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To cite this article: Cécile Renier *et al* 2025 *Environ. Res.: Food Syst.* **2** 025006

ENVIRONMENTAL RESEARCH
FOOD SYSTEMS

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OPEN ACCESS

RECEIVED
13 May 2024

REVISED
21 February 2025

ACCEPTED FOR PUBLICATION
24 April 2025

PUBLISHED
2 May 2025

PAPER

Direct and indirect deforestation for cocoa in the tropical moist forests of Ghana

Cécile Renier[1,*], Thomas Addoah[2], Valentin Guye[1], Rachael Garrett[2], Goedele Van den Broeck[1], Erasmus K H J Zu Ermgassen[1] and Patrick Meyfroidt[1,3]

[1] Earth and Life Institute, UCLouvain, Louvain-la-Neuve 1348, Belgium
[2] Department of Geography and Conservation Research Institute, University of Cambridge, Cambridge, United Kingdom
[3] Fonds de la Recherche Scientifique F. R. S.-FNRS, Rue d'Egmont 5, B-1000 Brussels, Belgium
[*] Author to whom any correspondence should be addressed.

E-mail: c.renier@uclouvain.be

Keywords: land balance, food crops, mining, plantations, food security, indirect land use change

Supplementary material for this article is available online

Abstract

Across the tropics, cocoa is one of the main drivers of deforestation. In Ghana, the world's second largest cocoa producer, the role of each of the main economic sectors in driving deforestation remains, however, contested—with cocoa, mining, logging, and plantations each blaming the others. Previous work has also suggested that food crops are displaced into forests by cocoa expansion, raising concerns about indirect land-use change and impacts on food availability. Here, using satellite-based maps and secondary data, we quantify the *direct* deforestation and forest degradation between 2000 and 2019 in the entire cocoa-growing region of Ghana which is attributed to the land uses (LUs) detected in 2019. Then, we use a land-balance approach to assess the *indirect* role of the expansion of LUs in deforestation and degradation for food crops. We find that cocoa was the major direct driver over that period (∼57%), followed by food crops and logging (∼39% in total), then by mining (3%), tree plantations (2%) and settlements (<1%). Roughly 30% of the deforestation and degradation of land used for food crops in 2019 was attributed to their displacement from elsewhere by other LUs—with 15% (9%–17%) due to cocoa expansion into food crops. In cocoa-saturated regions, indirect deforestation is likely to increase as forests only remain in gazetted areas, where growing food crops is either legal or more tolerated by officials than cocoa. Accounting for its direct and indirect role, cocoa was associated with ∼20% of the deforestation in gazetted areas. This research highlights the need to move away from sustainability efforts targeting one single commodity at a time to more transformative approaches that develop a coordinated vision across the food and land system. Such a vision would regulate multiple commodities holistically, address lock-ins, and reconsider the overall use of land systems in the region (how much land should be dedicated to cocoa, how and for whose benefits).

1. Introduction

Cocoa production is one of the most important economic sectors in Western Africa, employing millions of smallholder farmers and workers. With over 800 000 smallholder farmers producing ∼800 000 tonnes of cocoa beans yearly, Ghana is the second-largest cocoa producer in the world, accounting for about 20% of global cocoa production (FAO 2022). After gold and crude petroleum, cocoa is the third most important export of Ghana, worth $2.4 billion annually, or more than 17% of Ghana's total export earnings (OEC 2021).

Yet, the crucial importance of cocoa in the Ghanaian economy comes at a cost: Ghana lost over 60% of its forest cover from 1950 to the turn of the last century (Forestry Commission 2016). The REDD+ Strategy of Ghana (2016) states that the country has one of the highest deforestation rates in the world with an annual rate of 2% (i.e. 135 000 ha yr^{-1}). Although cocoa is widely discussed as a major driver of deforestation

(Pendrill *et al* 2019, Goldman *et al* 2020), its precise contribution to deforestation in Ghana remains contested. Pan-tropical or pan-African studies provide varying estimates of cocoa-driven deforestation, attributing tree cover loss to cocoa using national-level agricultural statistics (Pendrill *et al* 2019), coarse land use data (Goldman *et al* 2020), high-resolution remote sensing (Masolele *et al* 2024), or a mix of remote sensing data and agricultural statistics (Singh and Persson 2024) (SI table S1).

Aside from cocoa, other drivers are put forward as having a major role in the deforestation of the Ghanaian tropical moist forest (TMF), such as illegal artisanal mining (*galamsey)*, legal and illegal timber exploitation, tree plantations (oil palm, rubber, coconut), urban sprawl, or food crops, each of the sectors involved laying blame on the others (Yoda 2019). Food crops were for instance identified as the main driver of deforestation between 2019 and 2022 across the six priority cocoa landscapes in Ghana (CFI 2023). Mining has also been recently flagged as expanding not only into forests but also into cocoa plantations, threatening cocoa production (Onah 2023).

Beyond driving deforestation directly by expanding into forests, these various land uses (LUs) can cause deforestation indirectly by competing and expanding into other LUs that are themselves displaced into forests (Meyfroidt *et al* 2013, 2018, Kuschnig *et al* 2021). Indirect land-use change (iLUC) is a form of spillover where land-use change in one place is caused by land-use change in another place (Meyfroidt *et al* 2020). These complex land-use dynamics depend on the competitiveness of different crops and LUs, land suitability, opportunity costs, and policies (Meyfroidt *et al* 2018, Turner *et al* 2020). Studies in some regions of Ghana show that cocoa expansion is taking up a considerable share of available farmland and is linked to food crops being displaced in neighbouring forests, raising concerns about food availability for households converting their food crops into cocoa plantations (Ajagun *et al* 2022, Kumeh *et al* 2022). Food crops (mainly plantain, cocoyam and yam) are indeed often intercropped with tree crop seedlings, and are then displaced once the canopy closes (Asubonteng *et al* 2018, Acheampong *et al* 2019).

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 urgency behind these efforts has been further increased by the European Union's deforestation-free regulation (EUDR), requiring companies to demonstrate that imports of deforestation-risk products (such as cocoa or chocolate) do not originate from recently deforested nor degraded land (EC 2021). However, the effectiveness of 'narrow' zero-deforestation commitments (ZDCs) or traceability efforts focussed on specific commodities as 'solutions' to deforestation is increasingly questioned (Lambin *et al* 2018, Gardner *et al* 2019, Garrett *et al* 2019, Gollnow *et al* 2022, Panwar *et al* 2023, Renier *et al* 2023), as they ignore the complex land-use dynamics outlined above. Hence, even if supply chains are EUDR-compliant and companies claim deforestation-free sourcing, whether the cocoa sector can become free of all deforestation—direct and indirect—remains an open question.

A comprehensive picture of the land-use dynamics and their impacts on forests across the Ghanaian cocoa-growing area remains lacking, as previous studies focus on specific regions (Asubonteng *et al* 2018, Benefoh *et al* 2018, Acheampong *et al* 2019, Kyere-Boateng and Marek 2021, Ashiagbor *et al* 2022), do not disentangle the contribution of each crop in national agricultural deforestation (Forestry Commission 2016, Acheampong *et al* 2019), or only evaluate the LU following deforestation on a plot, without accounting for indirect land-use dynamics (Masolele *et al* 2024). Here, our objective is to better understand the role of cocoa and other land-intensive activities in driving pressure on land resources, and ultimately on forests, in the whole cocoa-growing region of Ghana (∼8 Mha), by assessing their direct (i.e. deforestation attributed to the detected LU in 2019) and indirect deforestation footprints (i.e. deforestation of land used for food crops in 2019 and attributed to the expansion of another LU) over the period 2000–2019. We use existing Earth observation and statistical datasets to assess direct deforestation, and a land-balance approach to quantify indirect deforestation.

2. Methods

To calculate the direct and indirect forest footprint of LUs, we followed five main steps summarized here and developed further below (see figure 1 for the summary of datasets and workflow, and figure 2 for definitions).

First, we quantified the direct deforestation and degradation footprint of cocoa, oil palm, rubber, coconut, mining, and urban sprawl using the most accurate and up-to-date satellite-based datasets available, thus covering the period 2000–2019 (section 2.2). Second, with the same data we calculated their expansion outside what was forest in 2000 (section 2.3.1). Third, absent a comprehensive food crop satellite-based dataset, we used statistical records and a land-balance approach to estimate how much of that expansion occurred on food crops, thus displacing food crops elsewhere, based on the relative importance of the food crop area in the region compared to other pools of land 'available' for expansion (section 2.3.2.1). Fourth, following the same approach, we estimated the area of food crops which expanded or were displaced onto

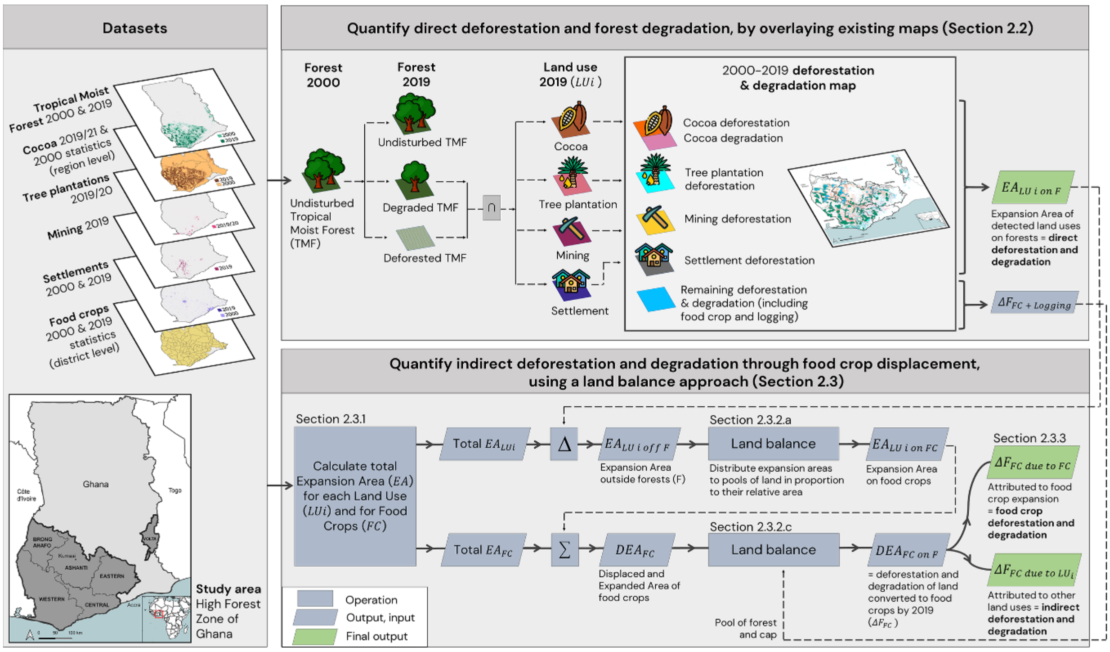

Figure 1. Study area, datasets and workflow. The top panel presents the steps of the production of the *direct* deforestation and degradation figures and map over 2000–2019 (cf figure 4(A)), and the bottom panel describes the steps to quantify the amount of deforestation and degradation of land used for food crops in 2019 for which the establishment of food crops is attributed to their displacement from elsewhere by other land uses (i.e. *indirect* deforestation and degradation).

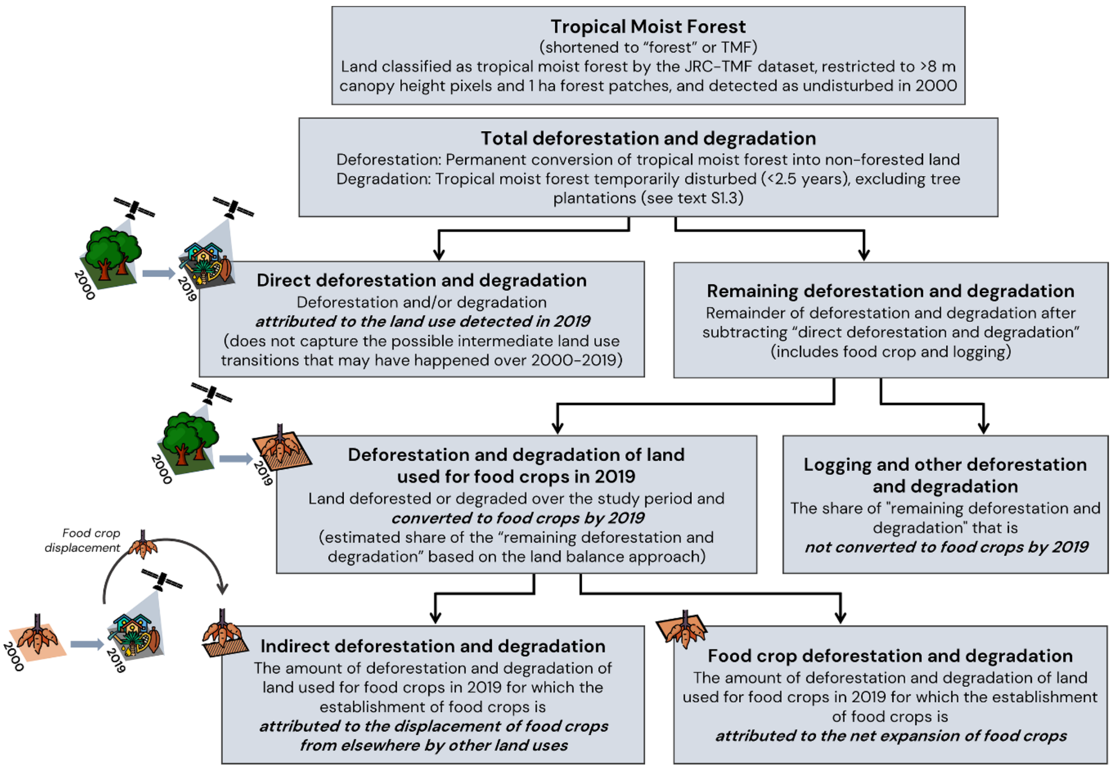

Figure 2. Land-use change definitions. 'Direct' in the context of this paper is used in contrast with 'indirect': 'direct' here means that there is a direct spatial association between deforestation and the detected land use, i.e., they both occur at the same location. 'Indirect', in contrast, means that they are linked but do not co-occur spatially. The term 'direct' is however not used for food crops to distinguish them from land uses observed by Earth observation data. For deforestation where the land use inferred in 2019 is food crops, we use 'deforestation and degradation of land used for food crops in 2019', and for the share of that that was attributed to the net food crop expansion, we use 'food crop deforestation and degradation', as opposed to the share attributed to the expansion of other land uses that we call 'indirect deforestation and degradation' (i.e. food crops in 2000 converted to one of these other land uses by 2019 and displaced in forests) and which, in our research, only refers to the displacement of food crops (no displacement of other land uses are considered).

forests (sections 2.3.2.2 and 2.3.2.3). Fifth, we attributed the total deforestation and degradation of land used for food crops in 2019 to the other LUs based on their relative expansion, to calculate their indirect footprint on forests through food crop displacement (section 2.3.3) (see SI figure S1 for the detailed steps of the land-balance). We performed the calculations at the region level, to capture the specific dynamics in each region, and then repeated the land-balance and indirect deforestation attribution with data aggregated directly at the level of the whole study area (Renier *et al* 2025).

2.1. Study area

The study area corresponds to the TMF zone of Ghana, called the high forest zone (HFZ), where cocoa is grown (figure 1). This is a ∼8 Mha area, located mainly in the Southwestern part of the country (Asante 2014). We excluded the transition zone and the savannah region of the country as they have different land-use dynamics, with different crops and deforestation drivers. To allow for a better understanding of local dynamics, the analysis was carried out at the level of six administrative regions rather than only at the HFZ level. To facilitate interpretation, in this work the 'Western' region refers to the previous region's delineation (pre-2020) and thus includes the current (2024) Western-North region, while the 'Brong Ahafo' region refers to the current Ahafo region plus a part of the new Bono region, and the 'Volta' region includes districts of the current Oti region. We restricted Brong Ahafo, Ashanti and Volta regions to the HFZ by removing 43 districts located beyond the delineation of the HFZ (hereafter, 'regions' thus refer to these trimmed regions, not including any district beyond HFZ) (SI figure S2).

2.2. Quantifying direct deforestation and forest degradation

To quantify the *direct* deforestation and degradation of the main LUs, in the absence of a publicly accessible national land cover map, we overlaid several remote-sensing maps with a map of TMF produced by European Commission's Joint Research Centre (JRC), depicting annually from 1990 to 2020 the extent of undisturbed TMF and its changes at 30 m resolution (Vancutsem *et al* 2021).

Due to the limitation in the data (LU maps being available for the year ∼2019 only, not as annual time series), we measured deforestation and degradation that occurred between 2000 and 2019, and we first attributed the change to the observable LU at the end of the period. Thus, in the context of this paper, 'direct' deforestation and degradation refers to land detected as undisturbed forest in 2000 converted to one of the considered LUs detected by satellite imagery in 2019. Therefore, our approach does not capture the possible intermediate land-use transitions—yet, this period covers ∼20 years, which is the IPCC default inventory period for land-use change attribution (Maciel *et al* 2022) and which we consider to be a reasonable timeframe to capture the major forces driving land-use dynamics over that period. In the HFZ, food crops are often intercropped with cocoa seedlings in the first years of cocoa plantation establishment after deforestation (Asubonteng *et al* 2018, Acheampong *et al* 2019), but in the context of the 2000s' cocoa boom and the comparative perceived advantages of cocoa, there is convincing evidence to consider that land where cocoa is detected in 2019 was initially deforested with the intention of growing cocoa—even if food crops were present at the outset (Ruf and Siswoputranto 1995, Clough *et al* 2009) (text S1.1).

The maps overlaid with the TMF map include (i) a **cocoa LU map** for the years 2019–2021 at 10 m resolution produced for Ghana and Côte d'Ivoire (Kalischek *et al* 2023) (hereafter, the '2019 cocoa map'); (ii) a **global tree plantations map** for the year 2019–2020 (Vancutsem *et al* 2021) which includes rubber and oil palm for 2019 at 10 m resolution (Descals *et al* 2021) and a global closed-canopy coconut map for 2020 at 20 m resolution (Descals *et al* 2023) (both cocoa and coconut being perennial crops, limited year-on-year variation is expected); (iii) a **global mining LU map** for the year 2019 produced at 10 m resolution, which includes large-scale, artisanal and small-scale mining, formal and informal, covering all ground features related to mining, e.g. open cuts, tailing dams, waste rock dumps, water ponds, processing infrastructure (hereafter, the '2019 mining map') (Maus *et al* 2020); (iv) a **global settlement footprint map** for the years 2000 (at 30 m resolution) and 2019 (at 10 m resolution) (Marconcini *et al* 2021). These spatial datasets inherently contain detection errors, but their accuracy spans from 84% to 99%, making them suitable for such an analysis (see SI table S2 for table of datasets and their accuracy, and table S3 and text S1.2 for overlaps).

We created a map of the land use change between 2000 and 2019 including deforestation and degradation, their association with LUs, 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), excluding tree plantations (text S1.3). Here, 'deforestation' corresponds to pixels that switched from undisturbed TMF to another land cover between 2000 and 2019, with at least 2.5 years of disturbance, and 'degradation' to pixels that switched from undisturbed to degraded TMF. We kept this distinction for pixels detected as cocoa in 2019—which were classified as 'cocoa deforestation' and 'cocoa degradation'. Cocoa degradation could be forest converted to cocoa but with a relatively dense remaining shade canopy cover, or cocoa plantations that were too recently established to be classified as deforestation (having less than 2.5 years of detected disturbance). Young cocoa farms are, to some extent, not detected by the cocoa map—thus very recent deforestation for cocoa is likely classified as non-cocoa deforestation or degradation. For the other LUs, i.e. mining, tree plantations and settlements, we merged degradation with deforestation (thus called 'mining deforestation', etc) because the areas of degraded TMF detected as one of these LUs were very limited compared to cocoa, and these activities are expected to lead to a full removal of the natural forest.

Due to the low quality of clouded satellite images of the HFZ of Ghana in the 1990s, highly shaded cocoa farms in 1990 (the starting point of the JRC TMF time series) may have been classified as undisturbed TMF—meaning that the removal of shade trees or the rehabilitation of old abandoned cocoa farms may be categorised as cocoa deforestation or degradation. To mitigate this and limit the misclassification of cocoa as forest, we filtered the pixels classified as undisturbed TMF, keeping those passing two thresholds: (i) vegetation must be >8 m in height (based on two global forest height datasets for 2000 (at 30 m resolution) and 2020 (at 10 m resolution) (Potapov *et al* 2022, Lang *et al* 2023)), and (ii) pixels must form a minimum of 1 ha patch to be considered as forest. These restrictions decreased the detected undisturbed forest in 2000 from 4.7 Mha to 2.6 Mha, which is similar to the 2000 HFZ forest area estimate of 2.7 Mha by the Forestry Commission (2021, p124–127).

For each remotely-sensed LU, we calculated the forest area that they replaced, thereby quantifying their direct role in deforestation and forest degradation over the 2000–2019 period (equation (1)) (SI figure S1(B)),

$$\mathrm{EA}_{\mathrm{LU}\,i\,\mathrm{on\,F}} = F_{y1} \cap \mathrm{LU}_{iy2}. \tag{1}$$

With $\mathrm{EA}_{\mathrm{LU}\,i\,\mathrm{on\,F}}$ the expansion area of LU i on forest (F_{y1}).

Deforestation or forest degradation detected by the TMF dataset but without detected post-clearing LU can correspond to logging, fuelwood collection, or clearing for food crops—for which no robust satellite-based dataset was available in the HFZ of Ghana (SI figure S3). Hence, once all other quantifiable drivers are subtracted from the total area of deforestation and degradation, we classify the remainder as the deforestation and degradation linked to food crops or logging/fuelwood. We analysed the dynamics of direct deforestation drivers across distinct types of gazetted and non-gazetted land using data from Resource Management Support Centre of Ghana.

2.3. Quantifying indirect deforestation and degradation through food crop displacement

2.3.1. Estimating the total expansion of LUs and food crops

To estimate the deforestation and degradation of land used for food crops in 2019 which was due to (i) the net expansion of food crops itself (linked to underlying drivers such as demographic growth) versus (ii) the expansion of other LUs that displace food crops into forest, we first needed to calculate the total food crop net expansion (i.e. the difference between 2000 and 2019), as well as the area of food crops displaced by the expansion of other LUs. For the latter, we needed to estimate the total expansion of these other LUs outside forests.

For estimating the net food crop expansion, in the absence of a remote-sensing dataset, we used statistical data of the land area farmed for a list of crops identified as food crops per district in 2000 and 2019, obtained from the Ghana Statistical Service.

The expansion area of each LU *outside forests* was obtained by subtracting the area of expansion into forest (i.e. direct deforestation) from the total expansion of each LU. To obtain the latter, we used different methods according to the availability of data for each LU (see table S4). For settlements, we subtracted the extent of the LU in 2000 from its extent in 2019, both observed in satellite data. For mining and tree plantations, we lacked data on the extent in 2000. Hence, we used the total 2019 area as the upper-bar expansion area (i.e. considering that all mining sites and tree plantations detected in 2019 were established after 2000). Conversely, we used the 2019 mining and tree plantation area detected as forest in 2000 as a lower-bar estimate (i.e. considering only the area directly replacing forest over 2000–2019 as new, and thus that all the area outside forest was established before 2000). Finally, for cocoa, we estimated the area in 2000 by dividing the cocoa production per region (COCOBOD 2023) averaged over 1999–2001 by the yields collected in 2001/2002 in five of the six cocoa regions (Ruf 2007b) (SI text S1.4). To account for uncertainty in yields, we computed 10% upper- and lower-bar estimates (SI table S5). For the sixth region, Volta, we imputed missing yield information from the other regions' average. The yield estimates were collected for productive cocoa plantations, yet, the total area of cocoa plantations also includes old plantations not harvested anymore as well as young, not yet productive areas. To account for these unproductive cocoa areas, the area was increased by 24%, as assessed for 2001/02 in Ashanti, Brong Ahafo and Western regions by Teal *et al* (2006). The expansion of cocoa was thus calculated as the difference between the satellite-based area in

2019 and the estimated cocoa area for 2000. The upper- and lower-bar estimates of the total expansion of mining, tree plantations and cocoa reflect the various data uncertainties and serve as robustness checks (referred to as 'max' and 'min' LU expansion scenarios).

2.3.2. Estimating food crop displacement

2.3.2.1. Expansion of LUs on food crops

To estimate the area of food crops displaced by other LUs, we used a land-balance approach similar to Pendrill *et al* (2019) and the World Business Council for Sustainable Development official guidance for land-use change accounting (WRI and WBCSD 2022). Land-balance is used as a way of accounting for overall LU expansion including iLUC and deforestation. The following analyses were conducted at two scales: the region level, with results of each region then summed to get the total at HFZ level, and directly with data aggregated at the entire HFZ level, in order to identify dynamics at different scales (Zu Ermgassen *et al* 2024).

First, we estimated how much cocoa, tree plantations, mining, and settlement LUs expanded on food crops over the 2000–2019 period (SI figure S1(C)). The total expansion calculated above may have occurred on various 'pools' of land: (i) forests (F); (ii) 'other' land not classified in one of our LULC categories[4]; (iii) food crops (FC); and, for LUs other than cocoa, (iv) abandoned cocoa farms[5].

Satellite data provides the direct expansion of LUs on forests (equation (1)) but no spatially-explicit data exist for the expansion which occurred outside forests, neither a robust quantification of the proportion of each LU expansion on specific land pools. We thus reconstructed the amount of expansion of LUs on those outside-forests landpools (Pool j) by assuming that they would expand without preferential bias towards any specific pool. We thus distributed the expansion area of LU i outside forests ($EA_{LU\,i\text{ off F}}$) to each pool in proportion to the relative area of these pools within the region (equations (2) and (3)).

$$EA_{LU\,i\text{ on Pool }j} = EA_{LU\,i\text{ off F}} * \frac{\text{Area pool } j}{\sum_j \text{Area pool } j}. \tag{2}$$

With

$$EA_{LU\,i\text{ off F}} = EA_{LU\,i} - EA_{LU\,i\text{ on F}}. \tag{3}$$

Each result was capped so that the expansion cannot exceed the overall pool area—any expansion in excess was redistributed to the other pools using the same method.

2.3.2.2. Amount of food crop displacement and expansion

The total expansion of all other LUs on food crops ($\sum_i EA_{LU\,i\text{ on FC}}$) was taken as an estimate of the area of food crops displaced, and which was relocated elsewhere[6]. This area was combined to the net expansion of food crops (i.e. new demand for food crops) to obtain the total displaced and expanded area of food crops (DEA_{FC}, equation (4)).

$$DEA_{FC} = EA_{FC} + \sum_i EA_{LU\,i\text{ on FC}}. \tag{4}$$

2.3.2.3. Distribution of food crop displacement and expansion

Similarly to the LU expansion shared among various pools of land, this area of food crop displacement and expansion was then distributed to (i) forests; (ii) 'other' land; and (iii) converted cocoa, based on their relative area in the region (equation (5)) (SI figure S1(D))[7]. We assumed that food crops do not replace the

[4] e.g. fallows, bush, woodland that are <1 ha or <8 m in height or, for regions fringing the transition zone, other land uses such as orchards or cashew plantations.

[5] Indeed, two regions (Eastern and Ashanti) have seen their net cocoa area *outside* forests contracting over 2000–2019—i.e. cocoa may have expanded on forests, but the area of cocoa already present outside forests in 2000 decreased, thus freeing space for other land uses. This contraction area is used as the potential pool of cocoa land that can be converted in iv). As we only look at net expansion of land use, we do not account for new cocoa expanding into old cocoa (because this does not create any net change).

[6] In theory, pressure on food crop area could induce intensification, reducing the amount of new cropland area needed to substitute for the area displaced, but we could not find any study or evidence suggesting that farmers are increasing their inputs (labour, capital inputs) on food crops for intensifying their cultivation as a result of land pressure. Rather, farmers tend to focus their limited amount of inputs on cash crops (KI6,7). Alternatively, though not accounted for either, converted food crops could also not be entirely displaced, either resulting in more food imports or worsened food security, or could lead to an increased food crop area if displaced on marginal land.

[7] As an example, in the Western Region where there was 812 Kha of forest and 243 Kha of 'other' land not converted to other land uses, and no converted cocoa, 77% of the food crop displacement and expansion is considered having moved into forests (812/(812 + 243 + 0)).

commercial LUs, which are more profitable (see section 4.2). The 'pool' of forest available for food crops was the total 2000 forest area, minus the forest replaced by the other LUs (i.e. these LUs are considered as having priority over food crops), and capped by the 'remaining' deforestation and degradation, i.e. deforestation and degradation which was not attributed to any other LU and that can thus be due to food crops. The pool of 'other' land on which food crops may have expanded or have been displaced is the total land area minus the land area occupied by all other LU (either already in 2000 or on which they expanded up to 2019), and minus the food crop area of 2000. Finally, the pool of converted cocoa is the same as above, minus the area onto which LUs other than cocoa are considered as having expanded,

$$\mathrm{DEA}_{\mathrm{FC\ on\ Pool}\ j} = \mathrm{DEA}_{\mathrm{FC}} * \frac{\mathrm{Area\ pool}\ j - \mathrm{EA}_{\mathrm{LU}\ i\ \mathrm{on\ Pool}\ j}}{\sum_j \mathrm{Area\ pool}\ j - \mathrm{EA}_{\mathrm{LU}\ i\ \mathrm{on\ Pool}\ j}}. \tag{5}$$

Again, each result was capped so that the expansion in each pool does not exceed this pool's area. This cap was reached for food crop expansion into deforested areas (thus exceeding the area of 'remaining deforestation and degradation') in Central Region (0–3 Kha excess depending on the expansion scenario) and Western Region (10 Kha excess in the upper-bar expansion scenario, redistributed to the other pools).

2.3.3. Attributing the deforestation and degradation of land used for food crops in 2019 to the expansion of other LUs

The total deforestation and degradation of land used for food crops in 2019—which corresponds to the total displaced and expanded area of food crops into forests ($\mathrm{DEA}_{\mathrm{FC\ on\ F}}$)—was then attributed to food crop expansion itself ($\mathrm{EA}_{\mathrm{FC}}$) (linked to underlying drivers such as population growth) versus displacement due to other LUs. The share of the former corresponds to the net expansion of food crops ($\mathrm{EA}_{\mathrm{FC}}$) relative to the total $\mathrm{DEA}_{\mathrm{FC}}$ (equation (6)) (SI figure S1(E)). The share of each other LU in indirectly driving the remaining food crop deforestation ($\Delta F_{\mathrm{FC\ due\ to\ LU}_i}$) was based on their relative expansion on food crops as compared to the total displaced and expanded area of food crops (equation (7)),

$$\Delta F_{\mathrm{FC\ due\ to\ FC}} = \mathrm{DEA}_{\mathrm{FC\ on\ F}} * \frac{\mathrm{EA}_{\mathrm{FC}}}{\mathrm{DEA}_{\mathrm{FC}}}, \tag{6}$$

$$\Delta F_{\mathrm{FC\ due\ to\ LU}_i} = \mathrm{DEA}_{\mathrm{FC\ on\ F}} * \frac{\mathrm{EA}_{\mathrm{LU}\ i\ \mathrm{on\ FC}}}{\mathrm{DEA}_{\mathrm{FC}}}. \tag{7}$$

We then summed the direct and indirect deforestation and degradation areas attributed to each driver over 2000–2019.

2.4. Validation of assumptions with key informants (KIs)

To complement the literature review, we conducted semi-structured interviews with a set of 18 KIs (cocoa farmers, community leaders, NGOs, academics, government officials), to analyse the main dynamics in food crop displacement and cocoa deforestation and to cross-check the main assumptions of our methods (e.g. yields and uncertainty range of cocoa productivity in 2000, percentage of unproductive cocoa, prevalence of logging, typical land-use trajectories and priorities of certain LUs over others (e.g. cash crop over food crops) (SI table S6).

3. Results

3.1. Direct and indirect drivers of deforestation and degradation

Over the 2000–2019 period, we found that, in the entire HFZ of Ghana, 1.5 Mha (58%) of the initial 2.6 Mha of undisturbed TMF was lost, either degraded or deforested, leaving the country with about 1 Mha of undisturbed TMF and 0.3 Mha of degraded TMF in 2019, representing respectively 14% and 4% of the HFZ (figures 3 and 4(A), SI table S7).

Cocoa replaced 848 000 ha of forest (354 000 ha deforested and 494 000 ha degraded), representing 57% of the total deforestation and degradation, making it the major direct driver of forest loss over this period. Mining (3% of the total deforestation and degradation), tree plantations (2%) and settlements (<1%) had, comparatively, a limited direct impact on forests over this period (figures 4(B) and (C), SI table S8) ('direct' drivers refer to LUs detected in 2019 on land deforested or degraded between 2000 and 2019).

We estimated that 23% (CI: 21.8%–23.3%) of the total deforestation and degradation was on land used for food crops in 2019 (348 000 ha, 327–350 Kha), separated into 17% (15.9%–17.0%) attributed to the net expansion of food crops itself, representing 249 000 ha (238–255 Kha), and 7% (4.8%–7.4%) (i.e. 99 000 ha, 72–112 Kha) coming from displacement (i.e., food crops driven out of a prior area by the expansion of other LUs). In total, 28% (22%–32%) of the forest converted to food crops was thus indirectly driven by other

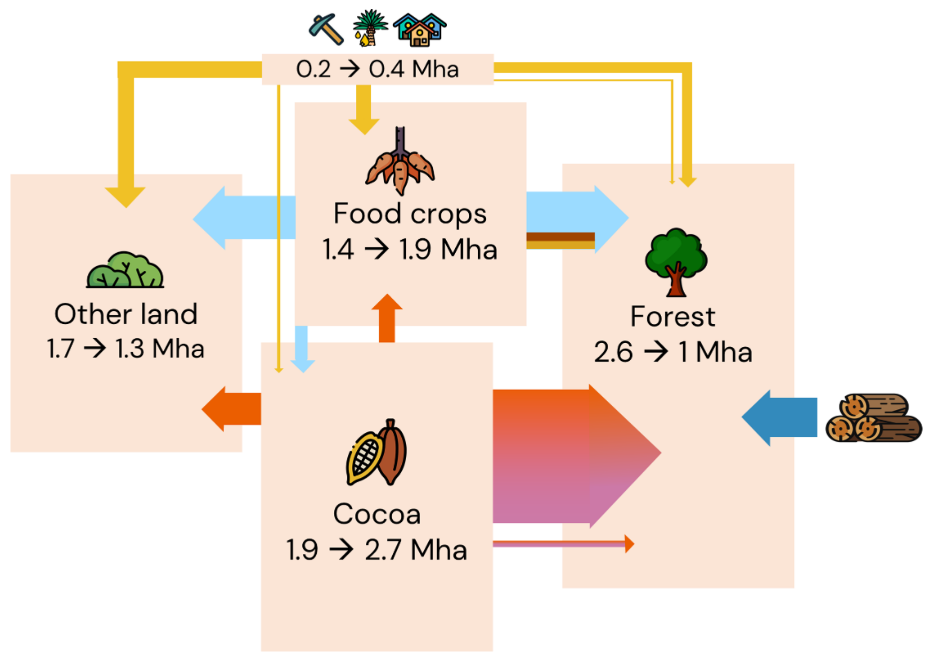

Figure 3. Schematic representation of the expansion of each land use over 2000–2019. The width of the arrows correspond to the area which expanded on and replaced the targeted land use (forest, food crops, other land or converted cocoa) according to our land-balance results aggregated at the high forest zone level. Box height represents the area in 2000. The numbers correspond to the area in 2000 and then in 2019. The thinner yellow (for mining, tree plantations and settlement) and orange/purple (for cocoa) arrows towards forests correspond to expansion on gazetted areas—as compared to the thicker arrows for off-reserve forests (cf section 3.2). The light blue arrow towards forests corresponds to the deforestation and degradation of land used for food crops in 2019, with the share displaced by cocoa (dark orange) and other land uses (dark yellow). The dark blue arrow represents the amount of remaining deforestation and degradation attributed to logging and other factors such as fuelwood collection. As food crop, logging and indirect deforestation and degradation are estimated based on statistical data, no distinction can be made between on- and off-gazetted area expansion for these drivers—their arrow thus represents the total amount of deforestation and degradation.

LUs—with 15% (9%–17%) due to cocoa, 6% (6.4%–6.6%) to mining, 4% (3.6%–4.4%) to settlements and 3% (1.9%–4.5%) to tree plantations (oil palm, rubber, coconut).

The remaining non-attributed deforestation and degradation (16% or 235 000 ha, 232–255 Kha) referred hereafter as 'logging', is considered to be mainly due to timber exploitation but also includes fuelwood collection (Ankomah *et al* 2020, Forestry Commission 2021, p50) and wildfires, especially in the upland evergreen and dry semi-deciduous zones of the HFZ which experience annual fire outbreaks.

When summing up direct and indirect deforestation and degradation for each driver, cocoa remains the major driver, representing 60% of the total deforestation and degradation (58.5%–60.6%), followed by food crops (17%) and logging (∼15%), then by mining (4%, 3.9%–4.0%), tree plantations (3%, 2.4%–3.0%) and settlements (1%, 0.9%–1.1%) (figures 4(B) and (C)). Results for the upper- and lower-bar estimates of LU expansion vary only marginally (SI figure S5). Direct cocoa deforestation and degradation occurred mainly in Western (306 Kha) and Ashanti regions (224 Kha) (figure 4(A)), and the majority of indirect cocoa deforestation and degradation took place in the Western Region (37 000 ha (17–43 Kha), i.e. 3.3%–8.3% of the total indirect deforestation and degradation through food crop displacement in the region).

3.2. Distinct on- and off-reserve deforestation and degradation patterns

In Ghana, forests are distinguished between those located in gazetted areas, comprising forest reserves (land often called 'on-reserve'), national parks, and game reserves, and those 'off–reserves', i.e. non-gazetted areas. Unlike off-reserve land, gazetted areas are protected by legal provisions restricting all forms of agricultural and forestry activities, at the exception of forest reserves where some activities are allowed in specific portions with the necessary permits, such as timber exploitation (Forestry Commission 1998, p22–29) and admitted farms, as well as food crops under the 'Modified Taungya System' (MTS) (Acheampong *et al* 2016).

Over 2000–2019, 79% of the total deforestation and degradation in the HFZ happened off-reserve, where 75% of the undisturbed forest of 2000 was deforested and 11% degraded (SI tables S7 and 8). Gazetted forests in the HFZ lost 26% of their 2000 undisturbed forest cover (314 000 ha of the initial 1.2 Mha, with 14% deforested and 12% degraded). 99% of this loss happened in forest reserves. Only 2074 ha were lost in the 5 national parks and game reserves of the HFZ (i.e. 3% of their 2000 undisturbed forest). In 2019, 83% of Ghana's remaining 1 Mha of undisturbed TMF were located in protected forests (93% in forest reserves).

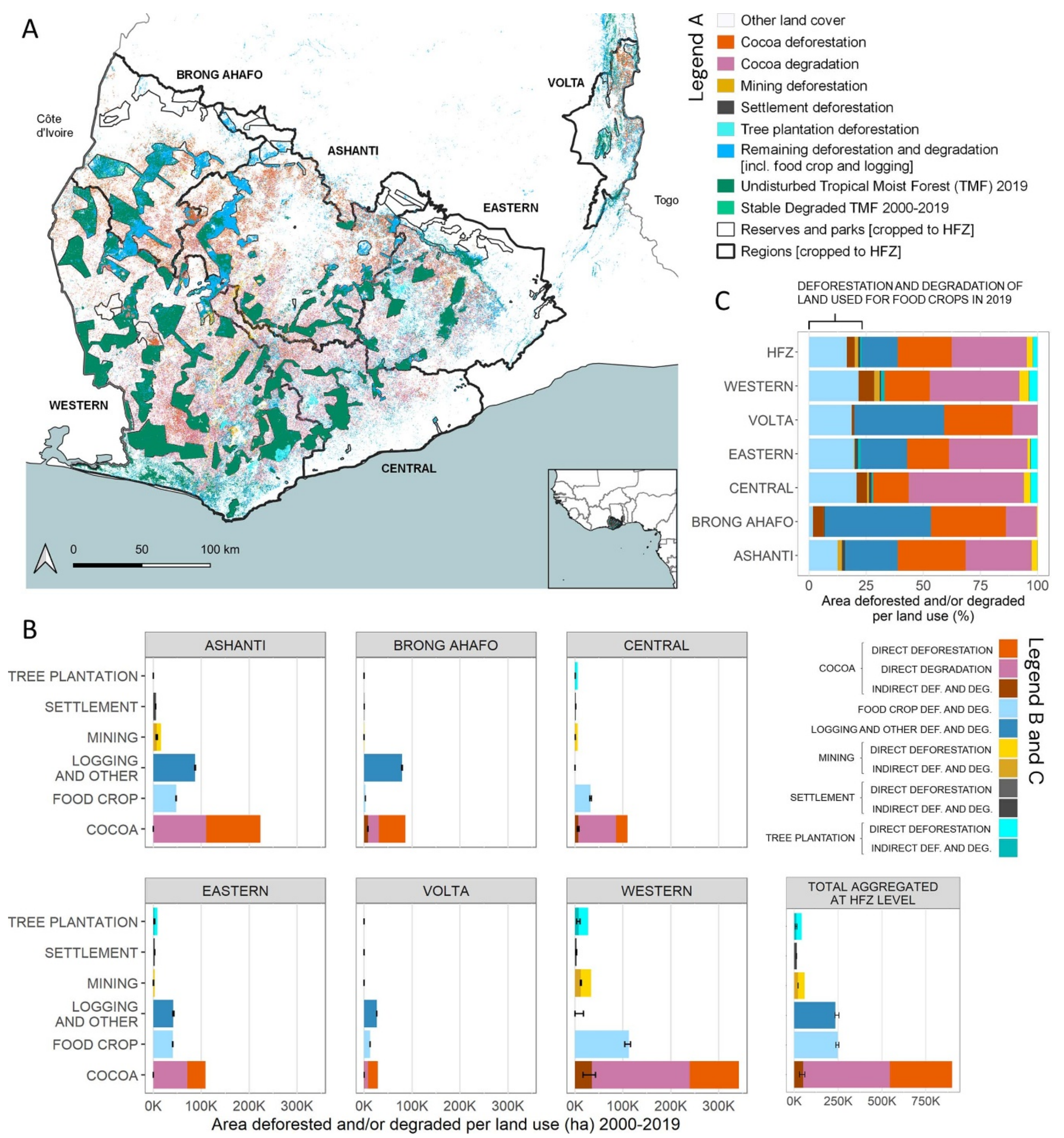

Figure 4. Deforestation and degradation per driver and per region over 2000–2019. (A) Direct deforestation and degradation map (i.e. undisturbed tropical moist forest of 2000 replaced by one of the considered land uses detected in 2019 or 2020). 'Remaining deforestation/degradation' refers to detected deforestation and degradation where none of the remotely-sensed land use was detected, thus mainly being due to food crops, logging and fuelwood collection. 'Other land cover' includes forest already degraded in 2000, as well as the areas where the considered land uses did not replace forest. (B) 2000–2019 deforestation and degradation per region of the high forest zone of Ghana, attributed to the considered land use drivers. 'Logging and other' refers to the remaining deforestation/degradation once food crop deforestation and degradation is subtracted, and is mainly due to logging. Regions here are limited to the districts part of the high forest zone. The last panel on the bottom right is the total deforestation and degradation aggregated at the high forest zone level. (C) Same as (B) but in percentage of the total deforestation and degradation in the region, or in the entire HFZ (for the last row). The deforestation and degradation of land used for food crops in 2019 and attributed to the net expansion of food crops (light blue) and—indirectly—to other drivers (dark colours) are gathered on the left side of each bar.

In gazetted areas (mostly forest reserves), 85% of the total deforestation and degradation is not directly attributed to any of the satellite-based LUs (264 000 ha—41% deforestation, 44% degradation), against only 27% off-reserve. Only 12% of the deforestation and degradation is directly attributed to cocoa (38 000 ha), 2% to tree plantations (6500 ha) and <1% to mining (2800 ha). The main direct drivers of deforestation and degradation within forest reserves between 2000 and 2019 were thus food crops and logging (figure 5), while cocoa was by far dominating off-reserve. Assuming a similar proportion of food crop (60%) vs logging (40%) in the 'remaining' deforestation and degradation in forest reserves as in the entire HFZ, we estimated that ~51% of the total deforestation and degradation in forest reserves was on land used for food crops in 2019 (60% of 85%), with ~8% indirectly driven by cocoa (15% of 51%). Accounting for both its direct

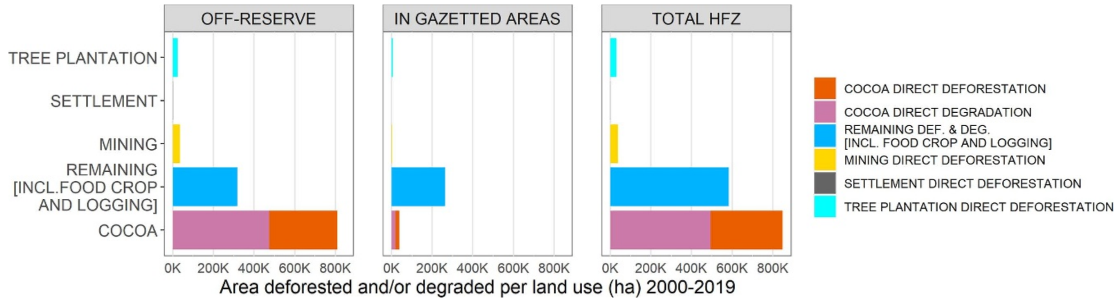

Figure 5. Deforestation and degradation per driver off-reserve, in gazetted areas and in the entire high forest zone over 2000–2019. Gazetted areas include forest reserves, national parks and game reserves. 'Remaining' refers to the deforestation and degradation not attributed to any satellite-based driver (thus including food crops and logging).

impact and indirect impact through food crops displacement, cocoa can be associated with at least 20% of the deforestation and degradation in the gazetted areas (12% directly, ∼8% indirectly).

3.3. Scale-dependent patterns

The above calculations were made at the region-level before being summed, capturing the local dynamics in each region. This approach thereby assumed that there were no land use dynamics across regions, i.e. each region functions in isolation. When repeating the same procedure directly at the level of the whole HFZ, the contraction and expansion dynamics occurring in distant locations average out and hence affect the overall outcome. Over 2000–2019 in the HFZ, cocoa is the LU which expanded the most, with a net expansion area of 790 000 ha (582–961 Kha), from 1.87 Mha (1.7–2 Mha) in 2000 (which, when removing the 24% unproductive cocoa farmland, is similar to the 1.3 Mha of harvested area reported by FAO for 1999–2001) to 2.66 Mha in 2019. Net expansion of food crops was 500 000 ha, mining 113–141 000 ha, tree plantations (including rubber, palm oil and coconut) 54–104 000 ha, and settlements 70 000 ha (SI figure S5).

Yet, at the HFZ level, the net expansion area of cocoa on land not forested in 2000 was negative over that period (−57 000 ha, −266 Kha/+113 Kha). Cocoa thus expanded massively into forests, replacing 848 Kha of forest, but on net, contracted or barely expanded outside forests, essentially in the Eastern and the Ashanti Regions. This reflects the historical shift of the cocoa frontier from eastern to western Ghana, in search for available land and fertile soils, while the old unproductive cocoa farms were slowly abandoned and converted to other LUs such as oil palm or food crops (Ruf 1987, Asubonteng *et al* 2018). In the Eastern Region, cocoa replaced 108 000 ha of forests but shrunk outside forests (−265 000 ha (−314/−224 Kha), with a net contraction of −156 000 ha (−205/−116 Kha). Similarly, cocoa moved into forests in the Ashanti Region, with 224 000 ha of forest converted to cocoa, but lost an area of 87 000 ha (−142/−41 Kha) outside forests, resulting in a net expansion of 137 000 ha (80 K–183Kha). In contrast, the other four regions experienced an expansion of cocoa both into and outside forests, particularly in the Western Region (which here includes Western North), where cocoa expanded by 427 000 ha (354–488 Kha) (62% of the total LU expansion in the region), of which 121 000 ha outside forests.

Cocoa expansion outside forests in the west-ward regions is smaller than contraction in Eastern and Ashanti Regions. As our methods use the expansion of cocoa outside forests to attribute indirect deforestation, the HFZ-level analysis attributes limited (0%–7%) food crop deforestation and degradation to cocoa.

3.4. Projecting trends in the future

Cocoa is the dominant LU in the HFZ of Ghana in 2019, occupying 34% of the entire area, and nearly half of the Western Region (figure 6(A)). This region, in addition, has no remaining pool of land other than food crops and forest into which cocoa or other commodity LUs could potentially expand, indicating a saturation of the landscape. As a simple thought exercise, we projected the past 2000–2019 annual expansion rates of each LU to the next 2020–2030 decade, and compared this to the remaining forest and other land area. In this exercise, the potential expansion, mainly of cocoa, would necessarily have to occur at the expense of the remaining undisturbed TMF in the Western Region (figure 6(B)). In the Central Region, the projected expansion of LUs would exhaust almost all the remaining forest area. In the Eastern Region, the contraction of cocoa area over the last two decades might release land for other LUs. Even when some 'other' land is available for expansion, converting them for food crops, cocoa or other commodity crops would entail trade-offs, as this land might include fallows that are part of the agricultural system, bushes and other natural vegetation providing various products and services.

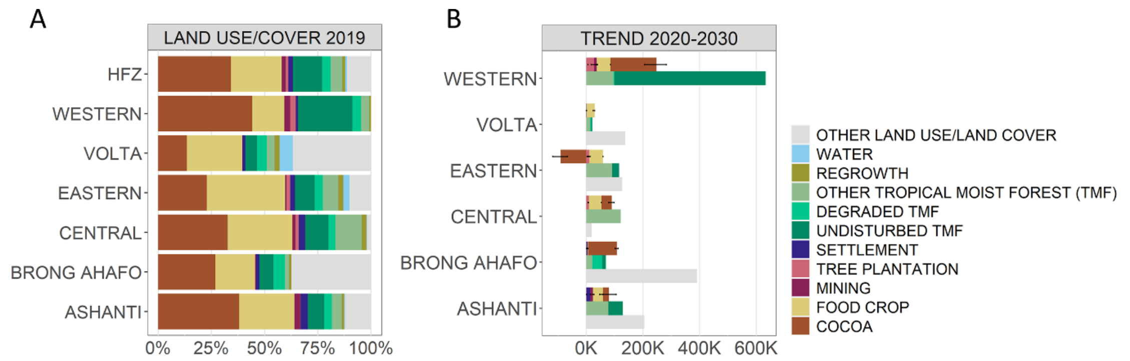

Figure 6. Land use in 2019 and projection over 2020–2030. (A) Percentage of each region (restricted to HFZ) occupied by each land use in 2019–2020. 'Other tropical moist forest' refers to trees lower than 8 m in patches smaller than 1 ha patches in 2019 (from which cocoa was masked out). 'Other land uses/land covers' refers to land not occupied by the other considered land uses—which could correspond to bush, fallows, grasslands, or cashew and orchards not included in our analysis. (B) Trend over 2020–2030 of the expansion area of each land use annualised over 2000–2019 and multiplied as a rough projection over 2020–2030 (above stacked bar), compared to the remaining tropical moist forest (TMF) in 2019 (middle stacked bar), and to the 'other land uses/covers' remaining in 2019 (bottom bar).

4. Discussion

4.1. Direct and indirect deforestation and degradation: comparison with other studies and limitations

4.1.1. Comparison with other studies

Our results show the large footprint of cocoa on Ghanaian forests, making it the major direct, but also indirect, deforestation driver over 2000–2019, ahead of food crops, logging, mining, tree plantations and settlement sprawl combined. Food crops and logging are the next two major deforestation drivers according to our analysis. Masolele *et al* (2024), while not accounting for indirect effects, similarly find that mining, tree plantations, and settlements were minor drivers of deforestation in Ghana, though their analysis at the national scale highlights the relative importance of food crops versus cocoa when including the transition zone and savannah regions (occupying 37% vs 25% of land deforested from 2000–2019, respectively). Ghana's REDD+ report (Forestry Commission 2016) attributes 35% of the national deforestation and degradation to wood harvesting (vs ∼16% from our findings for the HFZ), 10% to population and development pressures (vs <1%, knowing that the HFZ excludes the Greater Accra Region), 5% to mining and mineral exploitation (vs 3%) and 50% to agricultural expansion, versus 83% from our findings when accounting for all agricultural post-clearing LUs (i.e. cocoa, food crops and tree crops). Our estimate is close to Acheampong *et al* (2019)'s finding of 78% of the forest loss caused by the expansion of annual crop farms and tree crops in the Ashanti Region. Using Hansen *et al* (2013) data as a foundational layer to define natural forests (vs JRC TMF), Singh and Persson (2024) find ∼437 000 ha of cocoa deforestation over 2001–2019; 83 000 higher than our cocoa deforestation estimate (excluding degradation) which also restricts forests in 2000 to >8 m canopy height and >1 ha patches. Sub-regional landscape-level studies find a contribution of cocoa to forest loss between 24% in the Eastern Region (Asubonteng *et al* 2018) (vs 53% from our findings, SI table S7), and >50% in the Western Region (Benefoh *et al* 2018, Ajagun *et al* 2022, Ashiagbor *et al* 2022) (SI table S1) (vs 59%).

According to our analysis, mining was not a major deforestation driver between 2000 and 2019. The mining dataset used in our research (Maus *et al* 2022) detects 140 000 ha of large-scale and artisanal and small-scale mining sites in the study area in 2019 (191 Kha in the entire Ghana). Although the mining area has increased rapidly in Ghana over recent years (doubling from 31 to 67 Kha between 2019 and 2024 for artisanal and small-scale gold mining only, according to CERSGIS (2025)), the land footprint of mining remains limited compared to other LUs, especially cocoa (2.66 Mha) and food crops (1.86 Mha). Importantly, the environmental impacts of mining activities go well beyond deforestation and are significantly harder to reverse or restore, reducing the possibility of using the land for other purposes in the future (Boateng *et al* 2014, Eberhard *et al* 2022, Obodai *et al* 2024) (see text S4.1 for further details on mining).

4.1.2. Complex LU transitions

Land-use change dynamics are complex and deforestation or forest degradation rarely have a single underlying cause (Pendrill *et al* 2022a). In a context of unstructured, collective harm, building on Brülde *et al* (2023), and in the absence of annual time series of land use data, we attribute the impacts to LUs based on 'participation', here assessed as the contribution to additional land demand in the region, rather than counterfactual reasoning. We assessed deforestation drivers using the *net* LU expansion, thus not capturing gross transitions between LUs. It is possible that other LUs occurred between the deforestation event and the LU observed in 2019. Yet in the context of the 2000s' cocoa boom and the comparative perceived advantages of cocoa, there is convincing evidence that land detected as cocoa in 2019 was initially deforested with the intention of growing cocoa (Ruf 2007a, Clough *et al* 2009, Benefoh *et al* 2018, Ashiagbor *et al* 2022). Besides, our research was limited to the indirect deforestation linked to the displacement of food crops only, and thus does not reflect all indirect dynamics at stake. LUs like mining can also have other indirect effects such as attracting workers who will settle nearby and grow their own crops—thus increasing mining's indirect role in driving deforestation (Giljum *et al* 2022). The land-balance approach used here to identify indirect drivers of deforestation through food crop displacement captures how different LU expansions contribute to the overall pressure on land in a landscape but does not disentangle or trace these complex land-use trajectories and underlying causes. Although these limitations restrict our ability to precisely assess causal land-use dynamics, our analysis provides the most convincing evidence so far on these dynamics.

4.1.3. Entanglement of logging with other drivers

In addition, limitations inherent to spatial and statistical datasets may produce uncertainties in the results, though there is no evidence to suggest specific biases in one or another direction (table S2). The role of logging (legal and illegal) and wildfires in deforestation and degradation (∼16%, versus 35% in Ghana's REDD+ report) is particularly hard to disentangle from food crops and other LUs. They are highly intertwined, with for instance farmers felling trees to get enough light to start their crop, or establishing their crop on land originally cleared for timber. Within forest reserves, the 'MTS' allows specific community groups to temporarily farm degraded land for food crops, provided they plant tree seedlings within their farm and stop farming once the canopy closes. Though we could not access MTS maps to assess the proportion it represents, logging's prevalence in deforestation is certainly higher than we estimate. Logging could thus be involved in between ∼16% (our conservative estimate, which prioritises attribution to food crops) and up to ∼40% of the overall deforestation and degradation, if considering that all food crops in forests were established on already degraded land—or even higher, knowing that cocoa expansion also tends to follow the relics of previously logged areas (Benefoh *et al* 2018).

4.1.4. Land-balance model uncertainties

Similarly, our results represent a conservative—and probably underestimated—quantification of indirect deforestation, especially for cocoa. No preferential criteria were applied to the expansion of LUs; they had the same probability to expand on any of the available pools of land. However, as no quantified estimate of these land-use trajectories could be made, we maintained the neutral assumption as a conservative approach. Also, estimates of the LU areas in 2000 (and thus their expansion area) contain uncertainties (table S4, text S1.4). As an example, absent sub-national estimates, we added the same 24% of unproductive cocoa area in 2000 to each region, which may overestimate the initial cocoa area in regions having more productive farms. Consequently, the cocoa expansion after 2000 is probably underestimated, leading to an underestimation of the share of indirect deforestation attributed to cocoa. Further, in our land-balance model, regions at the periphery of the cocoa-growing landscape, such as Brong Ahafo, Central, Eastern and Volta Regions, include more 'other' land (figure 4(A)) which absorbs a substantial part of the LU expansion and food crop displacement. This reduces the share of food crop and indirect deforestation and degradation, and may thus not capture sub-regional realities. Finally, additional uncertainties arise from the fact that pressure on food crop area could induce a contraction (through intensification, or more food imports and/or worsen food security) or an increase in food crop area (if displaced on less productive land). In the absence of evidence suggesting one or the other, our model displaces 1 ha of food crop for each converted hectare.

4.1.5. Scale-dependent patterns

In attributing deforestation to LUs, the scale of analysis matters, especially for land-balance models (Zu Ermgassen *et al* 2024). This scale dependency can explain the difference between our results and those of Pendrill (2022b), who use a similar land-balance model for attributing deforestation but at national-level, based on FAO agricultural statistics. At national scale, local ecoregions and land-use trajectories are not accounted for, and cocoa is thus considered as expanding on pastures (though these are mostly located in the savannah regions where cocoa does not grow) rather than forests—resulting in no deforestation attributed to cocoa in Ghana according to their study (SI table S1). Using a land-balance approach, the role of cocoa thus appears when focusing on the regional dynamics within the HFZ. Similarly, the role of mining appears very important but at a more local scale, such as within mining concessions, where mining was found to be the major driver of deforestation and to displace farmland within forests (Schueler *et al* 2011).

4.2. The role of cocoa expansion in driving food crop deforestation

Over 2000–2019, most deforestation and degradation happened off-reserve, where cocoa has been the lead driver and is legal (Ashiagbor *et al* 2022). Our results indicate that cocoa directly drove little deforestation in forest reserves, where food crops and logging were the major direct drivers of forest loss. Yet, as observed by several studies (Ajagun *et al* 2022, Kumeh *et al* 2022) and as shown by our land-balance, though direct cocoa-driven deforestation in reserves is relatively limited, cocoa expansion indirectly plays a large role by displacing food crops into forests—mainly because the massive expansion of cocoa has led to a saturation of the landscape, especially in the Western Region, with cocoa occupying 44% of the region resulting in 'monotypic cocoa landscapes' (Ajagun *et al* 2022) (figure 6).

This relates to well-described cocoa cycles (Ruf and Siswoputranto 1995, Clough *et al* 2009). In a new cocoa basin, farmers take advantage of the 'forest rent', providing 'vacant' land and high yields from nutrient-rich soils generating good income, thus attracting more labour and creating a production boom (Benefoh *et al* 2018, Acheampong *et al* 2019). After ∼20 years, cocoa farms become less productive due to ageing farmers and trees, depleted soils and the increasing prevalence of pests and diseases. In parallel, the production surplus may have led to decreasing market prices when the affected area is large enough. The drop in production, combined with limited income for farm rehabilitation, eventually leads to a cocoa bust. As a result, market prices may rise again, favouring the start of a new cycle—with the opening of a new forest frontier and the emergence of a new cocoa production basin where forest and labour is available. This boom was observed for instance in the Western Region in the early 2000s (Ruf 2007a). The start of the cycle, involving many young cocoa farms, is coupled with high food production (intercropped with cocoa seedlings), while the end of the cycle is characterised by land saturation, which, coupled with population increase, makes available land off-reserve scarce (Benefoh *et al* 2018, Kumeh *et al* 2021, Kyere-Boateng and Marek 2021, Ashiagbor *et al* 2022, CFI 2023). When the land-balance model is applied at the HFZ level, the contraction of cocoa in the Eastern Region cancels out the displacement of food crops by cocoa in the western part. This reflects the east–west shift of cocoa in Ghana and the fact that, overall, the *net* cocoa area expansion across Ghana was smaller than the *gross* expansion in the western part of the country, but this hardly reflects the socio-ecological impacts of the dynamics at play. Displacement of LUs can happen within a locally-saturated area, with farmers forced to clear new patches of land—legally or illegally—to plant their food crops, even if land would be available in a distant location.

Local land saturation by cocoa can be considered as the main mechanism driving food crop deforestation, via two dynamics. First, cocoa replaces food crops off-reserves (Ajagun *et al* 2022, Asubonteng *et al* 2018, KI4,7). Farmers make this shift because they lack land and are searching for financial security, which can be better ensured by cocoa than food crops (as cocoa is paid in bulk, with a fixed price, and can pay for school fees for instance) (Ajagun *et al* 2022). To a lower extent, converting food crops to cocoa is also linked to societal norms (being a cocoa farmer provides a higher social status) and to the prevention of land tenure conflict—cocoa being a way of securing land ownership, at least for the lifetime of the cocoa trees (Hirons *et al* 2018, Ajagun *et al* 2022). Second, even if no further cocoa expansion would occur, by occupying a vast share of the landscape, cocoa leaves little land available for new food crops, as shown above. Farmers can sometimes find no other option than to look for land in forest reserves (Benefoh *et al* 2018, Kumeh *et al* 2021, 2022, Ashiagbor *et al* 2022). Growing food crops within forest reserves is perceived as less risky than growing cocoa, which requires more time to become productive and more investments—while being less tolerated by forestry officials. Thus, to avoid seeing their efforts cut down by forest guards, farmers tend to favour food crops over cocoa in forest reserves (KI2-4,6, FG1). This differential perception of risk also reinforces the conversion of food crops to cocoa; anticipating that growing food crops on-reserve is, at least to a certain extent, possible, farmers in communities fringing forest reserves may count on forest reserves as a pool of land for their food crops. This pattern may however vary among communities; e.g. cocoa happens to be illegally grown in forest reserves, particularly where admitted farms are located (Benefoh *et al* 2018, Brobbey *et al* 2020, Kumeh *et al* 2021).

The lack of land, the conversion of food crops to cocoa and their subsequent displacement in forests can be seen as 'push' factors—pushing food crops in forests. The MTS on the other hand acts as a 'pull' factor, facilitating the entry of food crops in degraded forest reserves—legally at first, but in many instances making way for further encroachment beyond the initial delineations (Ankomah *et al* 2020, Kumeh *et al* 2021). Other factors play a role, such as forest soils' fertility (Ruf and Siswoputranto 1995), weak law enforcement (Acheampong *et al* 2019), the 'right to food' and rights to the land claimed by some communities (Acheampong *et al* 2019, Kumeh *et al* 2021), and poverty and the lack of alternatives (Ashiagbor *et al* 2022). Land-use segregation is thus underway in communities fringing forest reserves, with off-reserve land increasingly dedicated to cocoa and other cash crops, and on-reserve land mainly used for food crops, either legally or illegally.

This may explain the seemingly contradictory discourses around deforestation in Ghana. Amidst the debates aiming at attributing the responsibility of the rise in deforestation and degradation between 2017 and 2018 (+60%) to specific drivers, Dekker (2019) pointed at large scale non-cocoa agricultural expansion (thus including food crops), logging, mining, and fire, while Weisse and Goldman (2019) emphasised the role of cocoa expansion. Reconciling these discourses requires to note that, although—as shown by our results—cocoa was historically by far the main direct driver of deforestation and degradation in Ghana, in recent years, forest has shrunk up to the point of being limited to forest reserves where cocoa is more strictly forbidden and thus more difficult to cultivate, making logging and food crop production the new main observed direct drivers of deforestation and degradation—as reflected by the assessment of the CFI priority landscapes identifying food crops as the main deforestation driver in 2019–2022 (CFI 2023). Yet, behind the scenes, cocoa continues to play a determining role in land-use dynamics and deforestation.

4.3. Is deforestation-free cocoa possible?

4.3.1. Deforestation leakage

iLUC, as shown by our results, can represent an important deforestation leakage for policies aiming at halting deforestation, such as private ZDCs (Lambin *et al* 2018) or the EUDR. First, as long as such policies remain individual company choices (i.e. ZDCs), or are enforced only for a single export-market (i.e. EUDR), the whole sector is not covered and a 'supply-chain leakage' can occur, where farmers continue to produce cocoa linked to deforestation but shift to other buyers (also referred to as 'market segmentation') or sell their products by 'laundering' them through intermediaries (Meyfroidt *et al* 2018). As an example, the state-owned Produce Buying Company—second largest licenced buyer in Ghana—has not adopted a ZDC, while Asia is the second largest destination for cocoa beans from Ghana (25%), offering a way out for cocoa that does not comply with ZDCs or the EUDR (COCOBOD 2020). Companies may favour sourcing from low-risk regions—away from remaining forests; however, non-compliant cocoa will still continue being traded by uncommitted intermediaries and/or will find its way to the non-EU market (Bakhtary *et al* 2020). Second, policies such as ZDCs or forest protection (e.g. forest reserves) limit the availability of land for further expansion of cocoa but lead, as shown by our results, to iLUC—with cocoa expanding on food crops and saturating space off-reserve and food crops being displaced in forests. This could be identified as an 'activity leakage', where the LU targeted by restrictions (cocoa) concentrates on allowed lands (off-reserve), and labour and capital used on these lands are reallocated to places with available and accessible land (here food crop farming being reallocated to forests) (Meyfroidt *et al* 2018). Though our results do not demonstrate the causal attribution of this displacement to ZDCs and forest protection interventions, the forthcoming EUDR may further strengthen this spillover mechanism by increasing the surveillance of cocoa deforestation.

In practice, these supply chain-focussed policies have had only limited success (Garrett *et al* 2018) and, because they do not account for deforestation leakage, their potential conservation outcome will continue to be curtailed (Lambin *et al* 2018, Gardner *et al* 2019, Garrett *et al* 2019, Gollnow *et al* 2022). Increasingly, landscape or jurisdictional approaches, where stakeholders collaborate in a specific landscape or jurisdiction to promote sustainable resource use (Reed *et al* 2016, von Essen and Lambin 2021), are put forward as a complementary tool in addressing deforestation. They indeed have the potential to internalise indirect sourcing and deforestation drivers beyond the focal commodity (Parra-Paitan and Verburg 2022, Zu Ermgassen *et al* 2022, Parra Paitan 2024). However, it is unlikely that these initiatives would rapidly cover all forests across the tropics, thus keeping the door open to deforestation leakage. Landscape approaches are thus highly relevant and necessary to preserve forests while ensuring a just transition for involved stakeholders, but require complementary tools to halt deforestation—including a way of addressing key underlying drivers of deforestation.

4.3.2. A more transformative vision: addressing key underlying drivers of deforestation, industry growth, and economic dependency

Ultimately, the saturation of the landscape by cocoa and thus the direct and indirect deforestation in Ghana and other similar cocoa-dominated regions is rooted in a growing cocoa sector, driven by an ever-growing international cocoa industry and a global demand increasing at ∼3% per year (Beg *et al* 2017), requiring more land. Yields could certainly be improved in order to slow the need for expansion, yet, with cocoa yields stagnating around ∼500 kg ha^{-1} in Ghana and Côte d'Ivoire for the past decade despite industry's efforts (Asante *et al* 2021), and the increasing adverse impacts of climate change (Schroth *et al* 2016), it is unlikely that cocoa yields could be raised enough to decouple the increasing international demand from land area used—as a comparison, the highest increase in yields during the Green Revolution was 5% per year for wheat (FAO 2004). Further, an increase in yield may generate a rebound effect, spurring even more forest conversion to cocoa (Byerlee *et al* 2014, Rodriguez García *et al* 2020, Goulart *et al* 2023). Though largely disregarded by deforestation-free policies (Kumeh and Ramcilovic-Suominen 2023), the overall level of consumption of cocoa and other deforestation-risk commodities by high-income countries should be part of the discussion to reach the goal of deforestation-free landscapes. Shifting from mass consumption of low-priced bulk cocoa to smaller consumption of well-paid cocoa could limit negative impacts on cocoa households and producing regions.

Nevertheless, beyond deforestation, whether or not Ghana (or Côte d'Ivoire, as another major cocoa producer) should keep focusing on cocoa as a key economic sector—leading to land saturation for a single commodity dedicated to export—can be questioned. Specialising in export-oriented cash crops generates multi-facetted dependencies to international market demand, energy prices (e.g. for transport, transformation, synthetic inputs), and domestic production capacities—all vulnerable to increasing climate shocks and, in the mid-run, to decreasing affordable fossil fuel resources (Daruich *et al* 2016, de Roest *et al* 2018, UNCTAD 2023). By occupying land, export-crops directly compete with food crops destined for the domestic market, and can put food availability and access at risk in case of disruptions in productivity or low international market prices of export crops relative to food crops (Anderman *et al* 2014, Feyaerts *et al* 2020). Recent signs of the emergence of a structural cocoa recession in Ghana and Côte d'Ivoire, following the cocoa cycles (Ruf 2024), highlight the risk of a strong dependency on cocoa. If planned with appropriate policies and political will, downsizing the importance of cocoa in the economy could free up land for diversification from export-dependent crops and participate in building resilience. Some farmers are currently making this move away from cocoa by establishing permanent food crops (Hirons *et al* 2018).

Yet, a progressive diversification away from the single dominance of cocoa (or other export-crops) in major producer countries would require lifting structural 'lock-ins' such as, at the country level, the dependency on earning foreign currencies—required notably to service financial debts (World Bank 2023), as well as the vested interests in cash-crop production and trade from actors in government, companies and some civil society organisations (Odijie 2018). At the farmer level, the 'cocoa poverty trap' acts as a major lock-in—where farmers are unable to gather the required capital to rehabilitate their farm or shift to another crop due to a combination of factors, including low cocoa income from low value capture by farmers in the cocoa supply chain (BASIC and FAO 2020) and low yields of ageing farms (van Vliet *et al* 2021, Hütz-Adams 2022).

Hence, policies addressing poverty to lift these lock-ins must also be part of the discussion—including a structural transformation in international trade relations, rebalancing power and wealth distribution (Hickel *et al* 2022). Scientists, indigenous people, policy makers and civil society around the world are now increasingly advocating for more transformative visions such as doughnut economies (Raworth 2017), foundational economies (Bentham *et al* 2013), socio-bioeconomies (Garrett *et al* 2024), democratic economic planning (e.g. Devine 1988) or degrowth (Weiss and Cattaneo 2017), among others. These calls include ideas that challenge continuous growth, support structural transformations of the economies away from extractive and degrading processes towards more regenerative and restorative approaches, and recentre policy objectives around sustainability, justice, diversity, and resilience. Compared to current isolated deforestation efforts, such approaches offer new avenues to address the lock-ins and complexities currently affecting the West African cocoa sector to tackle deforestation in a more systemic way.

5. Conclusion

We found that cocoa was the main direct but also indirect driver of deforestation and forest degradation in the HFZ of Ghana between 2000 and 2019, followed by food crops and logging. Mining, tree plantations and settlements had, comparatively, a limited direct impact on forests over this period, though rapid mining expansion has raised attention over the recent years. Cocoa mainly replaced off-reserve forests, with a relatively limited impact in forest reserves where food crops and logging, as well as other factors such as wildfires, were the major direct drivers of deforestation and degradation. Our land-balance approach shows that about a fourth to a third of the forest land converted to food crops corresponded to food crops being displaced by other LUs—with half of this displacement being due to cocoa expansion. In addition to the conversion of food crops to cocoa, the saturation of land by cocoa, especially in the Western and Western North Regions, forces farmers to search for land within forest reserves which they mainly use to grow food crops, either legally, under the MTS, or illegally. Accounting for both its direct and indirect impacts, cocoa is an important pressure on these gazetted forests. These findings show the need for private ZDCs and public legislations to move away from narrow, single commodity-focused initiatives aimed at halting deforestation. Instead, these initiatives should take into account the dynamics of the entire landscape, acknowledge the systemic linkages between cocoa, food crops and other LUs, integrate all drivers and anticipate rebound and leakages. Most importantly, underlying causes should be tackled, such as the industry growth, calling for demand-side actions, and poverty, demanding structural changes in international trade relations, rebalancing power and wealth distribution.

Data availability statement

The data and code that support the findings of this study are openly available at the following URL/DOI: https://doi.org/10.5281/zenodo.15267020.

Acknowledgment

This research is part of the SUSTAIN-COCOA project, funded through the 2019-2020 BiodivERsA joint call for research proposals under the BiodivClim ERA-Net COFUND programme, and with the funding from the *Fonds de la Recherche Scientifique*—FNRS under Grant n°PINT MULTI/BEJ - R.8002.20. We thank Sustain-Cocoa's teams for their guidance and feedback. This work contributes to the Global Land Programme glp.earth.

ORCID iDs

Cécile Renier https://orcid.org/0000-0002-8235-1183
Thomas Addoah https://orcid.org/0000-0001-8333-1283
Valentin Guye https://orcid.org/0000-0002-8530-7292
Rachael Garrett https://orcid.org/0000-0002-6171-263X
Goedele Van den Broeck https://orcid.org/0000-0002-8480-3526
Erasmus K H J Zu Ermgassen https://orcid.org/0000-0002-9168-6057
Patrick Meyfroidt https://orcid.org/0000-0002-1047-9794

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