



Cocoa expansion around Ghana's protected areas is associated with food crop displacement and forest loss inside them



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Cocoa farming is a major driver of deforestation in West Africa. While sustainability policies like zero-deforestation commitments aim to reduce forest loss from cocoa, they overlook a critical gap. When cocoa expands onto existing farmland, farmers may shift food-crop cultivation into nearby protected forest reserves instead. We analysed satellite imagery and farmer interviews in Ghana to test whether this land displacement occurs and whether sustainability programmes prevent it. From 2000 to 2019, areas with more intensive cocoa farming were associated with greater forest loss inside reserves from food crop cultivation. In 2022–2024, villages with greater exposure to sustainability programmes showed reduced forest loss. Agroforestry (growing shade trees on cocoa farms) showed no protective effect, likely due to minimal adoption. These associations suggest current policies fail to address indirect deforestation from land displacement and highlight the need for land use governance addressing both direct and indirect pressures from cocoa.

Land use change leading to deforestation and forest degradation in tropical forest regions has become a major global challenge, with implications for biodiversity loss, climate change mitigation, food production, and rural livelihoods¹. Agricultural expansion for both subsistence and commercial purposes remains the leading driver of tropical forest loss, contributing an estimated 90–99% of deforestation across the tropics between 2011 and 2015². Despite international commitments to halt deforestation and restore degraded ecosystems, tropical forests continue to disappear rapidly. In 2022 alone, 4.1 million hectares of tropical primary forest were lost, an increase of 10% from the previous year³.

In West Africa, agriculture, particularly cocoa cultivation, is a major driver of forest loss⁴. The region produces over 70% of the world's cocoa, with Côte d'Ivoire and Ghana dominating production, much of which has occurred through forest conversion, including in protected areas, especially in Côte d'Ivoire⁵.

In Ghana, cocoa cultivation plays a central role in rural economies and is the country's top agricultural export, but it has also been a key driver of forest loss^{3–7}. Since the 1950s, more than 60% of Ghana's forests have been cleared, with most of the remaining forest now located within protected areas, a broad category that includes national parks, wildlife sanctuaries, and forest reserves^{8,9}.

Forest Reserves, the focus of this study, are a subcategory of protected areas that permit regulated and sustainable use, such as the extraction of non-timber forest products, rather than strict protection¹⁰. This makes forest reserves a key area where conservation goals intersect and often conflict with community land-use pressures. Despite their protective designation, forest reserves continue to experience high rates of degradation and deforestation^{5,11,12}.

Deforestation in cocoa landscapes has been widely attributed to direct forest conversion for cocoa expansion^{12,13}. In response, a suite of supply chain sustainability initiatives (SSIs), including certification schemes, zero-

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deforestation commitments (ZDCs), and emerging regulations like the European Union Deforestation Regulation (EUDR), has aimed to curb cocoa-driven forest loss, and support smallholder livelihoods^{14,15}. However, these interventions often target cocoa production in isolation, overlooking broader landscape dynamics such as the displacement of other land uses into forested areas⁷.

In Ghana, cocoa's socio-cultural and economic appeal, including profitability, land tenure security, and status, has led to its dominance in village landscapes in the High Forest Zones^{16,17}. As cocoa occupies more arable land, farmers with unmet food needs may turn to cultivating food crops inside nearby forest reserves, where enforcement is weaker, and food production faces fewer sanctions than cocoa farming^{18,19}. This indirect displacement of food crops constitutes leakage when it results from sustainability policies that target cocoa production, such as zero-deforestation commitments in West Africa. Similarly, the EUDR regulates deforestation linked to specific forest-risk commodities, but not other agricultural products. In response, cocoa expansion may shift away from forests to comply with these policies, while staple food crops (e.g. plantain, yam, cocoyam) are displaced into forested areas, undermining broader conservation goals^{20,21}.

A growing body of literature examines supply chain sustainability initiatives (SSIs) and agroforestry in cocoa systems^{22–29}. Evaluations of SSIs in West Africa document mixed effectiveness. Some studies find modest improvements in good farm practices, productivity and income^{28,29}, while others highlight limited additionality, uneven implementation, and challenges related to monitoring and enforcement^{22,23}. Studies on the direct impact of SSIs on cocoa-driven deforestation are limited. Meanwhile, cocoa agroforestry, the integration of shade trees on cocoa farms, has become central to corporate sustainability strategies, promoted for its potential to improve productivity, microclimates, soil health, climate resilience, and biodiversity, while reducing pressure to expand into forests^{30–33}. Empirical evidence demonstrates the potential benefits of cocoa agroforestry at the farm scale, including carbon storage²⁵, improve income and productivity³⁴, and on-farm biodiversity support³⁵, though findings are context-specific and often highlight trade-offs, particularly between shade and short-term yields³⁴. Adoption across cocoa landscapes of Ghana and Côte d'Ivoire remains low and uneven, constrained by tree tenure insecurity, yield trade-offs, and inappropriate species promotion^{25,27,30,36,37}.

However, critical knowledge gaps remain. First, most SSI evidence focuses on direct deforestation within production areas, with limited attention to broader landscape spillovers, specifically, whether programmes operating outside protected areas influence forest outcomes inside reserves. Second, evidence linking agroforestry adoption to landscape-scale forest conservation is lacking. While plot-level studies show biodiversity benefits, it remains unclear whether farm-level adoption of shade trees reduces pressure on adjacent protected areas. These gaps are critical given the prominence of both SSIs and agroforestry in policy frameworks such as the Cocoa & Forests Initiative (CFI), a 2017 public–private partnership between Ghana, Côte d'Ivoire, and cocoa companies aimed at ending cocoa-related deforestation and promoting sustainable farming and forest restoration³⁸. They are also important because adoption remains low and uneven across the region, raising questions about whether agroforestry is implemented at a sufficient scale to influence forest outcomes.

An additional complexity in Ghana is the state-led Modified Taungya System (MTS), which allows farmers to grow food crops in degraded reserves while tending tree seedlings for the Forestry Commission³⁹. Although intended to support communities and aid restoration, the scheme can exacerbate land-use displacement and leakage by normalising farming inside reserves and enabling further degradation under weak enforcement.

While land systems science has emphasised examining indirect land-use changes (iLUC) and harmful policy spillovers^{40,41}, empirical evidence has primarily focused on biofuel-driven displacement and commercial land-use dynamics at national and regional scales^{40–46}. While coffee expansion in Vietnam indirectly displaced food crops into forests⁴⁷, village-scale evidence of export commodities displacing food crops into protected areas remains scarce, particularly in Africa, where tensions between staple farming and

commercial agriculture are central to sustainable development⁴⁸. Renier et al.⁷ estimated that cocoa indirectly contributes to 12% of food crop deforestation in Ghana's protected areas using a land balance approach, but did not econometrically test this relationship or evaluate policy effectiveness. Econometric, village-scale evidence examining cocoa-displacement associations and assessing sustainability intervention effectiveness remains limited.

Displacement affects policy “effectiveness” because it reduces the additionality that zero deforestation measures aim to achieve, constituting leakage when driven by the policy itself⁴⁹. Evidence on the effectiveness of cocoa zero deforestation supply chain policies is still limited, but studies on other forest-risk commodities (soy, beef cattle, oil palm) show that leakage can be substantial relative to additionality^{50,51}. This leakage is often linked to the narrow spatial focus of these policies, which target individual farms rather than whole landscapes. Additionality in these sectors is also highly variable^{52–54}. Cocoa policies differ somewhat because they promote agroforestry alongside zero deforestation commitments, yet evaluations of agroforestry in relation to forest outcomes remain scarce.

We address these gaps through a village-level analysis examining whether cocoa saturation outside Ghana's forest reserves (the proportion of non-reserve land under cocoa) is associated with food crop-driven forest loss within reserves, and whether exposure to sustainability programmes and agroforestry adoption correspond with forest outcomes. Specifically, we provide quantitative village-scale evidence of cocoa-driven food crop displacement; evaluation of whether sustainability programmes are associated with forest protection beyond cocoa production areas; and an assessment of agroforestry's landscape-level forest conservation associations. We contribute an indirect land use change perspective to the literature on forest-risk supply chain policies by including voluntary standards, zero deforestation commitments, and corporate sustainability programmes^{20,22,28,55–57}, as well as emerging trade regulations like the EUDR⁵⁸.

Analysing 76 villages with boundaries inside and outside forest reserves (Fig. 1), across two periods (2000–2019 and 2022–2024), we find that higher cocoa saturation outside reserves is associated with greater food-crop-driven forest loss inside reserves, while exposure to sustainability programmes corresponds with reduced recent forest loss. Agroforestry shows no detectable effect, likely due to low adoption. Together, these results highlight key gaps in current cocoa sustainability governance, which focuses on direct cocoa-driven deforestation but overlooks broader land-use displacement dynamics.

Results

Land use patterns and exposure to sustainability initiatives

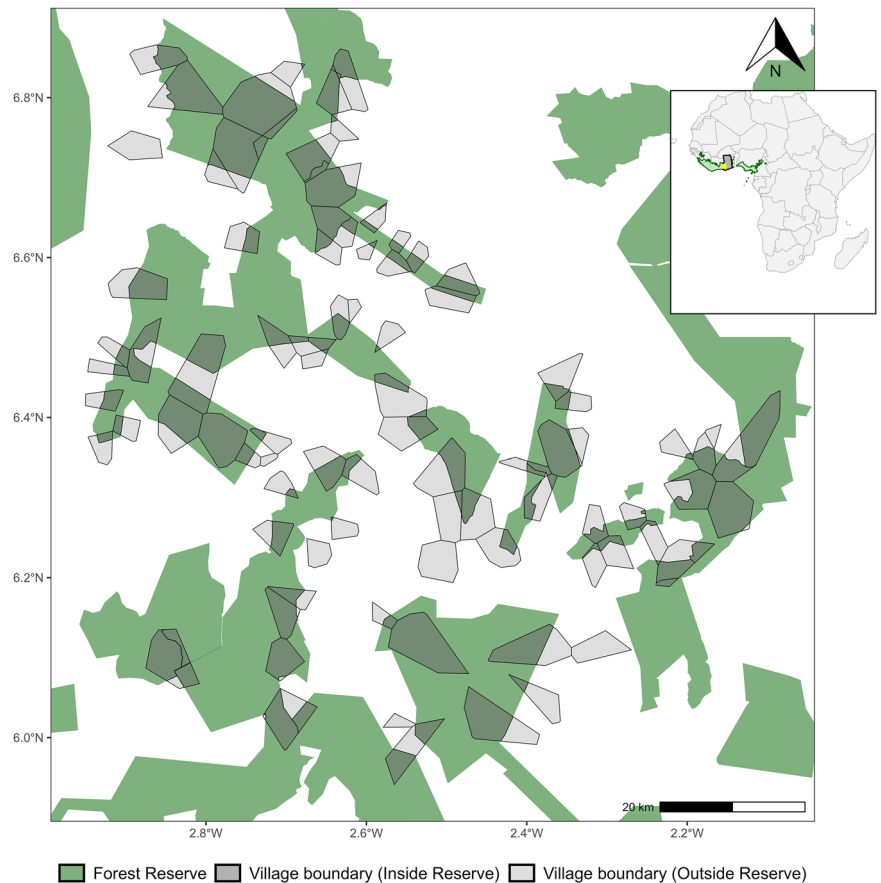
Integrating cocoa, agroforestry, and forest loss maps (see Methods), we find that cocoa cultivation covers a large portion of village land outside forest reserves, with a median saturation of 80%, but is mostly absent inside reserves (4.2%), except for a few cases likely due to unauthorised farms or to ‘admitted farms’, pre-existing farmlands within forest reserves that were formally recognised and legally permitted when the reserves were established¹⁷ (Fig. 2). As shown in Fig. 2, from 2000 to 2019, food crop-related forest loss was high inside reserves (median 31% of village land within reserves) but very low outside reserves (1.8%). Shade tree cover in cocoa areas is generally low (mean 14.7%, median 14.6%, range 10.9–21.1%) (Supplementary Table 1). These patterns show high cocoa presence outside reserves and notable food crop-driven forest loss inside.

Village surveys indicate that, on average, 35.7% of cocoa-buying companies active in a village reported implementing sustainability programmes (Supplementary Table S1 and Fig. 3).

Relationship between cocoa saturation and food crop-driven forest loss within forest reserves (2000–2019)

We examine food crop-driven deforestation across the 2000–2019 period, leveraging land use-specific data (see Methods). The beta regression analysis, as shown in Table 1, reveals a significant positive association between cocoa saturation outside forest reserves and the proportion of land inside

Fig. 1 | Map of study area in Ghana's High Forest Zone. Village boundaries (shown as white polygons) are delineated using Thiessen polygons constructed around village point locations. The study area spans eight districts in the Western North, Ashanti, and Ahafo regions of Ghana. Forest reserves are shown in green. Sampled village boundaries are shown as dark grey filled polygons with solid black outlines where they fall inside forest reserves, and as light grey filled polygons where they fall outside forest reserves. The inset map shows the location of the study area (indicated by a yellow rectangle) within Ghana, the Upper Guinean Forest ecoregion (shown in light green), and the African continent for broader geographic context. Scale bar represents 20 km. N indicates north. Basemap source: Google Satellite imagery.



reserves experiencing food crop-driven forest loss. Specifically, cocoa saturation outside reserves is positively associated with the proportion of land inside reserves experiencing food-crop-driven forest loss ($\beta = 2.762$, $SE = 1.056$, $p < 0.01$). The Average Marginal Effects (AME) results show that a 10-percentage point increase in cocoa saturation outside reserves is associated with a ~6.5 percentage point increase in the proportion of reserve land affected by food crop-driven forest loss ($AME = 0.654$, $SE = 0.250$, $p < 0.01$). In practical terms, if a village initially had 30% of its reserve land deforested for food crops, a 10-percentage point increase in cocoa saturation (e.g., from 70% to 80% of non-reserve land under cocoa) would be associated with that 30% rising to approximately 36.5%. This finding supports the hypothesis that cocoa expansion contributes to land scarcity, which in turn displaces food crop cultivation into nearby forest reserves.

Accessibility emerges as an important contextual factor. Villages located farther from district capitals show a lower proportional extent of food crop-driven forest loss inside reserves ($AME = -0.011$, $SE = 0.005$, $p < 0.05$), while more rugged terrain is marginally associated with reduced forest loss ($AME = -0.047$, $SE = 0.026$, $p < 0.1$), both suggesting that remoteness and difficult terrain may limit agricultural encroachment into reserves. Population density and distance to roads were not statistically significant.

These results provide strong empirical evidence of a spatial spillover effect (i.e., land-use displacement), where cocoa-driven land pressures outside reserves contribute to the encroachment of food crops into protected areas.

Predictors of forest loss within forest reserves (2022–2024)

For the 2022–2024 period, we examine recent total forest loss, capturing sustainability programmes and agroforestry dynamics. We estimated two beta regression models of total forest loss inside reserves, Model 1 without, and Model 2 with a control for baseline forest condition (see “Methods” for details). Across both models, as shown in Table 2, cocoa

saturation outside reserves is positively associated with total forest loss inside reserves (Model 1: $AME = 0.151$, $SE = 0.059$, $p < 0.05$; Model 2: $AME = 0.144$, $SE = 0.059$, $p < 0.05$).

In Model 1, a 10-percentage point increase in cocoa saturation is associated with a 1.5 percentage point increase in forest loss inside reserves. This effect remains statistically significant and similar in magnitude in Model 2, which includes the share of undisturbed forest inside reserves. In practical terms, if a village had 5% of its adjacent forest reserve deforested over the period, a 10-percentage point increase in cocoa expansion on village land outside forest reserves would be associated (on average) with the 5% increasing to about 6.5%.

Cocoa sustainability programme exposure shows a significant negative association with forest loss in reserves when controlling for baseline forest conditions (Model 2: $AME = -0.098$, $p < 0.05$). Specifically, a 10 percentage point increase in the share of companies implementing sustainability programmes is associated with approximately a 1.0 percentage point reduction in forest loss. For example, if 5% of a village area inside a forest reserve was deforested, increasing the share of active cocoa-buying companies implementing sustainability programmes by 10 percentage points from the current average of 35.7–45.7%, it would be associated with the 5% deforestation rate dropping to about 4.0%, on average.

This effect remained significant at the 10% level without controlling for baseline forest conditions (Model 1: $AME = -0.094$, $p < 0.1$), suggesting that forest availability influences programme effectiveness or placement patterns. However, these correlational findings may reflect selection bias (companies operating in lower-risk villages), reverse causality (companies implementing programmes in response to observed success), or omitted variables, emphasising the need for causal designs to establish programme impacts.

In contrast, shade tree cover in cocoa areas was not significantly associated with forest loss in any model ($AME = 0.004$, 0.003 , $p > 0.05$). This suggests that, at the village level, the adoption of cocoa agroforestry, as

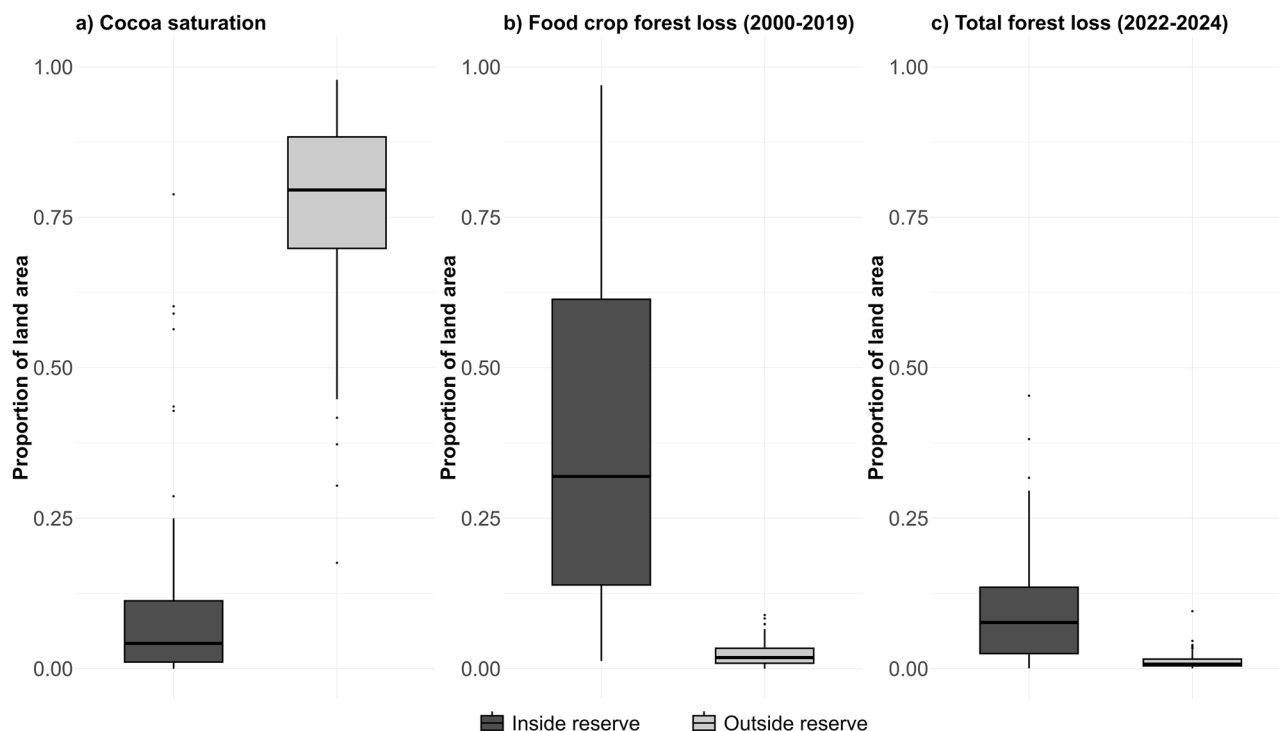


Fig. 2 | Cocoa saturation and forest loss patterns inside and outside forest reserves. Boxplots comparing the proportion of land area affected by cocoa cultivation, food crop-driven forest loss, and total forest loss inside and outside forest reserves. Dark grey-filled boxes represent areas inside forest reserves; light grey-filled boxes represent areas outside forest reserves. Boxes show the interquartile range (IQR), with the horizontal line indicating the median; whiskers extend to $1.5 \times$ the

IQR, and dots represent outliers. **a** Proportion of total land area occupied by cocoa inside and outside forest reserves. **b** Proportion of total land area inside and outside reserves that experienced food crop-driven forest loss over the 2000–2019 period. **c** Proportion of total land area inside and outside reserves that experienced total forest loss over the 2022–2024 period. The y-axis shows the proportion of village land area affected, ranging from 0 to 1 (or 0–100%).

proxied by shade tree cover in cocoa farms, did not have a measurable protective effect on forest reserves between 2022 and 2024, likely due to low adoption among the sampled villages.

Among control variables, the Modified Taungya System (MTS) is positively associated with forest loss (Model 1: AME = 0.030, $p < 0.05$; Model 2: AME = 0.034, $p < 0.05$; Supplementary Table S2). This raises concerns that the programme may inadvertently facilitate rather than prevent degradation. Population density shows a positive association (Model 2: AME = 0.010, $p < 0.05$), while distance to district capital shows a negative association (Model 2: AME = -0.005 , $p < 0.05$), indicating that proximity to administrative centres increases forest pressure. Distance to roads and terrain ruggedness were not significant (Supplementary Table S2).

Qualitative evidence of food crop displacement into reserves

To contextualise our quantitative findings, we draw on qualitative evidence from village group meetings across 76 villages and semi-structured interviews with six sector-level key informants. These qualitative data support the hypothesis that cocoa expansion is displacing food crop production into forest reserves. Farmers consistently cited declining land availability, more fertile soils inside reserves, and weaker enforcement against food crop farming (compared with cocoa) as key drivers of encroachment.

As one farmer explained:

“There is no more land left for food crops. We, especially tenant [migrant] farmers, used all our land for cocoa. Those of us near the forest have no choice but to farm inside. After all, those who live by the sea eat by the sea. The forest is for all of us.”

A representative of a conservation NGO working in the cocoa sector echoed this view:

“Because suitable land in the High Forest Zone is increasingly scarce due to cocoa expansion and population growth, some farmers have encroached into forest reserves, primarily for food crops. These crops can be grown under the canopy, and over time, more trees are cleared.”

Farmers also stressed that food crops remain critical for household food security, even as cocoa constitutes their primary income source:

“Farmers are trying to make a living, and this is driving them to encroach into forest reserves to farm.”

These accounts are consistent with our field observations, where we observed plantain and cocoyam farms established within reserve boundaries, often beneath a partially thinned forest canopy. Such observations reinforce the conclusion that cocoa-driven land scarcity is displacing food crop cultivation into protected areas.

Discussion

This study advances understanding of how cocoa expansion and sustainability interventions affect deforestation in West Africa. While previous work has documented direct cocoa-driven deforestation, traceability, and mapped agroforestry presence^{5,25,59}, links between cocoa expansion and indirect land use change have been examined only once⁷, and no prior village-level analysis has assessed how agroforestry or sustainability programmes relate to forest outcomes.

This analysis provides quantitative evidence at the village scale that cocoa production outside forest reserves is associated with food crop-driven forest loss inside reserves. Although the analysis is correlational, consistent patterns across spatial data, farmer interviews, and field observations indicate that as farmers convert arable land to cocoa, food crops such as plantain, cocoyam, and yam are displaced into reserves^{18,19,60,61}. The government’s Modified Taungya System (MTS) further amplifies this dynamic. Despite its

Fig. 3 | Map of village-level exposure to companies' sustainability programmes. Village polygons are shaded according to the percentage of active cocoa-buying companies implementing sustainability programmes on a continuous scale from 0% to 100%. Villages with no exposure (0%) appear in bright yellow, transitioning through orange and pink/magenta to dark purple for villages with full exposure (100%). Forest reserves are shown in dark green. The inset map (top right) shows the location of the study area (indicated by a yellow square outline) within Ghana, the Upper Guinean Forest ecoregion (shown in pale green), and the African continent for broader geographic context. Ghana is highlighted in orange. Scale bar and north arrow indicate spatial orientation. All village boundaries are outlined in white for clarity.

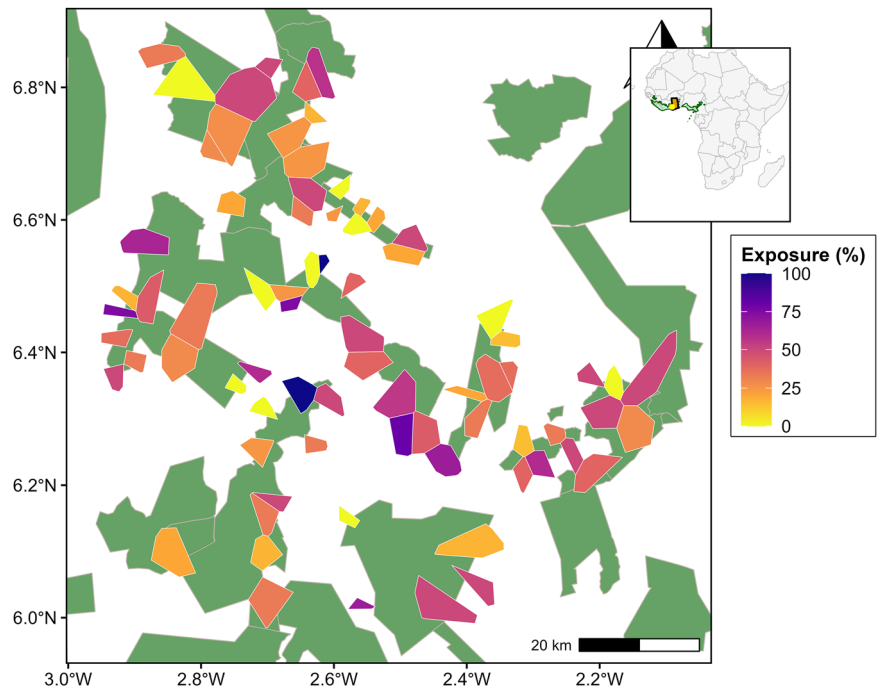


Table 1 | Beta regression results estimating the relationship between cocoa saturation outside forest reserves and food crop-driven forest loss inside forest reserves (2000–2019)

Variable	Coefficient (SE)	P-value
Dependent variable: proportion of land inside reserves with food crop-driven forest loss (2000–2019)		
Proportion of cocoa saturation outside reserves	2.77*** (1.06)	0.009
Population density (2010, per 1000)	−0.172 (0.113)	0.128
Terrain ruggedness Index inside reserves	−0.202* (0.110)	0.065
Distance from village to district capital (km)	−0.048** (0.021)	0.022
Distance from village to main road (km)	−0.006 (0.043)	0.893
Constant	−1.049 (0.904)	0.246
AME (proportion of off-reserve cocoa saturation)	0.654*** (0.250)	0.009
Observations	76	

Dependent variable is the proportion of land inside reserves with food crop-driven forest loss (2000–2019). Cocoa saturation is the proportion of land outside reserves under cocoa. Population density based on 2010 WorldPop estimates (Ghana census year), per 1000 persons/hectare. Beta coefficients are log-odds ratios; AME (Average Marginal Effect) shows the change in predicted forest loss due to food crop for a one-unit change in cocoa saturation, on the 0–1 scale. AME of 0.654 means that a 0.10 (10 pp) increase in cocoa saturation is associated with a ~6.5 pp increase in forest loss. Robust standard errors in parentheses. $N = 76$ villages. *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

restoration goals, villages participating in MTS experience higher forest loss, suggesting that the scheme may inadvertently legitimise farming within reserves. Given the critical role of food crops in household nutrition, income and rural livelihoods, especially during cocoa's off-season, this displacement highlights a troubling trade-off between conservation and food security^{17,62}.

In contrast, villages more exposed to zero-deforestation supply chain programmes show lower forest loss in reserves, even though these initiatives operate outside reserve boundaries. While selection bias remains a possibility, the pattern suggests that sustainability programmes may help curb forest loss across broader landscapes.

Finally, we find no association between agroforestry adoption and deforestation, leaving its landscape-level conservation benefits uncertain.

Implications for current policy effectiveness

The negative association between sustainability initiatives and deforestation in reserves suggests these programmes may offer some additionality in reducing cocoa-driven forest loss. In contrast, the positive relationship

between cocoa saturation and food crop-driven forest loss inside reserves (2000–2019) is consistent with displacement and may indicate policy leakage, though this cannot be confirmed without panel data. Nonetheless, the pattern aligns with displacement theory and is supported by farmer interviews and may reflect zero-deforestation policy leakage or broader structural pressures such as tenure insecurity, weak governance, poverty, and uneven enforcement and risk perception between cocoa and food crops^{7,11,18,60}. The Modified Taungya System (MTS) further complicates attribution. Moreover, most farmers were unaware of zero-deforestation criteria, reducing the likelihood that the observed displacement is directly driven by such policies.

Regardless of the underlying cause, this displacement highlights a major gap in current forest governance in cocoa landscapes such that policies focused solely on direct cocoa-driven deforestation, such as zero-deforestation commitments and the EU Deforestation Regulation, overlook indirect pressures, particularly food crop expansion into reserves. Without addressing land scarcity and food security in cocoa landscapes,

Table 2 | Beta regression results estimating the relationship between cocoa saturation outside forest reserves, percentage of cocoa shade cover, exposure to sustainability programmes and forest loss inside forest reserves (2022–2024)

Variable	Model 1 (without undisturbed forest in reserve)		Model 2 (with undisturbed forest in reserve)	
	Coefficient (SE)	p-value	Coefficient (SE)	p-value
Dependent variable Total forest loss (degradation and deforestation) in forest reserves 2022–2024				
Proportion of off-reserve cocoa saturation	2.158** (0.89)	0.010	2.06** (0.846)	0.015
Percentage of shade tree cover in cocoa area	0.055 (0.059)	0.349	0.037 (0.062)	0.552
Proportion of companies with SSI	−1.354* (0.693)	0.051	−1.403** (0.610)	0.022
Number of sourcing companies in village	−0.03 (0.071)	0.672	−0.034 (0.066)	0.605
Modified Taungya System (MTS)	0.431** (0.22)	0.049	0.488** (0.21)	0.020
Distance to district capital (km)	−0.054* (0.028)	0.052	−0.064** (0.027)	0.018
Population Density (2020, per 1000)	0.157* (0.081)	0.053	0.143** (0.072)	0.048
Distance to main road (km)	−0.011 (0.027)	0.689	−0.013 (0.028)	0.628
Terrain ruggedness Index inside reserves	0.044 (0.095)	0.641	0.011 (0.099)	0.911
Proportion of undisturbed forest in reserve (2021)			0.489 (0.401)	0.223
Constant	−4.391*** (1.473)	0.003	−3.955*** (1.523)	0.009
AME (proportion of off-reserve cocoa saturation)	0.151** (0.058)	0.010	0.144** (0.059)	0.015
AME (proportion of companies implementing sustainability programmes)	−0.094* (0.048)	0.051	−0.098** (0.043)	0.021
AME (Percentage of shade tree cover in cocoa area)	0.004 (0.004)	0.349	0.003 (0.004)	0.552
Observations	76		76	

Dependent variable: proportion of reserve land with total forest loss (2022–2024). Model 1 excludes baseline forest condition; Model 2 includes undisturbed forest (2021) as control. Cocoa saturation is the proportion of non-reserve land under cocoa. Population density from 2020 WorldPop (per 1000), coinciding with Ghana's decennial census. Beta coefficients represent log-odds ratios. AME (Average Marginal Effects) represent average changes in predicted forest loss for one-unit changes in predictors, on the 0–1 scale. Examples: cocoa AME = 0.144 means a 0.10 (10 percentage point) increase is associated with ~1.4 percentage point increase in forest loss. Robust SE in parentheses. $N = 76$. *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

these policies are unlikely to halt deforestation, undermining biodiversity, climate, and rural livelihood objectives.

Role of agroforestry adoption in reducing deforestation in forest reserves

Although cocoa agroforestry is widely promoted as a conservation strategy, we find no statistically significant association between shade tree cover in

cocoa farms and forest loss (Table 2). A likely explanation is that agroforestry adoption remains too limited, keeping shade levels below the threshold at which cocoa agroforestry can generate measurable conservation benefits at the landscape scale.

The median shade tree cover in cocoa farms in our study landscapes is only 14.7%, with limited variation (range 10.9–21.1%), which limits our ability to detect associations between shade tree cover and forest loss. More importantly, these levels fall far below thresholds identified elsewhere in Southeast Asia and Brazil^{35,63}. For instance, shade tree cover exceeding 30% in Southeast Asia landscapes has been associated with reduced deforestation, while approximately 65% shade was required to support biodiversity persistence in Brazilian cocoa systems^{35,63}. At current levels, shade tree cover in Ghanaian cocoa systems may therefore remain below the levels required to generate landscape-level conservation benefits. Indeed, previous studies indicate that full-sun cocoa systems continue to dominate across the country^{23,24}.

Several factors help explain the persistently low levels of agroforestry. First, tree tenure insecurity undermines farmer incentives. Under Ghanaian law, naturally occurring trees on farmland belong to the state, not the farmer⁶⁴. Village meetings during fieldwork revealed that the Forestry Commission of Ghana frequently grants harvest permits to external contractors who extract trees from farms, often damaging cocoa trees in the process. Farmers rationally respond by removing trees pre-emptively to avoid this risk, a perverse outcome that undermines both agroforestry and conservation goals. Second, farmers perceive shade-yield trade-offs that create immediate income costs³⁴, while long-term benefits (soil fertility, climate resilience) accrue slowly. Tenure-insecure migrant farmers heavily discount such delayed benefits. Third, sustainability programmes often promote timber species with long rotation periods and dense canopies that compete with cocoa, rather than farmer-preferred fruit trees offering food security and income diversification^{23,24}.

Our shade cover measure captures all trees in cocoa areas, not only those promoted by recent sustainability programmes. Because corporate agroforestry promotion intensified after the Cocoa & Forest Initiative (CFI) was launched in 2017, many newly planted trees may still be too young to be detected by satellite imagery. As a result, our 2022 cocoa shade cover data from Becker et al.²⁵ likely reflect legacy tree cover and natural regeneration rather than programme-induced adoption. The lack of detectable association may therefore also reflect the limited time that has elapsed for recent interventions to produce satellite-observable shade cover or landscape-level forest outcomes.

Where should policy approaches go next? Towards adaptive and integrative land system governance in cocoa landscapes

Land use dynamics in Ghana's cocoa-growing regions reflect a complex socio-ecological system in which cocoa provides not only income but also land tenure security and social status. As cocoa saturates land outside forest reserves, farmers increasingly shift food crop cultivation into reserves, a displacement pattern documented in this study and others^{7,17,19,47}. This pressure is reinforced by tenure systems that favour permanent tree crops and by cultural norms linking cocoa farming to prestige and long-term land access^{16,60}.

Addressing these interconnected pressures requires adaptive and integrative governance that links cocoa expansion, forest conservation, food security, and land tenure arrangements, particularly for migrant farmers. Adaptive governance emphasises flexibility, collaboration, and learning in response to changing local conditions, while integrative governance brings together conservation, agriculture, and rural development through participatory, landscape-level planning^{65,66}. Combined, these approaches better reflect local priorities and the trade-offs between forest protection, food security, and poverty reduction^{67,68}.

Practically, this means moving beyond fragmented, company-specific interventions toward coordinated, place-based efforts. One pathway is to strengthen the alignment of deforestation-free cocoa initiatives with Ghana's existing Hotspot Intervention Area (HIA) structures under the Cocoa

Forest REDD+ Programme. This would involve coordinated investments, shared monitoring responsibilities, and deeper engagement with local institutions. Pre-competitive collaboration among companies operating in the same landscape could also reduce duplication and strengthen support for agroforestry, forest monitoring, and community engagement. By embedding company-led initiatives within locally grounded governance structures, sustainability programmes can better integrate conservation, agricultural productivity, and rural development goals.

Improving governance also requires reforming current agroforestry approaches. Under existing conditions, agroforestry adoption is unlikely to curb displacement-driven deforestation because systemic barriers constrain uptake and prevent shade levels from reaching meaningful conservation thresholds. Key reforms include: (1) tree-tenure reform to grant farmers ownership of on-farm trees and remove incentives to clear vegetation pre-emptively; (2) farmer-centred tree species selection, drawing on evidence from Côte d'Ivoire, where farmers favour fruit-based systems⁶⁹, while balancing this with the need to avoid dense canopies that compete heavily with cocoa²⁷; (3) payment for ecosystem services or price premiums to offset establishment costs and perceived yield trade-offs; and (4) landscape-level integration that explicitly links farm-level agroforestry adoption to reserve protection strategies. Without such changes, cocoa agroforestry risks remaining a marginal practice with limited conservation impact.

Despite progress, cocoa deforestation policies continue to focus narrowly on avoiding direct cocoa-driven forest loss, often overlooking indirect drivers such as food-crop displacement^{7,22,70}. Forest governance also suffers from top-down approaches, overlapping land claims, and tensions between statutory and customary institutions, constraining effectiveness^{18,71}.

A more holistic model would strengthen tenure security, empower local institutions, and integrate food security into sustainability strategies. Adaptive, participatory governance offers a pathway to align local priorities with global conservation goals while supporting the long-term viability of cocoa-based livelihoods⁷². However, these landscape-level efforts must be matched by broader reforms in demand-side policies and global trade systems⁷³. Cocoa-driven land-use lock-ins shaped by pricing structures, market volatility, and international sustainability requirements limit farmer and community options^{7,74}. Addressing these structural pressures is essential for more equitable and environmentally sustainable land use transitions across the cocoa sector.

Limitations

This study provides insights into how cocoa saturation outside forest reserves relates to forest loss inside reserves, but with limitations. First, reliance on satellite data limited our ability to classify forest loss drivers after 2019, requiring a shift from food crop-specific outcomes (2000–2019) to total forest loss (2022–2024). For the earlier period, the use of residual forest loss as a proxy means we could not fully separate food crop cultivation from logging, though prior studies suggest food crops are the dominant driver of reserve deforestation^{7,14}, reinforcing our interpretation. Other activities, such as small-scale mining and settlements, may have expanded in recent years^{75,76}, yet remote sensing evidence indicates these remain relatively minor contributors compared with agriculture, particularly cocoa and food crops, especially in forest reserves⁴⁷.

Second, our cross-sectional design establishes associations but cannot prove causation. While multiple evidence sources support displacement, unobserved village characteristics could confound results. Future research could strengthen causal inference through panel data, spatial econometrics, quasi-experimental designs, or in-depth case studies tracing decision-making processes.

Third, our measure of sustainability programme exposure reflects original village-level survey data, which provides systematic estimates of programme coverage across cocoa villages, but it does not capture variation in programme type, implementation intensity, or farmer participation.

Fourth, our analysis of the 2000–2019 period as a single time period does not capture potential temporal variation in displacement dynamics.

Future research with annual time-series data on cocoa expansion could examine whether the strength of displacement effects changes.

Despite these limitations, the consistent associations observed across periods, together with triangulation from interviews and field observations, strengthen confidence in our main conclusion that cocoa expansion outside reserves contributes to land competition that displaces food crop production into forest reserves.

Conclusion

Our study provides quantitative evidence that cocoa expansion outside forest reserves is associated with food crop-related forest loss inside forest reserves at the village level in Ghana. Field observations and interviews confirm that land scarcity, along with weak enforcement, drives farmers to grow food crops in protected areas. We also find that exposure to cocoa-related sustainability programmes is associated with less forest loss, whereas the state-led Modified Taungya System, intended for restoration, is instead correlated with higher loss. These findings illustrate how market forces and public policies can unintentionally accelerate deforestation and forest degradation, highlighting the importance of integrated land-use governance that balances cocoa production, food security, and forest conservation.

Methods and data

Study design, site and sampling

We employ a mixed-methods approach that integrates econometric analysis of remotely sensed data with village-level surveys and qualitative insights from cocoa farmers and expert interviews in this study. This integrated approach provides a more comprehensive understanding of food crop displacement and land-use decisions than studies relying solely on either remote sensing or qualitative methods^{7,17,18,77,78}.

The study was conducted in Ghana's High Forest Zone, the country's primary cocoa-producing region. To define village boundaries in the absence of official administrative boundaries, we first identified all villages within 10 km of forest reserves across eight districts in the Western North, Ashanti, and Ahafo regions, using official village points from the Forestry Commission of Ghana, cross-validated them against OpenStreetMap, and visually inspected them using Google Satellite imagery. We used Thiessen (Voronoi) polygons constructed around village point locations to generate spatially explicit village boundaries, a method commonly used in regions without official boundaries^{79–82}. Including all villages within the 10 km buffer was necessary to ensure correct polygon geometry based on proximity to neighbouring settlements (see Supplementary Fig. S1).

We retained only villages with portions of their boundaries both inside and outside forest reserves, as these are the villages most relevant for analysing the relationship between land-use dynamics outside reserves and forest outcomes inside reserves. This yielded a sample frame of 298, all located within the Cocoa & Forests Initiative (CFI) priority landscapes, specifically, the REDD+ Hotspot Intervention Areas designated by Ghana's Forestry Commission and adjacent to forest reserves with similar deforestation trends.

This study analyses 76 villages out of the 298 that were selected as part of a broader research project using systematic random sampling: specifically, every second village from an ordered list of all villages within 2–3 km of forest reserve boundaries. The first author conducted extensive fieldwork in these 76 villages during June–September 2022, including village-level data collection and qualitative interviews. The villages are geographically distributed across all eight districts and lie adjacent to 14 different forest reserves (see Fig. 1 above).

To assess the representativeness of this sample, we conducted balance tests comparing key variables between the 76 surveyed villages and the full 298-village population. The results show no significant differences in mean cocoa saturation outside reserves (76% vs 75%, t -test $p = 0.645$), cocoa shade cover (15% vs 14%, $p = 0.439$), or distributions of these variables (Kolmogorov–Smirnov tests $p > 0.05$; see Supplementary Table S4). The surveyed villages show slightly higher food crop coverage inside reserves (8% vs 5%, $p = 0.030$), which, if anything, makes them more relevant for

studying food crop displacement dynamics. These tests confirm that the 76 villages are representative of the broader population of reserve-adjacent villages in our study area.

The analysis is conducted at the village scale, defined by Thiessen polygons that include areas both inside and outside reserves. For brevity, we refer to land-use dynamics within such village polygons as being ‘nearby’ or ‘local’.

Our study covers two periods: 2000–2019 and 2022–2024, with the intervening years (2020–2021) excluded to preserve temporal ordering between predictor measurement and outcome assessment. The longer period (2000–2019) allows us to assess long-term patterns of food crop-driven forest loss by disentangling it from forest loss linked to other land uses, using reliable remotely sensed data available only up to 2019.

The shorter period (2022–2024) reflects more recent dynamics, including the implementation of sustainability programmes and agroforestry interventions, for which reliable data are only available from 2019 onward. Importantly, this period is measured 3–5 years after the cocoa saturation patterns captured in our predictor variable derived from the Kalischek et al.⁵ cocoa land-use dataset, which captures cocoa plantations present between 2018–2021 and reflects established farms planted no later than 2019 (due to the time lag required for newly planted cocoa trees to become detectable in satellite imagery). This temporal lag aligns with the agronomic timeline of cocoa-food crop displacement. During the first 3–4 years after cocoa planting, farmers typically intercrop food crops (plantain, cocoyam) with young cocoa trees, as is common practice in Ghana^{83,84}. However, once cocoa matures, intercropping becomes unviable, and farmers must seek alternative land for food production. The 2022–2024 window, therefore, captures the period when displacement pressure from mature cocoa farms is expected to peak, while maintaining a clear temporal separation between predictor measurement (cocoa saturation circa 2019) and outcome assessment (forest loss 2022–2024). This design choice avoids simultaneity bias that would arise from measuring forest loss during the same period in which our cocoa predictor variable is being classified (2018–2021).

For the recent period, there are no reliable datasets allowing us to disentangle estimates of land use-specific causes of deforestation; hence we assess impacts on total forest loss (deforestation and degradation) inside reserves, rather than land use-specific deforestation patterns, though noting that a large share of this forest loss is likely due to food crops or combinations of food crops and logging.

Data

Remote sensing data and land-use attributions. We utilised a diverse set of remotely sensed datasets to measure forest loss, land-use, and village characteristics.

Using the village boundaries constructed in section 6.1 above, various spatial attributes were extracted for the portions of each village located both inside and outside forest reserves. We sourced cocoa area data from a 10 m resolution land use map covering Ghana and Côte d’Ivoire⁵. This dataset captures cocoa plantations present between 2018 and 2021 and was identified as one of the most reliable and accurate cocoa datasets in a recent evaluation study by the World Cocoa Foundation and CIAT⁸⁵. As recently planted cocoa trees are often not detectable in satellite imagery, we assumed the map reflects established cocoa farms planted no later than 2019. Using this map, we calculated the proportion of non-reserve land in each village catchment that was classified as cocoa. We refer to this measure as cocoa saturation throughout the paper, operationally defined as: Cocoa Saturation = (Area of cocoa plantations outside reserves)/(Total land area outside reserves within village polygon). This variable ranges from 0 (no cocoa present) to 1 (all non-reserve land is cocoa), with higher values indicating greater land-use pressure from cocoa expansion. It serves as a village-level indicator of long-term cocoa land accumulation and potential competition for agricultural land outside protected areas.

Due to the lack of reliable satellite data on food crop production in Ghana’s High Forest Zone, particularly in forest reserves, we followed the

steps outlined in ref. 7 to assess forest loss associated with food crops. To attribute forest loss to single drivers, we overlaid various remote-sensing maps of direct land uses with a map of Tropical Moist Forest (TMF) created by the European Commission’s Joint Research Centre, which provides annual data from 1990 to 2024 on undisturbed tropical moist forest and its changes at a 30 m resolution⁸⁶, and the Thiessen polygon village boundaries (both in and out of forest reserves). The TMF map was filtered to retain patches >1 ha with a canopy height greater than 8 m, defining them as ‘forest’ in 2000, based on⁸⁷.

We overlaid the following maps with the TMF map: (i) a cocoa land use map for the years 2018–2021 at a 10 m resolution⁵; (ii) a global tree plantations map for 2019–2020⁸⁶, which includes rubber, and oil palm data for 2019 at a 10 m resolution⁸⁸, as well as a global closed-canopy coconut map for 2020 at a 20 m resolution⁸⁹; (iii) a global mining land use map for 2019, produced at a 10 m resolution, which encompasses large-scale, artisanal, and small-scale mining activities and all associated ground features, such as open cuts, tailing dams, waste rock dumps, water ponds, and processing infrastructure⁹⁰; (iv) a global settlement footprint map for the years 2000 (at a 30 m resolution) and 2019 (at a 10 m resolution)⁹¹.

Using the year 2000 as a baseline, we estimated forest loss (degradation and deforestation) for each land use based on remotely sensed data, defining forest loss as the conversion from undisturbed tropical moist forest (TMF) to other land uses between 2000 and 2024. Forest loss matched to any of the classified post-clearing land uses above was attributed accordingly. Areas identified as forest loss in the TMF dataset without a clearly classified post-clearing land use were categorised as “residual forest loss”. In Ghana’s cocoa belt, such residual loss is primarily attributed to food crop cultivation, followed by logging, both of which are not directly captured in existing satellite land use classifications⁷. Visual inspection of global and continental crop-land maps^{4,87,92}, confirmed their limited reliability at the local scale, especially within protected areas of Ghana’s High Forest Zone⁷. Though acknowledging the entanglement of food crop and logging deforestation dynamics, previous studies found that food crop cultivation appears to be the dominant driver of forest loss in forest reserves of the cocoa-growing region of Ghana^{7,14}, a conclusion which we corroborated with our own fieldwork observations. Hence, we consider that this residual forest loss primarily reflects food crop expansion and refer to it as “food crop forest loss” throughout the paper.

For the period 2022–2024, we defined forest loss using the JRC TMF dataset as the sum of: (i) direct deforestation, (ii) deforestation that followed prior degradation, and (iii) degradation events that did not result in full clearing.

To estimate agroforestry adoption in each village, we used 10 × 10 m pixel-level estimates of shade-tree cover within cocoa growing areas in Ghana and Côte d’Ivoire, derived from²⁵. The dataset provides high-resolution, spatially explicit estimates of shade-tree cover for 2022 and is based on the cocoa map developed by ref. 5. As such, it specifically reflects shade-tree cover within cocoa production zones. To derive village-level estimates, we calculated the mean shade cover across all pixels within each village polygon, resulting in the percentage of cocoa shade tree cover used in our analysis.

To account for biophysical constraints on land use, we included a measure of terrain ‘ruggedness’, as rugged areas may be less accessible or less suitable for cultivation and therefore less likely to be deforested. We constructed a terrain ruggedness index (TRI) for each village, both inside and outside forest reserves, using NASA SRTM Digital Elevation (30 m resolution)⁹³. The TRI was calculated using the *terrain* function in the *terra* package in R, which computes the mean elevation difference between each grid cell and its neighbours to capture variations in terrain ruggedness⁹⁴. As a proxy for market access and urbanisation, we constructed two variables: distance to road and distance to the nearest district capital town. These two metrics reflect how remote or connected a village is, which can influence land use decisions and the strength of enforcement. Road network data came from a global vector dataset^{95,96} and was used to calculate each village’s distance to the nearest road. Distance was calculated as the Euclidean

distance from each village centroid to the nearest town with administrative or economic significance.

To account for population pressure, we used the WorldPop Unconstrained 2010 and 2020 UN-adjusted dataset (100 m resolution) for Ghana⁹⁷ due to the lack of official village-level census data. This dataset estimates population distribution using national census data and a random forest-based dasymetric method, adjusted to United Nations Population Division estimates^{97,98}. We then divided the total population estimates by the total size of the village polygon to obtain the population density per hectare.

Village-level surveys and qualitative data. We conducted village-level group meetings in all 76 sampled villages during fieldwork in June–September 2022. Each meeting brought together participants, including cocoa-buying clerks (purchasing clerks representing cocoa companies operating in the village), village leaders (chiefs, assembly members, unit committee members, village savings and loans association leaders), and, where available, Ghana Cocoa Board (COCOBOD, the state cocoa regulatory institution) extension officers. The number of participants varied from one village to another, depending, for example, on the presence and number of cocoa-buying agents in the village, as well as on village leaders and other key people.

These meetings served two purposes. First, we administered structured questions to systematically document: (a) all cocoa-buying companies active in the village during the 5 years before 2022, (b) which of these companies implemented sustainability programmes, defined as interventions related to agroforestry promotion, forest protection, livelihood support, or productivity enhancement, and (c) whether the village participated in the government's Modified Taungya System. To validate company presence and programme implementation, we triangulated reports from village participants with informal interviews with district-level company staff and publicly available company documents.

From this information, we constructed a village-level exposure variable defined as the proportion of active cocoa-buying companies in each village that implement sustainability programmes. For example, if four companies operate in a village but only two implement programmes, exposure is 0.5 (50%). Figure 3 shows the spatial distribution of village-level exposure to sustainability initiatives across the study area. Exposure varies widely, from villages where no active cocoa-buying companies implemented programmes to those where all active companies did. This heterogeneity underpins our analysis of whether programme exposure is associated with reduced forest loss inside reserves.

This variable serves as a proxy for the likelihood that a typical farmer in the village is exposed to sustainability interventions. Because no systematic dataset on programme coverage exists in Ghana, these village-level survey data provide comprehensive estimates of sustainability exposure across cocoa villages in the study region.

Second, following the structured questions, meetings transitioned to open-ended group discussions on broader issues, including local livelihood challenges, land-use decision-making, experiences with land scarcity, food crop cultivation practices, motivations for farming in or near forest reserves, deforestation dynamics, forest protection efforts, and perceptions of cocoa companies' deforestation policies. Participants were encouraged to share experiences and perspectives on how cocoa expansion affects land availability for food crops and whether this influences farming practices in forest reserves. These qualitative discussions provided valuable insights into the mechanisms linking cocoa saturation to food crop displacement, which complement and help interpret our quantitative spatial analysis. The quotes presented in “Where should policy approaches go next? Towards adaptive and integrative land system governance in cocoa landscapes” are drawn from these village-level discussions.

Key informant interviews. In addition to village-level data collection, we conducted semi-structured key informant interviews ($N = 6$) virtually in 2024, including government officials, research scientists, and NGO representatives working in Ghana's cocoa and forest sectors. These

interviews were designed to explore sector-level perspectives on the relationship between cocoa expansion and food crop deforestation in forest reserves, focusing on the push-and-pull factors driving displacement dynamics. Key informants were selected based on their expertise and direct involvement in forest conservation, cocoa sustainability programmes, or land-use policy in Ghana's cocoa-growing regions. Interview topics included drivers of encroachment into forest reserves, the role of cocoa expansion in creating land scarcity, the effectiveness of current conservation policies, and observed patterns of food crop displacement. These interviews provided expert contextualization that informed our interpretation of the quantitative spatial analysis and village-level findings.

Empirical approach

To investigate the relationship between cocoa saturation, sustainability interventions, and forest loss within forest reserves, we model cocoa saturation outside reserves and forest loss inside reserves (food crop forest loss for 2000–2019 and total forest loss for 2022–2024), each expressed as a proportion of village land, enabling consistent comparisons across villages. This allows us to consistently compare land use intensity across villages, distinguishing between areas inside and outside forest reserves. Our main predictors are: (i) cocoa saturation and agroforestry coverage outside reserves, and the exposure to sustainability programmes (measured as the proportion of active cocoa-buying companies in each village implementing sustainability initiatives as explained above), while the outcome variables are: (i) food crop–driven forest loss within reserves (2000–2019), and (ii) total forest loss (i.e., deforestation and degradation) within reserves (2022–2024).

Because the dependent variables are continuous proportions bounded between 0 and 1, we employ beta regression models with a logit link function^{99,100} in Stata. This approach accounts for heteroskedasticity and models the log-odds of proportional outcomes on an unbounded scale.

We specify the models as follows:

- For the 2000–2019 period:

$$\text{logit}(y_i) = \beta_0 + \beta_1 \text{Cocoa}_i + X_i\beta_2 + \epsilon_i$$

- For the 2022–2024 period:

$$\text{logit}(y_i) = \beta_0 + \beta_1 \text{Cocoa}_i + \beta_2 \text{Agroforestry}_i + \beta_3 \text{SSI}_i + X_i\beta_4 + \epsilon_i$$

Where:

- y_i : Proportion of forest loss (food crop–related in 2000–2019; total loss in 2022–2024) within the reserve area of village i .
- Cocoa_i : Proportion of off-reserve land under cocoa cultivation.
- Agroforestry_i : Percentage of off-reserve cocoa area under shade tree cover (2022–2024 only).
- SSI_i : Exposure to cocoa-focused sustainability programmes (2022–2024 only).
- X_i : Vector of control variables.
- ϵ_i : Error term.

The beta regression yield log odd ratios. To facilitate interpretation, we compute Average Marginal Effects (AMEs) for the key variables. AMEs represent the average change in predicted outcomes for a small change in each predictor, averaged across all observation¹⁰¹.

We weighted the beta regression models by the size of each village's area within reserves, as larger in-reserve areas represent a greater potential for deforestation and are therefore more informative for estimating the relationship between land-use drivers and forest loss.

We control for a set of covariates that may confound the relationship between the predictors and forest outcomes. These include terrain ruggedness (as a proxy for land suitability), proximity to roads and district capitals (proxies for market access and remoteness), and population density.

For the period 2022–2024, we estimated two beta regression models to examine total forest loss within reserves. Both models include cocoa saturation outside reserves, shade tree cover in cocoa areas, and village-level exposure to sustainability programmes, along with controls for sourcing company presence, participation in the Modified Taungya System (MTS), proximity to roads, distance to the district capital, population density, and terrain ruggedness. Model 1 estimates total forest loss without controlling for baseline forest condition, while Model 2 includes the proportion of undisturbed forest area inside reserves in 2021 to test the robustness of our results to initial pre-existing forest condition.

We control for baseline forest condition because the extent of forest influences the likelihood of subsequent forest loss. Areas with more forest remaining may be more likely to experience encroachment because there is still forest available to clear, especially where enforcement is weak. Including these baseline conditions helps isolate the association between cocoa saturation and forest disturbance, ensuring that observed effects are not simply due to greater availability of forest to lose.

The inclusion of additional predictors, namely shade-tree cover in cocoa farms and exposure to sustainability programmes, reflects evolving land-use dynamics and policy interventions. These variables were only included in the 2022–2024 period because reliable data on shade-tree cover in cocoa farms and sustainability programme implementation were only available from 2019 onwards. Finally, a Moran's I statistic in R was used to assess spatial autocorrelation of the outcome variable to check for spatial dependence (Supplementary table S3).

Ethics statement

Ethics approval was obtained from the ETH Zürich Ethics Commission, Switzerland (approval no. EK 2021-N-166). Informed consent was obtained from all participants.

Reporting summary

Further information on research design is available in the Nature Portfolio Reporting Summary linked to this article.

Data availability

Data to reproduce all analyses and figures are available on Figshare at <https://doi.org/10.6084/m9.figshare.30153256>. The dataset includes village-level aggregated data ($N = 76$) with anonymised village identifiers. Secondary spatial datasets used in this analysis are publicly available from cited sources: Kalischek et al. (2023) for cocoa plantation maps, the European Commission JRC Tropical Moist Forest dataset for forest loss, and Becker et al. (2025) for shade tree cover data. Due to ethical constraints regarding village identifiability, specific village coordinates are not provided; however, all aggregated village-level data necessary to reproduce the statistical analyses and figures are included in the Figshare repository.

Code availability

Stata do-files for statistical analysis, R scripts used to run the analysis and generate figures, and Google Earth Engine scripts for remote sensing data processing are available on Figshare at <https://doi.org/10.6084/m9.figshare.30153256>.

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Competing interests

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