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Transparency, traceability and deforestation in the Ivorian cocoa supply chain

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Abstract

Cocoa production has been identified as a major global driver of deforestation, but its precise contribution to deforestation dynamics in West Africa remains unclear. It is also unknown to what degree companies and international markets are able to trace their cocoa imports, and satisfy their sustainable sourcing commitments. Here, we use publicly-available remote-sensing and supply chain data for Côte d'Ivoire, the world's largest cocoa producer, to quantify cocoa-driven deforestation and trace 2019 cocoa exports and the associated deforestation from their department of origin, via trading companies, to international markets. We find 2.4 Mha of cocoa deforestation and degradation over 2000–2019, i.e. 125 000 ha y^{-1}, representing 45% of the total deforestation and forest degradation over that period. Only 43.6% (95% CI: 42.6%–44.7%) of exports can be traced back to a specific cooperative and department. The majority of cocoa (over 55%) thus remains untraced, either indirectly sourced from local intermediaries by major traders (23.9%, 95% CI: 22.9%–24.9%), or exported by untransparent traders—who disclose no information about their suppliers (32.4%). Traceability to farm lags further behind, and is insufficient to meet the EU due-diligence legislation's proposed requirement for geolocation of product origins. We estimate that trading companies in the Cocoa and Forests Initiative have mapped 40% of the total farms supplying them, representing only 22% of all Ivorian cocoa exports in 2019. We identify 838 000 hectares of deforestation over 2000–2015 associated with 2019 EU imports, 56% of this arising through untraced sourcing. We discuss issues of company- and state-led traceability systems, often presented as solutions to deforestation, and stress the need for transparency and for the sector to work beyond individual supply chains, at landscape-level, calling for collaboration, stronger regulatory policies, and investments to preserve the remaining stretches of forests in West Africa.

1. Introduction

International trade of agricultural products drives land use change and deforestation in distant regions across the planet, with large sustainability impacts including carbon emissions and biodiversity loss (Pendrill *et al* 2019). Supply chains are often opaque, little is known about the origin of the products, and even less about the sustainability risks associated with their production (Gardner *et al* 2019).

Global sales of chocolate-based confectionery products were estimated at 110 billion USD in 2019, up 33% from 2008/09 (BASIC and FAO 2020). Côte d'Ivoire is the world's largest producer of cocoa, with about one million smallholder farmers producing annually over 2 M tonnes of cocoa beans—40% of the world's cocoa harvest (FAO 2020). This trade is worth more than $4.7 billion in freight-on-board value per year, over one-third of Côte d'Ivoire's entire export revenue (OEC 2020).

Yet, the crucial importance of cocoa in the Ivorian economy comes at a cost: Côte d'Ivoire lost 80% of its forest cover over the past 60 years (IFFN 2021). Cocoa has been flagged as a major commodity driving deforestation (Goldman *et al* 2020b, Pendrill *et al* 2022a), but its precise contribution to deforestation in Côte d'Ivoire remains unclear. Pan-tropical studies provide coarse estimates of cocoa-driven deforestation, attributing tree cover loss to cocoa using national-level agricultural statistics (Pendrill *et al* 2019) or coarse land use data (Goldman *et al* 2020b). Within Côte d'Ivoire, studies are limited to specific regions (Brou *et al* 2005, Barima *et al* 2016, Andrieu *et al* 2018, Ongolo *et al* 2018, Carin *et al* 2019, Kouassi *et al* 2021, Ouattara *et al* 2021) or do not disentangle the specific role of cocoa in national deforestation (BNETD, FAO and SEP REDD+ CI 2017).

In response to civil society pressure, chocolate companies have made a series of zero deforestation commitments and investments in traceability, seeking to identify the origin of the cocoa they buy. The cocoa and forest initiative (CFI), in particular, is a public-private partnership launched in 2017 by a consortium of 35 chocolate and cocoa companies together with the governments of Ghana and Côte d'Ivoire, aiming to contribute to ending deforestation and forest degradation in the cocoa supply chain (CFI 2021). The urgency behind efforts to trace cocoa 'from bean to bar' has been further increased by the European Commission's proposed due-diligence legislation, requiring companies importing deforestation-risk products (such as cocoa or chocolate) to demonstrate that imports do not originate from recently deforested nor degraded land (EC 2021).

The information that companies have (i.e. their supply chain 'traceability') and disclose about their cocoa supply chains (i.e. their supply chain 'transparency') is, however, disparate and it is challenging to assess where companies source their cocoa from, let alone monitor progress in implementing sustainable sourcing initiatives (Dontenville *et al* 2022). Here, as part of the Transparency for Sustainable Economies (Trase) initiative (www.trase.earth), we address this gap, pulling together several publicly-available datasets for Côte d'Ivoire's 2019 land use and cocoa exports, to link cocoa production, and its associated deforestation, to specific companies and markets.

Farmers sell their cocoa to cooperatives, or to middlemen—'pisteurs'—who sell on to larger-scale local buyers—'acheteurs', also called 'traitants'—many of whom work unlicensed. Traders can buy 'directly' from cooperatives and licensed buyers ('acheteurs agréés'), or 'indirectly' from other local intermediaries, before exporting to various countries (Nitidae and EFI 2021). What the sector calls 'direct sourcing' is thus traceable to the first buyer, cooperatives in most cases, but not necessarily to farm. To map the supply chain, we make a distinction between three sourcing types: (a) the cocoa that is traced to known farmer cooperatives or licenced buyers, which were disclosed by traders (called 'direct' sourcing by actors in the cocoa sector), (b) cocoa which is indirectly sourced by those trading companies from other intermediaries, and is thus nearly impossible to trace under current traceability systems, and (c) cocoa which is 'unknown', i.e. exported by 'untransparent' traders, who disclose no information about their supply chain (figure 1).

Specifically, we tackle three research questions:

(a) What is the state of traceability and transparency in the Ivorian cocoa supply chain?
(b) What is the role of cocoa in recent deforestation in Côte d'Ivoire?
(c) How is deforestation exposure distributed among actors (i.e. traders and importing countries)?

2. Methods

We used the Spatially Explicit Information on Production to Consumption Systems (SEI-PCS) approach to link exports of agricultural commodities back to the jurisdiction of production (Godar *et al* 2016). We followed five steps (detailed in SI text S1): we first calculated total exports per trader and imports per importing countries. Second, we identified the intermediaries (cooperatives and 'acheteurs agréés') from which traders source from, and their location. Third, we estimated the volumes sourced from these intermediaries by the different traders, providing a map of the subnational origin of the cocoa traced to cooperatives. Fourth, we estimated the cocoa production per department, allowing to geographically distribute the cocoa indirectly sourced. Finally, we used remote sensing-based cocoa and deforestation maps to estimate deforestation due to cocoa (further: 'cocoa deforestation') across the country and link cocoa supplies with deforestation exposure.

2.1. Mapping cocoa sourcing

We calculated the volume of cocoa exported by distinct traders and imported by distinct countries using data on export shipments from 2019 (SI table S1). As no information is publicly-available on the location of farms supplying each trader, we map the supply chain up to the first buyer, and not to the farm. For traders that are transparent about their 'direct' suppliers, we identified the list of cooperatives

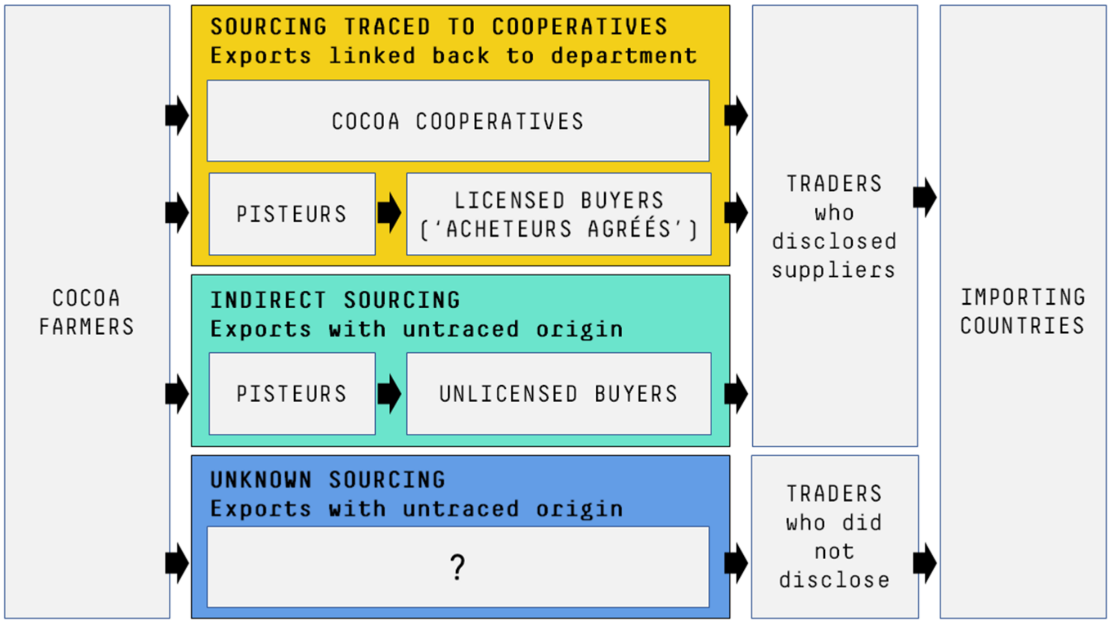

Figure 1. Schematic of the cocoa supply chain in Côte d'Ivoire with *Sourcing traced to cooperatives* in yellow, i.e. exports linked back to disclosed cooperatives, also including the small volumes sourced from known licensed buyers; *indirect sourcing* in green, i.e. exports that could not be linked back to cooperatives or buyers (purchased through unlicensed buyers) for traders who disclosed their suppliers; *unknown sourcing* in blue, i.e. exports of untransparent traders who did not disclose their suppliers.

from which they source from, and the department in which they are located, using Mighty Earth's 'Cocoa Accountability Map'. This map includes information on 4451 cooperatives and lists, for 710 of them, companies that are known to source from them (SI figure S2(A), table S2). The latter comes from self-disclosures in 2019 and 2020 by major cocoa traders and processing companies. A smaller volume is purchased from 'acheteurs agréés'; buyers licensed to source cocoa from specific departments (SI table S3). Their supply comes from an approximate known origin, much like a cooperative. When reporting the results, they are included under the term '**sourcing traced to cooperatives**'.

The volumes sourced by companies from individual cooperatives are estimated from the number of farmers per cooperative (provided for 592 cooperatives, SI figure S2(B)), and production volumes per farmer. For the remaining 119 cooperatives with a known trading company but no number of farmers provided, we simulated this number using 1000 Monte Carlo estimates (random sampling with replacement) drawn from the set of disclosed cooperative sizes. Next, we used recent production data (kg of dry beans/farmer/year) collected from 441 farms across the country (Bymolt *et al* 2018) (SI figure S3). We assigned a production volume to each cooperative-company connection using 1000 Monte Carlo estimates of this dataset, keeping the confidence interval. This calculation assumes that traders purchase the entirety of the cocoa of each of their supplier farmers (rather than each farmer selling to multiple traders), which provides an upper-bound estimate of the volumes traced to cooperatives. The latter are assigned to the department where the cooperative is located—thus assuming that the cocoa sourced by a distinct cooperative mainly comes from the department where it is registered.

We then estimated each trader's proportion of **indirect sourcing** by subtracting the volume traced to cooperatives from the total exported volume. This provides an estimate of the level of traceability for those traders that disclosed their sourcing. For untransparent trading companies that did not disclose any information on their sourcing (43 companies of 73 in total), the total exported volumes are marked as '**unknown sourcing**'. This provides an estimate of the level of transparency in the sector.

As an additional analysis, we compiled the number of mapped farms reported in CFI signatories' 2018–2020 progress reports and estimated the total number of farms that these companies are sourcing from based on their traded volume in 2019 (SI text S1.5, table S4).

2.2. Quantifying the role of cocoa in recent deforestation

To calculate cocoa deforestation, we overlaid a remote-sensing cocoa land use map for the years 2019–2021 at 10 m resolution (Kalischek *et al* 2022) (hereafter, the '2019 cocoa map') with a map of Tropical Moist Forest (TMF) produced by European Commission's Joint Research Centre (JRC), depicting annually from 1990 to 2020 the extent of undisturbed tropical moist forest and its changes at 30 m resolution (Vancutsem *et al* 2021) (SI figure S5).

We created a map of the land-use dynamics over the last 20 years including deforestation and degradation, their association with cocoa expansion, and the remaining undisturbed and degraded TMF cover. A degraded forest is defined by the JRC TMF dataset as a forest that has been temporarily disturbed (<2.5 years), which can include regrowth, but excludes tree plantations (SI text S1.6.1). Here, 'deforestation' corresponds to pixels that switched from undisturbed TMF to another land cover between 2000 and 2019, and 'degradation' to pixels that switched from undisturbed to degraded TMF. From those, pixels detected as cocoa were classified as 'cocoa deforestation' and 'cocoa degradation', the latter also including cocoa pixels detected as undisturbed forest by the TMF map in 2019 (0.3 Mha). Cocoa degradation could be forest converted to cocoa but with a relatively dense remaining shade canopy cover, or shaded cocoa plantations that were too recently established to be classified as deforestation (requiring 2.5 years of detected disturbance).

We tested the sensitivity of our findings to different remote sensing products by repeating our analyses using two other published cocoa maps (Vivid Economics 2019, Abu *et al* 2021) and two other deforestation datasets (Hansen *et al* 2013, BNETD, FAO and SEP REDD+ CI 2017). We used primarily the cocoa map and JRC-TMF maps because of their superior accuracy (SI table S5) and publicly-available methodologies.

2.3. Linking cocoa deforestation to sourcing

To link to the 2019 trade flows, we calculated the 'cocoa deforestation' as the area that lost its undisturbed TMF between 2000 and 2015 and is detected as cocoa in 2019. Thus, here, cocoa degradation and deforestation are merged into 'cocoa deforestation'. Cocoa trees need three to five years to become fully productive, so deforestation events after 2015 are not expected to have contributed to the 2019 cocoa harvest.

To link cocoa sourcing to cocoa deforestation, we calculated the relative cocoa deforestation per department, by dividing the annualised cocoa deforestation area by the 2019 cocoa production per department, to obtain annual hectares deforested per tonne of cocoa produced. In the absence of official publicly available data on subnational cocoa production in Côte d'Ivoire, we generated a map of cocoa production per department by weighting the 2019 cocoa map by a map representing the suitability to grow cocoa per pixel (Schroth *et al* 2016) (SI figure S6). We then allocated the national cocoa production (ICCO 2021) to each department according to their weighted cocoa area.

We calculated the 'cocoa deforestation exposure' of each trader or importing country, which provides a measure of the exposure of actors to cocoa deforestation based on their sourcing patterns. We multiplied the relative cocoa deforestation by the volume traced to cooperatives of each actor, per department, to obtain the cocoa deforestation exposure linked to their traced sourcing. We also calculated actors' annual relative cocoa deforestation exposure (i.e. number of hectares deforested per tonne of cocoa traced to cooperatives, divided by 15 years). The relative cocoa deforestation for untraced cocoa was estimated as an average of the relative cocoa deforestation per department, weighted by the proportion of total untraced volume supplied by each department. We multiplied this value by actors' untraced (unknown or indirectly-sourced) volumes to calculate each actor's exposure to cocoa deforestation linked to their untraced sourcing.

3. Results and discussion

3.1. What is the state of traceability and transparency in cocoa sourcing?

We trace 43.6% (95% CI: 42.6%–44.7%) of Côte d'Ivoire's exports back to a specific cooperative and department, i.e. 875 468 tonnes (95% CI: 855 360–896 993 tonnes) of 2006 406 tonnes exported in total in 2019. The majority of cocoa (over 55%) is thus untraced, either indirectly sourced from local intermediaries by major traders (23.9%, 95% CI: 22.9%–24.9%), or exported by untransparent traders (32.4%), i.e. 'unknown' sourcing (figure 2). Untraced sourcing dominates in the North–East and along the western border of the cocoa producing region of Côte d'Ivoire (80%–100% untraced sourcing) (SI figure S7).

In 2019, eight companies (Cargill, Barry Callebaut, Olam, Touton, Sucden, S3C, ECOM, and Africa Sourcing) handled 60% of exports (SI figures S8 and S9). The share of indirect sourcing among traders varied between 25% (95% CI: 10.4%–34.4%) (ECOM) and over 70% (95% CI: 66.4%–75.1%) (Sucden), posing strong traceability challenges. There are also gaps in transparency. A third of the cacao was exported by untransparent traders, among which S3C and Africa Sourcing, as well as many of the smaller companies, who disclose no information about their suppliers. Even traders who did disclose their supplying cooperatives can greatly strengthen their level of transparency: their disclosed data is scattered, incomplete, irregularly or never updated, and non standardised. The Accountability Framework Initiative provides unified guidance to companies on reporting and disclosure practices to increase the credibility of their claims.

Looking at importing markets, European Union countries imported 60% of Ivorian cocoa beans in 2019, of which only 45.6% (95% CI: 44.5%–46.8%) were traceable to cooperatives (figures 3(A) and

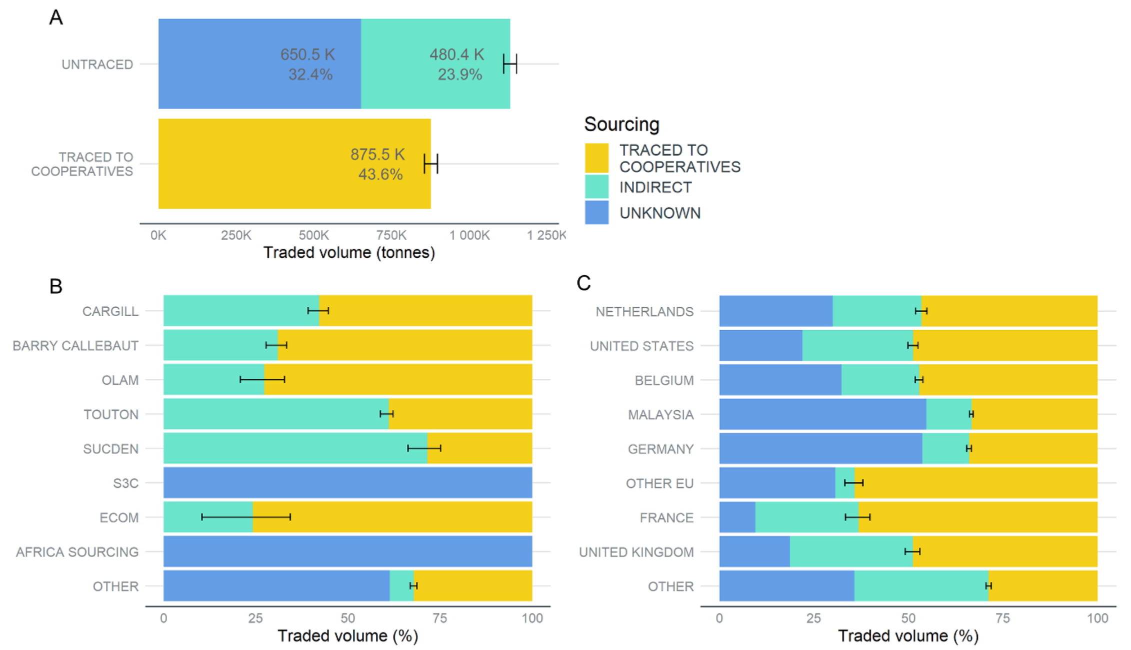

Figure 2. Share of 2019 cocoa sourcing traced to cooperatives, indirect and unknown sourcing: (A) total volume exported from Côte d'Ivoire in tonnes, (B) per major trading company and (C) per importing country in percentage. Error bars represent the 95% confidence interval of the estimates.

(B)). These data detail the country where cocoa was first imported—the Netherlands, for example, appears as the principal destination (27% of exports) because the port of Amsterdam is the main hub for cocoa imports into Europe, with cocoa then being re-exported or processed for consumption elsewhere. The rate of untraced imports among major importers varied between 36% (95% CI: 33.3%–39.8%) (France) and 66% (95% CI: 66.2%–67.1%) (Malaysia).

Traceability to farm lags further behind traceability to cooperatives. For the seven trading companies who disclose their farm-level mapping in Côte d'Ivoire as part of the CFI—handling 52% of the total traded volume—we estimated that 69% (95% CI: 64%–74%) of the volumes they source 'directly' from cooperatives was mapped to farm-level (343 207 farms of the estimated 495 000 farms supplying them 'directly' through cooperatives (95% CI: 465 K–533 K)). For comparison, this is consistent with the self-reported number across all CFI companies, which was 74% in 2020 and 72% in 2021 (CFI 2021). Yet, when including their indirect sourcing, this only represents 40% of the total 850 000 farms supplying these traders (95% CI: 845 K–854 K), which in turn only represents 22% of all cocoa exports in 2019. Approximately 579 000 farms (95% CI: 575 K–583 K) supply the EU market through these CFI traders (figure 3(C)), compared to the 343 207 farms that they had georeferenced in 2020 (465 400 reported in 2021). This shows that current levels of farm-level traceability are insufficient to meet the EU's future due-diligence legislation, expected to require geolocation of the product's origin. Overall, 838 000 hectares of deforestation over 2000–2015 were associated with 2019 EU imports (figure 3(D)). Nor is the EU the only market moving towards due-diligence for deforestation-free imports: similar legislation is also tabled in the United States, UK, Canada and Japan (OECD 2021)—the destination of 11.6%, 4.6%, 3.2% and 0.1% of Ivorian cocoa exports, respectively.

3.2. What is the role of cocoa in recent deforestation?

We found 2.4 Mha of cocoa deforestation and degradation over 2000–2019 (0.125 Mha per year), of which 1.25 Mha is cocoa degradation. This does not include the deforestation of already degraded forest in 2000. The remainder is linked to other agricultural crops such as palm oil, rubber or food crops, logging and mining (BNETD, FAO and SEP-REDD+ CI 2017). Over that period, 5.2 Mha of the initial 6.7 Mha of undisturbed TMF in 2000 was lost (i.e. 77%), either degraded or deforested, leaving the country with less than 1.5 Mha of undisturbed tropical moist forest in 2019, representing 4.7% of its territory. This percentage increases to 9.4% when accounting for the 1.5 Mha of degraded TMF (figure 4(A)). The latest national flora and fauna survey gives a similar total natural forest area of 2.5 Mha in 2020 (without wooded savanna) (IFFN 2021).

Some limitations inherent to spatial datasets may affect the results. For instance, the removal of shade trees or the rehabilitation of old abandoned cocoa farms may be categorised as cocoa deforestation or

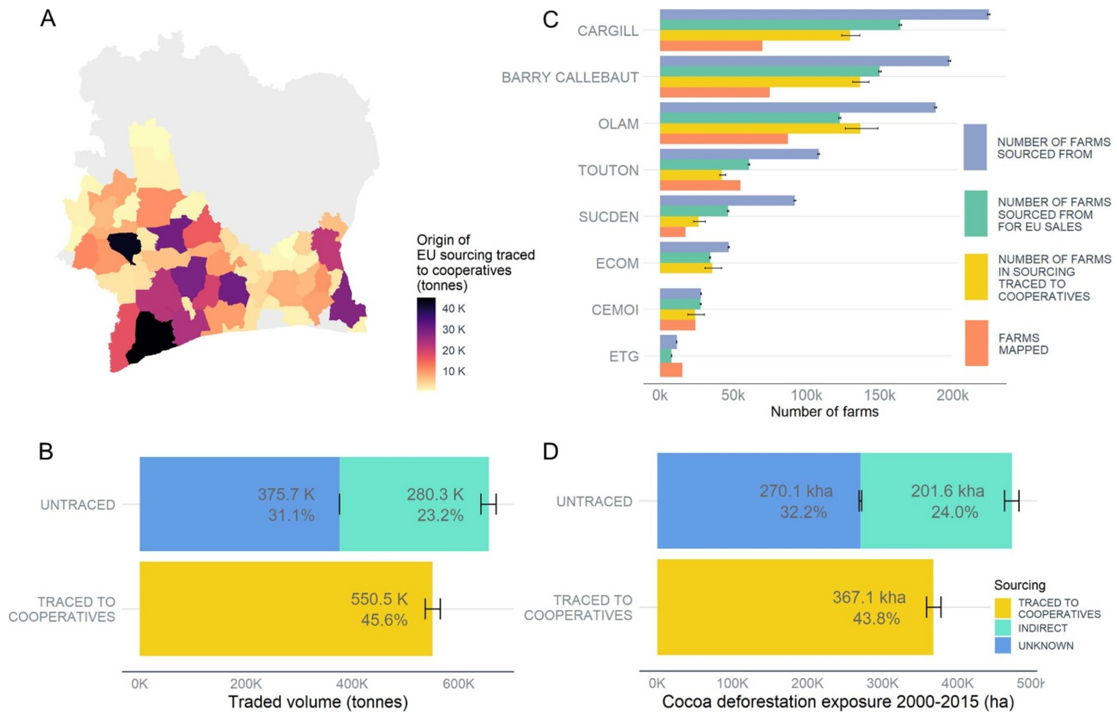

Figure 3. Data for the European Union market. (A) Map of the EU sourcing traced to cooperatives per department. (B) Volume imported into the EU in 2019 by type of sourcing. (C) Comparison of the number of farms mapped by CFI traders as reported in the 2018–2020 CFI reports (orange), the estimated total number of farms they sourced from in 2019 (blue), the estimated number of farms they sourced from for the EU market (green), and the estimated number of farms in their sourcing traced to cooperatives (yellow). Note: ECOM does not disclose the number of farms mapped in Côte d'Ivoire. (D) Cocoa deforestation exposure in hectares embedded in the EU imports in 2019, per sourcing type. Error bars represent the 95% confidence interval of the estimates.

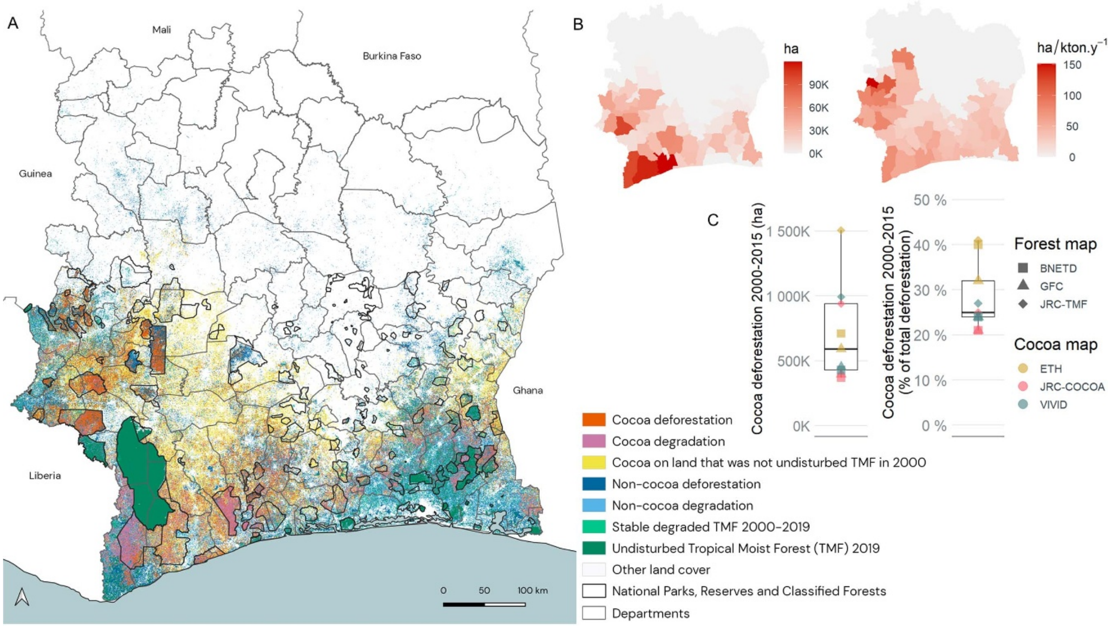

Figure 4. (A) Map of cocoa and non-cocoa deforestation and degradation between 2000 and 2019 in Côte d'Ivoire. 'Other land cover' includes forest already degraded in 2000 (data sources: EC JRC, Kalischek *et al* 2022, Ministère des Eaux et Forêts for protected areas). (B) Cocoa deforestation (2000–2015) in hectares (left) and annual relative cocoa deforestation in hectares per year per kilo tonne of cocoa produced by the department in 2019, per department with more than 500 tonnes of cocoa produced in 2019 (right). (C) Variations of results following the nine combinations of three cocoa maps and three forest maps, with the 2000–2015 cocoa deforestation (left) and the percentage of the total 2000–2015 deforestation being due to cocoa (right).

degradation, because highly shaded farms in 1990 (the starting point of the JRC TMF time series) may have been classified as undisturbed TMF. On the other hand, young cocoa farms are, to some extent, not detected by the cocoa map—thus very recent deforestation for cocoa is certainly classified as non-cocoa deforestation or degradation.

Drivers of land use changes are complex and deforestation or forest degradation rarely have a single underlying cause (Pendrill *et al* 2022b). It is possible that other land uses occurred in the period between deforestation or degradation and the detection of cocoa in 2019—such as other crops on deforested land, or timber extraction or the planting of highly shaded food crops on forests detected as degraded. We report, however, 'cocoa deforestation' and 'cocoa degradation', because cocoa was the major expanding land use during this time period, occurring on 45% of land deforested or forest degraded between 2000 and 2019, and other studies also find cocoa as the main driver of deforestation in Côte d'Ivoire (BNETD, FAO and SEP REDD+ CI 2017, Higonnet *et al* 2017, Ruf and Varlet 2017, Barima *et al* 2020). Cocoa was identified as the major export-oriented crop expanding in Sub-Saharan Africa in 2000–2013, at an annual rate of 132 000 ha, with Côte d'Ivoire being one of the countries most at risk of deforestation because of its low available cropland outside forest areas (Ordway *et al* 2017). Pantropical studies estimated annual cocoa deforestation rates in Côte d'Ivoire of 33 000 ha y^{-1} (Goldman *et al* 2020a) and 13 000 ha y^{-1} (Pendrill *et al* 2022a) over 2001–2015, while a perception-based study estimated the role of cocoa in deforestation at 23% (the highest of all drivers) between 1990 and 2015 (Nitidae 2016). These are considerably lower than our 125 000 ha y^{-1} of cocoa deforestation and degradation over 2000–2019.

Côte d'Ivoire has experienced several waves of cocoa expansion, first in the East, then expanding in the Southwest in the 1970s. The most recent belt of expansion in the Northwest, along the Guinea and Liberia borders (Sanial 2017), has heavily impacted protected areas (figure 4(A)) where the few remaining forests have been concentrated (BNETD, FAO and SEP REDD+ CI 2017). This is also mirrored by the concentration of cocoa deforestation in the western departments, with Sassandra, San-Pédro, Tabou and Guiglo amounting for 28.5% of the total cocoa deforestation over 2000–2015 (figure 4(B)). Over the 2000–2019 period, we found that protected areas (including classified forests) in the cocoa growing region lost in total over 60% of their undisturbed TMF of 2000 (representing 1.3 Mha), with 62% of this deforestation and degradation being due to cocoa (SI table S5). In 2019, 60% of the remaining protected undisturbed TMF was sheltered by the Taï National Park—the best preserved protected area of the country. 25% of the cocoa area in Côte d'Ivoire was located within protected areas and the area under cocoa production has still been expanding (FAO 2020, Vivid Economics 2020). Accounting for higher yields on recently cleared land (Ruf 1987), cocoa in protected areas very likely represents more than 25% of the national production of the world's largest cocoa producing country.

Multiple factors can explain the high rate of cocoa deforestation and degradation, including reduction in soil fertility and yields, migration, the lack of law enforcement, corruption, the lack of financial means and the 2000's political instability (Ruf *et al* 2015, Barima *et al* 2016, Andrieu *et al* 2018, Ongolo *et al* 2018). However, beyond all these factors, cocoa deforestation is rooted in the increasing international demand for cocoa.

3.3. How is cocoa deforestation exposure distributed among actors?

To link cocoa deforestation, here corresponding to all areas of undisturbed TMF lost to cocoa and thus also including areas detected as cocoa degradation, to 2019 trade flows, we consider the 2000–2015 period, during which 55% of the 2000 undisturbed TMF area was lost (from 6.7 Mha to 3 Mha). This is substantially more than the loss of forest cover reported by the National REDD+ Secretariat, i.e. from 4.7 Mha to 2.7 Mha (BNETD, FAO and SEP REDD+ CI 2017). This difference may be due to differing methodologies and forest definitions (see SI table S6). In total, 1.5 Mha were replaced by cocoa over that period (40.7% of the undisturbed TMF lost), at a rate of 100 000 ha per year. The relative cocoa deforestation (ha/tonne produced) is quite homogenous across the country, with slightly larger values in the West (figure 4(B)).

57.7% of the total cocoa deforestation exposure is attributed to untraced sourcing (24.5% to indirect and 33.2% to unknown sourcing), which, in relative terms, represents a slightly higher risk of being exposed to deforestation than sourcing traced to cooperatives (47.9 compared to 45.4 ha/kton.y^{-1}) (figure 5(A)). Cargill, Barry Callebaut, Olam and Touton each have 100–180 000 ha of cocoa deforestation exposure linked to their 2019 sourcing, but the exposure per tonne traced to cooperatives is similar for all traders (figure 5(B)). The exception is Touton whose higher relative cocoa deforestation exposure is due to its sourcing pattern concentrated on few departments among which some faced high cocoa deforestation, e.g. Guiglo—from which 18% of Touton's sourcing traced to cooperatives came from. The eight CFI traders, handling 55% of the total exports, encompass 53.4% of the total cocoa deforestation exposure. Their sourcing traced to cooperatives has a slightly lower relative exposure than non-CFI signatories' (44.3 compared to 48.6 ha/kton.y^{-1} for non-CFI traders). As the CFI was signed in 2017,

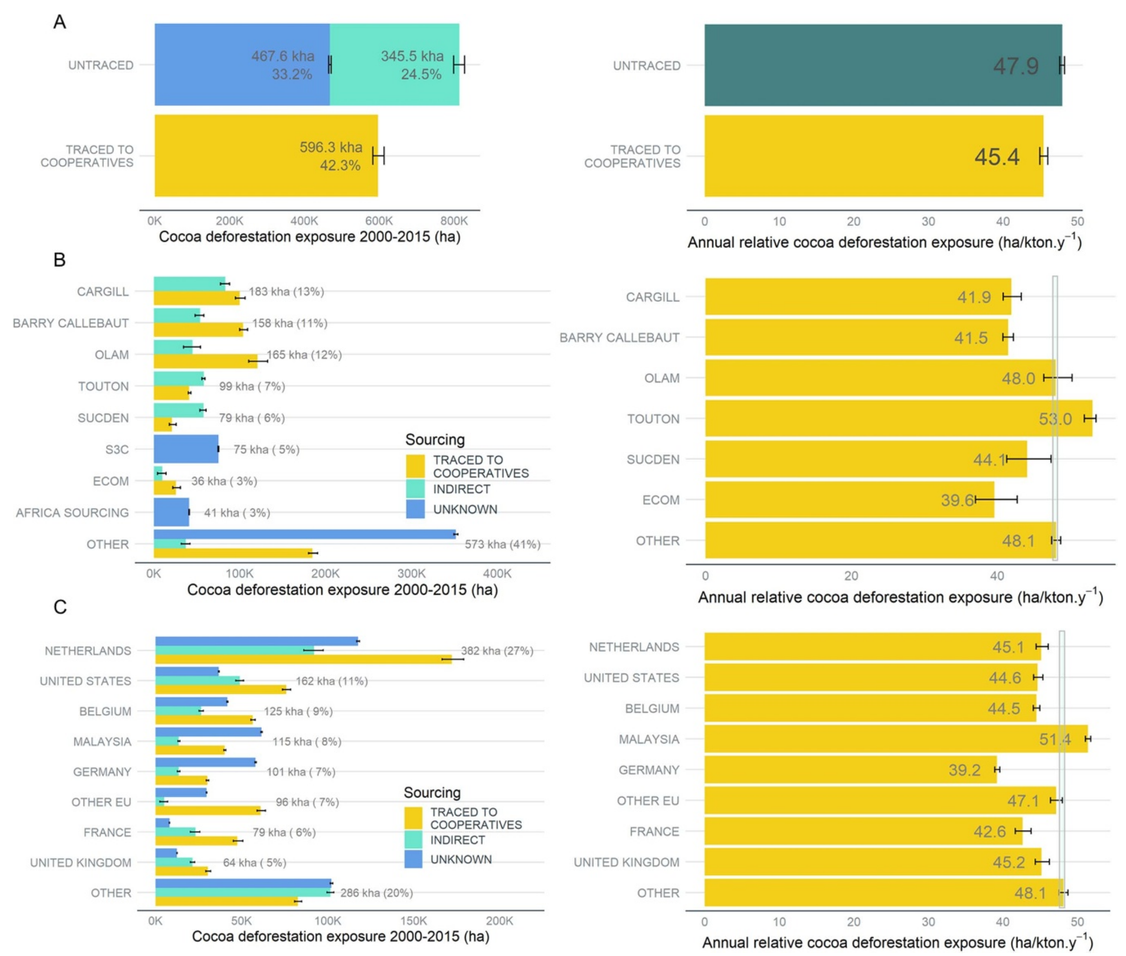

Figure 5. Cocoa deforestation exposure (CDE) in the cocoa supply chain: comparison of sourcing traced to cooperatives, indirect and unknown sourcing in absolute (left) and relative (right) exposure, for the national exports (A), per trader (B) and per importing country (C). The CDE is the share of cocoa deforestation (2000–2015) attributed to the importing country or to the trader based on the volumes and the origin of the cocoa they purchased in 2019. The annual relative cocoa deforestation exposure in yellow is the CDE weighted by the sourced volume traced to cooperatives and annualised (divided by 15). The vertical line represents the annual relative CDE for untraced sourcing. Error bars represent the 95% confidence interval of the estimates.

this difference should be considered as a baseline and not as the impact of the agreement (SI figure S10).

Deforestation exposure trickles down to importing countries, with a large share reaching the Netherlands and its cocoa processing facilities (figure 5(C)). In Germany, 72% of chocolate confectionery was certified according to sustainability standards in 2019 (79% in 2021) (BDSI 2021), but we show that the country imported 101 000 ha of 2000–2015 deforestation. Here, we mapped *physical* flows of cocoa imports, whereas certification credits for several certification standards are decoupled from physical flows, leaving room for deforestation to enter the market.

Tracing cocoa and linking sourcing to deforestation comes with some qualifications. We tested the sensitivity of our findings by repeating our analyses using different remote sensing products (SI text S2, tables S6, S7 and figures S11–S16). The combination of the ETH and JRC-TMF maps, which are the most accurate maps available for deforestation and cocoa plantations, shows a higher rate of cocoa deforestation than other datasets as ETH detects more cocoa and JRC-TMF more forest loss—notably because it includes forest degradation (figure 4(C)). But, importantly, regardless of the magnitude of cocoa deforestation, the relative attribution of the exposure to specific companies and international markets remains stable (figures S13–S16). Given the consistent patterns across datasets, uncertainty in remote sensing products should not be a barrier to corporate and government action on cocoa-driven deforestation. Yet, current approaches to attributing deforestation to cocoa and other crops, which intersect cocoa and forest maps developed in isolation, could be improved by developing harmonised land use products which simultaneously map multiple land covers and uses, and transitions over time, as Mapbiomas does in South America and Indonesia (Alencar *et al* 2020). Further, when attributing deforestation exposure to international markets, it is noteworthy that our results cover the country of import, rather than consumption. Consumption-based attribution studies, on the other hand, also introduce further methodological assumptions and modelling uncertainties and are agnostic as to the identity of which companies handle products along the supply chain (West *et al* 2022). Finally, though deforestation happens on farms, we map sourcing and deforestation exposure at the department-level, which is the finest resolution possible in the absence of publicly-available data about the location of farms supplying each company.

3.4. Prospects for curbing cocoa-driven deforestation

Companies, as well as the forthcoming EU due-diligence legislation, count on farm-level traceability to reach zero-deforestation supply chains. If traceability offers a unique opportunity to improve the living conditions of farmers, through better traced payments and a clearer cooperative system (INADES *et al* 2022), several loopholes may undermine its effectiveness in curbing deforestation.

Company-led traceability is challenging and could be improved, but is not sufficient to address deforestation. Large parts of the supply chain are not mapped; only 44% of the Ivorian cocoa is traced to cooperatives, and 22% is traced to farm under the CFI. Companies in the CFI reported lower traceability in 2021 (72%) vs 2020 (74%) in their 'direct' supply chain from cooperatives. This decline highlights the challenge of traceability, not least the year-on-year changes in farmer membership of cooperatives and company programs requiring frequent updates of the supply base data (Barry Callebaut 2020). As company-led traceability only covers a partial share of the whole supply chain, it leaves gaps in which deforestation is left unmonitored. Buyers less exposed to reputational risks and less committed to sustainability can continue sourcing from these regions—and their non-compliant cocoa can end up in the indirect sourcing of committed actors. Similarly, as the EU due-diligence only applies to volumes sold in the EU, there is a risk of market bifurcation, with non-compliant cocoa sold to non-EU markets (40% of exports). Considering the market dominance of the EU and the similar due-diligence legislations under development in other importing markets, this risk of leakage is limited compared to other contexts, such as the Brazilian cattle sector (le Polain de Waroux *et al* 2019, Zu Ermgassen *et al* 2020), but still remains. If traceability does not cover the whole supply chain, deforestation leakages risk undermining its conservation additionality (Lambin *et al* 2018, Gardner *et al* 2019, Garrett *et al* 2019, Gollnow *et al* 2022).

High hopes are placed in national farm-level traceability systems, as currently under development by the Coffee and Cocoa Council in Côte d'Ivoire (Aboa 2022), **but they remain challenging and have to be transparent to be effective.** First, cooperatives play a crucial role in traceability but they are poorly structured (El Makhloufi *et al* 2018). Many are the result of traders or local leaders' business interest, with a membership 'on paper', rather than farmers deciding to work together (Ruf *et al* 2019). As a result, links between farmers and buyers are fluid with farmers selling to multiple buyers to cope with delays in payments (El Makhloufi *et al* 2018, BASIC and FAO 2020, Nitidae and EFI 2021) and cooperatives buying from non-member farmers to meet the needs of their clients (IDEF 2021, Stoop *et al* 2021). As much of Côte d'Ivoire's forest were cleared before the cut-off date proposed by the Commission (31 December 2020), with less than 10% of the territory covered by tropical moist forest in 2019, the due-diligence's traceability requirements will be the major barrier to access the EU's market for Ivorian farmers and cocoa traders. Support from government and trading companies is thus required to improve the governance of cooperatives at the benefit of farmers and farm workers (Meemken *et al* 2019). Second, as non-compliant cocoa is widespread, it is crucial that the national traceability system is externally verifiable, and thus transparent. At least one-fourth of cocoa is produced within protected areas, and without transparency there is a risk that this cocoa continues to be hidden, jeopardising sustainability initiatives' impact (Gardner *et al* 2019). Making this data public would also alleviate companies' concerns about disclosing their competition-sensitive data, allowing for greater collaboration. Further, equitable frameworks are required to address non-compliant flows, otherwise leading to the exclusion of farmers who will have no other option than selling at low price to intermediaries (Bakhtary *et al* 2020).

Pre-competitive collaboration among traders and chocolate companies, at the landscape level, is one of the most promising ways to increase the effectiveness of sustainable sourcing initiatives, by delivering consistent impact at scale (Sayer *et al* 2013, Wolosin 2016, Carodenuto 2019, Bakhtary *et al* 2020, IDEF 2021). Companies buy from the same landscapes (figure 6(C)), but rarely collaborate and implement their separate sustainability programmes with cooperatives that are part of their 'direct' sourcing—ignoring regions where untraced sourcing dominates (SI figure S7). This lack of collaboration translates into scattered projects sprinkled over the territory, and into activities sometimes overlapping and redundant. For example, certification—which has been a major sustainability strategy in the sector for the past decade (Thorlakson 2018), led to considerable duplication of effort, with many double or triple certification of cooperatives (SI figure S17). Furthermore, a lot happens outside companies' supply chains, with about half of deforestation in Côte d'Ivoire not directly linked to cocoa.

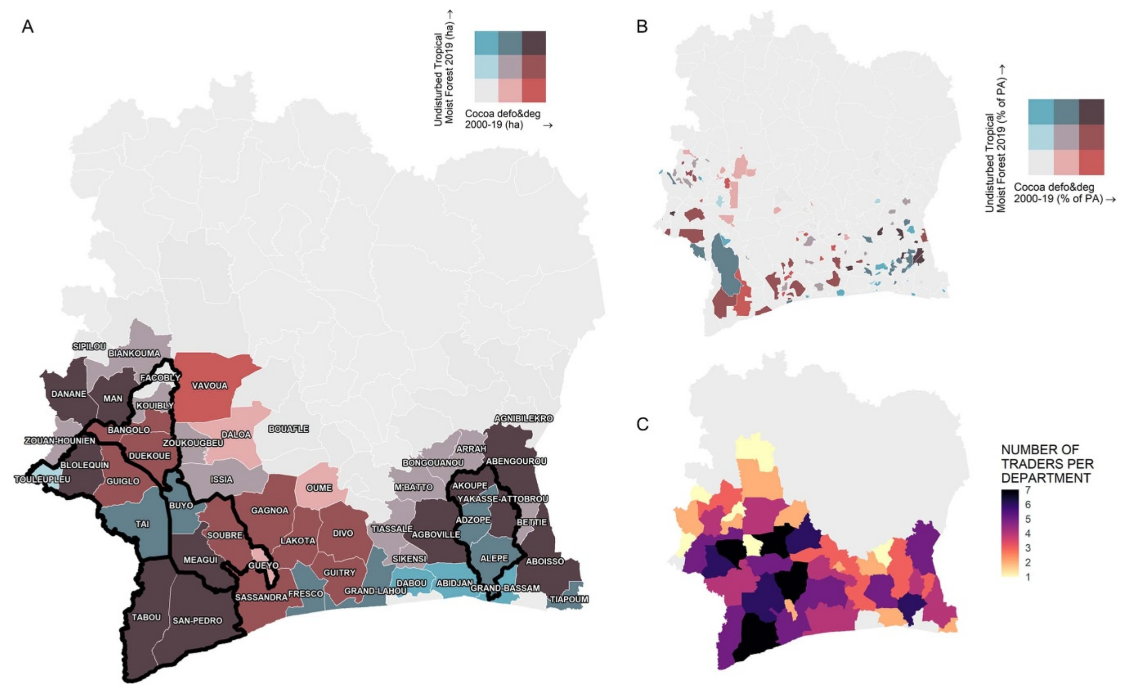

Figure 6. (A) Bivariate map per department (with >200 ha cocoa deforestation & degradation), with the remaining undisturbed tropical moist forest (TMF) in 2019 (blue vertical scale) and the 2000–2019 cocoa deforestation & degradation (defo & deg) (red horizontal scale) in hectares, highlighting key departments which could be considered as priority landscapes (i.e. classified as 3–3 (dark brown) and 2–3 (dark blue)). The breaks of the color scales correspond to quantiles and are as follows for cocoa defo & deg: [202, 12 000] (12 000, 40 400] (40 400, 193 000] and for undisturbed TMF: [99, 2100] (2100, 15 500] (15 500, 292 000]. CFI priority regions are outlined in black. (B) Bivariate map per protected area (PA) (including classified forests, with >0.005% undisturbed TMF in 2019 and cocoa defo & deg), with the remaining undisturbed TMF in 2019 (blue vertical scale) and the 2000–2019 cocoa defo & deg (red horizontal scale) in percentage of the PA area, highlighting key PA (i.e. classified as 3–3 (dark brown) and 2–3 (dark blue)). The breaks of the color scales correspond to quantiles and are as follows for cocoa defo & deg: [0, 26%] (26%, 58%] (58%, 92%], and for undisturbed TMF: [0, 2%] (2%, 13%] (13%, 98%]. (C) Number of traders with sourcing traced to cooperatives (in 2019) per department.

Yet, as cocoa occupies large parts of agricultural land (Kalischek *et al* 2022), it drives deforestation indirectly by pushing other crops inside protected areas (Ajagun *et al* 2022, Kumeh *et al* 2022). To address deforestation, cocoa companies need to work beyond their individual supply chains. Landscape or jurisdictional approaches, defined as governance initiatives promoting sustainable resource use in a specific landscape (e.g. jurisdiction) through a formalised collaboration between all stakeholders (Reed *et al* 2016, von Essen and Lambin 2021), have the potential to internalise indirect sourcing and deforestation drivers beyond the focal commodity (Zu Ermgassen *et al* 2022). The CFI identified priority regions to establish multi-stakeholder landscape governance (CFI 2018), but progress is elusive with only a few pilot projects initiated (CFI 2022). The current CFI regions only capture 23% of the 2000–2019 cocoa deforestation and degradation and 32% of the remaining undisturbed TMF—these numbers could increase by 10% if other key departments were included (figures 6(A) and (B)). Greater effort is needed, requiring government institutions to build the necessary enabling environment and companies to collaborate, support broader regulatory efforts, and provide funding beyond their own projects, focusing on landscapes most at risk of deforestation.

Beyond Côte d'Ivoire's borders, the above recommendations—i.e. implementing landscape approaches, regulatory policies, and a transparent national traceability system—also apply to highly forested countries, where cocoa is expanding (Sassen *et al* 2022).

4. Conclusion

Our findings show that the majority of cocoa exports from Côte d'Ivoire are either untransparent (sourced via traders that do not disclose any information) or indirectly sourced, with the origin unknown. Companies do not know where this indirectly sourced cocoa originates from and are therefore incapable of evaluating if it is tied to sustainability issues, including deforestation or child labor, and can thus hardly act directly to improve them.

Our results also demonstrate the role of cocoa as a major driver of deforestation in Côte d'Ivoire, with almost half of the undisturbed tropical moist forest lost between 2000 and 2019 converted into cocoa. Cocoa deforestation exposure varies among traders and destinations, but is fundamentally embedded in all the supply chain. Almost 60% of this deforestation exposure is linked to untraced sourcing, highlighting the crucial importance of incorporating indirect sourcing in zero deforestation commitments.

In the absence of strongly enforced land use policies, full farm-level traceability, as required by the forthcoming EU due-diligence regulation, is a prerequisite for zero-deforestation commodities. Yet, companies' traceability cannot be considered as a stand-alone solution to deforestation; if not implemented by the whole industry, it leaves gaps that are likely to cancel out its expected impact on deforestation. Furthermore, without transparency, committed actors cannot be held accountable. Transparent national traceability systems, coupled with a robust deforestation monitoring system, can thus be an essential stepping-stone to curb deforestation, but must be combined with land use policies, landscape initiatives, and increased means targeting remaining forests to ensure effective forest conservation.

Data availability statement

The data and code that support the findings of this study are openly available at doi: 10.5281/zenodo.7503845.

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References

Aboa A 2022 Ivory Coast tests new cocoa traceability system to fight deforestation *Reuters* (available at: www.reuters.com/world/africa/ivory-coast-tests-new-cocoa-traceability-system-fight-deforestation-2022-03-03/)

Abu I-O, Szantoi Z, Brink A, Robuchon M and Thiel M 2021 Detecting cocoa plantations in Côte d'Ivoire and Ghana and their implications on protected areas *Ecol. Indic.* **129** 107863

Ajagun E O, Ashiagbor G, Asante W A, Gyampoh B A, Obirikorang K A and Acheampong E 2022 Cocoa eats the food: expansion of cocoa into food croplands in the Juabeso District, Ghana *Food Secur.* **14** 451–70

Alencar A Z *et al* 2020 Mapping three decades of changes in the brazilian savanna native vegetation using landsat data processed in the google earth engine platform *Remote Sens.* **12** 924

Andrieu J, Barima Y S S, Moreno D, Vignal M and Zerbo R 2018 Modélisation rétrospective du défrichement de la forêt classée du Haut-Sassandra (Côte d'Ivoire) dans un contexte de conflits armés (2001-2013) *L'Espace Géographique Tome* **47** 219–34

Bakhtary H, Matson E, Mikulcak F, Streck C and Thomson A 2020 *Company Progress in Engaging Smallholders to Implement ZeroDeforestation Commitments in Cocoa and Palm Oil* (Climate Focus, Tropical Forest Alliance) (available at: https://climatefocus.com/wp-content/uploads/2022/06/20200312-Smallholder-Cocoa-Palm-Report-Edited_FINAL_0.pdf)

Barima Y S S, Konan G D, Kouakou A T M and Bogaert J 2020 Cocoa Production and Forest Dynamics in Ivory Coast from 1985 to 2019 *Land* **9** 524

Barima Y S S, Kouakou A T M, Bamba I, Sangne Y C, Godron M, Andrieu J and Bogaert J 2016 Cocoa crops are destroying the forest reserves of the classified forest of Haut-Sassandra (Ivory Coast) *Glob. Ecol. Conserv.* **8** 85–98

BASIC and FAO 2020 Comparative study on the distribution of value in European chocolate chains (available at: https://lebasic.com/wp-content/uploads/2020/07/BASIC-DEVCO-FAO_Cocoa-Value-Chain-Research-report_Advance-Copy_June-2020.pdf)

BDSI 2021 Initiative of the BDSI for sustainability in the Cocoa Sector—Bundesverband der Deutschen Süßwarenindustrie (available at: www.bdsi.de/en/association/priorities/sustainability/sustainability-in-the-cocoa-sector/initiative-of-the-bdsi-for-sustainability-in-the-cocoa-sector/)

BNETD, FAO and SEP-REDD+ CI 2017 *Données forestières de base pour la REDD+ en Côte d'Ivoire, Cartographie de la dynamique forestière de 1986 à 2015* (available at: (https://doi.org/www.fao.org/3/i8047f/i8047f.pdf))

Brou T Y O, Bigot S and Servat E 2005 Risques de déforestation dans le domaine permanent de l'État en Côte d'Ivoire : quel avenir pour ses derniers massifs forestiers? *Télédétection* **5** 105–21 (available at: https://www.researchgate.net/publication/264195874_Risques_de_deforestation_dans_le_domaine_permanent_de_l%27Etat_en_Cote_d%27Ivoire_quel_avenir_pour_ses_derniers_massifs_forestiers)

Bymolt R, Laven A and Tyszler M 2018 *Demystifying the Cocoa Sector in Ghana and Côte d'Ivoire* (KIT Royal Tropical Institute (available at: www.kit.nl/wp-content/uploads/2020/05/Demystifying-complete-file.pdf)

Callebaut B 2020 *CFI Progress Report 2018-2019* (available at: www.barry-callebaut.com/sites/default/files/2022-04/2018%20and%202019_CFI%20Progress%20Report_Barry%20Callebaut_0.pdf)

Carin J S V, Lucette A Y, Vincent A T, Fernand K K, Corgne S, Rudant J P, Abdoulaye T, Mathias S F, Noellie Y and N'dri K 2019 Suivi Par Télédétection Des Affectations Des Terres Pour la Promotion D'une Agriculture Intégrée Au Développement Forestier En Côte d'Ivoire *OSFACO : Des Images Satellites Pour la Gestion Durable Des Territoires En Afrique* (*Cotonou, Bénin)* (available at: https://hal.archives-ouvertes.fr/hal-02189403)

Carodenuto S 2019 Governance of zero deforestation cocoa in West Africa: new forms of public–private interaction *Environ. Policy Gov.* **29** 55–66

CFI 2018 *Republic of Côte d'Ivoire: Implementation Plan for the Joint Framework of Action 2018–2020* (Cocoa and Forests

Initiative) (available at: www.idhsustainabletrade.com/uploaded/2018/08/CFI_CDI_EN_130818_printversion_3.pdf)
CFI 2021 *Annual Report Cocoa & Forests Initiative 2020* (Cocoa and Forests Initiative) (available at: www.idhsustainabletrade.com/uploaded/2021/05/NUM_ANG_RAPPORT_ICF_VF1.pdf)
CFI 2022 *Rapport annuel initiative cacao et forêts, Côte d'Ivoire 2021* (Cocoa and Forests Initiative) (available at: www.idhsustainabletrade.com/uploaded/2022/07/Initiative-Cacao-Forets-C%C3%B4te-dIvoire-2021-Rapport-Annuel.pdf)
Dontenville A, Sembres T and Fountain A C 2022 *Transparency and Accountability, Towards building trust in the cocoa sector's sustainability efforts* (available at: https://voicenetwork.cc/wp-content/uploads/2022/10/221017-Transparency-Accountability.pdf)
EC 2021 Proposal for a regulation of the European Parliament and the Council on the making available on the Union market as well as export from the Union of certain commodities and products associated with deforestation and forest degradation and repealing Regulation (EU) No 995/2010 (available at: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52021PC0706)
El Makhloufi A, Mujica Mota M, van Damme D and Langenberg V 2018 *Towards a Sustainable Agro-logistics in Developing Countries: The Case of Cocoa's Supply Chain in San Pedro Region/Cote d'Ivoire* (Amsterdam: Amsterdam University of Applied Sciences (AUAS), Urban Technology) (available at: https://pure.hva.nl/ws/portalfiles/portal/5142836/HvA_Brochure_Techniek_Wereldbank_06_Final.pdf)
FAO 2020 FAOSTAT (available at: www.fao.org/faostat/en/#home)
Gardner T A *et al* 2019 Transparency and sustainability in global commodity supply chains *World Dev.* **121** 163–77
Garrett R D *et al* 2019 Criteria for effective zero-deforestation commitments *Glob. Environ. Change* **54** 135–47
Godar J, Suavet C, Gardner T A, Dawkins E and Meyfroidt P 2016 Balancing detail and scale in assessing transparency to improve the governance of agricultural commodity supply chains *Environ. Res. Lett.* **11** 035015
Goldman E, Weisse M J, Harris N and Schneider M 2020a Deforestation linked to agriculture—global forest review *World Resour. Inst.* (available at: https://research.wri.org/gfr/forest-extent-indicators/deforestation-agriculture)
Goldman E, Weisse M J, Harris N and Schneider M 2020b *Estimating the Role of Seven Commodities in Agriculture-Linked Deforestation: Oil Palm, Soy, Cattle, Wood Fiber, Cocoa, Coffee, and Rubber* (World Resources Institute) (available at: wri.org/research/estimating-role-seven-commodities-agriculture-linked-deforestation-oil-palm-soy-cattle)
Gollnow F, Cammelli F, Carlson K M and Garrett R D 2022 Gaps in adoption and implementation limit the current and potential effectiveness of zero-deforestation supply chain policies for soy *Environ. Res. Lett.* **17** 114003
Hansen M C *et al* 2013 High-resolution global maps of 21st-century forest cover change *Science* **342** 850–3
Higonnet E, Bellantonio M and Hurowitz G 2017 *Cholocate's dark secret: How the Cocoa Industry Destroys National Parks* (Mighty Earth) (available at: https://www.mightyearth.org/wp-content/uploads/2017/09/chocolates_dark_secret_english_web.pdf)
ICCO 2021 Quaterly Bulletin of Cocoa Statistics, Vol. XLVII No. 1, Cocoa Year 2020/21
IDEF 2021 *Lacunes et infractions majeures dans la filière cacao en Côte d'Ivoire* (available at: https://ongidef.org/wp-content/uploads/2022/03/Rapport-dobservation-independante-sur-la-filiere-cacao_IDEF2021.pdf)
IFFN 2021 *Inventaire forestier et faunique national, Rapport final de l'inventaire forestier de Côte d'Ivoire* (ONF International, ONF Côte d'Ivoire, IGN, IGN FI)
INADES, Oi-ren and IDEF 2022 Letter to the European Council and European Parliament, support for the geolocation requirement in the draft EU regulation on deforestation free supply chains (available at: https://ongidef.org/wp-content/uploads/2022/02/Lettre-aux-membres-du-conseil-et-du-parlement-europeen_Finale.pdf)
Kalischek N, Lang N, Renier C, Daudt R C, Addoah T, Thompson W, Blaser-Hart W J, Garrett R, Schindler K and Wegner J D 2022 Satellite-based high-resolution maps of cocoa planted area for Côte d'Ivoire and Ghana (available at: http://arxiv.org/abs/2206.06119)
Kouassi J-L, Gyau A, Diby L, Bene Y and Kouamé C 2021 Assessing land use and land cover change and farmers' perceptions of deforestation and land degradation in South-West Côte d'Ivoire, West Africa *Land* **10** 429
Kumeh E M, Bieling C and Birner R 2022 Food-security corridors: a crucial but missing link in tackling deforestation in Southwestern Ghana *Land Use Policy* **112** 105862
Lambin E F *et al* 2018 The role of supply-chain initiatives in reducing deforestation *Nat. Clim. Change* **8** 109–16
le Polain de Waroux Y, Garrett R D, Graesser J, Nolte C, White C and Lambin E F 2019 The restructuring of South American soy and beef production and trade under changing environmental regulations *World Dev.* **121** 188–202
Meemken E-M, Sellare J, Kouame C N and Qaim M 2019 Effects of fairtrade on the livelihoods of poor rural workers *Nat. Sustain.* **2** 635–42
Nitidae and EFI 2021 *Traceability and transparency of cocoa supply chains in Côte d'Ivoire and Ghana* (available at: www.nitidae.org/files/90b65fa3/document_technique_agriculture_redd_marche_ghana_cotedivoire_cacao_tracao.pdf)
Nitidae 2016 *Analyse qualitative des facteurs de déforestation et de dégradation des forêts en Côte d'Ivoire* (BNETD, SEP-REDD+ CI (available at: www.nitidae.org/files/b24e760c/161216081210_161214_analyse_facteurs_def_deg_ci_rapport_final.pdf)
OEC 2020 Côte d'Ivoire exports, imports, and trade partners (available at: https://oec.world/en/profile/country/civ)
OECD 2021 *Policy Trends in Environmental Due Diligence* (available at: https://mneguidelines.oecd.org/policy-trends-in-environmental-due-diligence.pdf)
Ongolo S, Kouamé Kouassi S, Chérif S and Giessen L 2018 The tragedy of forestland sustainability in postcolonial Africa: land development, cocoa, and politics in Côte d'Ivoire *Sustainability* **10** 4611
Ordway E M, Asner G P and Lambin E F 2017 Deforestation risk due to commodity crop expansion in sub-Saharan Africa *Environ. Res. Lett.* **12** 044015
Ouattara T, Kouamé F, Zo-Bi C, Vaudry R and Grinand C 2021 Changements d'occupation et d'usage des terres entre 2016 et 2019 dans le Sud-Est de la Côte d'Ivoire : impact des cultures de rente sur la forêt *Bois For. Trop.* **347** 91–106
Pendrill F *et al* 2022a Deforestation risk embodied in production and consumption of agricultural and forestry commodities 2005-2018 (available at: https://zenodo.org/record/5886600)
Pendrill F *et al* 2022b Disentangling the numbers behind agriculture-driven tropical deforestation *Science* **377**
Pendrill F, Persson U M, Godar J and Kastner T 2019 Deforestation displaced: trade in forest-risk commodities and the prospects for a global forest transition *Environ. Res. Lett.* **14** 055003
Reed J, Van Vianen J, Deakin E L, Barlow J and Sunderland T 2016 Integrated landscape approaches to managing social and environmental issues in the tropics: learning from the past to guide the future *Glob. Change Biol.* **22** 2540–54
Ruf F 1987 *Elements pour une théorie sur l'agriculture des régions tropicales humides. 1—De la foret, rente différentielle, au cacaoyer, capital travail* (available at: http://agritrop.cirad.fr/452880/)

Ruf F, Schroth G and Doffangui K 2015 Climate change, cocoa migrations and deforestation in West Africa: what does the past tell us about the future? *Sustain. Sci.* **10** 101–11
Ruf F, Uribe Leitz E, Gboko K C and Carimentrand A 2019 Des certifications inutiles? Les relations asymétriques entre coopératives, labels et cacaoculteurs en Côte d'Ivoire *Rev. Int. Études Dév* **240** 31
Ruf F and Varlet F 2017 The myth of zero deforestation cocoa in Côte d'Ivoire *Zero Deforestation: A Commitment to Change* vol 58 ed P Nick and H Savenije (Wageningen: Tropenbos International) (available at: https://www.tropicalforestalliance.org/assets/Uploads/ETFRN_News_58.pdf)
Sanial E 2017 La cacaoculture ivoirienne: moteur de la déforestation ou agent d'une "agro-reforestation"? Obstacles techniques, environnementaux et fonciers à l'appropriation des arbres de valeur par les planteurs de cacao ivoiriens *33ème journées ATM - "Agricultures, ruralités et développement"* (available at: https://www.researchgate.net/publication/317166607_La_cacaoculture_ivoirienne_moteur_de_la_deforestation_ou_agent_d%27une_agro-reforestation_Obstacles_techniques_environnementaux_et_fonciers_a_l%27appropriation_des_arbres_de_valeur_par_les_planteurs_de_ca)
Sassen M, van Soesbergen A, Arnell A P and Scott E 2022 Patterns of (future) environmental risks from cocoa expansion and intensification in West Africa call for context specific responses Land Use Policy **119** 106142
Sayer J *et al* 2013 Ten principles for a landscape approach to reconciling agriculture, conservation, and other competing land uses *Proc. Natl Acad. Sci.* **110** 8349–56
Schroth G, Läderach P, Martinez-Valle A I, Bunn C and Jassogne L 2016 Vulnerability to climate change of cocoa in West Africa: patterns, opportunities and limits to adaptation *Sci. Total Environ.* **556** 231–41
SEP-REDD+ CI 2017 *Stratégie Nationale REDD+ de la Côte d'Ivoire* (available at: http://reddplus.ci/download/strategie-nationale-redd-cote-divoire/?wpdmdl=8410)
Stoop P, Ramanan N, Greens H, Lambrecht A and Dekeister S 2021 *Technical Brief on Cocoa Traceability in West and Central Africa* (IDH, GISCO, C-lever.org) (available at: https://www.idhsustainabletrade.com/uploaded/2021/04/Cocoa-Traceability-Study_Highres.pdf)
Thorlakson T 2018 A move beyond sustainability certification: the evolution of the chocolate industry's sustainable sourcing practices *Bus. Strategy Environ.* **27** 1653–65
Vancutsem C, Achard F, Pekel J-F, Vieilledent G, Carboni S, Simonetti D, Gallego J, Aragão L E O C and Nasi R 2021 Long-term (1990–2019) monitoring of forest cover changes in the humid tropics *Sci. Adv.* **7** eabe1603
Vivid Economics 2019 Land use map for Côte d'Ivoire, available on demand through IMAGES online platform (available at: www.vivideconomics.com/images/)
Vivid Economics 2020 *State and Trends of Deforestation in Côte d'Ivoire (2019-2020)* (available at: https://www.vivideconomics.com/wp-content/uploads/2020/07/State-and-Trends-of-Deforestation-in-CdI-1.pdf)
von Essen M and Lambin E F 2021 Jurisdictional approaches to sustainable resource use *Front. Ecol. Environ.* **19** 159–67
West C, Croft S, Titley M, Ebrey R, Gollub E, Simpson J and Smythe J 2022 *Assessing tropical deforestation risk in Germany's agricultural commodity supply chains* (Trase) (available at: https://doi.org/10.48650/PV1P-Q331)
Wolosin M 2016 *WWF discussion paper: Jurisdictional approaches to zero deforestation commodities* (WWF) (available at: https://wwfint.awsassets.panda.org/downloads/wwf_jurisdictional_approaches_to_zdcs_nov_2016.pdf)
Zu Ermgassen E K H J *et al* 2022 Addressing indirect sourcing in zero deforestation commodity supply chains *Sci. Adv.* **8** eabn3132
Zu Ermgassen E K H J, Godar J, Lathuillière M J, Löfgren P, Gardner T, Vasconcelos A and Meyfroidt P 2020 The origin, supply chain, and deforestation risk of Brazil's beef exports *Proc. Natl Acad. Sci.* **117** 31770–9