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Deforestation and climate risk hotspots in the global cocoa value chain

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ABSTRACT

In this study, we produced a spatially explicit diagnosis of the deforestation hotspots and future climate risk (2050) of cocoa producing areas, zooming into the top 8 cocoa exporting countries and the main global cocoa traders. Cocoa-driven deforestation often co-occurs with deforestation driven by other agri-commodities, and thus needs to be tackled jointly. Climate risk will be substantially increased in Cote d'Ivoire and Ghana, the two most important suppliers of cocoa, which may lead to supply failures and severe socio-economic impacts if left unaddressed. Climate risk and deforestation have a high spatial variability between and within countries, calling for geographically differentiated approaches to mitigation and adaptation. Large transnational traders depending heavily on West African supplies, as well as the regionally based exporting farmer cooperatives and domestic firms, will be affected by the increased climate risk in that region. Traders operating in Latin America and Southeast Asia might only face a modest increase in climate risk, with subregional exceptions. These results raise concerns about the validity of sustainability commitments made by companies and other sector initiatives, which focus on single commodities and fail to consider the diversity of actors adding pressure on landscapes. Tackling these issues requires a collaborative effort from various sectors and stakeholders involved in land use decisions to prevent the geographical displacement of negative impacts, prioritize urgent action, and implement these changes efficiently and in a coordinated manner. Further, sustainability commitments often neglect climate change adaptation, with agroforestry and climate smart agriculture initiatives primarily focusing on carbon reductions and increased farmer income, paying less attention to farm practices that reduce cocoa vulnerability.

1. Introduction

Cocoa production is both a driver of climate change and is highly vulnerable to its impacts. Greenhouse gases (GHG) are primarily emitted during the removal of tropical forests for cocoa farm establishment (Parra-Paitan and Verburg, 2022). Deforestation is one of the most negative environmental impacts associated with cocoa production as, besides releasing GHG, it causes habitat destruction, biodiversity loss, and soil degradation (Maney et al., 2022; Sassen et al., 2022). Cocoa is produced worldwide by over 5 million farmers, the majority of whom are smallholder family farmers producing below cocoa yield potentials and without a minimum living income (Bermudez et al., 2022; Fountain and Huetz-Adams, 2020). Climate change is expected to exacerbate these concerns due to increasing climatic stress that will negatively affect cocoa producing regions with rising temperatures, changes in rainfall patterns, and more intense and frequent drought events (Ercin et al., 2021; Malek et al., 2022). In the absence of adaptation measures, climate change will increase the vulnerability of cocoa farmers and disrupt global cocoa supplies, with knock-on effects for the economies of cocoa producing countries and businesses across the cocoa value chain.

Given the urgency to act upon these challenges, coming regulatory initiatives are increasingly mandating governments and companies to take action. Across major cocoa consuming regions, approved and coming legislative regulations are set to grant market access only to businesses addressing sustainability issues related to human rights and the environment. The European Deforestation-free legislation will require companies to demonstrate that certain forest-risk commodities imported into the European Union have not been produced at the

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expense of natural forest cleared after December 2020 (European Commission, 2021). Complementarily, the proposed European Due Diligence legislation will request companies importing goods into the European Union to perform due-diligence assessments to identify, prevent, mitigate, monitor, remediate, and verify environmental damage and human-right abuses within their own and subsidiaries' operations (European Commission, 2022). Similar legislative initiatives are foreseen in important consumer markets such as the USA and the UK. Cocoa producing countries and cocoa value chain actors need to swiftly establish robust and transparent systems to account for, monitor, and remediate sustainability issues related to their operations, including deforestation and climate risk.

To prioritize action and guide the implementation of mitigation strategies, it is necessary to identify hotspots of risk across the global cocoa value chain. Such identification is crucial for informing decisions to mitigate local risks and to provide an overview of risk hotspots at a wider geographic range so that local mitigation actions implement measures to avoid displacing negative impacts across scales. Having this overview of risks can also help regulators to prioritize actions, balance the trade-offs of risk mitigation measures and avoid opportunistic behavior, thus ensuring net sustainable outcomes, and avoiding worsening inequality among farmers, producing regions, and companies. In this study, we applied spatial analysis and exploratory statistics to quantify and characterize the risk levels of the top 8 cocoa exporting countries and the major traders operating in these countries for two of the most pressing environmental issues affecting the global cocoa value chain: deforestation and climate risk. We build on datasets developed by previous studies to ask: (i) Where are climate risk and deforestation hotspots located? (ii) Where do climate risk and deforestation hotspots converge? (iii) What is the level of climate risk and deforestation attributable to cocoa of global cocoa traders? Earlier research quantified cocoa-driven deforestation (Pendrill et al., 2022, Goldman et al., 2020, Renier et al., 2023), and cocoa climate risks (Ceccarelli et al., 2021; Ercin et al., 2021; Gateau-Rey et al., 2018; Igawa et al., 2022; Läderach et al., 2013; Malek et al., 2022) within jurisdictional boundaries or from a global perspective. This study provides a more detailed analysis by examining jointly two of the most pressing environmental risks in the cocoa sector, in a spatially explicit manner. It dissects these risks for each of the world's cocoa trading companies based on their sourcing patterns. The latter is of utmost importance given that traders can be key actors in charge of operationalizing sustainability action (Grabs and Carodenuto, 2021; Parra-Paitan et al., 2023).

2. Methods

We combined four spatially explicit datasets providing information of cocoa production area, cocoa yield, deforestation driven by agri-commodities, and the future climate risk of cocoa (Table 1). Cocoa crop area and yield were obtained by the model "Mapping and Analysis of Agro-Ecosystems and their Potentials" (MapSPAM), which used a combination of satellite imagery, statistical modeling of biophysical factors, crop production primary data, and agriculture statistics to spatially allocate global production areas of 42 crops for 2010 (IFPRI, 2019). Sub-Saharan data exists for 2017, but for consistency, we utilized 2010 maps for all geographic areas. The maps linking deforestation to agricultural expansion (for each of these seven commodities: cocoa, robusta coffee, arabica coffee, oil palm, soybean, and pasture lands) were obtained from Goldman et al. (2020). That study quantified and spatially allocated the yearly extent of deforestation driven by each crop by combining crop distribution maps of MapSPAM or, depending on the crop, more detailed/recent sources, with yearly FAO statistics on farm area per country, and yearly deforestation maps (2001–2018) of Hansen et al. (2013). Goldman et al. (2020) allocated all commodity-driven deforestation proportionally to the crop area of seven commodities, potentially leading to overestimation and not necessarily implicating that a specific commodity was the primary deforestation driver.

Table 1
Detail of datasets used.

Variable	Description	Unit	Resolution	Source
Cocoa production area	Area of physical cocoa farms	ha	0.5 × 0.5-degree	IFPRI, (2019)
Cocoa yield	Average cocoa production in kilograms per ha.	kg/ha	0.5 × 0.5-degree	IFPRI, (2019)
Deforestation driven by agri-commodities	Area of forests replaced by cocoa, oil palm, robusta coffee, arabica coffee, pasture, and soybeans	ha	0.5 × 0.5-degree	Goldman et al., (2020)
Climate change risk (Drought severity index)	Indicator of drought severity (SE) based on duration and intensity modelled under RCP 6.0 and 2.6 scenarios for 2050.	SE	0.5 × 0.5-degree	Ercin et al., (2021)
Cocoa traders' sourcing matrix	Global cocoa trader types and market share in the top eight exporting countries.	-	-	Parra-Paitan et al., (2023)

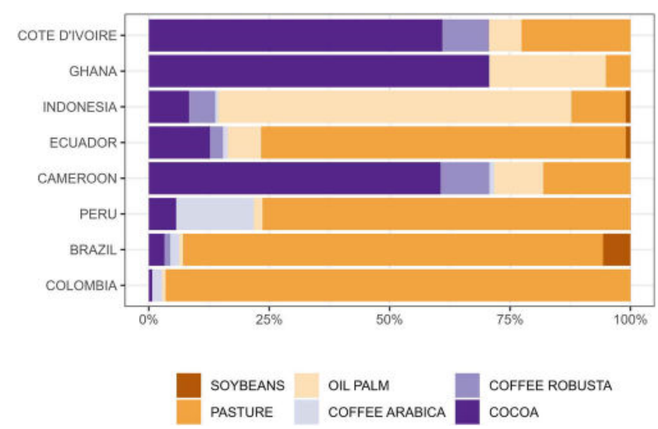

Fig. 1. Deforestation driven by agri-commodities in cocoa producing landscapes of top 8 cocoa exporters.

To characterize the future climate risk of cocoa production, we used the drought severity index, which reflects the change in the intensity, frequency, duration, and spatial spread of anomalous drought events between current and future climate change scenarios. We used the drought severity index as the only indicator of climate risk following research documenting that drought stress is the main limiting factor for cocoa physiology (Lahive et al., 2018). Therefore, we did not consider the effect of other important stressors linked to climate change such as heat stress, flooding, and carbon dioxide, and their potentially significant combined effect (Malek et al., 2022; Schroth et al., 2016). We used the drought severity index calculated by Ercin et al. (2021) for 2050 under the Representative Concentration Pathway (RCP) 6.0 scenario. This indicator is based on soil moisture variation and it is an aggregation of four different General Circulation Models and four Global Hydrological Models. The RCP 6.0 scenario assumes that temperatures continue increasing until 2100, greenhouse gases double by 2060 (relative to late-20th to early-21st centuries), and the total radiative forcing is stabilized after 2100 with the implementation of emission reduction strategies. Drought severity values <1 indicate less future frequent, intense, less widespread anomalous drought events compared to current drought severity levels, while values >1 indicate the opposite.

Following Ercin et al. (2021), positive values <1.2 indicate a low increase in climate risk, values >1.2 and <1.5 represent moderate levels, and values >1.5 indicate a high future climate risk. We provide results using the RCP 2.6 scenario in the Supplementary material, this scenario assumes that global warming remains below 2 degrees Celsius, with radiative forcing peaking in 2050 and stably decreasing until 2100 due to substantial mitigation strategies that lead to negative GHG emissions. Importantly, this study only focuses on the potential impacts of climate change on the agricultural state of cocoa production. It does not provide insights on potential impacts downstream of the cocoa value chain, such as logistic or infrastructure disruptions.

We used these spatially explicit data on deforestation and climate risk to characterize eight major cocoa exporting countries (Côte d'Ivoire, Ghana, Indonesia, Ecuador, Cameroon, Peru, Brazil, and Colombia, together responsible for 80% of global cocoa exports) and the traders operating their cocoa value chains. The country and trader selection was based on the work done by Parra-Paitan et al. (2023) which provided a typology of cocoa traders in these countries using 2018 shipping data compiled by the Transparency for Sustainable Economies (Trase) initiative (www.trase.earth). This typology distinguished six types of traders: large transnationals, medium transnationals, small transnationals, large domestic, small domestic, and farmer cooperatives. Additionally, this study details the traders' market share in each country and provides information on their vertical and horizontal integration and their public sustainability initiatives. We analyzed individually the large (Olam, Cargill, and Barry Callebaut) and medium transnational traders (Ecom, Touton, Sucden, and Guan Chong BHD) as defined in Parra-Paitan et al. (2023), while we keep aggregated small transnationals, large domestic, small domestic, and farmer cooperatives.

We used the MapSPAM data to create a mask by retaining all the 0.5 × 0.5-degree grid cells that contained more than one hectare of cocoa producing area (hereafter referred to as "cocoa producing landscapes"). We quantified the deforestation attributed to cocoa, deforestation attributed to all agri-commodities, and future climate risk for the cocoa producing landscapes of each country and the cocoa sourcing landscapes of each trader. For the country-level characterization, we assessed these risks across all cocoa producing landscapes within each country; when characterizing risks linked to each trader, we used a sample of locations (grid cells), weighing the sample of each trader based on their proportions of sourcing from different countries. This approach was used due to lack of data on subnational sourcing areas per trader, and it is thus only intended to represent the distribution range of these indicators considering how much each trader sources from the different countries. This is not expected to significantly alter our results, as recent research has shown that traders source from the same landscapes (Renier et al., 2023). We sampled a total of 5000 pixels for each type of trader, distributing this sample among exporting countries according to the country-sourcing proportion of each trader (Supplementary material). We sampled pixels randomly, with replacement, weighing the sampling probability of each pixel by its contribution to the cocoa production volume in each country (as reported by MapSPAM). To build the cumulative curves of cocoa production affected by drought severity and cocoa-driven deforestation shown in Fig. 2, we sequentially added the national proportion of cocoa produced by cocoa pixels having increasing drought severity or cocoa-driven deforestation.

Cocoa-driven deforestation (%) reflects the share of deforestation driven by agri-commodities attributed to cocoa (which, in the dataset used, is distributed between a set of commodities, i.e., robusta coffee, arabica coffee, cocoa, oil palm, soybean, and pasture), see Figs. 1, 2, and 3. The overall deforestation driven by agri-commodities (%) was calculated dividing the area (ha) of deforestation driven by agri-commodities by the cocoa producing landscape area (pixel area in ha), see Fig. 4b.

3. Results and discussion

3.1. Where are the hotspots of high deforestation attributed to cocoa?

Cocoa is responsible for more than 60% of deforestation driven by agri-commodities occurring since 2000 in cocoa producing landscapes of Cote d'Ivoire, Ghana, and Cameroon, three of the top 8 cocoa exporting countries (Fig. 1). Pasture for livestock feed and oil palm are the dominant drivers of agri-commodity deforestation in cocoa producing landscapes of South America and Indonesia, respectively. However, cocoa-driven deforestation always occurs alongside other commodities also driving deforestation, even in cocoa landscapes where it is the dominant driver. Robusta coffee and arabica coffee, for example, are grown in cocoa landscapes and are also important drivers for deforestation in those areas.

Disaggregating the association between cocoa production and cocoa-driven deforestation within each country shows contrasting patterns. In Côte d'Ivoire, Ghana, and Cameroon, most of the cocoa is produced in landscapes where cocoa is an important deforestation driver among agri-commodities (Fig. 2a), e.g., about 90% of the cocoa produced in Cote d'Ivoire is farmed in landscapes where cocoa dominates the landscape, and thus contributed to at least 75% of all deforestation driven by agri-commodities. In contrast, in South America, larger volumes are produced in landscapes where cocoa is a minimal contributor, e.g., in Colombia, about 75% of the cocoa is produced in landscapes where cocoa deforestation amounted to 25% or less of deforestation driven by agri-commodities, and only ~3% is produced in landscapes where cocoa drove more than half of the deforestation driven by agri-commodities. In Indonesia and Brazil, the contribution of cocoa to deforestation driven by agri-commodities is notable, with ~60% and ~35% of volumes linked to more than half of deforestation driven by agri-commodities.

More than 95% of the cocoa produced in Cote d'Ivoire, Ghana, and Cameroon is produced in landscapes where cocoa is the dominant crop and thus responsible for more than 50% of deforestation driven by agri-

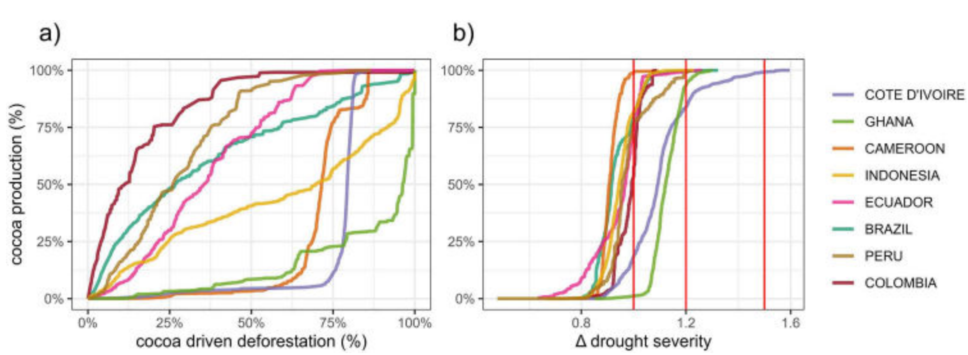

Fig. 2. (a) Cumulative cocoa production (%) affected by agri-commodity deforestation attributed to cocoa (%), and (b) future drought severity in cocoa producing landscapes of top 8 cocoa exporters. In (b), the red vertical lines indicate the thresholds for reduced (<1), modest (>1 & <1.2), moderate (>1.2 & <1.5), and high (>1.5) drought severity.

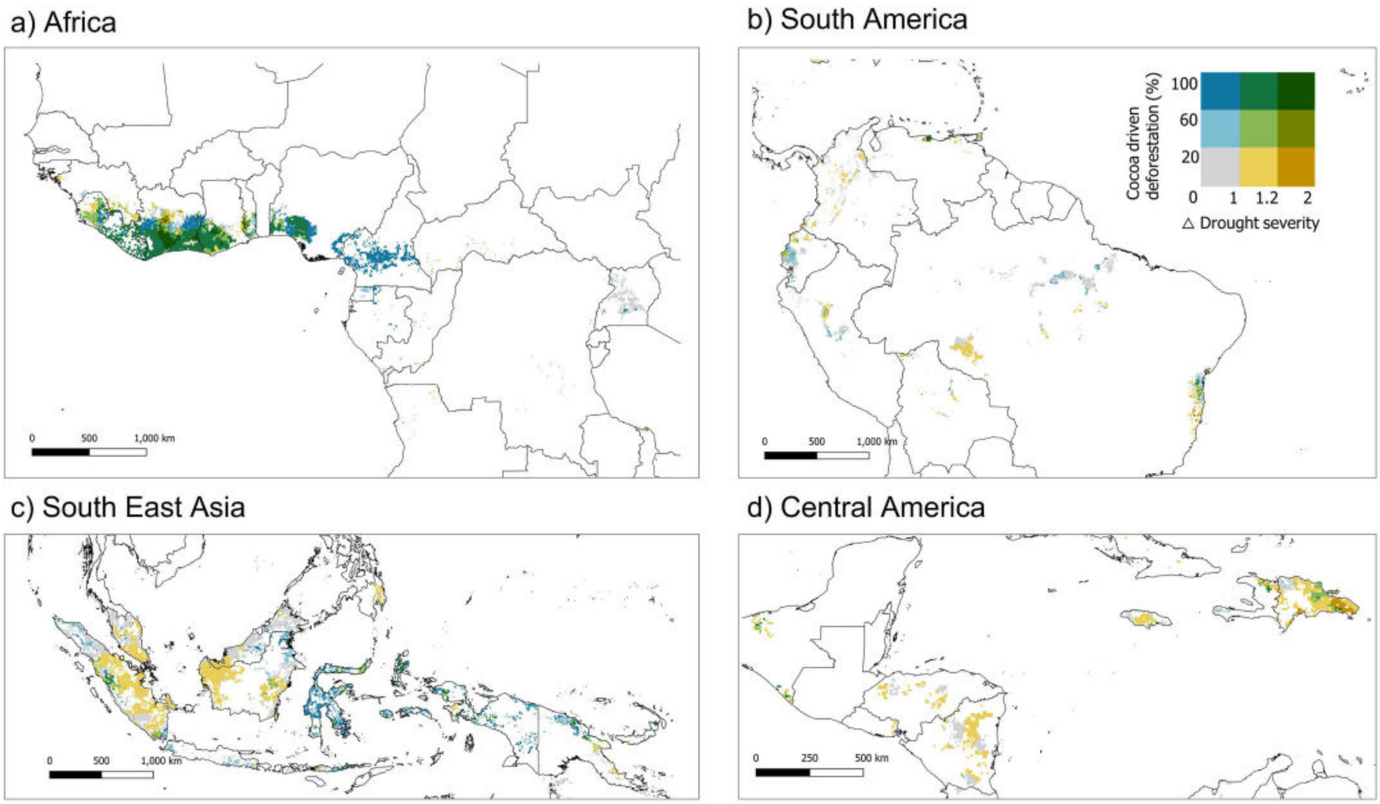

Fig. 3. Combined levels of drought severity change, and agri-commodity deforestation attributed to cocoa (%) in cocoa producing landscapes.

commodities (Fig. 2a). This share is even larger in Cote d'Ivoire, where almost 90% of the volume is produced in landscapes where cocoa is responsible for more than 75% of deforestation. In Indonesia and Brazil, yields are higher than in West Africa but cocoa still contributes importantly (~60% and ~35% of volumes respectively) to deforestation (>50%) in certain landscapes. In South America, cocoa appears to be the least responsible for deforestation, with only ~3%, 5%, and 30% of volumes in Colombia, Peru, and Ecuador, respectively, responsible for more than 50% of deforestation.

3.2. *Where are the climate risk hotspots located?*

The intensity of future climate risks is quite heterogeneous across countries (Fig. 2b). Active and old cocoa frontiers in Côte d'Ivoire and Ghana that sustain 60% of global exports will be exposed to increased climate risks in 2050, while landscapes where cocoa is a less dominant land use (Ecuador, Peru, Indonesia, Brazil, and Cameroon) will face fewer climate risks (Fig. 3). In Cote d'Ivoire, more than 66% of cocoa is produced in areas that will experience a modest increase in drought severity in 2050, 14% is in areas that will experience a moderate increase, and ~1% in areas that will experience a sharp increase in drought severity. In Ghana, areas producing more than 92% of cocoa will experience a modest increase in drought severity, and areas producing 7% will experience a moderate increase. Climate risk will be less severe in South American countries, with less than 1% and 25% of cocoa in Ecuador exposed to high and moderate climate risk, respectively, and less than 1% and 19% of cocoa in Brazil exposed to high and moderate climate risk, respectively. Similarly, less than 46%, 23%, 18%, and 1% of cocoa produced in Colombia, Peru, Indonesia, and Cameroon, respectively, will face a modest increase in climate risk, with remaining volumes experiencing reduced climate risk in 2050. In general, areas producing 1%, 6%, and 44% of cocoa supply in the eight countries studied will be affected by high (>1.5), moderate (>1.2 & <1.5), and a modest (>1 & <1.2) increased climate risk, respectively.

3.3. *Where climate risk and deforestation hotspots converge?*

As Fig. 3 shows, cocoa-driven deforestation and climate risks do not always co-occur and vary substantially between and within countries. The prioritization of sustainability actions by governments or value chain actors must be adapted to the severity of these phenomena in each of these regions. Southwestern areas of Cote d'Ivoire and Ghana (as well as of Nigeria, which is not formally part of our analysis) are some of the oldest and still active hotspots of *cocoa-driven deforestation* that will also be severely hit by *high future climate risk*. In the cocoa landscapes of these countries, livelihoods are highly dependent on cocoa and thus, urgently require climate adaptation measures to avoid the collapse of the local economy. Additionally, being the major cocoa exporting region, adaptation in West Africa should be of global concern, as the local impacts of climate change will likely generate a ripple effect across the entire value chain by disrupting global supplies.

Northern Cote d'Ivoire, Uganda, Cameroon, Brazil (Rondônia and Pará), Guayas and Manabí in Ecuador, and Ucayali in Peru have experienced *low to medium cocoa-driven deforestation* until 2018 and will experience *less future climate risks* in 2050. In Southeast Asia, only some confined areas have this level combination: North Sumatra, East Kalimantan, Sulawesi, East Sepik and Madang in Papua New Guinea, and Sarawak in Malaysia. These areas will become more attractive for cocoa expansion and might therefore experience an increased risk of deforestation. This can occur directly through forest encroachment or indirectly by the displacement of other land uses elsewhere (Meyfroidt et al., 2018), calling for policy interventions to organize territories before cocoa might boom. Areas with *low to medium cocoa-driven deforestation* that will experience *higher climate risks* are ubiquitous to all countries but heavily concentrated in West Africa, Sumatra, Kalimantan, Bahia, Malaysia, Dominican Republic. In these areas, cocoa might be replaced by more suitable crops or might experience the introduction of technological innovations that help to buffer drought stress. Finally, areas that have *high cocoa-driven deforestation* but will have *lower climate risks*

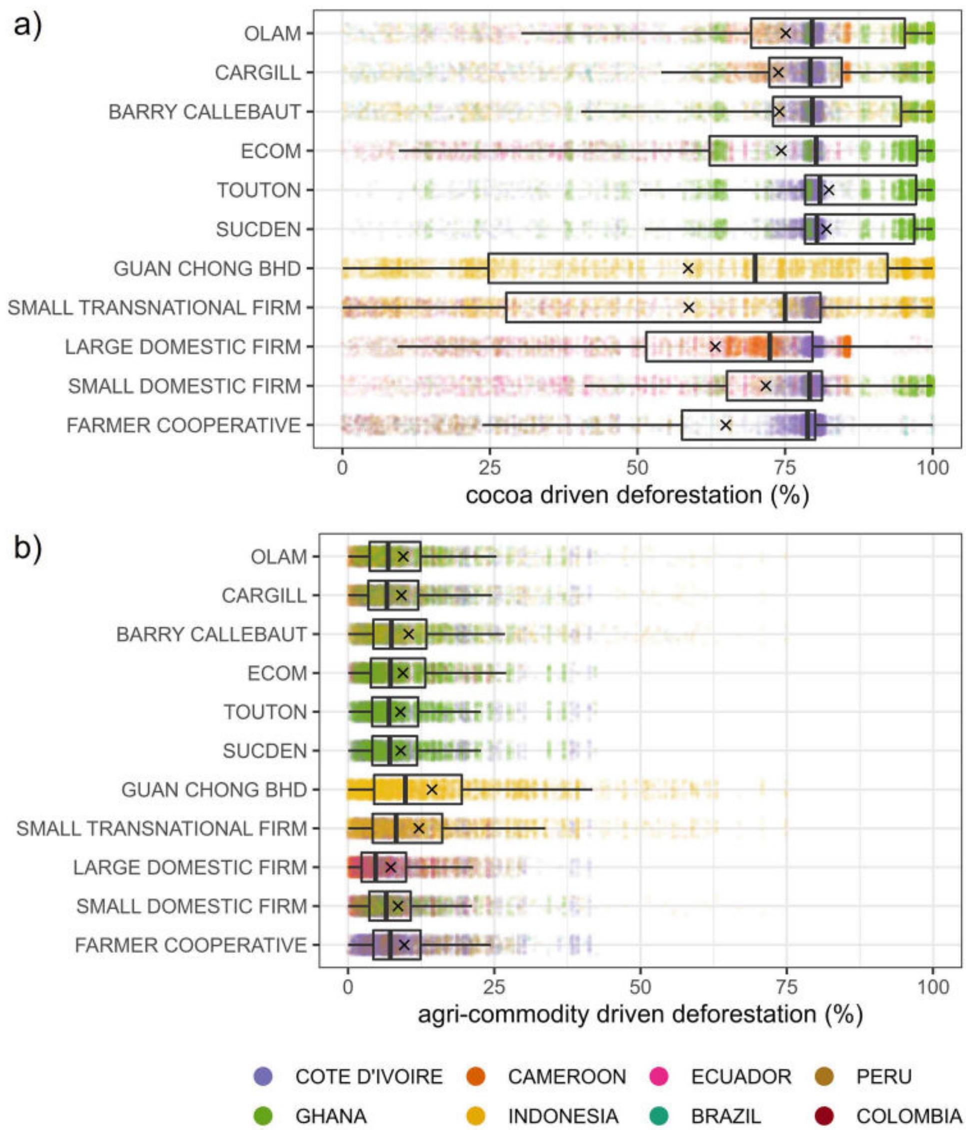

Fig. 4. (a) Agri-commodity deforestation attributed to cocoa (%), and b) overall deforestation driven by agri-commodities in cocoa producing landscapes (%) in the value chain of global cocoa traders. "X" indicates the mean.

are minimal and can be found in limited areas of Ucayali in Peru, and Pará in Brazil, and Sulawesi in Indonesia. These areas could experience increased deforestation rates in the remaining forest areas and could witness the consolidation of the cocoa sector in past deforested areas, requiring also preventive land use planning policy interventions to avoid deepening deforestation.

3.4. *What is the level of incidence of deforestation among global cocoa traders?*

Global cocoa traders, such as, Olam, Cargill, Barry Callebaut (large transnational firms) and Ecom, Touton, and Sucden (medium transnational firms), source cocoa from countries with cocoa producing landscapes in which most of the deforestation can be attributed to cocoa (Fig. 4a) and where deforestation driven by agri-commodities is about the same in cocoa producing landscapes (Fig. 4b). Cargill, by sourcing proportionally less from Ghana, has less deforestation linked to cocoa than Olam and Barry Callebaut. Among medium transnationals, Sucden, Touton, and Ecom have, in descending order, the highest levels of cocoa-driven deforestation due to their higher proportion of sourcing from Ghana, which has the highest levels of deforestation attributed to cocoa.

Guan Chong BHD, by sourcing almost entirely from Indonesia, has the lowest, among transnationals, average level of deforestation attributable to cocoa in its sourcing landscapes, however, it has the highest deforestation driven by other agri-commodities due to the dominant role of oil palm relative to cocoa in Indonesian cocoa-producing landscapes. Small transnational firms source importantly from Indonesia and have similar characteristics. Large Domestic Firms source from landscapes with relatively low fractions of cocoa-driven deforestation due to their stronger presence in Ecuador, Colombia, and Peru. Small Domestic Firms, and Farmer Cooperatives source from landscapes where most of the deforestation is linked to cocoa by being strongly present in Cote d'Ivoire.

3.5. *What is the level of future climate risk among global cocoa traders?*

Regarding climate change, small domestic firms and farmer co-operatives will be the most affected with moderate to highly increased future climate risk (Fig. 5). Guan Chong BHD, small transnational firms, and large domestic firms may benefit the most from reduced future climate risk. Transnationals Touton and Sucden, by relying strongly on Ivorian and Ghanaian supplies, have the highest levels of future climate

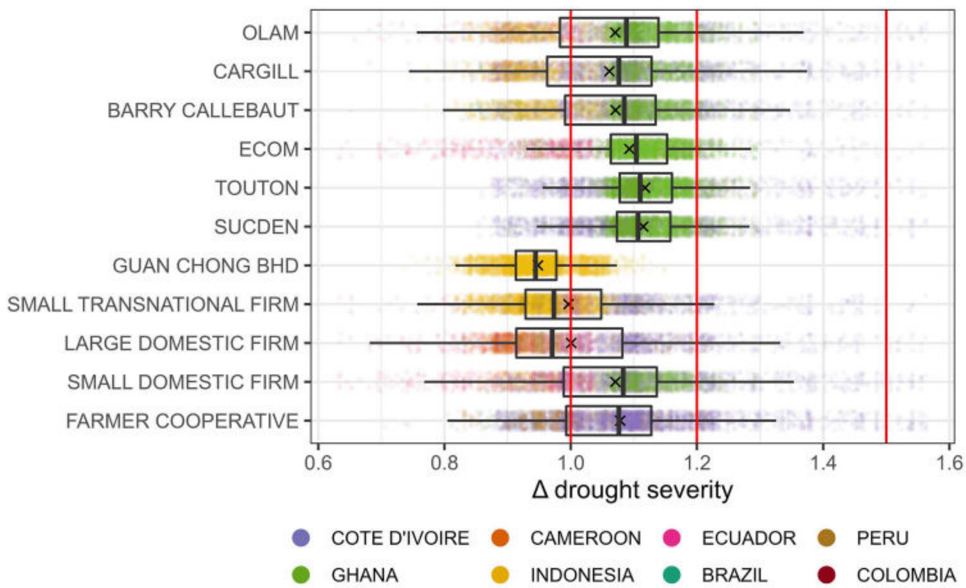

Fig. 5. Change in drought severity risk in cocoa producing landscapes in the value chain of global cocoa traders. "X" indicates the mean. The red vertical lines indicate the thresholds for reduced (<1), modest (>1 & <1.2), moderate (>1.2 & <1.5), and high (>1.5) drought severity.

risk (~9% of supplies exposed to moderate to high future climate risk, 84% of supplies exposed to a modest increase in future climate risk). Olam, Cargill, and Barry Callebaut, by having a more diversified sourcing matrix in countries with future favorable climatic conditions (Ecuador, Peru, Indonesia), have ~20–28% of their value chain that is exposed to a somewhat reduced future climatic risk, ~7–9% exposed to moderate to high future climate risk, and ~63–70% exposed to a modest increase in future climate risk. Guan Chong BHD and Small Transnational Firms, sourcing mainly from Indonesia, have an overall reduced future climate risk in 87% and 63% of their supply, respectively. The same applies to 41% of Large Domestic Firms' supplies. Small Domestic Firms and Farmer Cooperatives, by sourcing importantly from Cote d'Ivoire and Ghana, will have a modest and moderate-high increase in future climate risk in ~63–70% and ~10–13% of their supply.

3.6. Implications and possible avenues

The mix of factors driving deforestation in cocoa landscapes highlights the importance of articulating initiatives to curb deforestation with initiatives in other agriculture commodity sectors. In essence, it is necessary to design strategies that go beyond single commodities and have a narrow geographic focus, to transition towards tackling underlying factors driving deforestation (Carodenuto et al., 2015; Schaeffer et al., 2005; Staal et al., 2018). Existing national initiatives are focused on single commodities (e.g., all the cocoa sustainability boards-the ISCOs: Beyond Chocolate in Belgium, GISCO in Germany, DISCO in the Netherlands, SWISSCO in Switzerland) and need to be integrated with initiatives in other commodities to avoid repetition or cause geographical or sectoral displacement of deforestation (Wahba and Higonnet, 2020). Our results show that integrating sustainability action to curb deforestation in cocoa production landscapes could benefit from the articulation with active initiatives in the coffee, oil palm, and beef industries, which strongly overlap with cocoa production landscapes (Buckley et al., 2019; Lambin et al., 2018; Leijten et al., 2020; Levy et al., 2023; Zu Ermgassen et al., 2020)

Besides the agri-commodities included in this study, other factors are also important drivers of deforestation in cocoa landscapes, such as food crops, gold mining, and logging, with recent research also showing that land speculation is important (Kan et al., 2023; Renier et al., 2023). Strategic spatial planning and jurisdictional and landscape approaches are important examples of multi-stakeholder and multi-sectoral initiatives on how to leverage land use planning to navigate competing interests of actors in a landscape, so that all needs are covered within environmental boundaries (Boshoven et al., 2021; Oliveira and Meyfroidt, 2021). If rising cocoa demand is to be met without further deforestation (Bermudez et al., 2022), increases in productivity per area unit are required to limit the expansion of the cocoa producing area. However, land use planning is necessary to balance the environmental and socioeconomic trade-offs between expansion and intensification (Parra-Paitan and Verburg, 2022).

Cocoa traders must take the lead on the implementation of zero-deforestation action in landscapes where cocoa is responsible for the largest fraction of deforestation driven by agri-commodities. However, cocoa traders sourcing from areas where other commodities are important drivers of deforestation must articulate voluntary sustainability initiatives with public initiatives, initiatives of other land-based sectors, and with territorial initiatives. Horizontally integrated traders (i.e., those trading also other commodities produced in cocoa landscapes) are key in this articulation as they have the know-how of sustainability issues across commodities and have cross-commodity agency (Parra-Paitan et al., 2023). So far, private initiatives are strongly focused on individual commodities (e.g., Cocoa and Forest Initiative, Roundtable for Sustainable Palm Oil, Roundtable on Responsible Soy, etc.) and act in isolation from each other. On the other hand, the increasing landscape and jurisdictional programs supported by private actors or multi-stakeholder coalitions often target single commodities, overlooking other forest-risk commodities and other land use change drivers, and often lack government engagement when these are led by private actors. When these are led by state actors, they strongly focus on regulatory reforms to create enabling conditions but often have limited involvement of value chain actors (Carodenuto, 2019; von Essen et al., 2021). New initiatives are expanding their scope to include strategies across different commodities, contributing collectively to the sustainability of production landscapes (Tropical Forest Alliance et al., 2023).

Yet, this key role of horizontally integrated traders should be balanced with stronger efforts to involve smaller, often less horizontally integrated, traders. The EU legislation on deforestation-free value chains and due diligence might incentivize multi-sectoral and multi-stakeholder efforts to reduce overall risks, but it is important to evaluate the potential effects of softer requirements from Small and Medium Enterprises (SMEs), as currently framed in the legislation (European Commission, 2021). This is of particular concern, as 38% of global supplies are managed by small traders that rarely make zero deforestation commitments, which have even higher market participation in other cocoa exporting countries with high cocoa-driven deforestation (Parra-Paitan et al., 2023). Voluntary sustainability commitments to achieve zero deforestation value chains in the coming years have been mostly issued by the largest traders (large transnationals Olam, Cargill, Barry Callebaut), which are all horizontally integrated into other forest-risk commodities. However, the impact of these commitments in addressing such a multidimensional and cross-sectoral challenge is limited, as these commitments are strongly divided per commodity, lack a landscape approach to tackle drivers of land use change at a scale, target only direct value chains, and lack external verification (Parra-Paitan et al., 2023).

In terms of climate risk, countries with more diversified farming sectors and less economically dependent on cocoa will be the least affected in case of increased climate risk. Regions that will experience less climate risk will become more attractive to cocoa farming and would require early policy interventions to organize the use of land before cocoa booms and drives further deforestation. Traders having a more diverse sourcing matrix might be in a better position to navigate better future climate risks than those dependent on few exporting countries that will experience increased risks. Traders heavily reliant on supplies from Cote d'Ivoire and Ghana, such as Touton, Sucden, Barry Callebaut, Cargill, and Olam, will be severely affected if they do not assist in implementing adaptation measures among cocoa farmers. Besides being a priority for these traders, climate adaptation in these counties should be of global concern due to the current dependence of global supplies on Ivorian and Ghanaian cocoa. Potential actions include technological innovations such as precision agriculture, improved planting material, or farming practices more resilient to climate change, such as climate smart agriculture. Small traders sourcing from a single country depend entirely on the future climate risk of their current sourcing location and are thus less resilient to supply shocks (Kummu et al., 2020; Puma et al., 2015), which is especially worrisome for farmer cooperatives and domestic firms in West Africa. Smaller traders in Latin America will have an improved opportunity window to help secure global supplies while limiting deforestation. Large traders have a more geographically spread sourcing, larger financial resources, and larger agency than smaller traders (Parra-Paitan et al., 2023) and therefore more opportunities to adapt their sourcing matrix or implement ground-level climate adaptation strategies. Consequently, larger traders might be better prepared to take advantage of future reduced climate risks in certain locations, which could strengthen existing patterns of high market concentration and power accumulation by large companies (Parra-Paitan et al., 2023). Despite these alarming future risks, cocoa traders of all sizes have not issued explicit commitments to address climate vulnerability among cocoa farmers. At most, commitments focus on agroforestry and climate smart agriculture, but their narrative is strongly focused on increasing tree cover on farm, carbon, and biodiversity stocks, and raising farmer income through intercropping. Studies argue that this might be due to private actors prioritizing action that leads to increased value creation and brings reputation gains, leading to the abandonment of other pressing issues and their root causes (Parra-Paitan et al., 2023; Tennhardt et al., 2022). Instead, companies are testing strategies that go beyond smallholder systems, as it is shown by the increasing wave of large investments on cocoa plantations that try to unlock the most efficient and resilient way of doing cocoa farming. Barry Callebaut, Olam, Mars, and Mondelez have, for example, acquired cocoa plantations to conduct research and innovation with this purpose across Ecuador and Indonesia (Barry Callebaut, 2022; Confectionery News, 2016; Mondelez International, 2021). If these initiatives prove successful, smallholder farmers and smaller traders might be put out of business which, without proper transition plans, will put their livelihoods at risk. The choice of action cannot be left solely to private actors, as this risks initiatives to favor market imperatives rather than global net sustainable outcomes and opportunities for disadvantaged farmers.

3.7. Uncertainties and key monitoring needs

In this study, we used MapSPAM to identify cocoa production areas, which was also used by Ercin et al. (2021) and Goldman et al. (2020) for climate risk and deforestation studies, respectively. MapSPAM is one of the only spatially explicit global agricultural datasets and, although it is the most recent one, it represents data from 2010 (2017 for Sub-Saharan Africa), which underestimates the current extent of cropland area (and cocoa) given that this has expanded in 7% between 2008 and 2019 (Potapov et al., 2021). A 2020 MapSPAM dataset was released during the publication process of this manuscript. However, to maintain consistency with the other datasets, no analysis was updated. Several remote sensing innovations are being implemented to improve the mapping accuracy of cocoa farms though these are not yet available at the pantropical scale (Abu et al., 2021; Kalischek et al., 2022). One important aspect to consider in future work would be the differentiation of different cocoa farming systems (e.g., agroforestry vs., full sun), as they are expected to have different climate change vulnerability levels (Blaser et al., 2018; Niether et al., 2020).

On the other hand, it is important to improve the method used to identify deforestation drivers. Our reference study was based on Curtis et al. (2018) which allocates deforestation to the dominant driver among commodity-driven deforestation, shifting cultivation, forestry, wildfire, or urbanization. The deforestation linked to a specific commodity is then proportionally allocated to the crop area of the shortlisted commodities (cocoa, coffee, soybeans, oil palm, pasture). This can lead to the overestimation of deforestation allocated to each of these crops, and it obscures other important drivers of deforestation such as food crops or other crops. By doing so, this method does not allow to isolate the effect of cocoa as a direct or indirect driver of deforestation, which could arise, for instance, due to cocoa displacing other crops in the landscape (See Supplementary Figure S5). Due to this, we used Goldman et al. (2020) primarily to provide insights about the interaction of cocoa with other agri-commodities driving deforestation rather than as an absolute metric of cocoa deforestation risk.

In addition, our measure of deforestation is a historical one, based on forest loss from 2001 to 2018; deforestation is not, however, static, and it is possible that new frontiers of cocoa expansion could emerge in the future, meaning that companies must be continually vigilant to land use changes in the landscapes where they source. Efforts to improve pantropical deforestation mapping should be followed closely to update this analysis. Current maps could be improved by utilizing higher resolution and readily available satellite data and including more accurate and updated information on plantations and shifting agriculture where repeated cycles of tree cover removal occur (Finer et al., 2018; Pendrill et al., 2022).

Regarding climate risk data, the drought severity index should be combined with other climatic factors affecting cocoa physiology, such as heat stress, flooding, and the effect of increased carbon dioxide levels (Lahive et al., 2018; Schroth et al., 2016). This is important to have a complete understanding of the potential impacts of climate change, however, this also requires an improved understanding of the physiological responses of cocoa to climate variables (Ercin et al., 2021; Lahive et al., 2018; Malek et al., 2022). In addition, future work must consider a wider range of climate scenarios and impacts, as previous research has shown that substantial differences between climate forecasts can complicate efforts to identify which companies are exposed to the greatest climate risks (Stokeld et al., 2020).

Finally, we characterized the risk of global traders without specific information about their exact subnational sourcing areas within each country, by weighting deforestation and climate risk based on the volumes sourced from each cocoa-producing country. Our approach could be improved by having subnational maps to determine where each company sourced from within these countries, though subnational mapping is currently constrained by the limited traceability and transparency in the global cocoa value chain (Renier et al., 2023; zu

Ermgassen et al., 2022).

4. Conclusion

Deforestation and climate risk levels differ for producing countries and cocoa traders. Our results show that cocoa is hardly ever the only agricultural commodity driving deforestation in a landscape, even in cocoa-dominated landscapes. To tackle deforestation, therefore, it is necessary to articulate the sustainability initiatives of all commodity sectors competing for agricultural land. Our results show that coffee and pasture are also important drivers of deforestation in most cocoa landscapes and thus should be tackled together to avoid displacement between sectors and regions. Oil palm and soybeans play an important role in Indonesia and Brazil. Other crops (food crops like maize, sorghum, cassava, etc.) and non-agricultural drivers not addressed in this article should also be considered in efforts to halt deforestation, as well as gold mining and logging. Future climate risks vary substantially across countries and have variable co-occurrence with deforestation, which calls for context-specific strategic approaches to manage both. Current global supplies are at risk due to their dependency on West African supplies, which will experience high future climate risk. Due to the significant economic dependency of Cote d'Ivoire and Ghana on cocoa exports, climate change threatens the livelihoods and millions of farmers and the stability of the local economy. Areas with low future climate risk could become more attractive for cocoa expansion and risk further deforestation, calling for policy interventions to organize territories before cocoa might boom. Traders play a vital role in operationalizing risk reducing strategies, particularly traders horizontally integrated in the value chain, as they can enact action across commodities co-driving deforestation in the same landscapes. The value chains of traders with a more geographically spread sourcing matrix (large transnationals) are likely more resilient by having a diversified matrix with increased and reduced climate risks that could help them buffer climate change impacts on their business. Smaller traders have less flexibility because they source mostly from a single country and are less resourceful. Those in West Africa urgently require climate adaptation and deforestation mitigation support, while those in Latin America and Southeast Asia might possibly experience an improved window of opportunity in the global market. We call for multi-stakeholder and multi-sectoral initiatives that tackle sustainability risks beyond single commodities and limited geographies.

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CRediT authorship contribution statement

Claudia Parra Paitan: Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Patrick Meyfroidt:** Writing – review & editing, Visualization, Supervision, Methodology, Conceptualization. **Peter Verburg:** Writing – review & editing, Supervision, Methodology, Conceptualization. **Erasmus zu Ermgassen:** Writing – review & editing, Supervision, Methodology.

Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Claudia Carolina Parra Paitan currently works for Olam Food Ingredients, her engagement with Olam started after the completion of this research article and Olam had no influence over the content of this work. Erasmus zu Ermgassen: no competing interests. Patrick Meyfroidt: no competing interests. Peter Verburg: no competing interests

Data availability

Data will be made available on request.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.envsci.2024.103796.

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