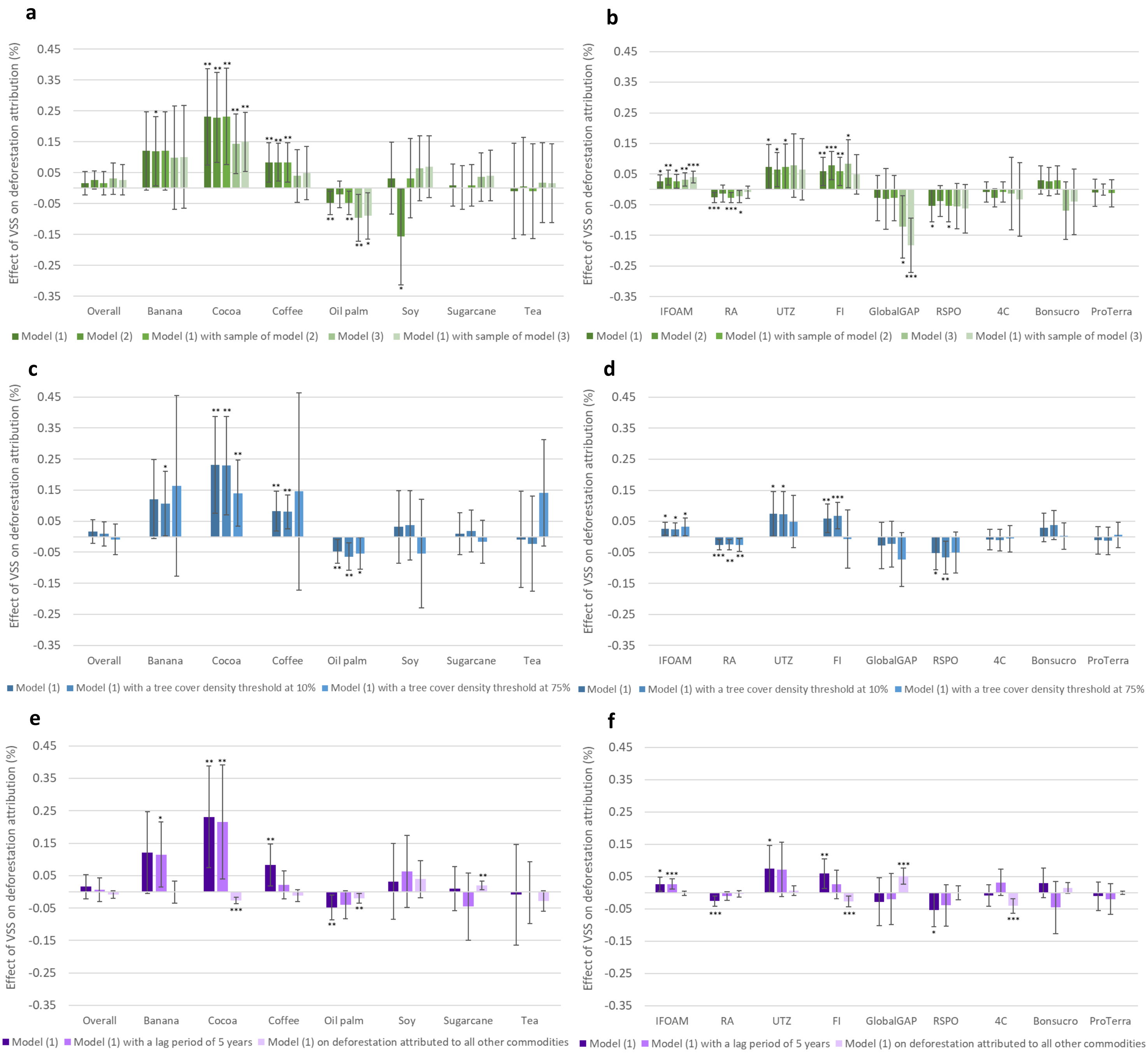


**Figure 3 | Estimated effects of certification on deforestation attribution under different model specifications.** Estimated effects (%) of a one percentage increase in the certified area on the deforestation attribution area across different estimation methods (**a-b**), different tree cover density thresholds (**c-d**), and different attribution with temporal and commodity spillovers (**e-f**). Heterogeneity in effects are shown across commodities (**a, c, e**) and VSS (**b, d, f**). Model 1: PPML estimation with commodity-country and year fixed effects (N=3,647). Model 2: PPML estimation with commodity-country, year and country-year fixed effects (N=3,315). Model 3: IV-PPML estimation with commodity-country and year fixed effects (N=82-1,689). No instrumental variables were found for Proterra due to a too small sample size. Models use a 25% tree cover threshold (**a, b, e, f**) or 10% and 75% tree cover thresholds (**c, d**); a 3-year attribution period (**a, b, c, d**) or a 5-year period and deforestation attribution to other commodities (**e-f**). *Notes*: Sample includes all non-OECD producer countries with a minimum area threshold of 500 ha and 0.05% of national cropland devoted to the commodity. Error bars represent 90% confidence intervals. Regression results reported in Appendix (Tables A10-13, A16-18). Significant estimates indicated as *** p < 0.01, ** p < 0.05, *p < 0.1. Abbreviations: PPML – pseudo-Poisson maximum likelihood; IFOAM – International Federation of Organic Agriculture Movements; RA – Rainforest Alliance; FI – Fairtrade International; RSPO – Roundtable on Sustainable Palm Oil.

To test the hypothesis of more indirect land-use change to all other commodities (*commodity spillovers*), we additionally estimate how certification of one commodity relates to deforestation attributed to all other commodities than the certified one (Figures 3e-f, Tables A16-18). While increases in certified area for cocoa and FI are associated with higher deforestation attribution to the certified commodity, this reduces deforestation attributed to other commodities, suggesting land or labour competition for other crops. Similarly, for 4C, while there is no estimated direct effect of VSS coverage, deforestation for other crops is reduced, possibly reflecting land sparing or improved land management and governance. Oil palm certification is linked to reduced deforestation both within and beyond the sector, pointing to potential broader positive spillovers, such as strengthened monitoring and enforcement, and enhanced land governance. Sugarcane and GlobalGAP certification are not associated with deforestation attributed to the certified commodity but are associated with increased deforestation for other commodities—indicating possible displacement to other crops with weaker environmental requirements.

**Stronger enforcement enhances VSS effectiveness in reducing commodity-driven deforestation**

VSS vary in the stringency of their deforestation-related requirements (*deforestation stringency*) and in the rigor of their control and enforcement mechanisms to ensure compliance with requirements (*enforcement stringency*). While all considered VSS prohibit production in high-conservation value (HCV), high-carbon stock (HCS), or protected areas (Table A7 and Supplementary Material 2), they differ in whether they ban primary and secondary forest conversion, have criteria to constrain land use within properties, set a deforestation cut-off date, provide a clear deforestation definition, and mandate adherence to national deforestation laws. Some VSS additionally include broader conservation and restoration measures, plot delineation requirements, and protection of local land rights. Among the considered VSS, RSPO has on average the highest deforestation stringency, followed by RA (Figure 4c). Control and enforcement are generally done via on-site audits through third-parties, stakeholder input, complaint and dispute settlement systems, corrective actions, and sanctions (Table A8). RSPO, RA, Bonsucro, and UTZ have the highest enforcement stringency (Figure 4c). Overall, we find a more widespread adoption for VSS with lower deforestation stringency (average score of 0.49) and moderate enforcement stringency (average score of 0.81) (Figures 4a-b). Particularly in Africa, less stringent VSS, both in terms of deforestation and enforcement stringency, are adopted.

We show that VSS stringency matters and partially explains observed heterogeneity in the relation between VSS coverage and deforestation across commodities and VSS (Figure 4d, Table A19). We find that more stringent deforestation requirements do not significantly moderate the link between deforestation and overall VSS coverage. Yet, enforcement stringency significantly strengthens the estimated deforestation-reducing effect of certification, in general as well as for sugarcane and tea specifically. We find that the estimate of a deforestation-reducing effect from a 1% increase in certified area strengthens with 0.16pp when enforcement stringency moves from the least stringent to the most stringent VSS. For cocoa, the estimated deforestation-increasing effect is not offset by enforcement stringency, which could stem from factors such as weak enforcement capacity or high fragmentation with many smallholder producers. Results imply that robust enforcement mechanisms are critical in ensuring compliance with zero-deforestation requirements.

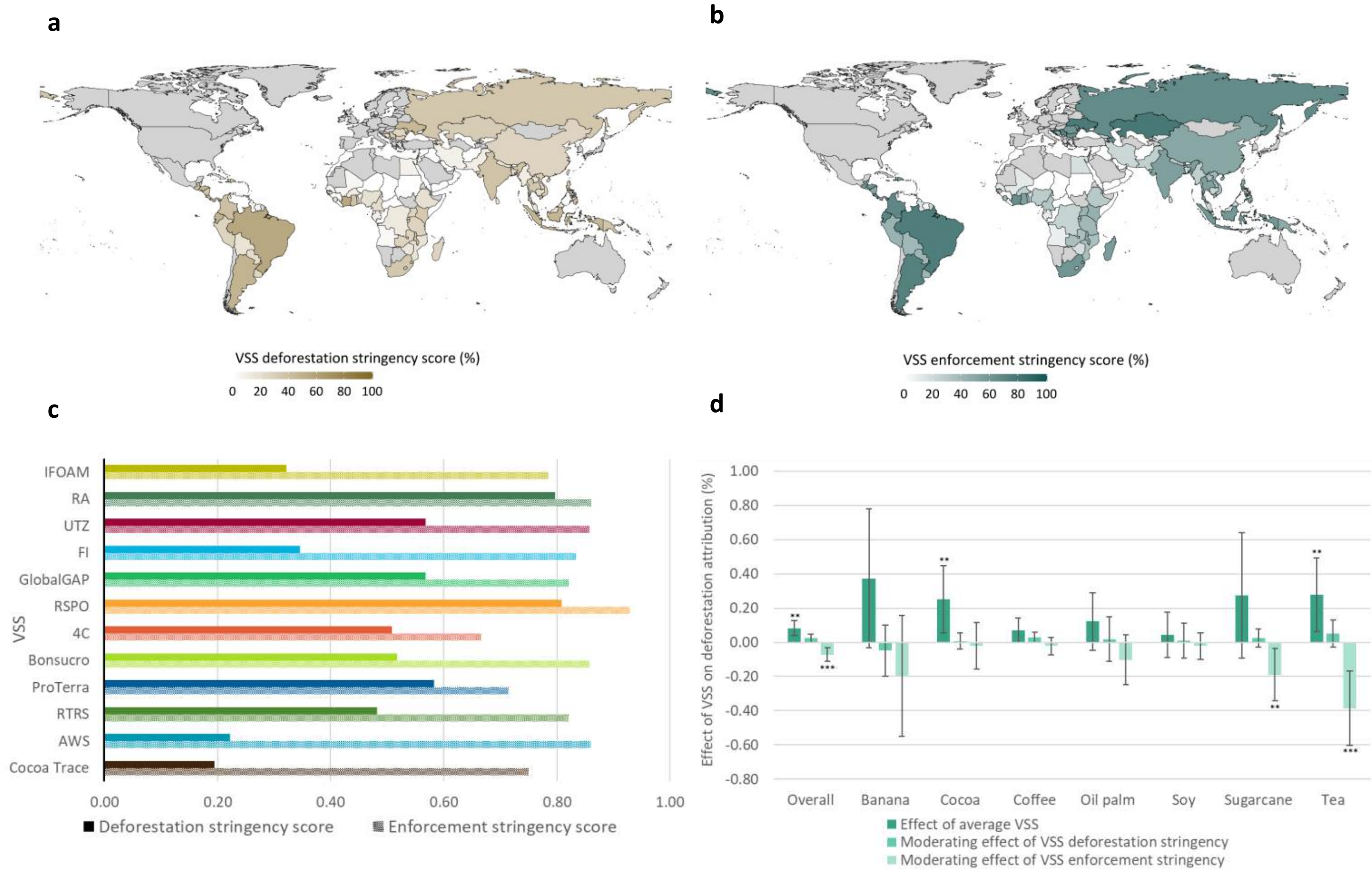


**Figure 4 | Distribution and moderating effect of VSS deforestation and enforcement stringency on deforestation attribution.** Geographical distribution of VSS adoption, averaged over VSS and commodities, by deforestation stringency (**a**), and enforcement stringency (**b**). Deforestation and enforcement stringency scores of VSS (**c**). Estimated deforestation attribution effects of VSS moderated by deforestation and enforcement stringency (**d**). Estimates derived from PPML estimation with commodity-country and year fixed effects (N=3,647). Effect of average VSS: deforestation attribution effect of a 1% increase in certified area for VSS with average stringency. Moderating effect: change in average effect from a one standard deviation change in stringency scores. *Notes*: Sample includes all non-OECD producer countries with a minimum area threshold of 500 ha and 0.05% of national cropland devoted to the commodity. Error bars represent 90% confidence intervals. Regression results reported in Appendix (Table A19). Significant estimates indicated as *** $p < 0.01$, ** $p < 0.05$, *$p < 0.1$. Abbreviations: PPML – pseudo-Poisson maximum likelihood; IFOAM – International Federation of Organic Agriculture Movements; RA – Rainforest Alliance; FI – Fairtrade International; RSPO – Roundtable on Sustainable Palm Oil; RTRS – Round Table on Responsible Soy; AWS – Alliance for Water Stewardship.

**VSS are associated with reduced deforestation per unit of export value and volume, but decoupling differs across commodities and VSS**

Finally, we find that, overall, VSS are associated with reduced deforestation per unit of export value at the country level (Figures 5a-b, Tables A20-A22 and A26). Combined results suggest a relative decoupling between export gains and deforestation: expansion of VSS coverage is linked to increased economic returns from export growth without affecting deforestation, thereby reducing the trade-off between export growth and forest conservation. These gains could result from yield increases, value-added processing, or price premiums associated with certification. In particular, we find that a 1% increase in the certified area is associated with decreases in deforestation per unit of export value for banana (0.36-0.72%), but increases for coffee (0.64-1.75%). Across VSS, a 1% increase in RA coverage is associated with a 0.63-0.65% reduction in deforestation per unit of export value, while FI is associated with a 0.12-0.51% increase. No consistent or non-significant estimates are found for other crops and VSS across different model specifications.

We find a similar association between overall certification and a reduction in the deforestation per unit of export volume, pointing to more land-efficient production for export (Figures 5c-d, Tables A23-A26). In particular, estimates point to a reduction for banana (0.36-0.83%), oil palm (0.33-0.68%), RA (0.42-0.56%), RSPO (0.31-0.32%), and 4C (0.34-0.36%), and to an increase for soy (0.66-0.96%), and FI (0.20-0.31%) . Estimates for other crops and VSS are less consistent or non-significant. Together, these findings imply that, with certification less forest is being lost for each dollar of commodity export earnings and each ton exported, signalling progress toward more sustainable agricultural trade—albeit with differences across crops and VSS.

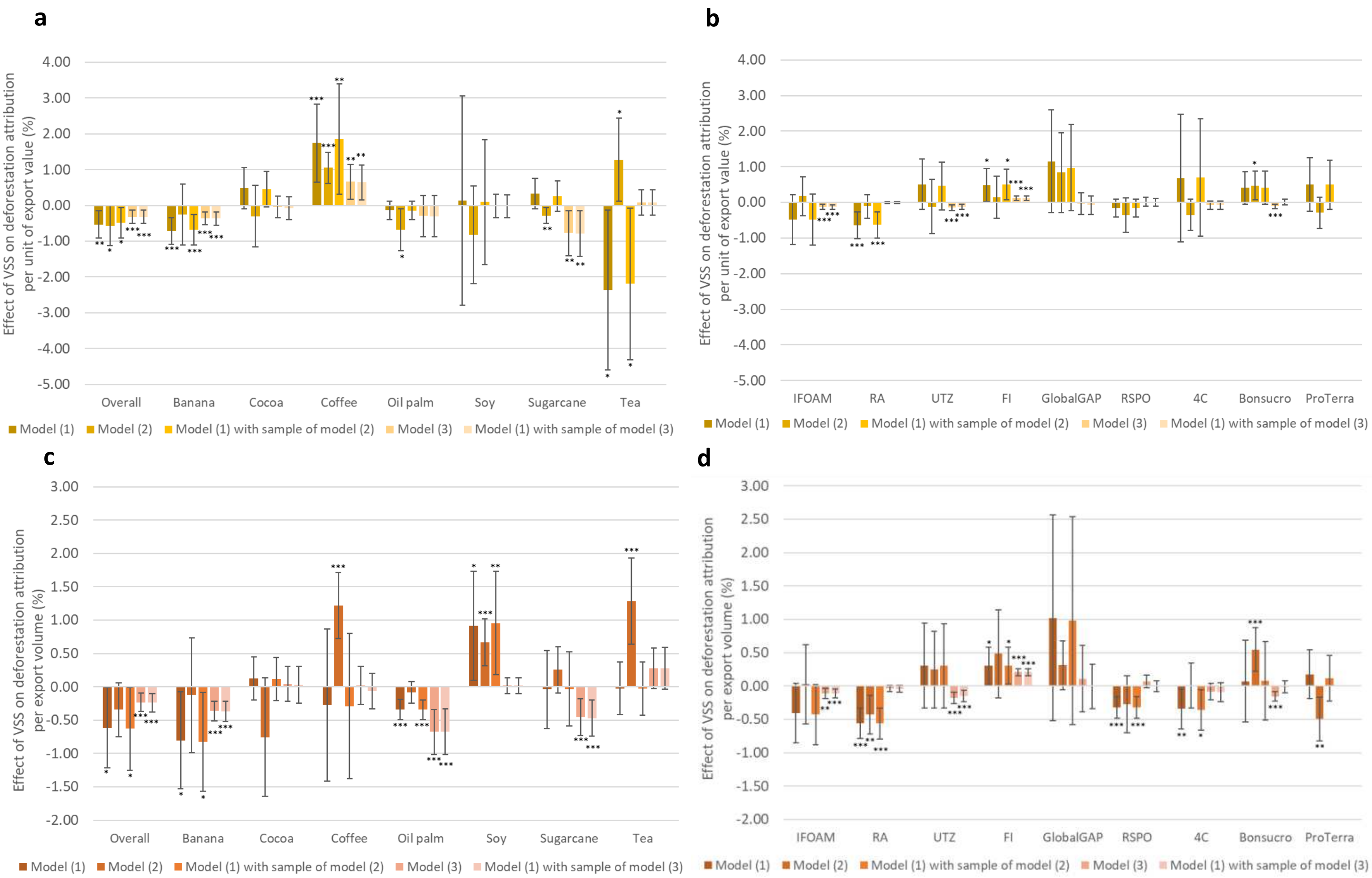


**Figure 5 | Estimated effects of certification on deforestation per unit of export value and volume under different model specifications.** Estimated effects (%) of a one percentage increase in the certified area on the deforestation per unit of export value (**a-b**), and deforestation per unit of export volume (**c-d**). Heterogeneity in effects are shown across commodities (**a, c**) and VSS (**b, d**). Model 1: PPML estimation with commodity-country and year fixed effects (N=3,548). Model 2: PPML estimation with commodity-country, year and country-year fixed effects (N=3,182). Model 3: IV-PPML estimation with commodity-country and year fixed effects (N=82-1,689). No instrumental variables were found for Proterra due to a too small sample size. *Notes*: Sample includes all non-OECD producer countries with a minimum area threshold of 500 ha and 0.05% of national cropland devoted to the commodity. Error bars represent 90% confidence intervals. Regression results reported in appendix (Tables A20-26). Error bars represent 90% confidence intervals. Significant estimates indicated as *** p < 0.01, ** p < 0.05, * p < 0.1. Abbreviations: PPML – pseudo-Poisson maximum likelihood; IFOAM – International Federation of Organic Agriculture Movements; RA – Rainforest Alliance; FT – Fairtrade International; RSPO – Roundtable on Sustainable Palm Oil.

## Discussion

The study demonstrates that, contrary to farm-level evidence[9–12], VSS are overall not significantly associated with reduced commodity-driven deforestation at scale, taking into account both direct and indirect land use change. Results reveal heterogenous associations across commodities, VSS, and forest types, as well as temporal and cross-commodity spillovers. While previous studies report no off-site deforestation effects for RSPO in Indonesia[27,28], our findings show that, globally, RSPO is linked to reduced deforestation at country level. We document that higher VSS coverage for UTZ, FI, and IFOAM is linked to increased deforestation attributed to the commodities these VSS certify, whereas previous research finds no strong associations between these VSS and overall tree cover loss in primary forest[29]. Additionally, we show that VSS design matters: stronger enforcement enhances effectiveness, rather than stricter criteria alone. Moreover, the findings highlight that VSS in general can contribute to mitigating the deforestation-export trade-off—reducing deforestation per unit of export value and volume—indicating relative, rather than absolute, decoupling, though again with commodity- and VSS-specific differences.

Patterns differ across commodities and VSS (Table 1). First, in the oil palm sector and for RA and RSPO, we observe that VSS coverage is associated with reductions in both deforestation and the deforestation-export growth trade-off, indicating a strong trade-off mitigation through absolute decoupling. VSS for oil palm seem to effectively limit deforestation across multiple forest types. This likely relates to oil palm certification being located in high deforestation-risk areas as well as to VSS stringency. Spatial data from 2012-2015 from Tayleur and co-authors[30] indicate that certified oil palm producers were more frequently located in deforestation hotspots than non-certified producers. The dominating VSS for oil palm—RA and RSPO—also score high on deforestation stringency, particularly for their strong primary forest conservation rules, clear cut-off dates, farm boundary mapping, and legal land use requirements. Furthermore, both VSS have the most stringent enforcement mechanisms, due to strict audits, stakeholder input, and dispute resolution systems, contributing to their stronger deforestation mitigation impact. High environmental stringency has been linked to greater consumer willingness to pay[31], supporting positive export value and volume effects. The estimated deforestation-reducing effects weaken when extending the attribution period, suggesting certification is less efficient in reducing oil palm expansion on previously deforested land, potentially leading to temporal deforestation spillovers. Encouragingly, oil palm certification still shows broader positive spillovers, as it is associated with reduced deforestation not only within the sector but also in other commodities. Oil palm, RA, and RSPO certification have also been shown to be linked with increased export values and volumes, which may contribute to mitigating the trade-off[25,26].

Second, in the cocoa and coffee sectors, as well as for IFOAM, UTZ, and FI, VSS coverage is associated with weak increases in deforestation, in particular in more sparse forests, and, in some cases, with increases in the deforestation-export growth trade-off, indicating no decoupling. In the banana sector, VSS coverage is associated with small deforestation increases and reductions in the trade-off, signalling relative decoupling. Estimated deforestation effects might be explained by skewed adoption, where certification is not adopted by farmers located in deforestation-prone areas, thereby limiting their deforestation reduction effect. Tayleur and co-authors[30] indicate that certified coffee producers were less frequently located in deforestation hotspots than non-certified producers over 2012-2015, while this was not the case for cocoa. Additionally, the main certifying VSS for these commodities—UTZ, FI, IFOAM, and 4C—exhibit rather low deforestation stringency scores, and IFOAM and 4C also low enforcement stringency scores. Weak enforcement has been linked to sustainability shortfalls in smallholder-dominated VSS sectors[10,32], and our findings corroborate the importance of effective enforcement mechanisms. Furthermore, VSS may result in market incentives that encourage producers to increase productivity and expand production, thereby increasing land values and triggering rebound effects that conflict with deforestation reduction goals. Results with extended attribution periods suggest that weak increases in deforestation are generally more short-term or direct in nature for coffee, UTZ, and FI, sustained for cocoa, and more delayed or indirect for banana and IFOAM. Moreover, while cocoa certification and FI are linked to increased deforestation at the country-level, there are positive spillovers through reduced deforestation attributed to other commodities. Banana and coffee certification have also been associated with an increase in export value and/or volume, which may contribute to mitigating the trade-off[14,25,26].

Third, for other commodities and VSS, we find no or no consistent association between VSS coverage and deforestation and no evidence of decoupling—except for 4C, where we find an indication of relative decoupling. Several factors could explain: VSS requirements and enforcement may not be strict enough (e.g., 4C, GlobalGAP, RTRS, Bonscuro, ProTerra), certification not targeting deforestation-prone areas leading to displacement effects (e.g., for tea, and sugarcane[30]), market incentives that conflict with deforestation reduction goals, or low certification uptake (e.g., for soy and sugarcane, and in Africa). The complementary spillover analysis suggests that 4C certification, while having no direct effect on deforestation attribution, is linked to reductions in deforestation from other crops—possibly reflecting land sparing or improved land management—and sugarcane and GlobalGAP certification appear to displace deforestation to other commodities, likely due to weaker sustainability requirements or indirect land-use change. Export effects may explain observed trade-offs for soy and 4C[14,25,26]. In other cases, improvements in export value or volume have been documented but these may not be large enough to translate into measurable trade-off reductions at country level.

Taken together, this study shows that VSS, as private governance instrument, hold the potential to reduce commodity-driven deforestation at scale, contingent on design improvements. VSS that are associated with reduced deforestation at the country level, such as RA and RSPO, are characterized by high stringency in deforestation-related requirements and enforcement procedures, and targeting of high deforestation-risk areas. Moreover, VSS seem to improve the deforestation-export growth trade-off by facilitating export growth, particularly in volumes, so that less forest is lost per dollar of export earnings or ton exported, signaling progress toward more sustainable agricultural trade. Hence, to improve the effectiveness of VSS in mitigating the trade-off, it is essential to prioritize requirements that address broader land use dynamics, ensure robust enforcement and monitoring at multiple spatial scales, target deforestation-risk areas, and stimulate uptake of certified commodities rather than weakening enforcement to expand market share.

This study provides the first global assessment showing that VSS may reduce commodity-driven deforestation at scale and may shift agricultural trade dynamics toward relative decoupling, with effectiveness depending critically on standard design. Future research could further explore the mechanisms driving these trade-offs, particularly how certification influences land-use dynamics at the landscape-scale, the role of displacement effects within and across national borders, and the interaction with other sustainability initiatives. Understanding these factors is key to designing more effective sustainability interventions that reconcile economic and environmental goals. Analysing displacement effects requires spatially explicit longitudinal data of certified producers which is currently unavailable or inaccessible. Anticipated changes, particularly with the enactment of the EU Deforestation Regulation, suggest a potential improvement in this regard. Additionally, linking spatially explicit data to supply chain and VSS data could help identify the portion of deforestation directly associated with export markets.

**Table 1 | Interpretation of the econometric results in Figures 3 and 5.**

| | | Deforestation-export growth trade-off | | |
|---|---|---|---|---|
| | | **Reduced** | **Increased** | **Non-significant** |
| **Deforestation attribution** | **Reduced** | Win-win and absolute decoupling<br>*Oil palm, RA, RSPO* | Win-lose and relative decoupling | No decoupling |
| | **Increased** | Lose-win and relative decoupling<br>*Banana* | Lose-lose and no decoupling<br>*Coffee, FI* | No decoupling<br>*Cocoa, IFOAM, UTZ* |
| | **Non-significant** | Relative decoupling<br>*4C* | No decoupling<br>*Soy* | No decoupling<br>*Sugarcane, tea, GlobalGAP, Bonsucro, ProTerra* |

*Notes*: Abbreviations: RA–Rainforest Alliance; FT–Fairtrade International; RSPO–Roundtable on Sustainable Palm Oil; IFOAM–International Federation of Organic Agriculture Movements.

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# Methods

**Data and variables.** Tables A3 and A6 provide an overview of all variables and data sources, and descriptive statistics, respectively.

*Deforestation attribution (DA).* We use country-commodity level *DA* data from the Deforestation Driver and Carbon Emission (DeDuCE) model, which is currently the most comprehensive available data on commodity-driven deforestation, covering large temporal (2000-2022) and spatial scales (all producing countries)[33]. *DA* reflects commodity-driven deforestation, derived from high-resolution (30m) spatial data on tree cover loss by identifying deforestation and attributing this to major land use classes and then to commodities based on either (1) spatial crop maps, if available, or (2) a land balance approach using (sub-)national agricultural statistics. To account for the time lag between forest clearing and subsequent land use establishment, changes in land use areas are averaged over the three years post-forest clearing. Deforestation is defined as the removal of tree cover in natural forests exceeding 5m in height and 25% canopy cover (threshold based on Sexton and co-authors[34]), excluding tree cover loss in managed forests and plantations, as well as forest loss resulting from fires not followed by agricultural land-uses. An advantage of the country-commodity level dataset is its ability to account for land-use linkages and displacement effects[35,36]. We provide additional estimates using alternative *DA* specifications with tree cover density thresholds of 10% and 75% instead of 25% (Figures 3c&d, Tables A10-12)—to assess variations across forest types. Moreover, we estimate alternative *DA* specifications using a five-year time lag instead of three years to analyse *temporal spillovers* (Figures 3e&f, Tables A16-18)—to better reflect the growth cycles of the studied perennial commodities, ranging from 3 months to 5 years[37], and to capture a broader range of indirect land use changes, which often unfold over extended periods. Furthermore, we estimate an alternative *DA* specification to analyse *commodity spillovers* by examining deforestation attributed to other commodities (Figures 3e&f, Tables A16-18), while controlling for certification of other commodities.

*Deforestation attribution per export value (DAEVA) and volume (DAEVO).* We calculate *DAEVA* and *DAEVO* to analyse potential synergies or trade-offs between *DA* reductions and export growth. We use export data from the Base pour l'Analyse du Commerce International (BACI) database at the Harmonized System Code HS6-digit level which we aggregate to commodity level (Table A1), available for the period 1996-2021. We focus on raw or minimally processed products to minimize the incidence of re-exports[38]. We exclude coffee and cocoa waste-products and plantains and cooking bananas as these are unlikely to be associated with VSS. Export volumes of agricultural products are represented in primary equivalents using Food and Agriculture Organization's (FAO) world average equivalence factors[39], to connect secondary (processed, e.g., soybean oil) to their primary (harvested, e.g., soybeans) products. Zero and small (<1,000 USD) trade flows not included in the original dataset are manually added based on the assumption that a country reporting at least one trade flow for a given year will declare all its bilateral flows[40]. Furthermore, we assign a value of zero to cases where deforestation occurs, but export value or volume is zero to prevent potential distortions from dividing by zero while preserving meaningful information from these observations.

*Certification to VSS.* We focus on seven commodities—banana, cocoa, coffee, oil palm, soy, sugarcane, and tea—selected for their high certification rates in 2023[41] and their role as deforestation drivers[33]. For these commodities, we identified all VSS that focus on deforestation prevention and have a third-party auditing system[42] using the ITC Standards Map, the FSA Benchmarking Scheme, and the Consumer Goods Forum. We obtained yearly country-level coverage data for the period 2012-2020 from the , c, through personal contact with the associated standard-setting organizations between August and October 2023 (Tables A4-5).

Certification to multiple VSS is common in the agrifood sector, but since reliable data on this is limited, we define certification area (*CA*) for a specific VSS, indexed by *VSS*, as the minimum certified area per commodity and country, equalling the certified area of the VSS with the largest coverage, which should be interpreted as a conservative measure. Hence, introducing additional, less prominent VSS would have a negligible influence on this variable. We use the absolute certified area instead of other metrics such as the number of certified producers or the certified production volume as this metric is more closely tied to *DA* and avoids discrepancies caused by differences in productivity and farm sizes.

*VSS stringency scores.* The literature on VSS effectiveness highlights that two VSS design aspects are relevant for their sustainability impact, namely substantive stringency, referring to the content and stringency of the requirements in VSS, and procedural stringency, referring to the rules and procedures VSS put in place to enforce compliance, build producer capacity, and provide market-based incentives for adhering to their requirements[43-47]. We apply these concepts specifically to the issue of deforestation, and construct scores for *deforestation stringency* (*DS*) and *enforcement stringency* (*ES*). For *DS*, we identify 14 criteria related to deforestation prevention, conservation and restoration of natural ecosystems, location and land rights, and agroforestry through existing comparisons and benchmarking schemes (Table A7; Supplementary Material 2). We evaluate the 12 VSS on these criteria (indexed *a*) based on the different versions of their standard during 2012-2020. The resulting criteria stringency scores (*DSscore*, Table A7) are weighted based on how explicit the criteria are included (*Explicitness*) and how critical they are for obtaining certification *(Criticality*) (Table A8). Because some criteria might capture closely related concepts, we weight the resulting scores using a factor analysis, as in (Eq. 1):

$$DS_{VSS,t} = \frac{\sum_{a=1}^{14} DSscore_{a,VSS,t} * \left(Explicitness_{a,VSS,t} + Criticality_{a,VSS,t}\right) * factor\ analysis\ weight_a}{\sum_{a=1}^{14} factor\ analysis\ weight_a} \quad (1)$$

For *ES*, we identify 14 criteria (indexed *b*) related to the auditing process, stakeholder inclusion, complaint and dispute settlement system, sanctions, and compliance status transparency (Table A9), relying on Depoorter and Marx[43]. We evaluate AWS and Cocoa Trace on these criteria and use the scores for the other 10 VSS from Depoorter and Marx, based on the most recent version of VSS procedural documents, assuming that core governance aspects are less likely to vary over time than substantive requirements. To address overlap between criteria, the resulting stringency scores (*ESscore,* Table A9) are weighted using a factor analysis, as in (Eq. 2):

$$ES_{VSS} = \frac{\sum_{b=1}^{14} ESscore_{b,VSS} * factor\ analysis\ weight_b}{\sum_{b=1}^{14} factor\ analysis\ weight_b} \quad (2)$$

Resulting *DS* and *ES* scores are given in Figure 4c. We aggregate both stringency scores to the country(*i*)-commodity(*c*)-year(*t*) level ($DS_{c,i,t}$, $ES_{c,i,t}$), assuming full overlap in certified areas (*CA*) between VSS. For each country-commodity-year observation, we sort the $CA_{c,i,t}$ of different VSS (indexed *k*) in ascending order and compute the overlapping areas at each step *k* as $\Delta CA_{k,c,i,t} = CA_{k+1,c,i,t} - CA_{k,c,i,t}$. We then assign the maximum stringency score among all VSS present at step $k$, assuming that the overlapping area has to be certified according to the most stringent VSS, as $DS_{k,t} = \max\{DS_{VSS,t} \mid CA_{VSS,c,i,t} \geq CA_{k,c,i,t}\}$ and $ES_k = \max\{ES_{VSS} \mid CA_{VSS,c,i,t} \geq CA_{k,c,i,t}\}$. The weighted stringency score for commodity *c* in country *i* in year *t* are then (Eq. 3):

$$DS_{c,i,t} = \frac{\sum_{k=1}^{12} \Delta CA_{k,c,i,t} * DS_{k,t}}{\sum_{k=1}^{12} \Delta CA_{k,c,i,t}} \text{ and } ES_{c,i,t} = \frac{\sum_{k=1}^{12} \Delta CA_{k,c,i,t} * ES_k}{\sum_{k=1}^{12} \Delta CA_{k,c,i,t}} \quad (3)$$

**Sample.** The sample includes all non-OECD countries producing at least one of the seven commodities of interest. We define producing countries as having a minimum commodity production area of 500 ha and 0.05% of total agricultural area based on FAOSTAT data[48]. We exclude OECD countries to avoid non-informative zero trade flows and re-exports, and because deforestation dynamics in these countries differ substantially—being largely historical and less associated with recent agriculture-driven deforestation. We exclude overseas territories because of data unavailability on land use and/or other statistics. We manually impute harvested area data for cases with non-zero certification and *DA* data based on online available sources. This results in a balanced panel of 125 producing countries and 3,929 observations over the 2012-2020 period (Table A2).

**Modelling framework.** We estimate the overall effect of VSS (*CA*) on three outcome variables, *DA*, *DAEVA*, and *DAEVO*, using a baseline regression model (model 1, Eq. 4):

$$\text{Model (1): } Y_{c,i,t} = \beta_0 + \beta_1 CA_{c,i,t} + \beta_2 \mathbf{X}_{(c,)i,t} + \mu_{c,i} + \gamma_t + \epsilon_{c,i,t} \tag{4}$$

where $Y_{c,i,t}$ represents the outcome variable for commodity *c* in country *i* in year *t*. The variable $CA_{c,i,t}$ is the independent variable of interest, measured as the absolute certified area for commodity *c* in country *i* in year *t*. The vector $\mathbf{X}_{(c,)i,t}$ encompasses (commodity-)country-year level control variables, as detailed below. $\mu_{c,i}$ are commodity-country fixed effects, removing time-constant unobserved confounders specific to a country and commodity (e.g., geographical, legal, economic, technological, or cultural features), $\gamma_t$ are year fixed effects, removing time-varying unobserved confounders affecting all commodities and countries (e.g., global economic conditions, international regulations), and $\epsilon_{c,i,t}$ is the error term. We do not include commodity-year fixed effects, as this might capture economic commodity trends that might be affected by certification (e.g., commodity price trends). As robustness check, in an alternative specification (model 2, Eq. 5), we additionally include country-year fixed effects $\rho_{i,t}$, which capture time-varying country-specific factors beyond the ones already controlled for:

$$\text{Model (2): } Y_{c,i,t} = \beta_0 + \beta_1 CA_{c,i,t} + \beta_2 \mathbf{X}_{(c,)i,t} + \mu_{c,i} + \gamma_t + \rho_{i,t} + \epsilon_{c,i,t} \tag{5}$$

This inclusion substantially reduces the within variation we are interested in (30%) and drops many singletons (one eighth of the sample)—for comparison we re-analyse model 1 with the sample of model 2. We cluster standard errors at the commodity-country level to correct for arbitrary serial correlation and heteroscedasticity. We convert all monetary variables to constant 2020 USD using the consumer price index from the World Bank[49]. We transform *CA* and continuous control variables to account for the non-linear relationship and limit the influence of outliers using the inverse hyperbolic sine transformation, which approximates the natural logarithm while allowing for zero-valued observations. The scale parameter of the inverse hyperbolic sine transformation is chosen using a combination of the log pseudolikelihood and the Ramsey Regression Equation Specification Error (RESET) test, as recommended by Aihounton and Henningsen[50]. Results of these models are reported in Figures 3 and 5 and Tables A10, A20, A23.

To analyse heterogeneity across commodities and VSS, we estimate Eq. 4-5 with an interaction term between $CA_{c,i,t}$ and the seven commodities of interest (Figures 3a and 5a, Tables A11, A21, A24), and using a vector of the nine largest VSS (Figures 3b and 5b, Tables A12, A22, A25), respectively. In the latter analysis, we exclude RTRS, AWS, and Cocoa Trace as their coverage is too small to yield meaningful results. To analyse the effect of VSS stringency, we estimate Eq. 4 with an interaction term between $CA_{c,i,t}$ and the standardized stringency scores $DS_{c,i,t}$ and $ES_{c,i,t}$ (Figure 4d, Table A19)–standardization minimizes collinearity in estimating moderation effects and enables a useful interpretation.

*Control variables for the DA analysis.* We select control variables based on a literature review on deforestation drivers[51-58] (Tables A3 and A6). To control for the level of production, we incorporate national (level and squared) and global commodity-specific harvested area (level), with data sourced from FAOSTAT[48].

Additionally, various country-level control variables are considered in the analysis. We control for population size, population growth, and foreign direct investment within the country using World Bank data[49], and gross domestic product using United Nations (UN) data[59]. Political climate is factored in through the governance index from the World Bank[49], which captures regulatory quality, rule of law, control of corruption, voice and accountability, political stability and absence of violence/terrorism, and government effectiveness. The stringency of environmental laws is proxied by the number of national forest-related policies[60]. To control for accessibility of forests, the logistics performance indicator from the World Bank is utilized[49]. Furthermore, we control for country-level environmental factors, encompassing precipitation and temperature anomalies with data from the Climatic Research Unit[61].

*Control variables for the DAEVA and DAEVO analyses.* In alignment with the deforestation analysis, we incorporate the same control variables, as well as additional control variables relevant to trade dynamics based on prior research[38,62,63] (Tables A3 and A6). We control for national trade-related factors, such as WTO membership status obtained from WTO's official website[64], and the number of export-restricting non-tariff measures (NTMs) of the countries of interest, using data sourced from the Global Trade Alert[65]. Further, we account for trade costs at the border by including data on the number of regional trade agreements from the Mario Larch dataset[66], the number of import-restricting NTMs of trading partners from the Global Trade Alert database[65], and the average applied tariff rates from the Trade Analysis Information System (TRAINS) database[67] (with imputations following Bemelmans and co-authors[38]).

**Estimation approaches.** To estimate models 1 and 2, we employ a Poisson pseudo-maximum likelihood (PPML) estimator, which is suitable for handling skewed outcome variables with excess zeros and is unbiased in the presence of heteroscedasticity (in contrast to log-linear models)[68,69]. The PPML estimator is also scale-invariant compared to log-like transformations and allows to analyse relative changes in the outcome variables. It is consistent under the assumption that the conditional mean is correctly specified, which is confirmed based on the RESET test. Observations that are either singletons or separated by a fixed effect are automatically dropped. The PPML estimator implies that the coefficient $\beta_1$ in Eq. 6 can be interpreted as the percentage change in the outcome variable associated with a one percentage increase in *CA* in a country. In all cases, models were estimated on the same full sample and significance of coefficient estimates was tested with two-sided z-tests.

The PPML models estimate within changes in the outcome variables for changes in $VSS$, while controlling for all observed and unobserved time-constant commodity-country level characteristics and time-varying year-level characteristics through fixed effects ($\mu_{c,i}$ , $\gamma_t$), and for other potential time-varying confounding factors via the control variables ($\mathbf{X}_{c,i,t}$). The descriptive statistics on the fixed effects (Table A6) indicate that 29% of the variation in *CA* remains in the sample when using country-commodity fixed effects, and 99% for year fixed effects. To reduce potential remaining endogeneity bias—e.g., arising from country-commodity specific shocks that correlate with VSS (e.g., unobserved policy changes)—we use an IV-PPML estimator on Eq. 4 as robustness check (model 3, Eq. 6), via a control function approach with first-stage residuals $Residuals_{c,i,t}$,, as proposed by Lin and Wooldridge[70] (Tables A10-13 and A20-26):

$$\text{Model (3): } Y_{c,i,t} = \beta_0 + \beta_1 CA_{c,i,t} + \beta_2 \mathbf{X}_{(c,)i,t} + \mu_{c,i} + \gamma_t + \epsilon_{c,i,t} + Residuals_{c,i,t} \quad (6)$$

Instrumental variables (IVs) are based on the (commodity-specific) certified area in neighbouring countries—a similar approach employed by other studies[38,71,72]. VSS coverage in neighbouring countries is likely to influence certification uptake within the country of interest due to regional spillover effects through shared market networks, harmonized policies, pressure or competition from regional trade partners, and learning effects. We consider multiple indicators in neighbouring countries, continents, or regions (using different categorizations of both the World Bank and UN): (i) absolute certified area, (ii) the ratio of certified to total area, and (iii) the rate of change in certified area. For each indicator, we compute various statistical metrics, including the sum, mean, median, maximum, and standard deviation, as well as the share of an individual VSS in the total maximum certified area and the proportion of certified countries. To ensure robust IV selection from a comprehensive set of 850 options per VSS and minimize the risk of weak IVs, we apply a machine learning approach, namely the rigorous least absolute shrinkage and selection operator (LASSO) approach[73]. For the VSS-specific effects, IV-PPML estimation is done separately for each VSS and the combined VSS coverage of the remaining VSS instead of jointly instrumenting for nine endogenous VSS coverage variables, which would otherwise lead to an unwieldly large number of IVs. No suitable IVs are found for RA in the model with *DA* as outcome variable, and for 4C for all three outcome variables. Instead, the set of IVs with the highest correlation is selected. No IVs are found for Proterra for all three outcome variables due to a too small sample size. The IV-PPML estimator is not used as the main specification since it reduces the sample size substantially. The Chi² statistics of the first stage provide a test for instrument relevance, and the coefficients for the generalized residuals a test for endogeneity.

**Robustness checks.** We conduct several robustness checks related to the sample and key variables in the analysis (Tables A15, A27-28). First, we re-estimate the model to test the sensitivity of the estimated effects to the non-linear transformation of the *CA* variable. We use a dummy variable approach, where the coefficient on *CA* captures the effect only for non-zero certification cases, while a separate dummy variable accounts for units with no VSS coverage, representing the expected difference in the outcome between uncertified units and those with the smallest non-zero VSS coverage. Second, we use the maximum certified area instead of the minimum, assuming no overlap between VSS—representing a less conservative measure. We estimate this specification both with and without applying a cut-off for certification ratios exceeding 100% (2.7% of the cases). This specification implies that the *DS* and *ES* scores are calculated differently than in Eq. 3, as $DS_{c,i,t} = \frac{\sum_{k=1}^{12} CA_{k,c,i,t}*DS_{k,t}}{\sum_{k=1}^{12} CA_{k,c,i,t}}$ and $ES_{c,i,t} = \frac{\sum_{k=1}^{12} CA_{k,c,i,t}*ES_{k,t}}{\sum_{k=1}^{12} CA_{k,c,i,t}}$. Third, we exclude commodity-specific harvested area as a control variable, as it may itself be influenced by VSS through land expansion, despite being a key driver of commodity-driven deforestation[51-58]. Fourth, we control for remaining forest area to account for initial forest extent, although this variable may also influence, or be influenced by, VSS adoption. Fifth, to test robustness against potential measurement error, we restrict the sample to *DA* data with a quality index above 0.3 to focus on observations of higher quality only. Sixth, we extend the analysis to include overseas territories. Seventh, we apply a cut-off for cases where export volume exceeds production volume. Overall, the robustness checks support the main results as well as the results of the commodity- and VSS-specific models, though we find a borderline non-significant effect for *DAEVO* in some specifications. Additionally, we estimate the results of the *DA* specification for *commodity spillovers* without controlling for other certified commodities as these might introduce multicollinearity (Tables A16-18). Finally, we re-run the analysis on deforestation and enforcement stringency scores using equal weights instead of weights obtained via factor analysis (Table A19).

**Data availability**

The data on annual VSS coverage at the country-commodity level used in this study are subject to confidentiality agreements with VSS organizations and cannot be publicly shared. Researchers seeking access to this data may contact the corresponding author for guidance on obtaining the necessary permissions from the relevant VSS organizations. Substantive stringency scores for VSS are available in the Supplementary Material, and enforcement stringency scores are from Depoorter and Marx[43]. All other datasets used in this study are publicly available. A replication dataset is available on Zenodo (https://zenodo.org/records/17174494). This dataset contains all publicly available secondary data used in the study, together with simulated certified area variables constructed to comply with data-sharing agreements with standard-setting organizations. The Zenodo repository also includes full documentation of data sources and cleaning procedures.

**Code availability**

The custom Stata do-file for the analysis is available via Zenodo: https://zenodo.org/records/17174494.

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**Competing interests:** The authors declare no competing interests.

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