

# 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<sup>1–3</sup>, but contributes to significant environmental impacts, including deforestation<sup>4,5</sup>. The governance of sustainability in global food systems is shifting from the public to the private sector<sup>6</sup>, with Voluntary Sustainability Standards (VSS) as the most widespread private governance instrument promoting sustainability through trade<sup>7,8</sup>. However, their effectiveness in reducing deforestation at scale remains poorly understood as studies predominantly focus on farm-level analyses<sup>9–12</sup> and overlook indirect land use change, spillovers, and broader trade-offs<sup>12–14</sup>. 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<sup>12,14</sup>, and further assess the role of VSS design<sup>15,16</sup>. 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<sup>4,17,18</sup>. 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<sup>4</sup>. As trade in forest-risk commodities increases<sup>4,19</sup>, 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.

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

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

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

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

## 100 Results

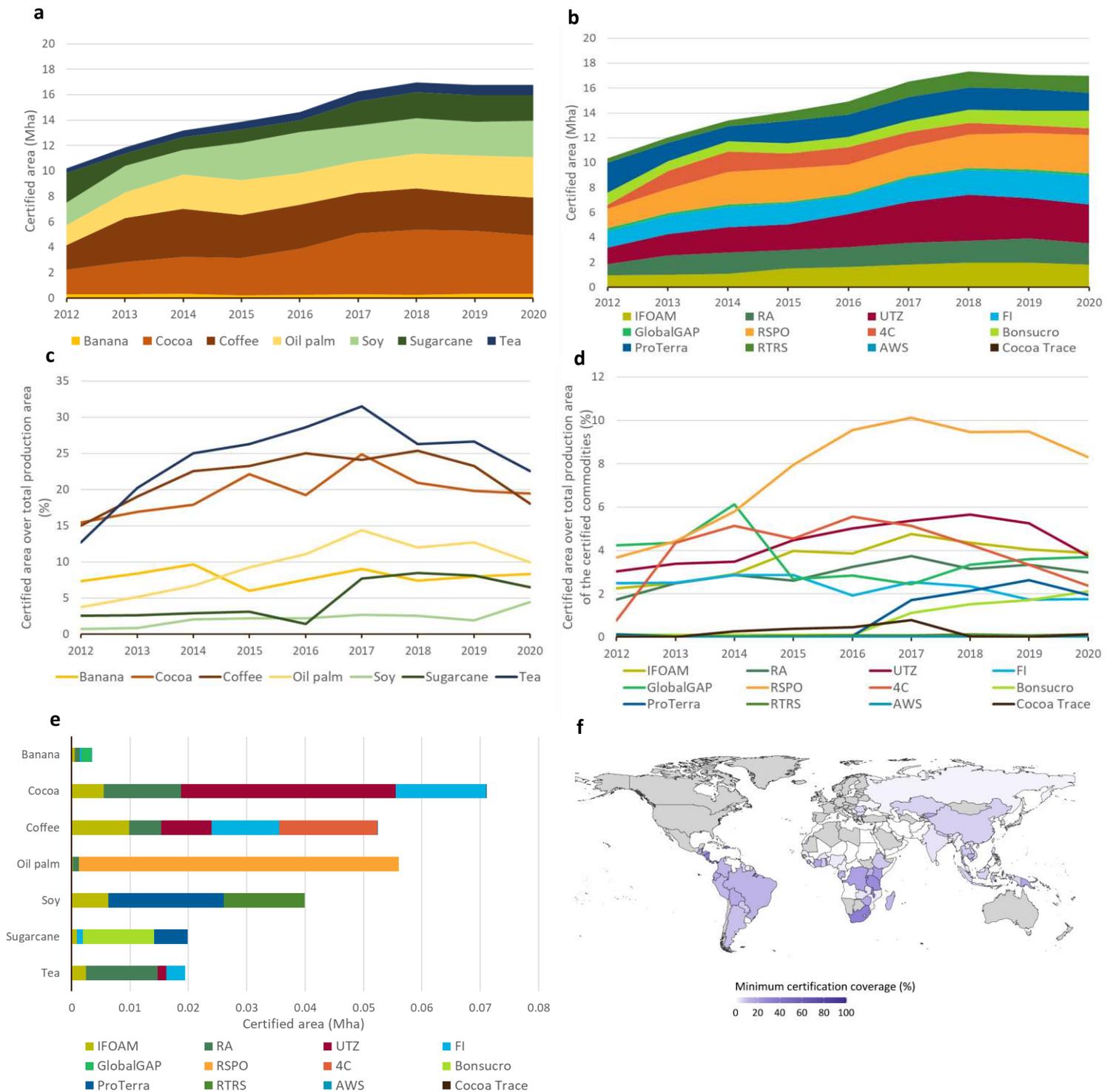
### 101 Certified area and export volumes grow while commodity-driven deforestation and export values decline

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

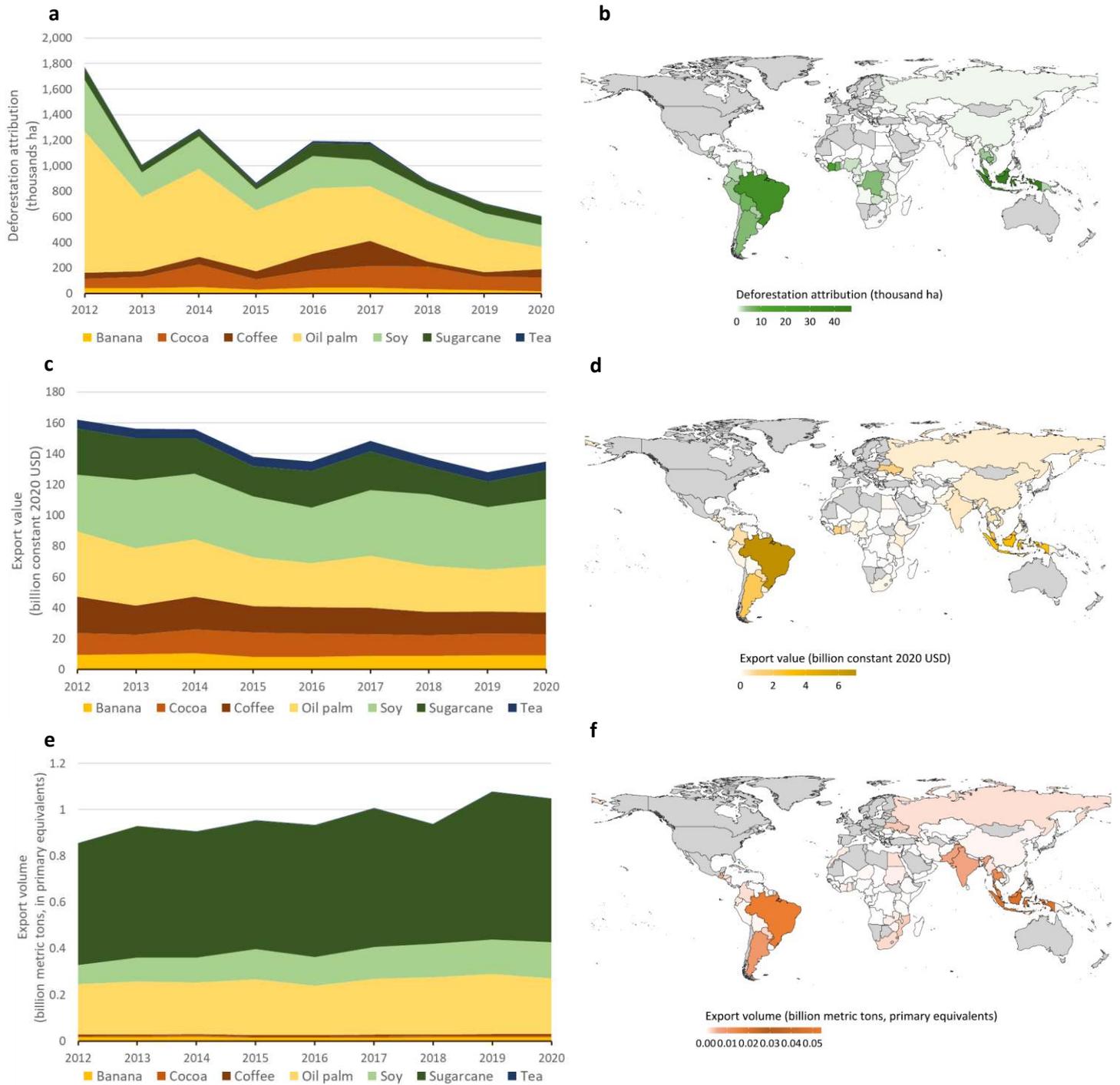
115 Over the same period, commodity-driven deforestation associated with the seven studied commodities  
116 declined at the country-level at an average annual rate of 7.3% (Figure 2a). This decline was largely driven by  
117 reductions in deforestation for oil palm in Indonesia and Malaysia and soy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

123 Taken together, these trends raise several questions about the linkages between VSS and deforestation. First,  
124 does the simultaneous expansion of VSS coverage and decline in deforestation at the country level indicate a  
125 possible association between VSS and commodity-driven deforestation mitigation? Second, does the  
126 concurrent drop in export values suggest an influence of VSS in the apparent trade-off between forest  
127 protection and export growth? Third, does the simultaneous increase in export volumes reflect a relative or  
128 absolute decoupling of the trade-off between deforestation and export growth under certification? To address  
129 these questions, we assess these linkages more rigorously through econometric analyses that estimate

130 conditional associations. Specifically, we estimate how changes in VSS coverage relate to changes in  
131 deforestation and deforestation per unit of export value and volume, and analyze how VSS design moderates  
132 these effects. We control for a suite of covariates that are known to affect the outcomes in three ways: fixed  
133 effects to capture time-constant commodity-country level characteristics, and time-varying year- and country-  
134 year level characteristics; control variables for observed time-varying confounding factors; and an IV estimator  
135 with machine learning-based instrument selection to reduce remaining sources of endogeneity to the extent  
136 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.

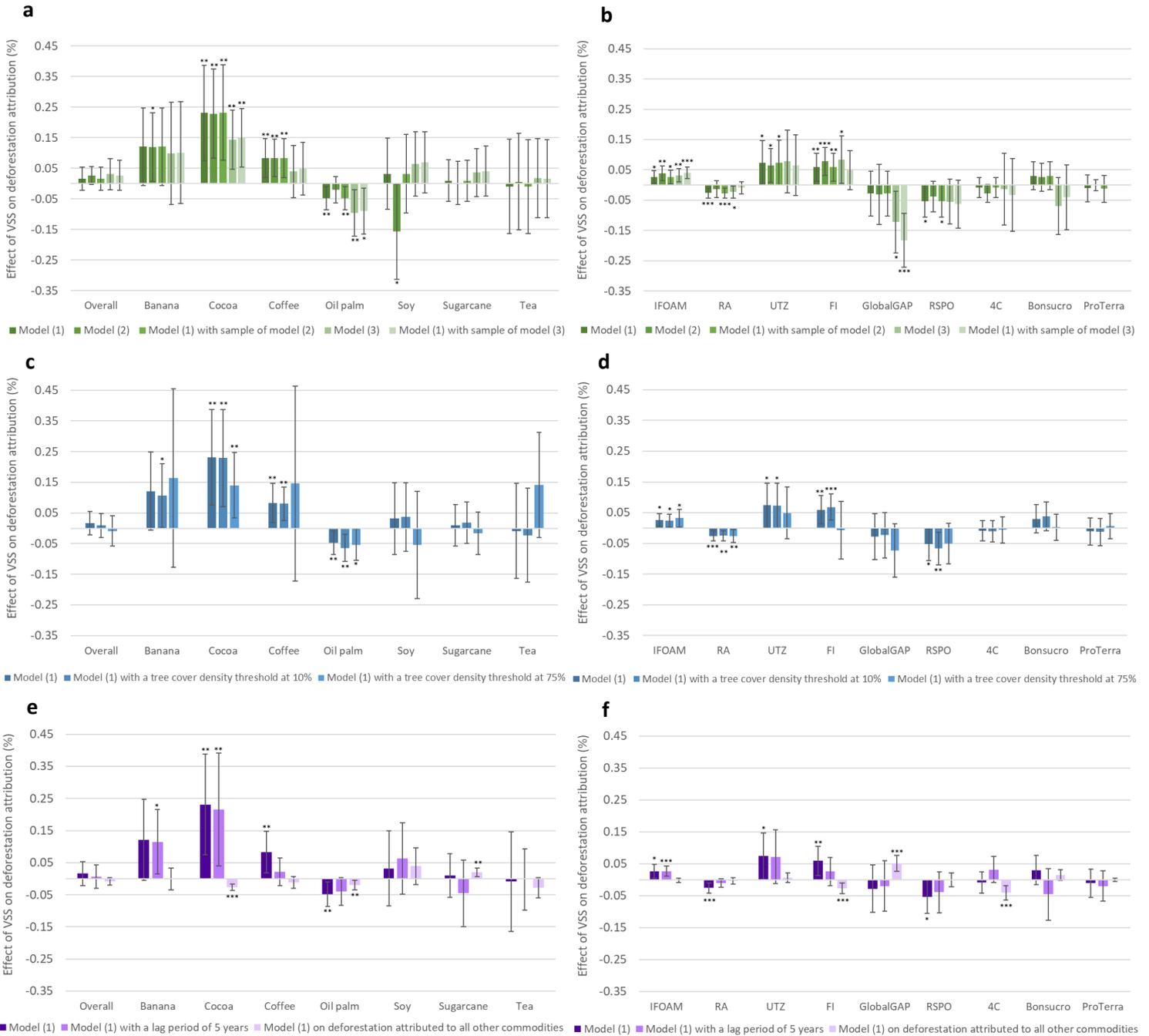
137 **No consistent association between VSS and commodity-driven deforestation but variations across**  
138 **commodities and VSS**

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

156 To assess variation across forest types, we use alternative tree cover density thresholds (Figures 3c-d, Tables  
157 A10-12). A 10% threshold captures more open woodlands and sparse tree cover compared to the main analysis  
158 (25% threshold), while a 75% threshold focuses on dense, closed-canopy forests. The results show that the  
159 estimated deforestation-increasing effect for banana, cocoa, coffee, IFOAM, UTZ, and FI is similar using a 10%  
160 threshold, while the association weakens (cocoa), vanishes (coffee, UTZ, FI), or remains (IFOAM) using a 75%  
161 threshold. This suggests that the estimated deforestation-increasing effect of VSS for these commodities and  
162 VSS mainly occurs in more degraded or fragmented forests, rather than in dense forests. Apart from RSPO,  
163 where the estimated conservation effect is more pronounced in less dense forests, the estimated  
164 deforestation-reducing effects of oil palm certification and RA hold across forest types.

165 Certain VSS set their own forest definitions with specific tree cover density thresholds (Table A14). Aligning  
166 with these thresholds, the results show that the estimated deforestation-reducing effect of RA remains  
167 significant using its 10% threshold (2020 standard), whereas RSPO's reduction effect disappears at its higher  
168 60-80% threshold (2018 standard). Similarly, the positive association between deforestation and UTZ vanishes  
169 at its 10% threshold (2014 standard). We find no significant associations for 4C (10% threshold, 2020 standard)  
170 and Bonsucro (10–30% threshold, 2011 standard).

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



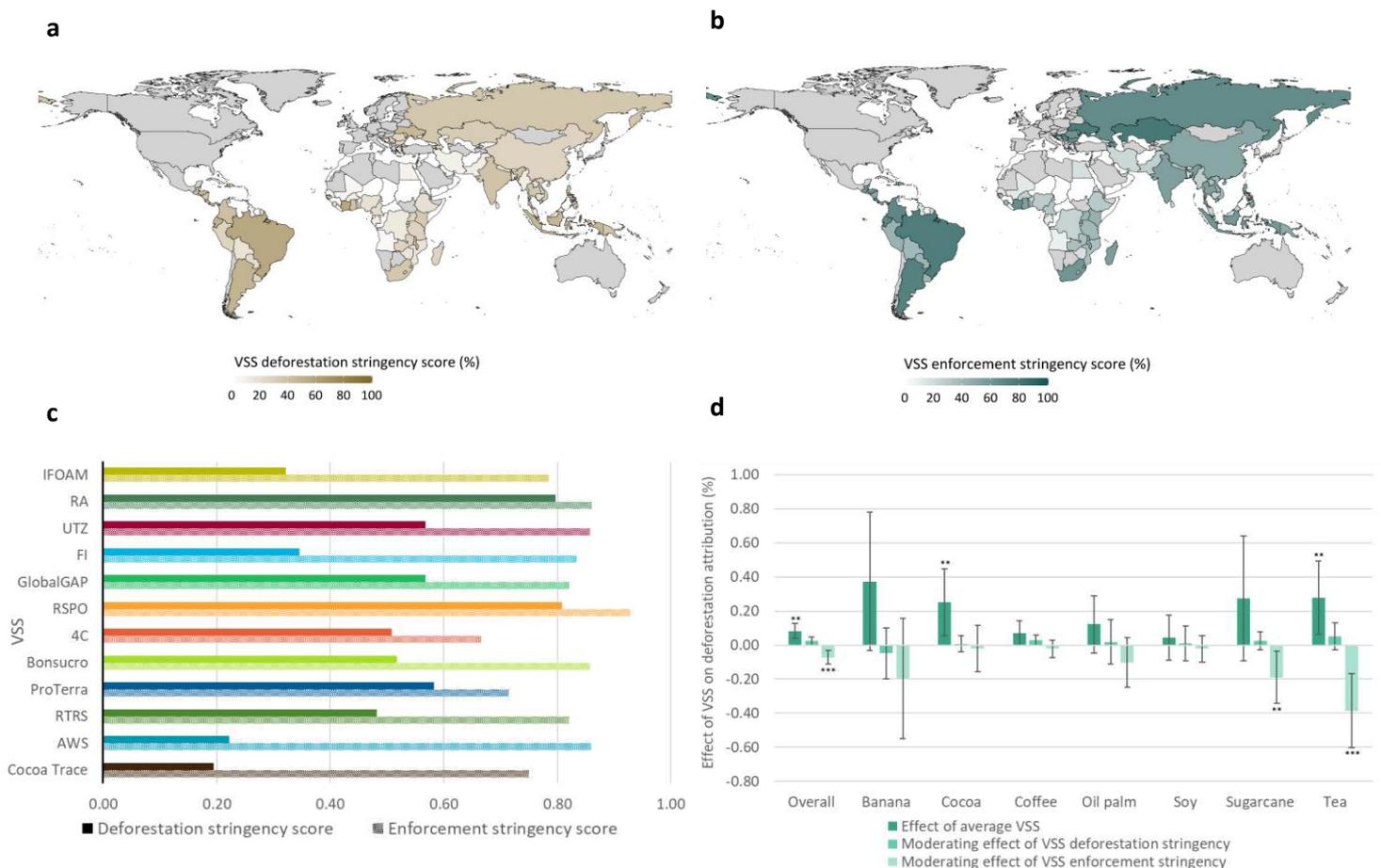
**Figure 3 | Estimated effects of certification on deforestation attribution under different model specifications.** Estimated effects (%) of a one percentage increase in the certified area on the deforestation attribution area across different estimation methods (a-b), different tree cover density thresholds (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.

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

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

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

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



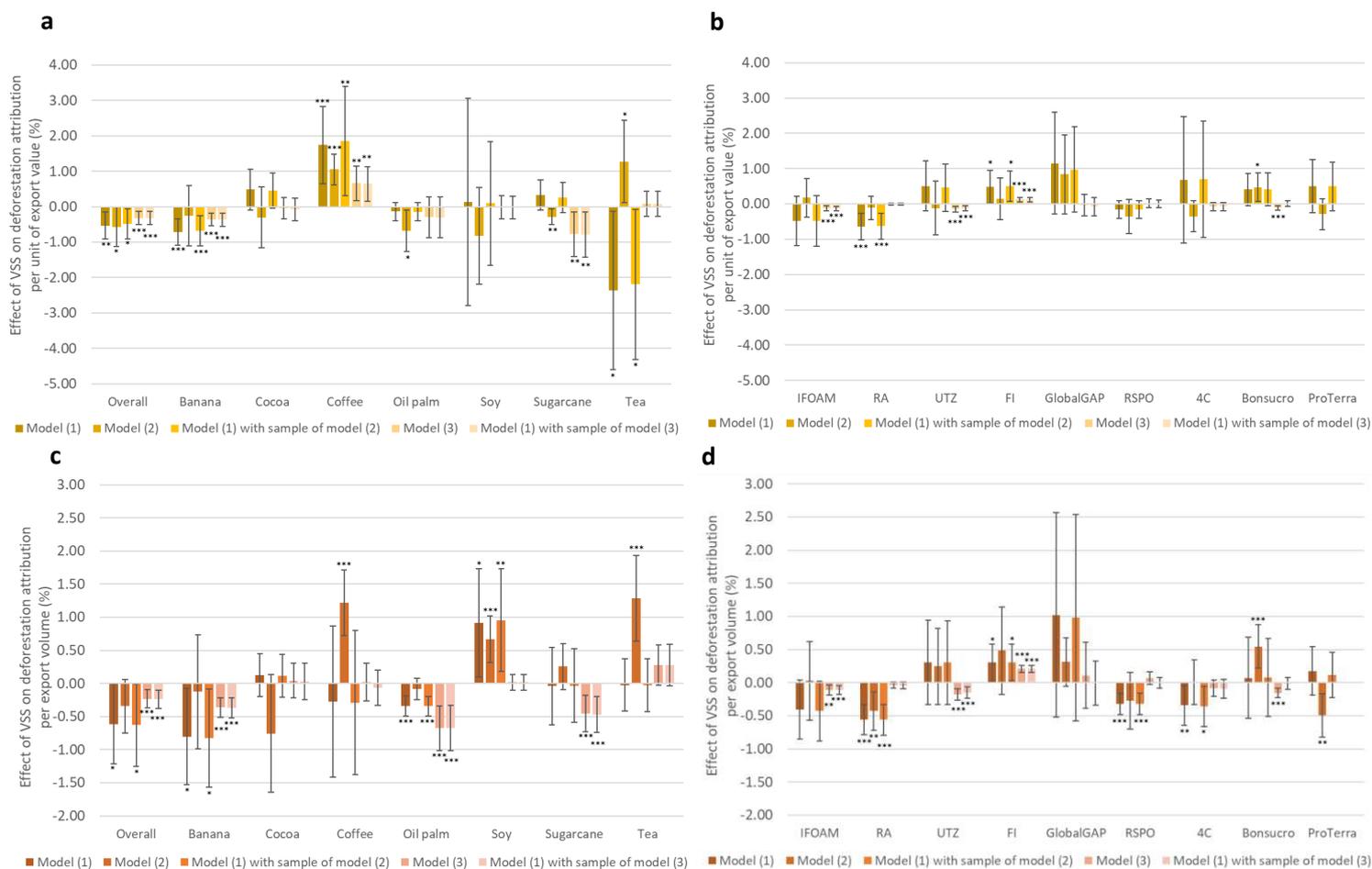
**Figure 4 | Distribution and moderating effect of VSS deforestation and enforcement stringency on deforestation attribution.**

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.

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

221 Finally, we find that, overall, VSS are associated with reduced deforestation per unit of export value at the  
 222 country level (Figures 5a-b, Tables A20-A22 and A26). Combined results suggest a relative decoupling between  
 223 export gains and deforestation: expansion of VSS coverage is linked to increased economic returns from export  
 224 growth without affecting deforestation, thereby reducing the trade-off between export growth and forest  
 225 conservation. These gains could result from yield increases, value-added processing, or price premiums  
 226 associated with certification. In particular, we find that a 1% increase in the certified area is associated with  
 227 decreases in deforestation per unit of export value for banana (0.36-0.72%), but increases for coffee (0.64-  
 228 1.75%). Across VSS, a 1% increase in RA coverage is associated with a 0.63-0.65% reduction in deforestation  
 229 per unit of export value, while FI is associated with a 0.12-0.51% increase. No consistent or non-significant  
 230 estimates are found for other crops and VSS across different model specifications.

231 We find a similar association between overall certification and a reduction in the deforestation per unit of  
 232 export volume, pointing to more land-efficient production for export (Figures 5c-d, Tables A23-A26). In  
 233 particular, estimates point to a reduction for banana (0.36-0.83%), oil palm (0.33-0.68%), RA (0.42-0.56%),  
 234 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%) .  
 235 Estimates for other crops and VSS are less consistent or non-significant. Together, these findings imply that,  
 236 with certification less forest is being lost for each dollar of commodity export earnings and each ton exported,  
 237 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.

## 238 Discussion

239 The study demonstrates that, contrary to farm-level evidence<sup>9-12</sup>, VSS are overall not significantly associated  
 240 with reduced commodity-driven deforestation at scale, taking into account both direct and indirect land use  
 241 change. Results reveal heterogenous associations across commodities, VSS, and forest types, as well as

242 temporal and cross-commodity spillovers. While previous studies report no off-site deforestation effects for  
243 RSPO in Indonesia<sup>27,28</sup>, our findings show that, globally, RSPO is linked to reduced deforestation at country  
244 level. We document that higher VSS coverage for UTZ, FI, and IFOAM is linked to increased deforestation  
245 attributed to the commodities these VSS certify, whereas previous research finds no strong associations  
246 between these VSS and overall tree cover loss in primary forest<sup>29</sup>. Additionally, we show that VSS design  
247 matters: stronger enforcement enhances effectiveness, rather than stricter criteria alone. Moreover, the  
248 findings highlight that VSS in general can contribute to mitigating the deforestation-export trade-off—  
249 reducing deforestation per unit of export value and volume—indicating relative, rather than absolute,  
250 decoupling, though again with commodity- and VSS-specific differences.

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

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

287 have also been associated with an increase in export value and/or volume, which may contribute to mitigating  
288 the trade-off<sup>14,25,26</sup>.

289 Third, for other commodities and VSS, we find no or no consistent association between VSS coverage and  
290 deforestation and no evidence of decoupling—except for 4C, where we find an indication of relative  
291 decoupling. Several factors could explain: VSS requirements and enforcement may not be strict enough (e.g.,  
292 4C, GlobalGAP, RTRS, Bonscuro, ProTerra), certification not targeting deforestation-prone areas leading to  
293 displacement effects (e.g., for tea, and sugarcane<sup>30</sup>), market incentives that conflict with deforestation  
294 reduction goals, or low certification uptake (e.g., for soy and sugarcane, and in Africa). The complementary  
295 spillover analysis suggests that 4C certification, while having no direct effect on deforestation attribution, is  
296 linked to reductions in deforestation from other crops—possibly reflecting land sparing or improved land  
297 management—and sugarcane and GlobalGAP certification appear to displace deforestation to other  
298 commodities, likely due to weaker sustainability requirements or indirect land-use change. Export effects may  
299 explain observed trade-offs for soy and 4C<sup>14,25,26</sup>. In other cases, improvements in export value or volume have  
300 been documented but these may not be large enough to translate into measurable trade-off reductions at  
301 country level.

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

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

323

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 <i>Oil palm, RA, RSPO</i>	Win-lose and relative decoupling	No decoupling
	Increased	Lose-win and relative decoupling <i>Banana</i>	Lose-lose and no decoupling <i>Coffee, FI</i>	No decoupling <i>Cocoa, IFOAM, UTZ</i>
	Non-significant	Relative decoupling <i>4C</i>	No decoupling <i>Soy</i>	No decoupling <i>Sugarcane, tea, GlobalGAP, Bonsucro, ProTerra</i>

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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## 388 **Methods**

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

391 *Deforestation attribution (DA).* We use country-commodity level *DA* data from the Deforestation Driver and  
392 Carbon Emission (DeDuCE) model, which is currently the most comprehensive available data on commodity-  
393 driven deforestation, covering large temporal (2000-2022) and spatial scales (all producing countries)<sup>33</sup>. *DA*  
394 reflects commodity-driven deforestation, derived from high-resolution (30m) spatial data on tree cover loss  
395 by identifying deforestation and attributing this to major land use classes and then to commodities based on  
396 either (1) spatial crop maps, if available, or (2) a land balance approach using (sub-)national agricultural  
397 statistics. To account for the time lag between forest clearing and subsequent land use establishment, changes  
398 in land use areas are averaged over the three years post-forest clearing. Deforestation is defined as the  
399 removal of tree cover in natural forests exceeding 5m in height and 25% canopy cover (threshold based on  
400 Sexton and co-authors<sup>34</sup>), excluding tree cover loss in managed forests and plantations, as well as forest loss  
401 resulting from fires not followed by agricultural land-uses. An advantage of the country-commodity level  
402 dataset is its ability to account for land-use linkages and displacement effects<sup>35,36</sup>. We provide additional  
403 estimates using alternative *DA* specifications with tree cover density thresholds of 10% and 75% instead of  
404 25% (Figures 3c&d, Tables A10-12)—to assess variations across forest types. Moreover, we estimate  
405 alternative *DA* specifications using a five-year time lag instead of three years to analyse *temporal spillovers*  
406 (Figures 3e&f, Tables A16-18)—to better reflect the growth cycles of the studied perennial commodities,  
407 ranging from 3 months to 5 years<sup>37</sup>, and to capture a broader range of indirect land use changes, which often  
408 unfold over extended periods. Furthermore, we estimate an alternative *DA* specification to analyse *commodity*  
409 *spillovers* by examining deforestation attributed to other commodities (Figures 3e&f, Tables A16-18), while  
410 controlling for certification of other commodities.

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

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

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

437 *VSS stringency scores*. The literature on VSS effectiveness highlights that two VSS design aspects are relevant  
 438 for their sustainability impact, namely substantive stringency, referring to the content and stringency of the  
 439 requirements in VSS, and procedural stringency, referring to the rules and procedures VSS put in place to  
 440 enforce compliance, build producer capacity, and provide market-based incentives for adhering to their  
 441 requirements<sup>43-47</sup>. We apply these concepts specifically to the issue of deforestation, and construct scores for  
 442 *deforestation stringency (DS)* and *enforcement stringency (ES)*. For *DS*, we identify 14 criteria related to  
 443 deforestation prevention, conservation and restoration of natural ecosystems, location and land rights, and  
 444 agroforestry through existing comparisons and benchmarking schemes (Table A7; Supplementary Material 2).  
 445 We evaluate the 12 VSS on these criteria (indexed *a*) based on the different versions of their standard during  
 446 2012-2020. The resulting criteria stringency scores (*DSscore*, Table A7) are weighted based on how explicit the  
 447 criteria are included (*Explicitness*) and how critical they are for obtaining certification (*Criticality*) (Table A8).  
 448 Because some criteria might capture closely related concepts, we weight the resulting scores using a factor  
 449 analysis, as in (Eq. 1):

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

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

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

457 Resulting *DS* and *ES* scores are given in Figure 4c. We aggregate both stringency scores to the country(*i*)-  
 458 commodity(*c*)-year(*t*) level ( $DS_{c,i,t}$ ,  $ES_{c,i,t}$ ), assuming full overlap in certified areas (*CA*) between VSS. For each  
 459 country-commodity-year observation, we sort the  $CA_{c,i,t}$  of different VSS (indexed *k*) in ascending order and  
 460 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  
 461 maximum stringency score among all VSS present at step *k*, assuming that the overlapping area has to be  
 462 certified according to the most stringent VSS, as  $DS_{k,t} = \max\{DS_{VSS,t} | CA_{VSS,c,i,t} \geq CA_{k,c,i,t}\}$  and  $ES_k =$   
 463  $\max\{ES_{VSS} | CA_{VSS,c,i,t} \geq CA_{k,c,i,t}\}$ . The weighted stringency score for commodity *c* in country *i* in year *t* are  
 464 then (Eq. 3):

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

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

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

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

475 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  
 476 independent variable of interest, measured as the absolute certified area for commodity  $c$  in country  $i$  in year  
 477  $t$ . The vector  $\mathbf{X}_{(c),i,t}$  encompasses (commodity-)country-year level control variables, as detailed below.  $\mu_{c,i}$  are  
 478 commodity-country fixed effects, removing time-constant unobserved confounders specific to a country and  
 479 commodity (e.g., geographical, legal, economic, technological, or cultural features),  $\gamma_t$  are year fixed effects,  
 480 removing time-varying unobserved confounders affecting all commodities and countries (e.g., global  
 481 economic conditions, international regulations), and  $\epsilon_{c,i,t}$  is the error term. We do not include commodity-  
 482 year fixed effects, as this might capture economic commodity trends that might be affected by certification  
 483 (e.g., commodity price trends). As robustness check, in an alternative specification (model 2, Eq. 5), we  
 484 additionally include country-year fixed effects  $\rho_{i,t}$ , which capture time-varying country-specific factors beyond  
 485 the ones already controlled for:

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

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

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

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

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

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

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

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

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

543 Instrumental variables (IVs) are based on the (commodity-specific) certified area in neighbouring countries—  
 544 a similar approach employed by other studies<sup>38,71,72</sup>. *VSS* coverage in neighbouring countries is likely to  
 545 influence certification uptake within the country of interest due to regional spillover effects through shared  
 546 market networks, harmonized policies, pressure or competition from regional trade partners, and learning  
 547 effects. We consider multiple indicators in neighbouring countries, continents, or regions (using different  
 548 categorizations of both the World Bank and UN): (i) absolute certified area, (ii) the ratio of certified to total

549 area, and (iii) the rate of change in certified area. For each indicator, we compute various statistical metrics,  
550 including the sum, mean, median, maximum, and standard deviation, as well as the share of an individual VSS  
551 in the total maximum certified area and the proportion of certified countries. To ensure robust IV selection  
552 from a comprehensive set of 850 options per VSS and minimize the risk of weak IVs, we apply a machine  
553 learning approach, namely the rigorous least absolute shrinkage and selection operator (LASSO) approach<sup>73</sup>.  
554 For the VSS-specific effects, IV-PPML estimation is done separately for each VSS and the combined VSS  
555 coverage of the remaining VSS instead of jointly instrumenting for nine endogenous VSS coverage variables,  
556 which would otherwise lead to an unwieldy large number of IVs. No suitable IVs are found for RA in the model  
557 with *DA* as outcome variable, and for 4C for all three outcome variables. Instead, the set of IVs with the highest  
558 correlation is selected. No IVs are found for Proterra for all three outcome variables due to a too small sample  
559 size. The IV-PPML estimator is not used as the main specification since it reduces the sample size substantially.  
560 The Chi<sup>2</sup> statistics of the first stage provide a test for instrument relevance, and the coefficients for the  
561 generalized residuals a test for endogeneity.

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

### 583 **Data availability**

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

594 **Code availability**

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

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