The telecoupled sustainability impacts of global agricultural value chains

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The telecoupled sustainability impacts of global agricultural value chains

Assessing the cross-scale sustainability impacts of the cocoa sector

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The telecoupled sustainability impacts of global agricultural value chains

Assessing the cross-scale sustainability impacts of the cocoa sector

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"If you think you can do it alone you are not thinking big enough"

- Manfred Aben

Contents

Summary

Agriculture is a major contributor to the global environmental crisis. Natural ecosystems are being replaced by agricultural land, which leads to the extinction of species and the release of tons of carbon emissions. Farming activities also contribute to environmental pollution, water scarcity, soil erosion, and thus to the disruption of biosphere dynamics. Global agricultural value chains (GVCs) have grown due to the intensification of international trade. While GVCs have undeniably created economic opportunities for the agriculture sector, they have also led to the escalation of local environmental issues.

GVCs are complex systems that involve multiple actors across various locations. GVCs trigger multiple cause-effect pathways that can lead to the non-linear transmission of impacts. For example, a policy incentive in one country can motivate farmers to switch from crop A to crop B, which can lead to the expansion of crop A in another country, shift the environmental burdens, and alter the market of the agricultural inputs needed for each crop. This is known as a telecoupled system.

Several initiatives have been implemented to reduce the negative impacts of agriculture, including government regulations, sustainability certification labels, and voluntary sustainability commitments. However, the effectiveness of these initiatives has been questioned due to several reasons, including the mismatches between the scale of the problem and the solution, the lack of monitoring and verification of sustainability actions, and their weak enforcement. Sustainability initiatives are informed by studies assessing the impacts of agriculture that often only focus on local impacts, while disregarding larger-scale – telecoupled– dynamics that can trigger impacts across geographic and temporal scales. It is necessary to gain a deeper understanding of the causal mechanisms that determine the impacts of GVCs on sustainability. To achieve this, we need to understand the role of the GVC's network configuration in catalyzing telecoupled impacts.

This thesis aims to help bridge these knowledge gaps by examining the impacts of agricultural GVCs across scales, studying the role of GVC's configuration in modulating these impacts, and investigating the role of GVC actors in mitigating sustainability risks across scales. The global cocoa value chain is used as a case study to answer the following research questions:

I. How can we evaluate the telecoupled sustainability impacts of agricultural GVCs, such as those involving cocoa?
II. How do the environmental impacts triggered by the cocoa GVC at different scales compare to each other?
III. How can cocoa GVC actors mitigate environmental risks at different scales?

Chapter 2 examines various impact assessment methods and their ability to capture the effects caused by telecoupled dynamics across different scales. As land use change plays a significant role in agriculture, this chapter particularly focuses on the capacity of these methods to capture direct and indirect impacts caused by land use dynamics. The study concludes that no single method is sufficient to capture all telecoupled cross-scale dynamics and to quantify the full range of impacts of agricultural GVCs. The integration of different methods is necessary to bridge gaps between methods and complement their scope. Finally, this chapter suggests that to better assess the impacts of agricultural GVCs, it is important to improve the understanding of cause-effect mechanisms and make context-specific impact factors available.

Chapter 3 implements the recommendations outlined in Chapter 2 by analyzing the impacts caused by cocoa production in Ghana within and beyond the farm-level. This chapter integrates scenario modeling, land use modeling, life cycle assessment, and spatial assessment to capture the impacts caused by telecoupled land use dynamics beyond the cocoa farm. By defining three different demand scenarios, it tested the impacts of promoting cocoa agroforestry and cocoa full-sun systems on carbon, biodiversity stocks, and environmental pollution in the Ghanaian cocoa belt. This chapter reveals that findings drawn from farm-level assessments can contradict those from landscape-level assessments. Decision-makers focused on sustainability should be wary of extrapolating farm-level assessment results to larger scales, as this can be misleading.

Chapter 4 expands the scope to the global scale by examining the role of the cocoa GVC configuration on the capacity of the sector to address sustainability challenges across scales. The chapter identifies different types of cocoa traders and their sustainability commitments, indicating that the high market concentration among top cocoa traders can have both positive and negative impacts on realizing visions for sustainable trade. While the dominance of a handful of traders can be used to scale up sustainability action, it can also undermine the objective by marginalizing smaller traders with less visibility and investment capacity to implement sustainability transformations. This could be why, despite significant sustainability challenges in top cocoa exporting countries, only seven companies have consistently adopted sustainability commitments, leaving more than 60% of traded cocoa uncovered by such commitments. The chapter highlights that to address the telecoupled impacts of the cocoa GVC, coordinated action between traders is required, along with government interventions to balance power asymmetries.

Chapter 5 aims to measure the degree to which cocoa traders, as identified in Chapter 4, are exposed to two sustainability issues that are critical in the cocoa value chain: deforestation and climate change. It is important to understand how these problems impact the various actors in the cocoa value chain to prioritize actions and locations that can help minimize any unintended negative consequences that may arise due to telecoupled dynamics across

scales. This chapter highlights that sustainability challenges in any single agricultural value chain cannot be resolved in isolation as farming systems are constantly interacting with other farming systems (e.g., other crops) and competing sectors that use land (e.g., mining). To avoid displacing negative impacts across scales, it is necessary to have a coordinated and collaborative effort from stakeholders and sectors involved in making decisions related to land use.

This thesis shows that addressing the telecoupled impacts caused by agricultural value chains needs a good understanding of the cause-effect dynamics at play. This requires the quantification of impacts caused by agriculture across scales and the characterization of the GVC network of actors modulating these impacts. Interdisciplinary methods need to be leveraged and integrated to generate actionable insights. The findings of this thesis can assist decision-makers and private actors in devising customized sustainability strategies, prioritizing action, and addressing the most vulnerable hotspots while being mindful of global teleconnections and avoiding spillovers. To address sustainability problems caused by telecoupled systems, cross-scale, and cross-sector collaboration must be facilitated by multiple governance approaches that bridge the gaps between the scope of governance action and the scale of the problem. Current efforts in the sector are increasingly acknowledging the need to manage complex dynamics arising from telecoupled agricultural GVCs.

S

1. Introduction

This thesis addresses the environmental impacts of agriculture and its implications for the sustainability of global agricultural value chains, using cocoa as a case study. A special focus is given to impacts spanning across geographical and temporal scales and stakeholder efforts to minimize these. To that end, this thesis first provides a literature review identifying knowledge gaps among the available impact assessment methods applicable to agricultural systems. It then moves on to answer some of the research gaps identified by empirically evaluating the impacts of the cocoa value chain and studying the sustainability initiatives taken by value chain actors. To frame these debates, this chapter introduces the main concepts used throughout this thesis (global value chains, telecoupled systems, land use dynamics, and sustainability commitments), describes the state of the art in this research field, identifies research gaps, and lays down guiding research questions.

1. Global value chains and telecoupled impacts

Global value chains (GVCs) have become one of the main vehicles of globalization and international trade, connecting producers and consumers across the world at a speed hardly imaginable a century ago. International trade has virtually reduced the geographical distance between consumption and production regions and has expanded the offer of purchasable products across the globe. This has opened several economic opportunities and has made GVCs one of the most important mechanisms for pursuing economic growth (Gereffi and Lee, 2012; Lee and Gereffi, 2015). GVCs have helped to maximize the cost-efficiency of production networks by promoting the strategic use of resources and the specialization of actors (e.g., countries, regions, and companies) in specific value-adding production stages (Meliciani and Savona, 2015). By providing access to larger markets, facilitating technology transfer, boosting innovation, and enhancing employment opportunities, GVCs have been used by countries as a vehicle to advance poverty alleviation (Gereffi, 2018; Ponte et al., 2019). Nonetheless, recent studies have shown that GVCs can also have mixed effects on the socioeconomics of participating nations by reducing employment, raising income inequality, intensifying poverty through higher prices, and lowering the wages of low-skilled workers. Negative socioeconomic impacts are reportedly more likely to arise in less consolidated economies than in more consolidated ones, with the latter being better equipped to reap the benefits of GVCs thanks to, among other factors, better institutional, technological, and labor force preparedness (Ha and Huyen, 2022; Lopez Gonzalez et al., 2015; OECD, 2013; Saliola and Zanfei, 2009; Selwyn, 2019).

Some studies suggest that GVCs can help reduce environmental impacts, such as in developed economies where the level of GVC embeddedness is decoupled from carbon emissions (Ali and Gninigué, 2022; Ambikapathi et al., 2022; Huang and Zhang, 2023). However, there is mounting evidence that GVC networks can help amplify negative environmental impacts at a scale that can threaten the integrity and functionality of the biosphere. In GVCs resource extraction, resource transformation, manufacturing, consumption, and disposal of products can occur thousands of miles away, which facilitates the spread of environmental impacts. In addition to their geographical spread, the amplification of the environmental impacts caused by GVCs is driven by the aspirations for continued economic growth and value creation that dominate the global economy. This economic model encourages the creation of economies of scale and the exponential accumulation of capital, which leads to market concentration, ever-growing GVCs, and an ever-increasing demand for resources regardless of the physical limits of the Earth (Raworth, 2017; Rockström et al., 2009). In a resource-limited world, the scale of GVC's operations thus amplifies in an unprecedented manner the impacts linked to economic activities, such as pollution, water scarcity, soil erosion, biodiversity loss, deforestation, and land conversion in biosphere-wide phenomena, such as global warming, mass species extinction, ocean acidification, and ozone depletion (Clapp et al., 2021; Folke et al., 2019; Rockström et al., 2009; Schneider et al., 2020).

Complex causality pathways can arise due to the multiple factors that agents must navigate to operate GVCs, such as resource availability, regulatory policies, capital availability, and opportunity costs, which complicates the attribution of impacts caused by GVCs. The telecoupling framework provides a suitable theoretical foundation to understand the factors driving "telecoupled systems", such as GVCs, and the potential causality mechanisms influencing their final impacts. In telecoupled systems, agents in sending (e.g., exporting countries) and receiving systems (e.g., consuming countries) are linked by multi-directional flows (e.g., information, materials, financial flows, emission flows), and their exchange is modulated by social, economic, and environmental factors that lead to a non-linear transmission of impacts. These non-linearities arise due to feedback loop mechanisms and path-dependencies between the agents and systems making up GVCs and can take the form of spillover effects, leakage, cascading effects, legacy effects, and time lags. (Liu et al., 2013, 2018). These indirect impacts occur, for instance, when the intervention in one place or system triggers unintended impacts in another one (spillovers), when regulatory policies inadvertently reduce the intended consequence of an intervention (leakage), when the impact of an intervention extends over a much longer period than anticipated (legacy effect), when an intervention affects multiple other systems (cascading effects), or when the impact of an intervention does not become apparent until years or decades later (time lags) (Lima et al., 2018; Liu et al., 2013; Meyfroidt et al., 2020).

The impacts caused by GVCs have been the subject of increasing research in the last decades. The value chain transparency research field has focused on providing visibility to the agents and transactions connecting upward and downward sections of value chains (i.e., value chain mapping). This has been targeted as one of the most important initial steps to understand the final socioeconomic and environmental outcomes of GVCs and as a starting point for designing effective governance arrangements that help limit their negative externalities (Gardner et al., 2018; Godar et al., 2016; Schleifer et al., 2019). The land systems research field has focused on increasing the understanding of the interconnection of land across geographic scales, the causal mechanisms of impacts, and the quantification of impacts that are strongly modulated by GVC dynamics (Meyfroidt et al., 2013, 2018; Oberlack et al., 2018; Sun et al., 2017). The global value chain research field has focused on understanding how business strategies and GVC governance arrangements can influence the socioeconomic and environmental outcomes of GVCs (Gereffi et al., 2005; Ponte, 2019; Reis et al., 2020). The life cycle assessment research field has focused on improving the methods for quantifying the multidimensional, non-static, and spatially heterogeneous impacts caused by GVCs (Chaplin-Kramer et al., 2017; Hellweg and Canals, 2014; Park et al., 2016; Yang and Heijungs, 2018a). Nonetheless, research is still needed to improve the understanding of the diverse value chain configurations and their potential effect on sustainability impacts, improve the causal attribution of GVC telecoupled impacts, and quantify the array of multidimensional impacts derived from GVC's activities with sufficient granularity.

2. The impacts of land use change, agriculture, and the global cocoa value chain

The agriculture, forestry, and other land use sector (AFOLU) occupies a special position among drivers of environmental degradation as it is the largest driver of natural ecosystem conversion, the second largest contributor to anthropogenic greenhouse gas emissions (23% between 2007-2016), and one of the main drivers of the sixth mass extinction of species (Davison et al., 2021; IPCC, 2019). Of all the ice-free terrestrial surface once covered by natural ecosystems, 35% has been converted to agricultural land, and of all freshwater resources, 70% is used for agriculture (IPCC, 2019). Of all the different forms of land use change, tropical deforestation driven by agricultural expansion is one of the largest contributors to global environmental degradation as it releases the vast reserves of carbon stored in tropical forests and destroys the natural habitat of countless species (Ramankutty et al., 2008; Rosa et al., 2016). Among tropical agri-commodities, cocoa is of particular concern as it has been identified as one of the top agricultural drivers of tropical deforestation contributing together with oil palm, soybeans, cattle pastures, coffee, and rubber to more than half of tropical deforestation between 2001-2018 (Goldman et al., 2020; Pendrill et al., 2019).

Agricultural land is embedded in socioecological systems and is therefore influenced by multiple socioeconomic factors, such as market dynamics (e.g., pricing, supply-demand), land competition dynamics (within the sector and across land competing sectors), land supply elasticity (i.e., the ease with which the land can be converted to another use), land ownership status, spatial policies, and the suitability, accessibility, and availability of land (Van Asselen and Verburg, 2013). Agricultural land is also exposed to the dynamics of adjacent and distant systems (e.g., social, economic, cultural, and political systems), such as financial flows in other sectors (e.g., mining), price dynamics (e.g., land speculation), technology (e.g., availability of agro-industrial machinery), labor shortages (e.g., lack of seasonal workers), etc. (Neilson, 2007). This interplay of factors can trigger unpredictable and sudden changes in the use of agricultural land, such as land regime shifts (e.g., sudden changes from one crop to another), land transitions (i.e., structural non-linear changes, such as reforestation in abandoned land), land abandonment, land expansion, or land use intensification. The complex causality chain that arises thereof, complicates the identification of drivers and final impacts and makes them difficult to anticipate and mitigate (Meyfroidt et al., 2018, 2020, 2022). Consequently, to understand the impacts triggered by agriculture it is necessary to study not only the immediate local responses but also the indirect impacts triggered at larger geographical scales. For instance, it has been documented that sustainable agricultural practices can bring local gains in ecosystem services but, due to their lower production per unit of area, they can drive large-scale natural land conversion to satisfy demand (Cucurachi et al., 2019; Seufert and Ramankutty, 2017).

Besides deforestation and biodiversity loss, cocoa farming has been linked to different degrees of environmental pollution, human health risks, and ecosystem services degradation depending on the farm management practices utilized (e.g., agroforestry, full-sun, intercropping, high/low agrochemical inputs, agroecology) (Blaser et al., 2018; Jacobi et al., 2014; Niether et al., 2020; Ntiamoah and Afrane, 2008). In addition, cocoa has been linked to socioeconomic issues due to the child-labor cases and poverty that often prevail among millions of cocoa small-holder farmers (Fountain and Huetz-Adams, 2020). These concerns are only expected to grow due to the continued expansion of cocoa farmland, the increasing demand for chocolate products across high- and middle-income countries (Beg et al., 2017; KPMG, 2014), and the predicted increase in future climate risks (Ercin et al., 2021; Malek et al., 2022; Schroth et al., 2016).

Several research studies have quantified the environmental impacts caused by cocoa production on biodiversity (Bennett et al., 2022; Maney et al., 2022; Sassen et al., 2022), environmental pollution, human health (Ntiamoah and Afrane, 2008; Ortiz-R et al., 2014; Recanati et al., 2018; Utomo et al., 2016), and carbon stocks (Asigbaase et al., 2021; Blaser et al., 2018; Middendorp et al., 2018). However, despite this wealth of knowledge, most studies have focused only on the impacts occurring within the farm plot (or immediate surrounding areas), limiting their scope to small case study areas or a collection of study areas through meta-analysis. In addition, due to limitations in data, most studies have used generalized approaches (e.g., generalized impact factors) to quantify environmental impacts, which obscures the role of spatial heterogeneity and context-specific factors in determining final impacts. To my knowledge, studies rarely account for the impacts caused by cocoa production beyond the farm-level in a spatially explicit manner, considering the indirect impacts that different management practices can trigger due to land use dynamics. More research is needed to better understand the trade-offs that adopting different cocoa production systems may cause within and beyond the farm across different impact categories. Finally, studies analyzing the impacts of cocoa production are rarely linked to the private actors making up the GVC, which is an important step for allocating responsibility and designing action plans for effective sustainability governance.

3. Addressing the telecoupled impacts of GVC and the cocoa value chain

Global value chains confront us with a new challenge: how to assess, monitor, mitigate, and prevent the negative environmental impacts triggered across multiple geographic and temporal scales while still generating economic opportunities? This poses not only an environmental challenge but also an operational one due to the involvement of multiple actors (e.g., companies, countries, consumers, regulatory bodies, etc.) having their own institutional configuration, scope, and scale of action, and following their own operational procedures. Multiple actors play a role in the causal chain of environmental impacts, with no single governance institution having a response mandate that matches the scale of GVCs dynamics, which is a phenomenon described as institutional mis-match or mis-fit (Coenen et al., 2023). Following collective concerns calling for global action, multiple governance mechanisms have been proposed to tackle this problem. Some have argued for the establishment of a global authority that defines rules, monitors action, and implements sanctions against GVC actors driving negative cross-scale impacts. Besides the importance of a potential coordinating and legally binding authority, other scholars have criticized the approach by arguing that the complexities of setting up such a system could bring delays that compromise the purpose and are not affordable in the face of the current climate and environmental crisis. Thus, the need to migrate from a market-state dichotomy approach towards a decentralized system of action (i.e., polycentric governance) has been proposed as a necessary strategy to govern systems causing multidimensional cross-scale impacts, such as GVCs (Newig, 2018; Oberlack et al., 2018; Ostrom, 2010a, 2010b).

The decentralization of sustainability actions in GVCs is being facilitated by emerging public, private, and civil society initiatives. Private governance has emerged as one of the most extended mechanisms aiming to minimize sustainability risks in GVCs voluntarily, with a diverse set of tools at its disposal, such as third-party certification labels, multi-stakeholder platforms, own-company sustainability standards, and voluntary sustainability initiatives (Bager and Lambin, 2020; Grabs and Carodenuto, 2021; Lambin et al., 2018; Lambin and Thorlakson, 2018). These mechanisms have been tested in value chains with contested social and environmental outcomes (DeFries et al., 2017; Garrett et al., 2021), some studies suggested that private initiatives can have positive long-term impacts only under specific conditions. (Garrett et al., 2019; Gollnow et al., 2022; Grabs et al., 2021; Levy et al., 2023), while others described mediocre results due to negative spillovers resulting from inadequate enforcement (Meemken et al., 2021; Sonderegger et al., 2022; Tayleur et al., 2017). Overall, it is difficult to assess the concrete contribution of these initiatives to solve the sustainability problems linked to GVCs due to the lack of transparency on company transactions, the lack of standardized definitions, the lack of third-party monitoring and verification systems, and the imbalanced dominance of large companies pioneering these voluntary initiatives (Gardner et al., 2018; Garrett et al., 2019). Due to these factors, voluntary sustainability initiatives are often accused of greenwashing and exacerbating inequality in GVCs. The latter can occur because larger corporations are better equipped to invest in voluntary schemes and benefit from market competitivity gains without the need to demonstrate impacts (known as green capital accumulation). This can undermine the very purpose of these initiatives by increasing the risk of weakened environmental regulations in favor of ever more powerful actors lobbying for lighter regulations (known as sustainability agenda setting) (Clapp, 2021; Ponte, 2019).

Voluntary private initiatives in the cocoa sector are led by different stakeholders and vary in focus. These have evolved from industry-led initiatives and certification labels (e.g., Fairtrade, Rainforest Alliance) to voluntary own-company sustainability initiatives and programs, pre-competitive multistakeholder initiatives, and, recently, transboundary regulatory initiatives (Grabs and Carodenuto, 2021; Ingram et al., 2018; Thorlakson, 2018). In 2017, the Cocoa and Forests Initiative (CFI) was established to address the issues of deforestation, forest degradation and social risks arising from cocoa production, and to ensure effective sustainability monitoring and reporting in the cocoa GVC. This initiative brought together the largest cocoa companies and the governments of Cote d'Ivoire and Ghana to work towards these goals. In 2002, the International Cocoa Initiative (ICI) was formed as a multi-stakeholder initiative to address child-labor by setting a framework for the identification, monitoring, and remediation of cases. In addition, some of the most important consumer markets (such as The Netherlands, Belgium, Switzerland, and Germany) have installed pre-competitive multistakeholder initiatives for sustainable cocoa (ISCOs) with the goal of improving the sustainability conditions for farmers and nature in the cocoa GVC. Recently, the European Commission has approved the deforestation-free legislation and is in the process to pass the due-diligence legislation. These legislations have legally binding conditions to ensure that only cocoa produced in farms free of deforestation and human rights abuses can be sold in the European market (European Commission, 2021, 2022).

Research has focused on understanding the different forms of private governance mechanisms in GVCs and on quantifying their potential additionality in solving sustainability issues (Garrett et al., 2016; Gollnow et al., 2022; Leijten et al., 2023). However, in the cocoa sector, it is still necessary to map the private initiatives that tackle various sustainability dimensions and the key players leading these initiatives. It is also crucial to evaluate to what extent these voluntary private initiatives help to address the cross-scale impacts of the telecoupled cocoa GVC.

4. Research gap and objectives

Despite the diversity of sustainability initiatives in the cocoa GVC, several knowledge gaps jeopardize their strategic design and effectiveness. In the environmental dimension, three important research gaps exist:

First, despite the accumulated knowledge on the impacts of cocoa farming systems, there are no studies analyzing the potential impacts of these farming systems beyond the farm, at a landscape, regional, or global scale. Arguably, this might be related to the interdisciplinary nature of such questions and the complexities of integrating the multiple dynamics at play. Applying farm-level assessment methods to larger geographic scales may not capture the interactions that arise due to land use dynamics, spatial heterogeneity, and context-specific socioeconomic factors (Prestele and Verburg, 2020). This information is crucial for developing sustainable strategies and policies that balance trade-offs across scales, prioritize actions, and provide tailored solutions. Cocoa farming systems that have the least impact at the farm-level are being promoted for larger-scale implementation. However, scientific research suggests that due to the land use dynamics triggered by low production volumes per area, these systems may actually cause much larger impacts at the landscape level, which could potentially counteract any local benefits (Cucurachi et al., 2019; Seufert and Ramankutty, 2017).

Second, the understanding of the potential impacts of cocoa production at even larger geographic scales (e.g., across countries or globally) is hindered by the lack of visibility on the global cocoa value chain configuration. This information is a crucial starting point for understanding the interconnections between local and distant actors in the value chain that can trigger telecoupled impacts across the globe. This understanding could help identify leverage points for environmental upgrading and effective partnerships for sustainability initiatives. At present, there are only a few national-level studies available that focus on the configuration of value chains. These studies primarily examine the commercial risks of various value chain configurations (Barrientos et al., 2007; Guzmán and Fajardo, 2019), the effectiveness of various business models (de Boer et al., 2019), the identification of value chain actors influencing farming activity (García-Cáceres et al., 2014), and the mapping of subnational cocoa sourcing areas (Renier et al., 2023). However, to my knowledge, no study has provided quantitative insights on how agency and power are distributed in the global cocoa value chain and how this can impact the effectiveness of sustainability initiatives in the sector. Since value chain actors send out market and non-market signals that can influence sustainability outcomes in cocoa production areas, this is an important knowledge gap.

Third, despite the steep increase in public voluntary sustainability initiatives made by cocoa value chain actors, no study has analyzed to what extent these cover the entire value chain, and whether they address the most pressing sustainability dimensions and the main geographic hotspots of sustainability risk. Recent studies have suggested that these initiatives often overlap, duplicate actions, and focus on topics attracting the most media attention while distracting from addressing underlying issues (Renier et al., 2023; Zu Ermgassen et al., 2022). Climate change and deforestation are some of the most pressing environmental issues affecting the cocoa GVC. To design more effective sustainability initiatives that increase climate resilience and contribute to improved livelihoods, it is important to understand the spatial variability of these phenomena and the value chain actors involved. This can help minimize the risk of displacing negative impacts across regions while focusing on the most needed areas.

Given these knowledge gaps, this thesis aims to fill the gaps in our understanding of the role of agricultural GVCs in triggering environmental impacts across different scales. It also seeks to explore how a better understanding of GVC dynamics can help mitigate these impacts and create opportunities for sustainable transitions. To address this objective, the cocoa GVC will be used as a case study to answer the following research questions:

I. How can we evaluate the telecoupled sustainability impacts of agricultural GVCs, such as those involving cocoa?
II. How do the environmental impacts triggered by the cocoa GVC at different scales compare to each other?
III. How can cocoa GVC actors mitigate environmental risks at different scales?

5. Thesis outline

This thesis is composed of six chapters: an introduction (Chapter 1), a review study, three research studies, and a synthesis chapter.

Chapter 2 presents a descriptive analysis and comparison of methods used to account for the environmental impacts caused by agricultural value chains at different geographic and temporal scales. It analyzes the capabilities and limitations of methods for accounting the impacts triggered by telecoupled dynamics, with emphasis on the importance of capturing the spatial heterogeneity of the direct and indirect impacts caused by land use dynamics.

Building on the recommendations of Chapter 2, Chapter 3 presents a comparative assessment of the impacts caused by agricultural value chains within and beyond the farm-level, emphasizing the direct and indirect impacts triggered by telecoupled land use dynamics across cocoa producing landscapes. Using the case of cocoa production in Ghana, this chapter discusses the limitations and practical implications of using non-spatially vs. spatially explicit assessment methods to capture the full range of impacts within and beyond the farm.

Moving from the landscape to the global scale, Chapter 4 examines the role of the global cocoa value chain configuration on the capacity to realize visions of sustainable production and trade, by first building archetypes of value chain actors and describing the coverage of sustainability initiatives adopted by cocoa traders. This chapter helps to visualize the value chain network and the interactions between actors that lead to telecoupled dynamics and impacts.

Chapter 5 provides a spatially explicit characterization of two of the most pressing sustainability problems in the cocoa value chain that lead to telecoupled dynamics: deforestation and climate change. Building on Chapter 4, this chapter characterizes the incidence of deforestation and future climate risk in the value chain of global cocoa traders and exporting countries. It also discusses the implications of differentiated risk profiles on operationalizing sustainability action across distant places.

Finally, Chapter 6 revisits the research questions laid out, synthesizes the main findings of all chapters, and discusses the broader implications of operationalizing sustainability in agricultural value chains and the cocoa GVC.

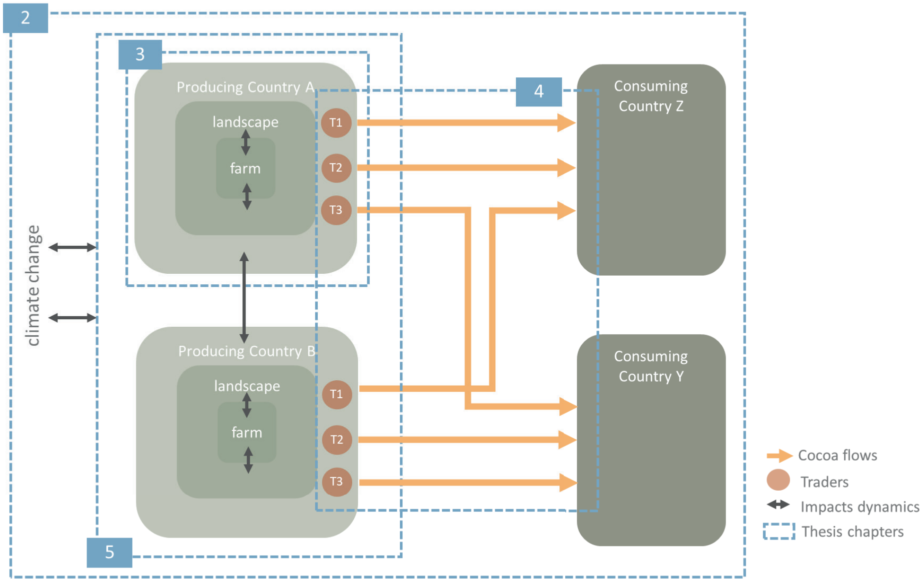

Figure 1. Overview of the scope of the chapters of this thesis.

2. Methods to assess the impacts and indirect land use change caused by telecoupled agricultural value chains: a review

Abstract

The increasing international trade of agricultural products has contributed to a larger diversity of food at low prices and represents an important economic value. However, such trade can also cause social, environmental, and economic impacts beyond the limits of the countries directly involved in the exchange. Agricultural systems are telecoupled because the impacts caused by trade can generate important feedback loops, spillovers, rebound effects, time lags, and non-linearities across multiple geographical and temporal scales that make these impacts more difficult to identify and mitigate. We made a comparative review of current impact assessment methods to analyze their suitability to assess the impacts of telecoupled agricultural value chains. Given the large impacts caused by agricultural production on land systems, we focused on the capacity of methods to account for and spatially allocate direct and indirect land use change impacts. Our analysis identified trade-offs between methods in addressing different elements of the telecoupled system. Hybrid methods are a promising field to navigate these trade-offs. Knowledge gaps in assessing indirect land use change should be overcome to improve the accuracy of assessments.

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1. Introduction

In current globalized economies, the stages of the life cycle of a product (from raw material extraction, manufacturing, distribution, and consumption to end of life) occur across geographical scales. The increasing international trade of agricultural products brings high revenues but has environmental externalities across the globe (Henders and Ostwald, 2014; Ramos et al., 2016; Schaffartzik et al., 2015). The value chain of agricultural products, defined as the set of processes and activities needed to produce and deliver a product (Fasse et al., 2009; Webber and Labaste, 2007), demands many resources such as water, land, energy, fertilizers, and pesticides and it produces significant amounts of waste, pollutants, and emissions (Borsato et al., 2018; Ramos et al., 2016). These can contribute largely to climate change, eutrophication, land use change, biodiversity loss, resource depletion, water, soil, and air pollution that pose local and global environmental threats (Ramos et al., 2016; Rebitzer et al., 2004). Global forces play an important role in modulating local impacts, therefore, correct environmental impact assessments require a better understanding of the telecoupled drivers and effects (Lambin et al., 2001). The term "telecoupled" refers to the interactions between the social, economic, and environmental factors that occur over long distances and have an impact on a particular system, such as an agricultural value chain (Liu et al., 2013). Addressing the several dimensions of the global sustainability challenges can generate trade-offs among them. Therefore, working towards more sustainable value chains requires a deep understanding of the global telecoupled dynamics to limit negative trade-offs between sustainability dimensions or locations.

The telecoupling framework (Liu et al., 2013) is helpful to conceptualize the relevant processes involved in international trade as it describes how the life cycle stages of a given product and the impacts generated might occur across temporal and geographic scales due to the complex socioeconomic and environmental interactions between the multiple systems embedded. Beyond its geographic and temporal outreach, international trade involves complex dynamics such as cause-effect feedback loops, spillovers and leakage of impacts, legacy effects, time-lags, cascading effects, and non-linearities (Liu et al., 2013; Verburg et al., 2015). Despite being inherently present, impact assessment methods often describe these dynamics as external variables and fail to capture them (Chaplin-Kramer et al., 2017; Hoekstra and Wiedmann, 2014; Onat et al., 2017). One reason for this is the little integration between methods from social, environmental, and economic sciences that are needed to capture these complex dynamics (Onat et al., 2017). Another reason is the inexistence of suitable methods able to fully incorporate these telecoupling dynamics across different spatial and temporal scales.

Previous reviews of environmental impact assessment methods of agricultural products had a different focus to this study. Ness and colleagues (2007) categorized tools for sustainability assessments including indicators, product-based assessment tools, and integrated methods.

Herva and colleagues (2011) compiled environmental indicators commonly used by corporations to evaluate the environmental performance of their products and processes. Čuček and colleagues (2012) clarified the definitions, calculation methods, and units used by several social, economic, environmental, and composite footprint indicators. Henders and Ostwald (2014) analyzed methods used to account for leakages originating by policy actions and international trade that affect land systems globally. Bruckner and colleagues (2015) analyzed the capacity of some physical, environmental, economic, and hybrid assessment methods to calculate the land footprints of agricultural, forestry, and livestock products. Verburg and colleagues (2016) reviewed methods to model human-environment dynamics, emphasizing on feedbacks and teleconnections as key characteristics of the Anthropocene. Millington and colleagues (2017) described the capacity of agent-based models, system dynamics, and equilibrium models to depict telecoupled food trade systems and propose a method for their hybrid integration. Previous reviews referring to telecoupled dynamics focused on top-down approaches arguing that these can address the global dynamics characterizing telecoupled systems. However, no study has specifically analyzed the capacity of methods to assess, in a spatial explicit manner, the indirect land use changes (iLUC) caused by agricultural value chains in specific locations (bottom-up approach) while considering at the same time the non-local drivers (top-down approach) shaping the impacts of telecoupling systems.

In this study, we identified and compared the following methods used to assess the direct and indirect environmental impacts caused by the value chain of traded agricultural products: life cycle assessment, environmental footprints, agent-based models, system dynamics models, equilibrium models, and land use models. We aimed to compare the capacity of these impact assessment methods to capture the impacts of telecoupled systems. Agricultural production is inherently embedded in socio-ecological systems where humans and the environment interact. Since socio-ecological systems show high spatial variation, the methods to model them are better suited if they have a spatially-explicit character (Filatova et al., 2013). Socio-ecological systems also have high temporal variations; therefore, our analysis emphasized on the capacity of methods to capture temporal and spatial dynamics. Land use change was used as a bridge concept to analyze the social, economic, and environmental impacts caused by telecoupled agricultural, livestock, and forestry value chains (Turner et al., 2007). Therefore, we emphasized on the capacity of methods to account for direct and indirect land use changes. We identified the strengths and weaknesses of these methods, highlighted knowledge gaps, and proposed future improvement pathways.

2. Materials and Methods

To frame our review, we first built a representation of a telecoupled system for a generalized agricultural value chain using concepts available in the field. This diagram (Figure 1) includes the main systems and agents modulating social, economic, political, and environmental dynamics and the flows, feedbacks and impacts arising from their interaction. This leverages the concepts of telecoupling, and land use dynamics introduced by Liu et al. (2013) and Meyfroidt et al. (2018a), respectively. The representation of political and economic dynamics was informed by Lambin et al. (2018) and Albareda et al. (2007), social dynamics were informed by Lenzen et al. (2007), Vermeir and Verbeke (2006) and Cummins et al. (2014), and environmental dynamics by Rasmussen et al. (2018) and Lambin and Meyfroidt (2010).

Subsequently, a search of methods used to assess the environmental impacts of agricultural commodities was done in Science Direct, Web of Science, and Google Scholar, using a combination of the following words: impact assessment, telecoupling, agricultural value chain, sustainability assessment, agricultural products, land use change, international trade, footprints, indicators, life cycle assessment, input-output analysis, deterministic equilibrium models and agent-based models. The first search round included the keyword 'review' to find review articles. A snowball approach was used to find more detailed studies on specific methods, starting from the references used by these studies. A second search round did not include the word 'review' to capture case studies. Finally, we conducted a comparative analysis of the capacity of methods to assess telecoupled impacts. This analysis was based on the following criteria:

- System boundary definition: The ability of methods to capture impacts strongly depends on the system boundary scope. We evaluated the capacity of methods to account for top-down (global scale) and bottom-up (local scale) dynamics. Truncation points either limit the capacity to capture global interactions or limit the granularity and capacity of these to capture fine-scale dynamics.
- Geographic and temporal approach: Because the impacts of telecoupled systems occur across distances and time, it is important to evaluate the spatial and temporal scope of methods. Methods can have a local, regional, or global scope and can have a static or forward-looking approach (Sala et al., 2015; Verburg et al., 2016a).
- Spatial explicitness: Landscape heterogeneity and context-specific factors modulate environmental impacts (Chaplin-Kramer et al., 2017; Henders and Ostwald, 2014). Therefore, the capacity of methods to spatially allocate impacts was analyzed, particularly direct and indirect land use change impacts.
- Integratedness: The extent to which a method can incorporate social and economic dimensions along with environmental ones, as suggested by the triple bottom line criteria of sustainability (Sala et al., 2015).

- Telecoupling dynamics: The capacity of methods to account for complex dynamics arising within telecoupled systems such as indirect impacts, feedback loops, spillovers, leakage, rebound effects, time lags, legacy effects, and non-linearities (Liu et al., 2013).

The methods were classified according to the following general method families: life cycle assessment (LCA), footprints and related indicators, rule, and process-based models, deterministic equilibrium models and land use models (LUMs). Rule and process-based models included agent-based models (ABMs) and system dynamics models (SDMs). Deterministic equilibrium models included computable general equilibrium models (CGE), partial equilibrium models (PE), and input-output analysis (IO). These general method families were based on the categories previously set by Verburg et al. (2016), Millington et al. (2017), Herva et al. (2011), Henders and Ostwald (2014), and Bruckner et al. (2015). Finally, we suggested some pathways for methodological improvements.

3. Results

A conceptual representation of the components and dynamics embedded in a generalized telecoupled value chain is displayed in Figure 1. In this diagram, we show a simplified version of the most important agents embedded in consuming (receiving), producing (sending), and spillover systems and the most important drivers and impacts arising from their interactions. The different color frames give indications of the components addressed by the different. Short definitions of the terms included in this graph are included in Table 1.

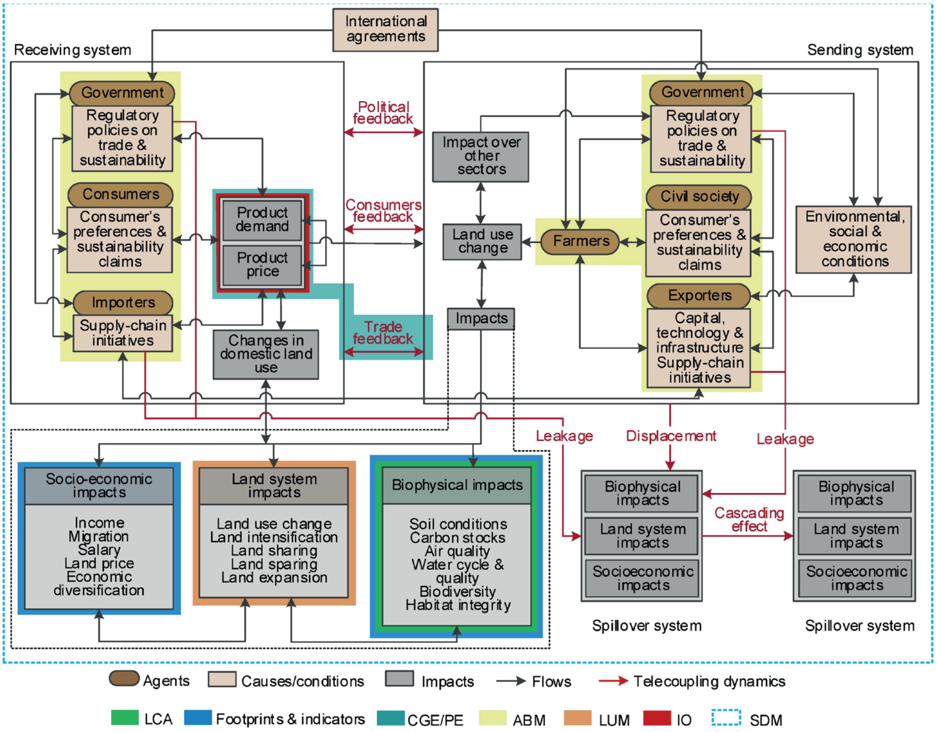

Figure 1. Representation of the main elements (systems and agents) and dynamics (flows, causes/conditions, and impacts) embedded in a generalized telecoupled agricultural value chain. Land system impacts, socio-economic impacts, and biophysical impacts are represented repeatedly in spillover systems to describe the chain of impacts that can occur due to telecoupled dynamics. Different color frames indicate the scope of the methods reviewed. LCA: life cycle assessment; CGE: computable general equilibrium models; PE: partial equilibrium models; IO: input-output analysis; ABM: agent-based models; LUM: land use models; SDM: system dynamics models.

Table 1. Telecoupling definitions used based on Liu et al., (2013).

Term	Definition
Feedback	Process by which an effect caused by one system into another system, impacts back to the first system.
Spillover system	System that is affected by/or affects the direct interaction of other two different systems (sending and receiving systems).
Leakage	Unintended negative effect of a sustainability action elsewhere than the target place.
Cascading effect	Process by which a system affects other multiple systems in sequence as a result of telecoupling dynamics.

The following sections describe the main groups of methods to assess the environmental impacts caused by telecoupled agricultural value chains. The main characteristics of the methods are summarized in Table 2. The description provided in this table refers solely to the main and most basic version of each method. Features of hybrid or integrated methods are analyzed along with the results and discussion.

3.1 Life cycle assessment

3.1.1 General description

Life cycle assessment (LCA) is a quantitative screening tool used to identify environmental impacts occurring along the value chain of a product or service, starting from raw material extraction to disposal or end-of-life. LCA allows the identification of environmental hotspots, therefore it has been used as a decision-tool for initiatives promoting sustainability (Guinée et al., 2011; Hellweg and Canals, 2014). LCA follows four steps: goal and scope definition, inventory analysis, life cycle impact assessment (LCIA), and interpretation (Hellweg and Canals, 2014; Rebitzer et al., 2004). The first phase defines the objectives of the study, sets the boundaries of the system, and selects a functional unit to be used as a reference for impact calculations. The inventory phase compiles data on material and energy inputs and outputs from each life cycle stage. LCIA uses this information to calculate indicators for selected impact categories, which can include, for instance, global warming potential, biodiversity damage, eutrophication, ozone depletion, and land use change. The conversion of data into final impact units is done through weighting and standardization processes. The interpretation stage answers the questions set in the objectives of the study. LCA is attributional when it analyzes current or past processes and consequential (CLCA) if it aims to forecast the impacts of a policy decision over the system under study (Earles and Halog, 2011; JRC-IES, 2010).

3.1.2 General limitations

LCA is mainly designed to perform fine-scale analysis on specific products or services, studies with a broader focus are often constrained by the high data demand. LCA can analyze the entire value chain of a product, however, in practice, it is often applied to selected life cycle stages, excluding input or outputs that generate high impacts. New applications with a broader scope allowing the evaluation of sectors or entire economies are being developed (Guinée et al., 2011). The choice of impact categories and indicators is arbitrary (Reap et al., 2008) and depends on the goal of the assessment. This makes LCA lack standardization and comparability. Although there are guidelines available for selecting impact indicators (Hauschild et al., 2013; Steinmann et al., 2016; UNEP-SETAC, 2016), current LCA practices still have limitations to include important categories such as biodiversity, land-use change, and social-economic aspects (Chaplin-Kramer et al., 2017a; Curran et al., 2011; Jolliet et al., 2018; UNEP-SETAC, 2016). Other limitations include the reliance on average (not place-specific) data of representative industries (Bruckner et al., 2015) and the use of a linear approach to impacts (de Haes et al., 2004). This generalist approach limits the capacity of LCA to capture spatial heterogeneity and context-specific factors. Spatially-explicit LCAs are needed to facilitate decision-making but they might be difficult to achieve because data about the location of suppliers and final consumers are rarely found (Hellweg and Canals, 2014). Moreover, the use of pre-defined and year-specific conversion factors for the calculation of impacts (Castellani et al., 2016) constrains the application of LCA to specific time periods, complicates comparison, and prevents the construction of long-time series. Furthermore, applications of LCA that integrate social and economic factors need to be encouraged to provide better insights for sustainability (Dreyer et al., 2006; Guinée, 2016; Hutchins and Sutherland, 2008; Onat et al., 2017; UNEP-SETAC, 2009).

Table 2. Comparative description of main attributes of methods to assess telecoupled system impacts.

Method family	Telecoupling aspects analyzed	System boundary definition	Considers landscape heterogeneity and iLUC	Integratedness	Geographic scale suitability	Temporal approach
LCA	Except for CLCA, it cannot account for feedbacks. Spillovers can be accounted with system boundary expansion.	Boundaries around a product or service usually exclude indirect impacts. Considers large-scale forces as external variables. Potential for expansion.	No	Usually only focus on biophysical impacts but the incorporation of social and economic ones is possible.	Local scale	Static
Footprints/ other indicators	Feedbacks are not accounted. Spillovers can be accounted with system boundary expansion.	Boundaries strictly around territorial units or agents. Exclude several upstream and downstream impacts. Consider large-scale forces as external variables.	Limited because of the use of average transformation factors.	Indicators available for social, economic, and environmental impacts.	Regional to global. Finer scale depends on data availability.	Static
CGE/PE/IO	CGE and PE analyze economic feedback loops and spillovers occurring at large scale. IO cannot include feedbacks.	Broad boundaries but poor granularity that ignores important intermediate causes and impacts. Boundaries around global economy or sectorial economies.	No. Some CGE and PE can account for iLUC from an economic perspective.	Based on economic factors but hybrid approaches can integrate social and environmental variables.	Regional to global	Forecast (CGE/PE). IO is static.
ABM/SDM	Can parameterize feedback loops and spillovers at least in a qualitative manner. Can analyze multi-temporal, multi-level, and multi-disciplinary dynamics.	Flexible boundaries from narrow to broad ones. Boundaries around agents of the system (ABM) or around the entire system (SDM). Multiple temporal and spatial scales.	No	Can parameterize environmental, social, and economic factors.	From local to global depending on data availability.	Allow for scenario analysis.
LUM	Some models allow the integration of feedbacks and spillovers but only within the spatial extent of the study area.	Boundaries depend on the modeling approach but are more often broad. However, this means poor granularity that ignores important intermediate causes and impacts. Boundaries around the territory (ies) under study.	Yes	Depends on the model but they often emphasize more on biophysical factors.	Mainly regional to global depending on the model.	Forecast

Abbreviations stand for: LCA: life cycle assessment; CGE: computable general equilibrium models; PE: partial equilibrium models; IO: input-output analysis; ABM: agent-based models; SDM: system dynamics models; LUM: land use models.

3.1.3. Suitability for telecoupled systems

Despite the high flexibility of LCA, most current applications are product-centered and assume that the dynamics occurring beyond the strict value chain of a product (e.g., global economy, indirect impacts) are external to the model. Therefore, LCA applications need to expand the system boundaries to be able to account for upstream and downstream spillovers caused by telecoupling dynamics. Standardized guidelines for good practices are required. Nevertheless, the flexibility in the selection of impact categories is a valuable feature because it allows to reflect on several dynamics. To quantify spillovers, it is necessary to understand the cause-effect dynamics arising in different life cycle stages and procure the necessary data. The first is a challenge that extends beyond the LCA community and the second one faces limitations due to limited data transparency and accessibility. CLCA is a promising application because it extends beyond the purely biophysical focus of LCA by also analyzing the influence of the global economy over the system under study (Curran, 2013; Earles and Halog, 2011; Stefanie Hellweg and Canals, 2014; Yang and Heijungs, 2018). CLCA can also include non-linear impacts to study complex dynamics extended over time such as time-lags and legacy effects. However, it requires the integration of tools having a forecasting capacity. The integration of other telecoupling dynamics, such as feedbacks, requires the integration of LCA with other methods capable of addressing these processes. LCA studies that integrate input-output analysis, computable general equilibrium (CGE), and partial equilibrium models (PE) go in that direction (Earles and Halog, 2011; Kloverpris et al., 2008; Onat et al., 2017). Large-scale spatial-explicit analysis might be difficult to achieve or might carry high uncertainties due to the lack of place-specific data and the use of generalized weighting and transformation factors (Rebitzer et al., 2004). The calculation of place specific transformation factors is needed. Studies such as van Zelm et al., (2018) and Koellner and Scholz (2007) shed light on this challenge.

Currently, the few LCAs that account for land use impacts are mainly based on indicators of land occupation and land transformation and disregard the importance of iLUC caused by land competing forces, market forces, and social dynamics (Arodudu et al., 2017; Chaplin-Kramer et al., 2017; Loiseau et al., 2018; Mattila et al., 2012). In this sense, the integration of LCA with land use models could contribute to improving the quantification and spatial location of land use impacts. There are several methodological approaches proposed to incorporate land use change in LCA (Geyer et al., 2010; Koellner and Scholz, 2007; Milà i Canals et al., 2007; Saad et al., 2013; Udo de Haes, 2006). Some recent applications in this direction include LUCI-LCA (Chaplin-Kramer et al., 2017). Using land use change modeling and ecosystem services assessment, LUCI-LCA spatially assesses and forecasts the impacts of agricultural products on land use change and ecosystem services. Other explicit approaches to address iLUC and LCA include Di Fulvio and colleagues (2019), who coupled LCA with the global land use model GLOBIOM (see Table 2 from Appendix A) to quantify and allocate iLUC and biodiversity loss caused by the international trade of biofuels. Other LCAs coupled with equilibrium models include Leip et al. (2010) and Searchinger et al. (2008). Schmidt et al. (2015) proposed a conceptual framework to assess iLUC in LCA studies based on a biophysical model. Although the product-focus of LCA makes it an interesting tool to operationalize sustainable agricultural value chains, there is no consensus on how to include iLUC in LCA to date (Schmidt, 2015).

3.2 Footprints and related indicators

3.2.1 General description

Environmental footprints are quantitative indicators used to assess environmental performance (Čuček et al., 2012; Ewing et al., 2012; Herva et al., 2011). Footprints are frequently used to assess human populations, countries, companies, and, products (Borsato et al., 2018). Footprint indicators have different definitions, scopes, and calculation methods depending on the footprint developer (Čuček et al., 2012). Footprints calculate the number of resources consumed (e.g., water, land, etc.) or released (e.g., greenhouse gases, nitrogen, etc.) and standardize these into particular units (usually area units or other units specific to the footprint indicator) (Čuček et al., 2012; Turner et al., 2007). While LCA integrates different impact categories, most footprints account for a specific type of impact, such as impacts on water resources, greenhouse gases, biodiversity damage, land erosion, nitrogen pollution, among others and, as such, they can be incorporated into LCA as impact factors. Footprints that are focused on social and economic impacts are in the early development stages (Čuček et al., 2012). The well-known ecological footprint (EF) is a composite measure aiming to evaluate environmental sustainability in a comprehensive manner. EFs account for the direct and indirect demand of resources and the required capacity to assimilate the waste and emissions generated. EF can be applied to cropland, fishing grounds, grazing land, forest, built-up land, and carbon uptake land (Wackernagel et al., 2014; Zhang et al., 2017). EF calculations are based on biocapacity, which is the capacity of a system to regenerate resources and assimilate environmental emissions (Brooks et al., 2018; Čuček et al., 2012; Galli et al., 2012). To allow comparability, specific biocapacities are converted into global hectares by using equivalence factors to relate a place-specific biocapacity to the average global biocapacity.

The human appropriation of net primary production (HANPP) is another footprint indicator that represents the capacity of the land to produce biomass (net primary productivity, NPP) accounting at the same time for the land depletion caused by human activities (Krausmann et al., 2013). The embodied HANPP (eHANPP), measures the amount of HANPP caused by the value chain of a product and has been used to evaluate the impacts of trade. eHANPP accounts for the non-linear impacts of production activities by using net primary production (NPP) as a basic measure, which is an attribute of land that can only be used once (Schaffartzik et al., 2015a). Contrary to EFs, eHANPP is measured in biomass units (i.e., tons of carbon or dry-matter biomass) (Erb et al., 2009; Haberl et al., 2009).

3.2.2 General limitations

EF and eHANPP are indicators usually calculated for defined units, often jurisdictions. These indicators do not account for upstream nor downstream resource demands and emissions generated beyond the studied system. They are usually better suited for regional or global studies because they rely on highly aggregated data (normally at the national level) that lack geographic granularity. Fine-scale data at product or corporate levels are usually not available. Due to their highly aggregated nature, the identification of environmental hotspots is complicated. These indicators are static, meaning that they measure environmental performance only at a given point in time and, thus, cannot consider long-term effects (Fiala, 2008; Zhang et al., 2017). This means that EFs have limitations in incorporating impacts from dynamic processes affecting the biocapacity of land such as land degradation, intensive land use, and resource depletion. These methods provide easy-to-understand single measures, but the trade-offs generated by their highly aggregated approach need to be considered (Fiala, 2008).

3.2.3 Suitability for telecoupled systems

Most footprint studies set the boundaries of the system in political borders and exclude the telecoupling dynamics interacting with national accounts. EFs, for instance, account for the resources consumed and emissions generated within a territory in a certain year without considering impacts from exports and other external dynamics (Fiala, 2008). However, there are recent applications of EFs based on input-output data that allow to account for the impacts generated by international trade (Fiala, 2008; Galli et al., 2012). eHANPP is based on the differential HANPP consumed and produced by a nation and as such, allows to account for the impacts of international trade. The incorporation of spillovers in the calculations would demand enhanced traceability of the primary products used for the consumption or production of a country or agent and the waste generated. A concrete example in this direction is provided by Kastner et al. (2011) who introduced an algebraic algorithm allowing to trace the origin of the primary products used in a product consumed elsewhere based on bilateral trade data. Moreover, the inclusion of spillovers will demand broadening the scope of the environmental dimensions considered in these footprint indicators (such as emission flows) (Turner et al., 2007). The same applies for iLUC spillovers because land footprints only account for direct land use change impacts and exclude the indirect impacts triggered by market dynamics, social dynamics, and the competition between different land uses. The inclusion of long-term effects into the calculations would need an improved understanding of cause-effect mechanisms and the calculation of impacts across time. These methods are not designed to account for feedbacks but could be coupled with methods able to address them. To achieve spatial-explicit footprints, it is necessary to overcome data limitations and to produce place-specific conversion factors. Finally, footprint indicators can help to incorporate specific environmental dimensions to other methods.

3.3 Deterministic equilibrium models

3.3.1 General description

The economic and environmental impacts embodied in international trade have been modeled with economy-based methods such as Input-Output analysis (IO), Computable General (CGE), and Partial Equilibrium (PE) models. IO is an empirical method to model market dynamics by calculating linear equations to describe inter-industry relationships in a given economy based on demand data (Miller and Blair, 2009; Rose et al., 1995). It is traditionally based on transaction tables of yearly monetary flows between economic sectors of countries (Miller and Blair, 2009). Recent IO analysis based on biophysical input-output tables have been proposed (Weisz and Duchin, 2006). IO can be considered as a component of CGE and PE models (Miller and Blair, 2009; West, 1995). CGE and PE are dynamic models that are built on the conceptual basis of IO but with important differentiations (Rose et al., 1995; West, 1995). CGE and PE model markets and economic sectors respectively and provide future economic projections for a defined time frame based on optimized equilibriums (long term economic equilibrium solutions) generated by demand, supply, and price (Henders and Ostwald, 2014; West, 1995). CGE uses the technical coefficients obtained with IO but incorporates, among other things, supply, and price data (Miller and Blair, 2009; Rose et al., 1995). CGE and PE consider that both supply and demand regulate each other in perfect equilibrium through feedback loops (market feedbacks), which allows them to model international economic competition (Rose et al., 1995). IO is better suited for small-scale analysis (e.g., national) whereas CGE are more adequate for larger scales (e.g., regional, or global). Both methods have as a core data from input-output tables of global databases such as EoRA, GTAP, EXIOBASE, or WIOD (Dietzenbacher et al., 2013; Inomata and Owen, 2014; Lenzen et al., 2013; Moran and Wood, 2014; Wood et al., 2015) (see Table 1 from Appendix A). These tables report on the monetary transactions between countries and economic sectors including exports, capital formation, and final consumption (Tukker et al., 2006).

3.3.2 General limitations

Due to the highly aggregated input data (non-differentiated production sectors) and the large set of assumptions, these methods often carry large uncertainties and lack granularity for fine-scale studies (e.g., product level) (Henders and Ostwald, 2014; Hoekstra and Wiedmann, 2014; Ramos et al., 2016). IO is static (no forecast capacity) because it only analyzes past data and because it is based on constant coefficients that do not incorporate dynamics (e.g., price changes, technological changes, and capital instability) that would allow to provide future projections (West, 1995). Moreover, IO assumes an unlimited supply of products and homogeneous global prices for products (West, 1995). CGE and PE assume rational economic behavior, economic equilibrium between supply and demand, homogeneous, global prices, and perfect economies (perfectly competitive markets, zero transaction costs and homogeneous product quality) (Henders and Ostwald, 2014; Rose et al., 1995; Verburg et al., 2016). Additionally, IO databases are available only for certain years, for certain countries, and with distinct sector-detail information (usually highly aggregated). Finally, by coming from the economic field, these methods do not include environmental and social interaction that can feedback on the economic dynamics.

3.3.3 Suitability for telecoupled systems

The system boundaries of IO, CGE, and PE are set at broad scales (e.g., national, global, and sectoral) which allows the incorporation of large-scale economic dynamics into the analysis and makes them very appealing to study telecoupled systems. However, one disadvantage of such an approach is that these methods cannot consider place-specific dynamics, so fine-scale studies are difficult to address with these models. Because CGE and PE models integrate non-linear economic dynamics by using complex solution algorithms (West, 1995), they are capable of accounting for market feedbacks loops and non-linear responses. Single IO analysis (at the country level, only) cannot integrate feedback loops but multi-regional IO (MRIO) analysis can (Wiedmann et al., 2007). Therefore, CGE, PE and MRIO are promising methods to assess telecoupled systems at a global scale. Moreover, by considering the broader economic spectrum, CGE, PE, and IO help to calculate economic spillovers and indirect, economy-linked, impacts. These features have inspired LCA practitioners to integrate IO into their analysis with the goal of expanding the product-centered analysis of a normal LCA with the impacts of international trade on a value chain (Tukker et al., 2006; Wiedmann et al., 2007). The improvement of the resolution of these methods would need more disaggregated data about production sectors in databases. Continuous time-series and data about more countries are also needed. CGE and PE provide forecasts but to account for time-related telecoupling dynamics (such as time-lags, legacy effects, and cascading effects) they would need improved algorithms.

The integration of environmental and social variables would also improve the forecasting practices and the capacity of these methods to reflect the full spectrum of dynamics. There are several hybrid approaches documented in this direction, such as the environmentally extended input-output analysis that aims to analyze the impacts that international trade has on the environment (Kitzes, 2013; Wiedmann et al., 2007). Besides, by integrating IO, footprints could estimate the embodied environmental impacts of production, consumption, imports, and exports (Turner et al., 2007; Wiedmann et al., 2007). Regarding land systems, CGE, PE, and IO have been combined with land use allocation models to analyze the iLUCs caused by international trade in a spatially-explicit manner (Havlik et al., 2014; Prell et al., 2017; Van Asselen and Verburg, 2013; Wiedmann et al., 2007; Yu et al., 2013). These methods are highly suitable to evaluate feedbacks and spillovers (including iLUC) in a spatially-explicit manner if coupled with land use models and methods accounting for specific environmental impacts (Bruckner et al., 2015; Henders and Ostwald, 2014) as done by Di Fulvio et al. (2019), Leip et al. (2010), and Searchinger et al. (2008) with LCA. Such combinations are often made by downscaling the aggregated results with simple spatial algorithms following some kind of land suitability map (Irwin and Geoghegan, 2001). However, transformations from monetary data to land use change values are based on global or regional average yields that deny the importance of land heterogeneities (Henders and Ostwald, 2014). Moreover, the downscaled land change patterns do not feedback on the global equilibrium calculations.

3.4 Rule and process-based models

3.4.1 General description

Agent-based models (ABMs) and system dynamics models (SDMs) are rule and process-based models relevant to telecoupling systems. ABM is a computer-simulated method designed to understand the dynamics of a system and make forecasts about it. ABMs model agents' behavior (agency) (e.g., humans, institutions, and any social structure) in relation to the environment based on defined decision rules (Groeneveld et al., 2017; MacPherson and Gras, 2016; Verburg et al., 2016). These decision rules are defined in a finite space and time in a quantitative or qualitative manner in ABM models (An et al., 2014; Hare and Deadman, 2004). ABMs allow the parameterization of human interactions, adaptation, and learning processes and can capture the diversity and uncertainty of human behavior in a flexible and context-specific way (Groeneveld et al., 2017; Hare and Deadman, 2004).

SDM is a flexible computer-modeling framework used to understand the dynamics of a given system by representing the processes and relationships occurring between their elements. SDMs aim to go beyond the representation of cause-effect relationships towards a more holistic understanding of the functioning of systems (Ercan et al., 2016). To do so, SDM uses mathematical equations and decision rules to parameterize processes and relationships (Filatova et al., 2016; Ramankutty and Coomes, 2016). Because SDMs and ABMs are general modeling frameworks they can be applied at local, regional, or global scales (Millington et al., 2017).

3.4.2 General limitations

Although both ABMs and SDMs are flexible modeling frameworks, the large data needed challenges the expansion of system boundaries and their application to broad geographic scales in practice (Verburg et al., 2016a). Therefore, ABMs are better suited for fine-scale studies, and global applications are limited. The flexibility of ABMs and SDMs has been criticized for including several decision rules and assumptions that do not rely on economic, physiological, or sociological theories (Groeneveld et al., 2017). Due to the strong bottom-up approach of ABMs, the integration of exogenous dynamics operating at larger scales (e.g., global trade and price development of agricultural commodities) is limited (Verburg et al., 2016a). Although ABMs and SDMs in theory allow forecasting based on past trends, most of them are not used for this purpose but rather to understand system dynamics (Groeneveld et al., 2017; Mai and Smith, 2018).

3.4.3 Suitability for telecoupled systems

The possibility to parameterize agents' behavior has made ABMs useful to model socio-ecological systems (e.g., to model land use change) (An et al., 2014; Filatova et al., 2013; Groeneveld et al., 2017; Hare and Deadman, 2004; Judson, 1994; MacPherson and Gras, 2016; Valbuena et al., 2010). Recent articles argue that ABMs are a highly valuable tool to parameterize the complex dynamics occurring in telecoupled systems because they can parameterize feedbacks and address spillovers (An et al., 2014; Tonini and Liu, 2017)t al., 2014; Tonini and Liu, 2017). This is because ABMs can represent external forces (such as climate change, global market influences, etc.) and can integrate data across multiple spatial and temporal scales (An, 2012; An et al., 2014a). SDMs are also suitable for incorporating these and other telecoupling dynamics (e.g., feedback loops, rebound effects and indirect impacts) (Mavrommati et al., 2013; Millington et al., 2017; Onat et al., 2017). The conceptualization and parameterization of feedback loops between system components is done with decision rules and is a central component of SDMs (Millington et al., 2017; Onat et al., 2014). Moreover, because the data demand of these methods is flexible (ranging from qualitative to quantitative), the inclusion of the telecoupled dynamics finds less constraints than purely quantitative methods (Coyle, 2000; Millington et al., 2017). ABMs and SDMs also allow the simultaneous parameterization of several processes affecting human interactions such as biophysical, socioeconomic, and demographic ones (An et al., 2014a). This can be done through the integration of footprint measures or environmental indicators (Mavrommati et al., 2013). This feature is interesting for telecoupled systems, but the assumptions set in models must be improved if the integration of multi-level and multi-disciplinary variables is to be done consistently.

There is no analytical framework for forecasting in SDMs, while the strong fine-scale focus of ABMs limits this possibility. However, the integration of these models with other methods, such as general equilibrium models and land use models, could help to overcome this limitation. While many ABMs provide a spatially explicit representation of impacts (Filatova et al., 2013; Groeneveld et al., 2017; Matthews et al., 2007), SDMs usually lack this type of representation. Spatially-explicit ABMs are important to capture the spatial heterogeneity of the behavior and factors parameterized in the model (Filatova et al., 2013) and are key to capturing iLUC caused by the agents. Examples of this are available (Happe et al., 2011; Schouten et al., 2013; Valbuena et al., 2010) and have been reviewed by Filatova et al. (2013), Groeneveld et al. (2017), and Matthews et al. (2007). Millington et al. (2017) proposed a conceptual framework for the integration of ABMs, SDMs, and CGE models to simulate the dynamics between international food trade and land use change under different social, political, economic, and environmental scenarios. This hybrid proposal could certainly improve the analysis of multi-temporal and multi-level dynamics and feedbacks. However, the spatial-explicit allocation of impacts (e.g., iLUC) and the operationalization of land heterogeneity would remain a challenge that could be overcome with land use models.

3.5 Land use models

3.5.1 General description

Land use change modeling can be achieved with specialized land use models (LUMs) and integrated assessment models (IAMs) that often include simplified land use modules (Verburg et al., 2016a). Modeling parameters can be informed by the outputs from other models (usually on CGE and PE) and are based on hybrid data (e.g., economic or biophysical data) (Alexander et al., 2017). LUM can be process-based (e.g., representing agent behavior) or pattern-based (e.g., describing changes) (Brown et al., 2013). Different models simulate land use changes using similar rationale but have different allocation procedures. LUMs have forecast capacity and allow the evaluation of impacts under different scenarios. LUMs can use diverse data sources, have diverse spatial and temporal resolutions, and include different assumptions. For instance, CLUMondo, GLOBIOM, IMAGE and MagPIE use the outputs of CGE and PE models to define demand shifts of crops (Alexander et al., 2017; Havlik et al., 2014; Nelson et al., 2014; Popp et al., 2014; Schmitz et al., 2014; Stehfest, E., van Vuuren, D., Kram, T., Bouwman, L., Alkemade, R., Bakkenes, M., Biemans, H., Bouwman, A., den Elzen, M., Janse, J., Lucas, P., van Minnen, J., Müller, C., Prins, 2014) (See Table 2 from Appendix A). All models calculate location suitability to determine the likelihood of land use changes across space.

3.5.2 General limitations

Each LUM is designed to answer specific questions at a specific scale. Therefore, the system boundary can be either narrowed to study fine-scale changes or broadened to study global or regional changes. Models integrating these cross-scales face several technical and practical challenges. Due to the complexity of highly integrated models (IAMs), these are subject to very high uncertainties (Alexander et al., 2017) and are difficult to validate due to the lack of historical observational data (Prestele et al., 2016). These uncertainties come from the underlying assumptions, input data, scenario assumptions, scale mismatches, and defined land cover classes (Prestele et al., 2016). These models can include multiple variables, but some are still challenging to incorporate. For instance, few models incorporate land use management categories as drivers of land use change (Pongratz et al., 2017). Fine-scale models integrate actors' behavior, but large-scale ones often do not (Brown et al., 2013). In many cases, the complexity of underlying processes leads to the simplification and exclusion of certain social, economic, and environmental variables.

3.5.3 Suitability for telecoupled systems

Land systems are important for telecoupling analysis because they reflect the outcome of the interaction of social, economic, and environmental dynamics. Land use models are of special interest to telecoupled systems because they can account for land-related spillovers (iLUC) and can be used for scenario analysis (Verburg et al., 2015). Land use models with global coverage are relevant because they can analyze multiple large-scale processes (Lambin et al., 2001). However, large-scale models can sacrifice granularity and have limited applicability at the scale needed by decision makers (Schaldach et al., 2011). Hybrid land use models that can represent human decisions, socioeconomic and environmental factors simultaneously are available and have been reviewed by Brown et al. (2013). Although most LUMs are very capable of calculating and allocating iLUC, the full parameterization of cross-scale processes and feedbacks face limitations due to a lack of understanding of the processes embedded, computation capacity, and the availability of data (Verburg et al., 2015). However, despite this advantageous capacity, LUMs are not product-centered and as such have limited capacities to analyze the value chains of products. IAMs are designed to incorporate feedbacks within the studied systems, however, the simulation of feedbacks between causal mechanisms and impacts beyond them is still limited (Verburg et al., 2016a). Other impact categories such as biodiversity loss, carbon release, or other related to ecosystem services can be calculated using the simulated land use changes as a basis (Chaplin-Kramer et al., 2017). Moreover, in some models the data about demand is based on aggregated groups of products so the analysis of specific products is not possible. However, novel applications have modeled the demands for subsistence commodities and marketed commodities, which allows to distinguish locally-driven processes from those driven by telecoupled dynamics (Debonne et al., 2018; Ornetsmüller et al., 2016).

4. Discussion

In the previous section, we identified the challenges related to impact assessment methods. In this section, we discuss the overarching challenges that require attention to account for the telecoupled impacts of agricultural value chains.

4.1 Systems boundaries

The definition of boundaries has an important effect on the capacity of methods to account for the impacts caused by telecoupling dynamics (Filatova et al., 2016; Friis and Nielsen, 2017). Nevertheless, these are often chosen arbitrarily without a science base. Truncation points that exclude large-scale dynamics or context-specific factors and responses are commonly defined and lead to over-simplification. Setting a correct system boundary depends on the goals of the study and the scale of the analysis. Top-down approaches, such as CGE and PE, have the advantage of capturing large-scale processes but lack the capacity to account for place-specific impacts. Therefore, for this type of methods, system boundary expansion means allowing the inclusion of place-specific factors to improve the global average factors commonly used. Bottom-up approaches (such as LCA and ABM) are well suited to capture place-or product-specific dynamics but have limitations to account for large-scale dynamics influencing the impacts of a value chain. For this type of methods, system boundary expansion means capturing large-scale dynamics, which could be achieved by coupling them with other methods having this capacity. The integration of top-down and bottom-up modeling approaches is needed to capture telecoupled dynamics (Hellweg and Canals, 2014; Sala et al., 2013).

4.2 Hybrid models to assess telecoupled impacts

The multi-disciplinary nature of telecoupled systems requires the integration of various methods to be able to address the broad variety of sustainability dimensions with sufficient detail (Verburg et al., 2016a). Hybrid approaches could bridge the gaps between different methods. Examples of hybrid methods available and their contribution to the assessment of telecoupled impacts are provided in Table 3.

Footprints and impact indicators can be included in LCA to add environmental dimensions to the analysis. LCA studies can also be complemented with the integration IO of analysis (Ewing et al., 2012; Hertwich and Peters, 2009; Turner et al., 2007; Weinzettel et al., 2013) and SDMs (Jin et al., 2009) to expand the system boundaries in the inventory phase. LCA can be coupled, and with equilibrium models to capture economic feedbacks influencing value chains impacts. Examples of LCA coupled with equilibrium models (Di Fulvio et al., 2019; Earles and Halog, 2011; Kloverpris et al., 2008; Leip et al., 2010; Lenzen et al., 2003; Searchinger et al., 2008), IO (Hawkins et al., 2007; Igos et al., 2015; Kennelly et al., 2019; Yi et al., 2007) and other methods (Onat et al., 2017) are available. In addition, LCA has been coupled with LUMs to calculate direct and indirect land use change impacts and capture spatial variability (Chaplin-Kramer et al., 2017; De Rosa et al., 2016; Di Fulvio et al., 2019; Kloverpris et al., 2008). The calculation of spatially-explicit conversion factors needed to conduct such assessments are under development (Milà i Canals et al., 2007; Saad et al., 2011; van Zelm et al., 2018). Therefore, LCA has the potential to capture telecoupled impacts caused by value chains. To achieve a comprehensive scope, LCA practitioners could benefit from clear guidelines.

Deterministic equilibrium models allow to capture economic feedback loops and account for economic spillovers at large scales. Equilibrium models that incorporate the environmental dimension have already been used to assess direct and indirect land use changes (e.g., GLOBIOM and MagPIE) (Alexander et al., 2017). Efforts to add the environmental dimension to economic-centered IO analysis include the environmentally extended-IO analysis (Kitzes, 2013; Tukker et al., 2006) and IO studies that integrated environmental footprint indicators (Ewing et al., 2012; Hertwich and Peters, 2009; Kitzes, 2013; Prell et al., 2017b; Tukker et al., 2006).

Human behavior and agency are important modulating factors of telecoupled impacts that are absent or simplified in the scope of LCA, footprints, CGE, PE, and IO analysis. ABMs can model decision making processes of actors about the biophysical systems they are part of. ABMs and SDMs could be coupled with LUMs to address environmental spatial variability and calculate indirect land use changes more explicitly. Studies coupling ABMs with environmental and spatially-explicit methods are available (Filatova et al., 2013; Groeneveld et al., 2017; Matthews et al., 2007). The fine scale level of analysis of ABMs and SDMs complicates their application to large scales, but they can be coupled with equilibrium models to incorporate global economic dynamics, for instance (Millington et al., 2017).

From a producer perspective, Value Chain Analysis (VCA) is an important tool to evaluate the sustainability performance of value chains by supporting the identification of environmental risk hotspots (Bolwig et al., 2010; Kaplinsky and Morris, 2000). Industry has a long tradition of using VCA to improve the strategic and operational steps of their value chains (Fearne et al., 2012) and the increased awareness of the environmental dimension has encouraged its use as a tool to improve the environmental sustainability of value chains. This has usually been done by coupling VCA with other methods such as LCA, material flow analysis, and footprints (Fasse et al., 2011, 2009; Fearne et al., 2012). Because the factors affecting the quality and efficiency of value chains can modulate environmental impacts, VCA can play an important role in the identification of factors and agents triggering telecoupled impacts. This is possible because VCA goes beyond the product-level and adopts a multi-dimensional approach by integrating vertical and horizontal elements of value chains (Bolwig et al., 2010; De Marchi et al., 2013; Kaplinsky and Morris, 2000; Mahutga, 2012). VCA could be coupled with LUMs to analyze indirect land use changes in a spatially explicit manner.

Finally, method integrations should be done carefully to avoid conceptual, technical, and semantic contradictions and avoid the use of dysfunctional hybrid models of unmanageable complexity (Millington et al., 2017; Panichelli and Gnansounou, 2015; Voinov and Shugart, 2013). Technical differences might include geometry and spatial resolution, data scope, non-standardized ontologies, and conceptual mismatches that could lead to the loss of important individual properties of models when coupled with others (Voinov and Shugart, 2013). Despite the hybrid proposals presented in this paper; it is important to mention that the improvement of individual methods must go together with method integration to avoid overwhelmingly complex methods where the individual tools still face difficulties in addressing basic questions.

4.3 Long term impacts

The inclusion of long-term impacts in methods is important because agricultural activities can cause impacts that extend over time (e.g., soil depletion and toxicity) and can also be affected by long-term phenomena such as climate change. This also applies to the socio-ecological dynamics linked to agricultural value chains (Meyfroidt et al., 2018) that could generate regime shifts (i.e., abrupt structural changes) and cascade effects (Filatova et al., 2016). Because the dynamics of telecoupled systems occur at diverse temporal and spatial scales, methods should be able to reconcile these scales (Verburg et al., 2016a). Despite some attempts, there is little consensus about how to integrate short- and long-term dynamics in impact assessments

(Hellweg and Frischknecht, 2004; Verburg et al., 2016). The inclusion of long-term dynamics in impact assessments could facilitate the implementation of early contingency measures and support decision making processes.

Table 3. Examples of hybrid methods to analyze telecoupled agricultural systems.

Abbreviations stand for: LCA=life cycle assessment; CGE= computable general equilibrium models; PE= partial equilibrium models; IO= input-output analysis; ABM= agent-based models; SDM= system dynamics models; LUM= land use models.

Method Family	Description	Main contribution to the assessment of telecoupled impacts	Examples
LCA and LUM	Uses LUMs to predict, calculate and allocate the impacts of land use change in LCA.	Spatially-explicit forecasting of land-related spillovers (iLUC change).	(Chaplin-Kramer et al., 2017) (Geyer et al., 2010) (De Rosa et al., 2016)
LCA and CGE/ PE-based LUM	Couples LCA with CGE/PE-based LUMs (e.g., GLOBIOM) to quantify and spatially allocate direct and indirect land use change impacts and calculate other environmental impacts caused by international trade.	System boundary expansion (to the global economy), integration of economic feedbacks, analysis of land-related spillovers (iLUC).	(Di Fulvio et al., 2019) (Searchinger et al., 2008) (Leip et al., 2010) (Kloverpris et al., 2008)
IO and footprints or indicators	Uses simple or multi-regional IO tables coupled with environmental data, footprints, and indicators to calculate the environmental impacts caused by trade.	System boundary expansion and integration of economic feedbacks (only for the case of MRIO).	(Kitzes, 2013) (Tukker et al., 2006) (Prell et al., 2017) (Ewing et al., 2012) (Hertwich and Peters, 2009) (Weinzettel et al., 2013) (Turner et al., 2007)
IO and LCA	Uses input-output tables to track resources used in the life cycle of a product to calculate the environmental impacts caused in response to market changes.	System boundary expansion.	(Hawkins et al., 2007) (Igos et al., 2015) (Kennelly et al., 2019) (Yi et al., 2007)
SDM and footprints or indicators	Represent wider system dynamics and link it to environmental indicators to represent the relationship between environmental impacts and socio-economic drivers.	System boundary expansion, integration of feedback loops and spillovers.	(Mavrommati et al., 2013)
ABM, SDM and CGE	Uses ABM to represent land use decision-making, CGE to represent markets and SDM to represent flows.	System boundary expansion (to the global economy), integration of feedback loops and spillovers caused by agents.	(Millington et al., 2017)

4.4 Geographic heterogeneity

Land heterogeneity and land management practices get little attention in most methods assessing the impacts of agricultural value chains. Pongratz and colleagues (2017) described the importance of representing land management practices in models to significantly increase their comprehensiveness (Ercan et al., 2016). Critical aspects of land heterogeneity and land management practices need to be first identified, understood, prioritized, and parametrized to be included in methods. Methods would need to implement place-specific information to increase their accuracy (Henders and Ostwald, 2014). Moreover, the use of baseline information (e.g., land cover maps, biome maps, etc.) should ideally be homogenized to allow comparability between studies using the same scale. One of the most extended practices leading to the exclusion of landscape-specific considerations in methods is the use of generalized assumptions and highly aggregated data (Galli et al., 2012; Schaffartzik et al., 2015). To overcome these limitations, it is necessary to increase the understanding of the importance of context-specific factors and spatial heterogeneity and the calculation of impact factors having this level of detail. Empirical studies play an important role in filling this gap and can contribute to improving available method scopes (Filatova et al., 2013; Magliocca et al., 2014; Verburg et al., 2016).

4.5 Suitability for different user types and hands-on approach

There is a wide range of stakeholders using impact assessment studies to help improve the environmental performance of a given product, territory, service, or value chain. Since the choice of a given impact assessment method carries different implications (Franzen and Mader, 2018), this selection must be carried out carefully. Regardless of the technical criteria described in this paper, the choice of an adequate method is strongly influenced by the practical goals of the analysis, which are closely related to the target audience. Different stakeholders rule over different subjects (products, value chains, territories, consumers, laws, etc.) and therefore, need distinct approaches.

The methods analyzed in this article have either a consumption, production, geographical, or a system approach. The allocation of responsibility is highly influenced by the chosen approach and has been widely discussed in the literature (e.g., for the case of carbon emissions). For consumption-based approaches (e.g., EF), the responsibility of a given agent relies solely on the products consumed regardless of all the impacts caused through their own production activities (Ferng, 2003; Steininger et al., 2014). Therefore, this approach assesses the impacts embedded in products and attributes them to the agents consuming them. While this approach accounts for the impacts caused by product demand, it has limitations in promoting management strategies because consumers might have no interference power above the producers of the services and products (Schaffartzik et al., 2015a). For production-based approaches (e.g., LCA), the responsibility is allocated to production processes regardless of the final consumer (Steininger et al., 2014). This approach accounts for the impacts of supply, but it can be problematic when it comes to use it for effective management, as it can negatively incentivize producers to outsource harmful activities or inputs to avoid responsibility (Galli et al., 2012). Methods with a spatial approach (e.g., LUM) focus on a spatially defined area where diverse human and natural forces interact and cause impacts over that territory. Therefore, its main goal is to spatially allocate impacts caused by a set of activities. One limitation of this approach is that it does not provide explicit decision-support information to producers or to consumers because it describes impacts over territorial areas without assigning responsibility to specific actors. The system approach (e.g., ABM and SDM) includes methods whose goal is to understand the dynamics and processes embedded in telecoupling systems without necessarily quantifying impacts or allocating responsibility (Millington et al., 2017). An advantage is that they are flexible enough to emphasize both the consumption and production sites.

Additionally, it is important to note the trade-offs between the applicability and comprehensiveness of methods. Single impact scores (e.g., from EF) have a communicative advantage for decision-making because they facilitate comparison. At the same time, the application of studies having a large spatial coverage (e.g., LUM and CGE) is limited because they do not provide information at the scale needed for practical actions (Verburg et al., 2016a). Interdisciplinary science-policy collaborations should be encouraged to achieve meaningful and hands-on assessments.

4.6 Reference points for sustainability

“A given indicator does not say anything about sustainability, unless a reference value or threshold is given to it” (Lancker and Nijkamp, 2000). LCA for instance, is mainly designed for comparison between products but does not provide information about the sustainability of the products themselves. Similarly occurs with EFs and LUMs. These methods are strongly criticized for oversimplifying the concept of sustainability and authors have discouraged their use for that purpose (Fiala, 2008). ABMs and SDMs are more focused on understanding the functioning of systems than on quantifying impacts. CGEs and PEs, when coupled with other methods, can quantify environmental impacts but do not provide references to sustainability. To solve these limitations, Heck, and colleagues (2018) proposed reference levels for maximum land-use capacities within planetary boundaries. Bjorn and Hauschild (2015) proposed the use of carrying capacities as reference points for environmental sustainability. Zhang and colleagues (2017) re-defined and re-calculated biocapacities for the calculation of EF. Hoekstra and Wiedmann (2014) proposed the definition of maximum environmental footprints. The cited initiatives are important steps toward increasing the application of impact assessment studies, but more empirical studies are needed to analyze their suitability.

5. Conclusions

The implementation of sustainable agricultural value chains can be informed by impact assessments capable of accounting for the direct and indirect social, environmental, and economic impacts occurring along the value chain of products (Herva et al., 2011a). Although there is a wide range of tools available to assess the different impacts of telecoupled systems, there is no method that can fully assess these impacts while considering the telecoupling dynamics in a spatially explicit manner. This is not necessarily a single desired goal, but rather the confluence of independent achievements to improve methods and their smart hybridization. The technical challenges of hybrid models described in this paper must be surpassed to succeed in this path. The improvement of impact assessment methods requires the expansion of system boundaries to capture bottom-up and top-down dynamics, improving the geographic resolution and time-coverage of databases, the integration of landscape heterogeneity, the calculation of location-specific impact factors, improved data transparency, and the careful review of assumptions embedded in methods. Improving the understanding cause-effect mechanisms that modulate value chain impacts is of particular importance to these goals. Additionally, it is important to acknowledge the trade-offs between the simplicity and comprehensiveness of methods for decision making. Finally, the definition of sustainability reference points is needed to go from product benchmarking towards methods that provide straight forward advice about the sustainability of value chains.

3. Accounting for land use changes beyond the farm-level in sustainability assessments: the impact of cocoa production

Abstract

Impact assessments are used to raise evidence and guide the implementation of sustainability strategies in commodity value chains. Due to methodological and data difficulties, most assessments of agricultural commodities capture the impacts occurring at the farm-level but often dismiss or oversimplify the impacts caused by land use dynamics at larger geographic scale. In this study we analyzed the impacts of two cocoa production systems, full-sun, and agroforestry, at the farm-level and beyond the farm-level. We used life cycle assessment to calculate the impacts at the farm-level and a combination of land use modeling with spatial analysis to calculate the impacts beyond the farm-level. We applied this to three different future cocoa production scenarios. The impacts at the farm-level show that, due to lower yields, cocoa agroforestry performs worse than cocoa full-sun for most impact indicators. However, the impacts beyond the farm-level show that promoting cocoa agroforestry in the landscape can bring the largest gains in carbon and biodiversity. The impacts at the landscape level show large nuances that depend on the cocoa farming system adopted, market dynamics, and nature conservation policies. Providing that sustainable land management and sustainable intensification are adopted, increasing cocoa demand does not necessarily result in negative impacts for carbon stocks and biodiversity. Landscape-level impacts can be larger than farm-level impacts or show completely opposite direction, which highlights the need to complement farm-level assessments with assessments accounting for land use dynamics beyond the farm-level.

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1. Introduction

Life cycle assessment (LCA) is one of the most used tools to assess the environmental performance of value chains and guide the implementation of sustainability strategies (Frankl and Rubik, 2000; Hellweg and Canals, 2014; Ibáñez-Forés et al., 2016; Lozano, 2020; Perminova et al., 2016; Stewart et al., 2018). As defined by international standards, LCA is a flexible and versatile tool capable of accounting for a wide range of impacts caused by industrial activities, especially those of highly manufactured products (ILCD and ILCD Handbook, 2010; ISO 14044, 2006; UNEP-SETAC, 2016, 2019). Despite of this flexibility, existing data and methodological challenges can limit the completeness of LCA studies, especially for value chains that involve an agricultural commodity (Curran, 2014; Finkbeiner et al., 2014; Godar et al., 2016; Haas et al., 2000; Kløverpris et al., 2020; Notarnicola et al., 2017; Reap et al., 2008; Roy et al., 2009). Agricultural practices are highly diverse, and their impacts are strongly dependent on contextual factors such as biophysical factors, climatic conditions, and landscape configurations. Therefore, accounting for the impacts of value chains using agricultural commodities requires highly specific data on farming practices, local conditions, and contextual factors of the landscapes where farming occurs (De Rosa, 2018; Stefanie Hellweg and Canals, 2014b; Milà i Canals et al., 2007b; Notarnicola et al., 2017). However, this information is often difficult to obtain due to the limited traceability and transparency of sourcing areas faced by global commodity value chains such as cocoa (Boström et al., 2015; Gardner et al., 2018; Hellweg and Canals, 2014).

Land use change is one of the main drivers of global environmental change and is responsible for about a third of total greenhouse gas emissions (Crippa et al., 2021; Foley et al., 2005; IPCC, 2019a; Lambin et al., 2001). Agriculture is a major driver of land use change; therefore, it is important that impact assessments of agriculture account for the land use change effects that farming causes beyond the farm-level (Finkbeiner et al., 2014; Notarnicola et al., 2017; Searchinger et al., 2008b; Teillard et al., 2016; Van Asselen and Verburg, 2013b). The impacts of agriculture are partly determined by the agrochemical usage, farm management practices, and biophysical conditions on the production site (Dijkman et al., 2012; Millard et al., 2021; Seufert and Ramankutty, 2017). However, giving that agriculture is embedded in socioeconomic systems and therefore competes for land resources with other economic activities, agriculture can trigger land use displacements and cause environmental degradation beyond the farm-level (Liu et al., 2013; Meyfroidt et al., 2018, 2013). These land use changes depend on land suitability and opportunity costs and are regulated by spatial policies and market forces (Turner et al., 2020; Van Asselen and Verburg, 2013). Therefore, the environmental impact of agriculture, especially of that on biodiversity and carbon stocks, is ultimately determined by the landscape configuration, the location of farming and intensity of agricultural practices (Chaplin-Kramer et al., 2015; Dullinger et al., 2021). Previous studies have found that these indirect impacts of agricultural production on carbon and biodiversity span beyond the agricultural field and may far exceed the impacts occurring on the farmland. The conclusions of impact assessment studies accounting for land use changes beyond the farm-level may therefore contradict conclusions taken based on farm-level assessments (Barnes et al., 2017; Stefanie Hellweg and Canals, 2014b; Lapola et al., 2010; Magliocca et al., 2020; Richards et al., 2014; Searchinger et al., 2008b). If indirect land use impacts are not considered, sustainability governance initiatives of agriculture-based value chains may unknowingly displace environmental burdens across places and reward seemingly harmless practices (Curran, 2014; Hellweg and Canals, 2014).

Recent developments in the LCA community are helping to close this gap by increasing the spatial resolution of impact characterization factors (Blonk Consultants, 2021; BSI, 2012; Bulle et al., 2019; Chaudhary et al., 2015; Verones et al., 2020), expanding LCA agricultural databases (Blonk Consultants, 2019a, 2019b; Koch and Salou, 2014; Weidema et al., 2013), and complementing LCA with additional methods (Chaplin-Kramer et al., 2017; Crawford et al., 2018; Othoniel et al., 2019). Nevertheless, most of the methods used to account for land use change impacts in LCA have limitations to capture the fine-scale spatial dynamics arising from socioecological interactions (Earles and Halog, 2011; Finkbeiner, 2014; Milà i Canals et al., 2007; Schmidt et al., 2015). These assessments are usually based on economic models, biophysical models or normative rules and often define coarse units of impact (e.g., administrative units) or generalize cause-effect relationships to some degree (Schmidt et al., 2015). Consequential LCA is one of the methods most suited to assess the impacts beyond the farm-level, however, it also does so from a broader perspective by accounting for the effect of global market dynamics (ILCD and ILCD Handbook, 2010; Weidema, 2003). Despite these efforts, LCA methods that anticipate and account for impacts caused by land use change are far from mainstream and often address limited components of land use dynamics (Roca and Searcy, 2012; Schmidt et al., 2015). Sustainability governance initiatives in agricultural producing landscapes will benefit from complementing farm-level assessments with methods capable of accounting for fine-scale land use dynamics (Hellweg and Canals, 2014; Notarnicola et al., 2017; Parra Paitan and Verburg, 2019).

While several LCA studies accounting for land use change exist for biofuels, other crops have gotten limited attention and no study on cocoa exist to our knowledge (Di Lucia et al., 2012; McManus and Taylor, 2015; Palmer and Owens, 2015; Prapaspongsa and Gheewala, 2016; Searchinger et al., 2008b; Somé et al., 2018). We use the case of cocoa production in Ghana, the second-largest cocoa producing country, to advance the assessment of impacts caused by land use dynamics beyond the farm-level. Cocoa is an important agricultural commodity whose value chain is responsible for the conversion of large areas of tropical rainforest (Fountain and Huetz-Adams, 2020; Goldman et al., 2020; Pendrill et al., 2019). Our goal is to complement a farm-level LCA with a method that captures fine-scale spatial dynamics beyond the farm-level and analyze differences in the magnitude of impacts accounted. We conduct an attributional

LCA to assess impacts of cocoa the farm-level and a combination of land use modeling and spatial analysis to account for the impacts beyond the farm-level. We define three future demand scenarios that differ in the type of cocoa farming system encouraged in the landscape (agroforestry and full-sun monocrops) and other socioeconomic factors. Finally, we discuss the implications of land use dynamics for impact assessments and the sustainability governance of value chains that involve an agricultural phase.

2. Methods

We used LCA to quantify the farm-level environmental impacts of producing one kilogram of cocoa beans under two different farming systems: cocoa full-sun (e.g., cocoa monocrops) and cocoa agroforestry (e.g., cocoa cultivated along with shade trees). In this stage, our goal was to calculate the impacts caused by cocoa production at the farm-level, therefore we use an attributional life cycle assessment. We complemented this farm-level accounting with the impacts caused beyond the farm-level due to land use dynamics. We combined land use modeling and spatial analysis to calculate changes in biodiversity and carbon stocks beyond the farm-level. We accounted impacts in three different future scenarios depicting increases in cocoa demand (Figure 1). We then compared the impacts calculated at the farm-level and beyond. See Table 1 for an overview of the main methods and data sources used.

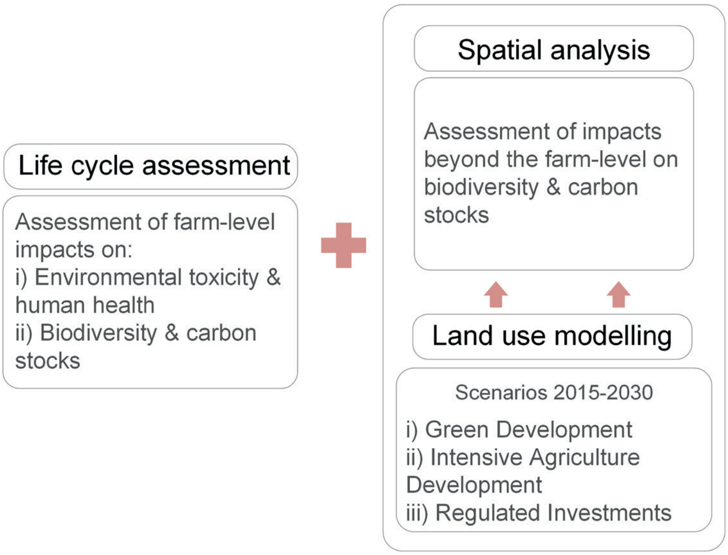

Figure 1. Overview of the methods used to account for the impacts of cocoa production in Ghana.

2.1 Attributional life cycle assessment

Although multiple life cycle inventory databases and life cycle impact assessment methods exist, we decided to use open-source tools as these are accessible to most stakeholders.

2.1.1 Goal and scope definition

The boundaries of the system were defined strictly around the agricultural phase, including the application of agrochemicals and the use of land. Cocoa production in Ghana is mainly rain-fed and is not mechanized. Therefore, water consumption was not considered, and the use of machinery comprised only the use of pesticide sprayers. We defined the functional unit as one kilogram of cocoa beans ready for further processing (post-fermentation on farm or field).

2.1.2 Life cycle inventory

The life cycle inventory was based on a previous LCA of cocoa production in Ghana (Ntiamoah, 2009; Ntiamoah and Afrane, 2008). Based on this study we defined inventories for two cocoa production systems: cocoa agroforestry and full-sun. This inventory differentiation was based on literature reporting farming inputs and yields for these cocoa systems (Abdulai et al., 2018; Asare et al., 2019; Bymolt et al., 2018). To set cocoa yields, we multiplied the average yields reported by Abdulai et al. (2018), for low and medium shade cocoa systems in non-dry cocoa areas (511 and 643 kg/ha for agroforestry and full-sun systems, respectively), by and adjustment factor (0.82). The latter was calculated by dividing the total cocoa volume produced in the study area (Ghana Statistical Service, 2019) with the total cocoa volume produced based on Abdulai et al. (2018). The final yield values were set to 418 and 525 kg/ha of cocoa beans for cocoa agroforestry and full-sun systems, respectively. The quantity of fertilizers used per area in cocoa full-sun systems was set as twice that of cocoa agroforestry systems (Abdulai et al., 2018). Pesticide usage per area was considered equal for both cocoa systems because these are applied homogeneously by the Cocoa Pest and Disease Control agency (CODAPEC) (Abdulai et al., 2018). Petrol for pesticide spraying application was considered equal for both systems for the same reason. The inventory of emissions caused by pesticide application was based on the PestLCI 2.0 model (Dijkman et al., 2012). The inventory of emissions caused by the application of fertilizers was based on Ecoinvent methodologies (Nemecek and Kagi, 2007; Nemecek and Schnetzer, 2011; Prasuhn, 2006). A more detailed description of the inventory of inputs and outputs can be found in Table 1 from Appendix B.

2.1.3 Life cycle impact assessment

The life cycle impact assessment of the following indicators was based on the IMPACT World+ model (Bulle et al., 2019): acidification potential, eutrophication potential, freshwater eco-toxicity potential, global warming potential, human toxicity potential, and disability-adjusted life years (DALY). The DALY indicator refers to the number of years of life lost due to the negative impacts of toxic substances on human health. We used the potential permanent disappeared fraction of species (PDF) indicator to calculate the impacts of land use change on biodiversity loss (Chaudhary et al., 2015; Jolliet et al., 2018). We selected this method over the one proposed by De Baan et al. (2013) following the suggestion of the UNEP/SETAC Life Cycle Initiative (UNEP-SETAC, 2016). This choice also allows comparability with the biodiversity indicator used in the spatial assessment. However, since the meaning and unit of this indicator is different than other indicators from the IMPACT World+ model (Bulle et al., 2019), its interpretation was done independently from other impact indicators. Consequently, the damage indicator used for biodiversity only accounted for the effects of land use change and not the effect of the use of agrochemicals. The impact of land use change on carbon emissions was calculated based on the PAS 2050-1 methodology (BSI, 2012) according to the "country known, previous land use known" treatment, which amortizes impacts over 20 years. As advised, we replaced the default emission factors with those reported for each type of land conversion in each type of vegetation zone of Ghana (Kongsager et al., 2013). More details about the impact assessment methods used can be found in Tables 3, 10 and 12 Appendix B.

2.2 Land use modeling of future scenarios

We defined three scenarios to simulate future land use conversions caused by cocoa production: a) Green Development, b) Intensive Agriculture Development, and c) Regulated Investments. This was done for the main cocoa producing area of Ghana, the high forest zone (Forestry Commission, 2017). We used the CLUMondo model (Van Asselen and Verburg, 2013) to simulate future land use changes. CLUMondo makes a spatially explicit allocation of future land use changes following an iterative process in which land use types compete for land to satisfy external demands of resources. This allocation is based on location suitability (e.g., biophysical factors), spatial policies (e.g., protected areas), land conversion elasticity, and the capacity of each land use type to provide specific resources.

The scenarios differ slightly in terms on market demands but mainly in the cocoa farming systems adopted to satisfy this demand (agroforestry or full-sun), forest protection policies (Table 2). Population growth and food demand are similar among all scenarios. The definition and quantification of scenarios was done according to the shared socioeconomic pathways

(SSPs) (O'Neill et al., 2017). The Green Development, Intensive Agriculture Development, and Regulated Investments scenarios were framed around SSP1, SSP5, and SSP3, respectively. Simulations were done for 15 years starting in 2015. In short, Green Development tried to satisfy an increase in cocoa demand while avoiding deforestation and promoting cocoa agroforestry systems. In Intensive Agriculture Development there was a slightly higher increase in cocoa demand, little attention to forest protection, and a strong adoption of cocoa full-sun systems. Regulated Investments was an intermediate scenario where cocoa agroforestry and full-sun were given equal opportunity while also protecting forests. We set specific demand changes for rubber production as it is an important cash crop in Ghana. Cocoa yields changed over time to simulate agricultural intensification. In the Green Development scenario, only cocoa agroforestry yields were gradually increased up to the national target (1000 kg/ha) (Ministry of Food and Agriculture of Ghana, 2016). In Intensive Agriculture Development, only cocoa full-sun yields were similarly increased, and in Regulated Investments yields were increased for both cocoa farming systems up to the same threshold (Ministry of Food and Agriculture of Ghana, 2016; Wessel and Quist-Wessel, 2015). These yield increases followed government targets and are moderate in contrast to yields reported by other experimental studies (Bymolt et al., 2018; Wessel and Quist-Wessel, 2015).

We used a previous map of the high forest zone of Ghana (Wolff et al., 2020) as initial land cover map for the year 2015. This map reported nine land use classes: built-up areas, water bodies, mining, rubber plantations, closed forest, open forest, cocoa, mixed forest with agriculture, and agriculture with sparse tree cover (Figure 3). Closed forest differs in tree cover percentage from open forest (>50% and <30%, respectively), and the last two land use classes are primarily food crop production areas with different tree cover values (>30% for mixed forest with agriculture, and <30% for agriculture with sparse tree cover). We differentiated cocoa agroforestry and cocoa full-sun from the general cocoa class of the initial map. This differentiation was done using high-resolution tree cover data (Hansen et al., 2013). In cocoa producing areas, we calculated the tree cover for 2015 by adding tree cover gains (2000-2012, only data available) and subtracting tree cover loss (2000-2015) to the tree cover map of the year 2000. We defined the last quantile of these pixels as cocoa agroforestry pixels and the remaining ones as cocoa full-sun. This threshold was chosen according to data sources citing that complex cocoa agroforests have a similar tree cover structure to open forests (FAO, 2014; Tutu Benefoh et al., 2018). The suitability of pixels to each land use type was defined using a combination of 17 physical and socioeconomic variables (see Table 7 from Appendix B). Suitability was defined after testing the relationship between these variables and the actual distribution of land uses using logistic regression functions with stepwise elimination. The capacity of each pixel to provide resources (e.g., cocoa, food, rubber, tree cover, and built-up areas) was defined using subnational production statistics of cocoa, rubber, and food crops (based on cassava, maize, and plantain) for 2015 (Ghana Statistical Service, 2019). Future demands and yield increases were defined according to country-level quantifications of SSPs for built-up areas, food crops, and cocoa (IFPRI, 2017; IIASA, 2020; Riahi et al., 2017; Sulser et al., 2015). We used official national targets on forest protection, restoration, and forest plantation to define future tree cover (Dave et al., 2019a; Forestry Commission, 2016; Republic of Ghana, 2017). Due to the lack of official projected data on future rubber demand and yield increases, we used linear projections of historical rubber production statistics (2000-2015) (FAOSTAT, 2020). Further details on the settings of the model can be found in Tables 4, 5,6, 8, and 9 from Appendix B.

2.3 Spatial analysis of impacts on carbon and biodiversity

Using spatial analysis, we identified the pixels converted from and into cocoa in each scenario projection result. Consequently, we calculated changes in carbon stocks and biodiversity using official carbon emission factors for Ghana (Forestry Commission, 2017) and the GLOBIO-InVEST model (Alkemade et al., 2009; Natural Capital Project, 2020; Sharp et al., 2018), respectively.

The Forestry Commission of Ghana reports carbon emission factors (t CO_2eq/ha per vegetation zone and for land use conversions between closed forest, open forest, cocoa, oil palm, rubber, cropland, grasslands, settlements, and bare land. We used the same methodology to recalculate emission factors that in the original report were given zero values to avoid perverse incentives on deforestation. We adapted these emission factors to our specific land use classes based on literature reporting carbon content in these systems. The reported cocoa emission factors were assumed to apply to cocoa agroforestry because the source study was done in cocoa farms with the same characteristics (Kongsager et al., 2013). Cocoa full-sun emission factors were calculated based on the reported cocoa agroforestry/full-sun carbon ratio for Ghana (Isaac et al., 2007). The emission factors reported for cropland were assigned to the agriculture sparse tree land cover class. The values for the mixed forest with agriculture land use class were calculated as the average of cocoa agroforestry and cropland. To find the final cocoa-driven carbon stock change in each scenario at the landscape level, the corresponding emission factors were multiplied by the respective area of converted land.

The GLOBIO-InVEST model calculates changes in biodiversity associated with land use change, habitat fragmentation, and infrastructure (Sharp et al., 2018). This model uses the mean species abundance indicator (MSA) as an indicator of biodiversity, which is an aggregate metric reflecting the richness and abundance of species in a certain area in comparison to its pristine state. Mean species abundance (MSA) values due to land use change are calculated based on a systematic review of biodiversity studies in eleven land use types. Accordingly, a MSA of value 1 indicates that biodiversity is in a pristine state while 0 indicates that it has been decimated. We adapted our land use classes to the eleven land use classes considered by GLOBIO-InVEST as follows: rubber plantation = plantation forest; open forest = secondary vegetation; mixed forest with agriculture and agriculture with sparse tree cover and cocoa full-sun = low input agriculture; cocoa agroforestry = agroforestry. Finally, we applied the standard values of forest fragmentation on MSA (Alkemade et al., 2009) and used the road network of Ghana to calculate impacts of infrastructure (UN-OCHA, 2020). The GLOBIO-InVEST model calculates changes in biodiversity by multiplying the MSA values of land use change, habitat fragmentation, and infrastructure per pixel. The impact of cocoa production on biodiversity corresponded to the average MSA value of the land areas converted. Same as for carbon, this was used to calculate the impacts of cocoa production in the entire resulting landscape of each scenario. Further details about the calculation of carbon and biodiversity changes can be found in Tables 10, 11, and 12 from Appendix B.

3. Results

3.1. Impacts of cocoa production at the farm-level

According to LCA, the production of one kilogram of cocoa beans under cocoa full-sun farming systems caused on average 22% less negative impacts to air, water, and soils (indicators: acidification potential, freshwater ecotoxicity, freshwater eutrophication, and global warming potential) than under cocoa agroforestry systems. This was due to the higher yields of cocoa full-sun using the same quantity of pesticides per hectare. However, cocoa full-sun was on average 60% more harmful to human health (human toxicity and disability-adjusted life years-DALY) due to the higher use of fertilizers, particularly because of the emissions released to surface water (Cu, Zn, Pb) (see Table 2 from Appendix B). Nevertheless, due to its farming intensity, cocoa full-sun was almost three times more harmful to biodiversity (potential disappeared fraction of species, PDF). Because of higher yields, cocoa full-sun farms requires less land than cocoa agroforestry to produce one kilogram of cocoa beans. Therefore, carbon emissions due to land use change were 18% lower for cocoa full-sun than for cocoa agroforestry. Interestingly, the carbon emissions caused by land use change were almost 300 times higher than those caused using agricultural inputs (Figure 2).

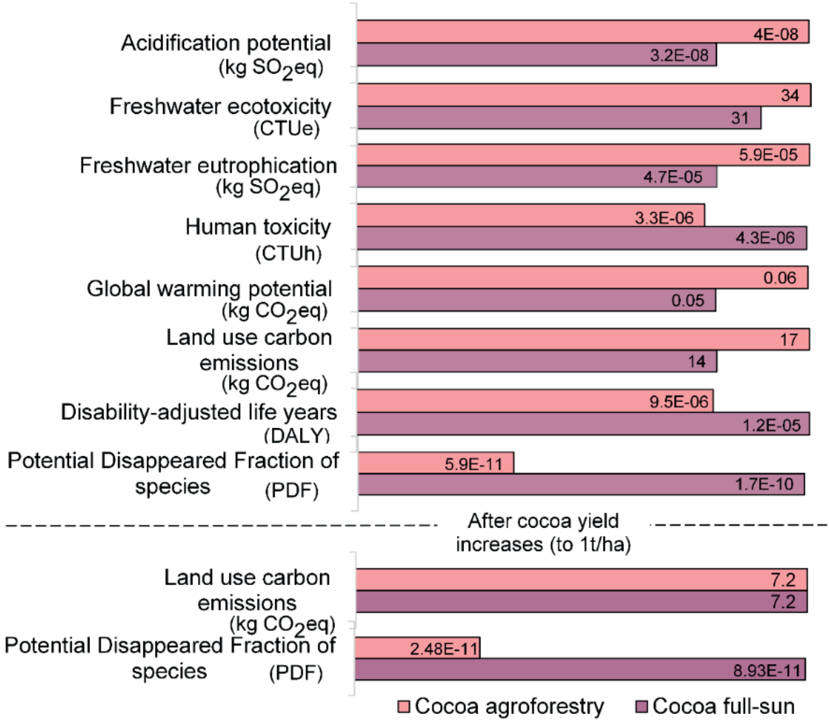

Figure 2. Impacts of cocoa full-sun and agroforestry per kilogram of cocoa beans at the farm-level. Units for each impact category are shown within parenthesis. The first six are mid-point indicators and the last two are end-point indicators. Land use carbon emissions correspond to the weighted average reported by PAS2050-1 method.

3.2. Land use change impacts of cocoa production

The landscape configuration obtained with the land use model determined the magnitude of the impacts of cocoa production beyond the farm-level (Figure 3). Combining a land-sharing approach while conserving primary forests, as in the Green Development scenario, led to a trifold expansion of cocoa agroforestry systems (Figures 4 and 5). This expansion was mainly achieved by replacing degraded forest areas and slightly reducing the rubber plantation area. At the same time, 30% of primary forests areas (ca. 294 Kha) were restored and 44% of cocoa full-sun areas were converted into more sustainable food agroforestry systems. The Intensive Agriculture Development scenario achieved land-sparing, thereby reducing in 21% the cocoa full-sun area. However, the limited environmental protection in this scenario led to the displacement of cocoa full-sun into the south-western region, displacing 43% of the remaining primary forest areas (ca. 426 Kha). In the Regulated Investments scenario, cocoa full-sun and agroforestry areas were reduced in 31% and 30%, respectively, while 10% of primary forests areas were restored.

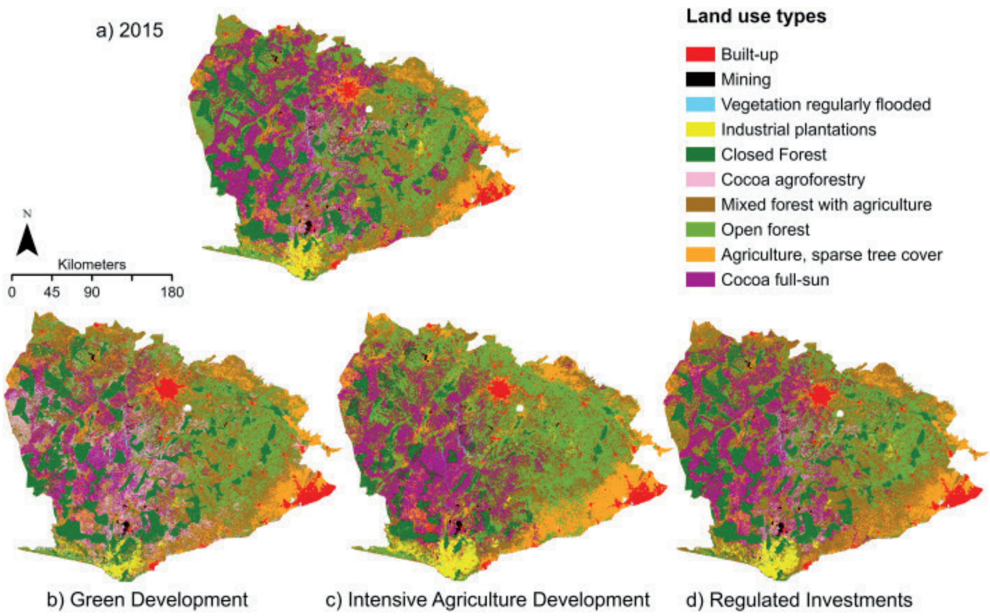

Figure 3. Spatial distribution of land use types in initial (a) and modeled years (b-d).

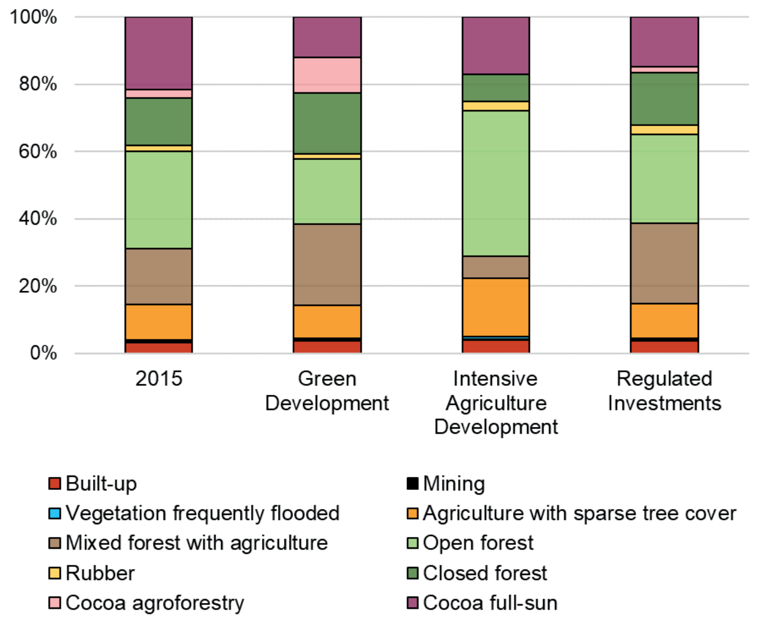

Figure 4. Changes in the area of land use types between the initial (2015) and modeled years (2030, the last three bars).

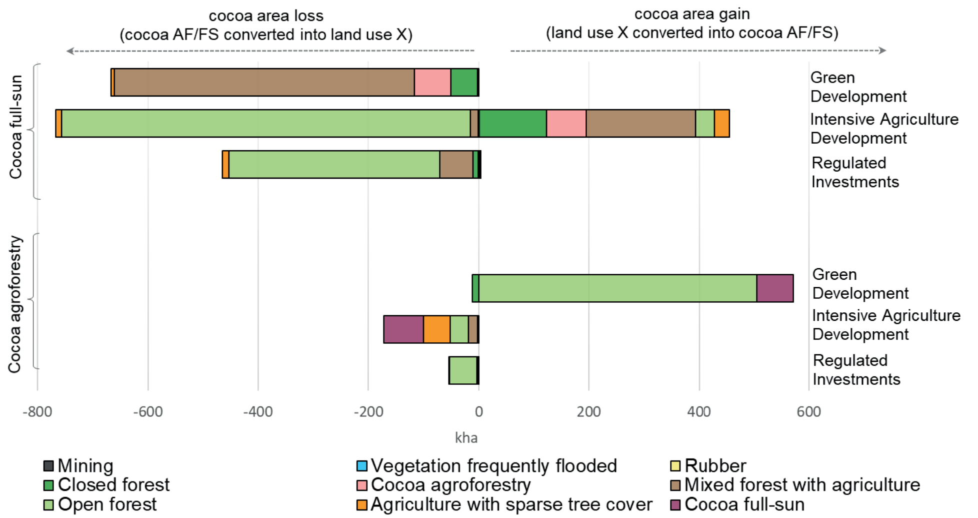

Figure 5. Area of cocoa full-sun (a) and cocoa agroforestry (b) gained and lost to other land use types in each scenario. Positive values represent cocoa areas gained to previous land uses while negative values represent cocoa areas lost to other land uses.

3.3 Impacts of cocoa production beyond the farm-level in each scenario

The impacts of land use change on carbon and biodiversity in each scenario were strongly nuanced at the landscape level (Figure 6). Land conversions to meet cocoa demand caused 62 MtCO_2eq of net carbon gains in the Green Development scenario, 14 MtCO_2eq of net carbon gains in the Regulated Investments scenario, and 52 MtCO_2eq of net carbon losses in the Intensive Agriculture Development scenario. The Regulated Investments scenario showed the largest net biodiversity gains, closely followed by the Green Development scenario, while the Intensive Agriculture Development scenario showed net biodiversity losses. In the Green Development scenario carbon and biodiversity gains were due to the expansion of cocoa agroforestry into formerly degraded forest areas (ca. 30 MtCO_2eq gain, ca. 0.006 MSA gain) and the large conversion of cocoa full-sun farms into food agroforestry systems (ca. 31 MtCO_2eq gain, ca. 0.2 MSA gain) (Figures 6). The Regulated Investments scenario showed carbon and biodiversity gains (ca. 14 MCO_2eq t, ca. 0.04 MSA) mainly due to reduction of cocoa full-sun areas. This reduction created abandoned areas that were later followed by ecological succession and resulted in gains of carbon and biodiversity. The Intensive Agriculture Development scenario showed large carbon and biodiversity loss (ca. 52 MtCO_2eq, ca. 0.1 MSA) due to the replacement of primary forests with cocoa full-sun plots. This occurred because the weak forest protection policies encouraged the migration of cocoa full-sun farms into highly fertile forest soils.

At the farm-level, life cycle assessment calculated larger carbon losses for cocoa agroforestry systems while, at the landscape level, the spatial assessment calculated larger carbon losses for the scenario discouraging cocoa agroforestry (Intensive Agriculture Development) and calculated net carbon gains in scenarios promoting cocoa agroforestry. Carbon losses at the landscape level were 6% larger than at the farm-level in the Intensive Agriculture Development scenario. The two scenarios calculated net carbon gains at in the landscape level. Biodiversity loss at the farm-level occur in all scenarios while at the landscape-level losses occur only in the Intensive Agriculture Development scenario (almost double the farm-level loss). The impacts of cocoa production at the landscape level are a result of the different scenarios settings and show the important role of the socioeconomic context.

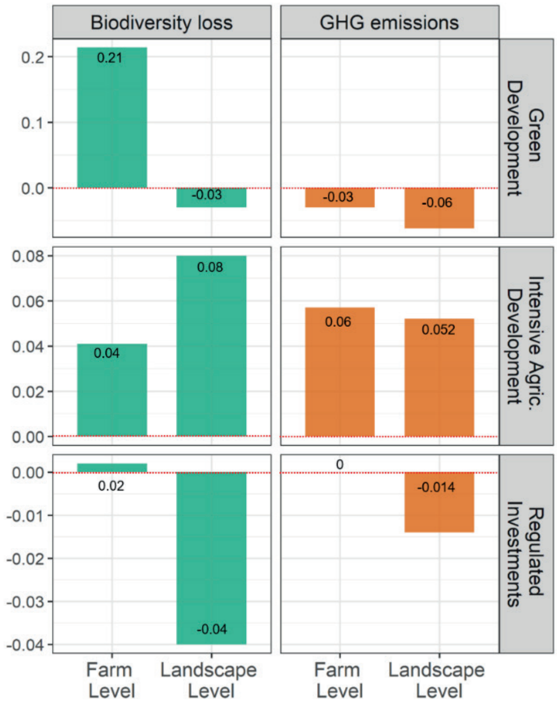

Figure 6. Impacts of cocoa production on biodiversity and greenhouse gas emissions (GHG, in $MtCO_2eq$) at the farm-level and beyond the farm-level (landscape). Zero is indicated with a dashed red line. Impacts are shown for each scenario and for the entire study area. Positive values indicate losses in biodiversity or carbon (emissions) and negative values indicate gains (e.g., gains in biodiversity or carbon sequestration).

4. Discussion

Our results reinforce previous findings in the field and contribute to highlight the importance of analyzing the impacts of land use dynamics caused by agricultural production. Our study finds that: 1) the impacts of land use change are best accounted for when placed in the corresponding spatial context, 2) the impacts of land use change span beyond agricultural production units and trigger indirect impacts that need to be analyzed in impact assessments, 3) land use interactions need to be evaluated in a non-linear manner by considering the dynamics of competing land uses in light of context-dependent factors, 4) farm management choices have a strong influence the on the intensity of impacts beyond the farm-level and these differences need to be captured in impact assessments. We elaborate on these findings and the policy implications in the coming paragraphs.

4.1 Trade-offs of including or excluding land use dynamics in impact assessments

This study finds that for full accounting, impact assessments of cocoa production need to be contextualized in the producing landscape to be able to capture fine-scale land use dynamics. The impacts of cocoa production do not increase linearly with increasing demand but are strongly dependent on local socioeconomic factors that ultimately determine the spatial configuration (Chaplin-Kramer et al., 2017; Garrett et al., 2013; Koellner and Scholz, 2008; Richards, 2021). Market forces, land use planning, agricultural policies, farm management strategies, and environmental regulation policies influence the final spatial allocation and, therefore, the impacts of cocoa production beyond the farm-level (De Rosa, 2018; Stefanie Hellweg and Canals, 2014b; McManus and Taylor, 2015; Meyfroidt et al., 2018b; Turner et al., 2020; Van Asselen and Verburg, 2013b). According to our study, increasing cocoa demands do not have to necessarily go together with negative environmental impacts. If sustainable intensification, forest protection, and more sustainable farming systems (cocoa agroforestry) are encouraged in the landscape (Regulated Investments and Green Development scenarios), positive impacts can be achieved. Increasing demand threatens forest areas only in the absence of these regulatory and protection measures.

When the impacts of cocoa production are calculated at the farm-level, cocoa full-sun seems to balance better the trade-offs between sustainability and productivity by having higher yields and showing lower impacts for most midpoint impact indicators than cocoa agroforestry. These findings are in line with other studies reporting that, due to lower yields, sustainable production systems perform better per unit of area than per unit of product (Andres et al., 2016; Blaser et al., 2018, 2017; Cucurachi et al., 2019; Jacobi et al., 2014; Mortimer et al., 2018;

Seufert and Ramankutty, 2017). Our results on the impacts of cocoa production on carbon and biodiversity at the farm-level are in line with previous studies reporting larger negative impacts for cocoa full-sun systems (Andres et al., 2016; Blaser et al., 2018; Jacobi et al., 2014). The analysis beyond the farm-level shows that, in the absence of other protection measures, the promotion of cocoa full-sun systems could generate more detrimental impacts at the landscape-level, especially for biodiversity and carbon emissions due to land use change. This means that promoting high-yield cocoa systems could help reduce the net cocoa area but, without sustainable intensification and forest conservation measures, this jeopardizes the sustainability of cocoa landscapes. The largest carbon fixation and biodiversity gains are obtained when promoting forest conservation and encouraging cocoa agroforestry systems at the same time (Green Development scenario). However, to also deliver socioeconomic benefits, this strategy must consider adequate shade levels in agroforestry systems to avoid negative trade-offs between cocoa yields and biodiversity (Andres et al., 2016; Asare et al., 2019; Blaser et al., 2017; Phalan et al., 2011). Moreover, restored closed forest areas could only bring the expected carbon in biodiversity gains if they remain standing for at least 80 years (Cole et al., 2014; Martin et al., 2013).

The characterization factors used for carbon emissions due to land use change differ from those reported by the intergovernmental panel on climate change (IPCC). The latter reports much lower carbon emission factors for agroforestry and perennial monocrops in tropical areas (88 and 110- 146 tCO_2eq, respectively) (IPCC, 2019b) than those used by this study (on average 250 and 187 CO_2eq, respectively). This difference might arise because IPCC factors were obtained by averaging the emissions from various cropping systems within a wide range of tropical forests, while the values used by this study follow local carbon measurements in cocoa farms in each vegetation zone of Ghana. This once again highlights the importance of using spatial explicit assessments that take into account previous land uses.

4.2 Practical implications for practitioners and potential ways of improvement

The large negative impacts of cocoa full-sun on human toxicity could be solved with improved fertilizer use. The low productivity of cocoa agroforestry systems could be improved through sustainable yield increases. Sustainable yield increases balance environmental benefits with productivity increases by combining improved use of agrochemicals, sanitation practices (weeding, pruning, thinning), and, in some cases, cocoa tree replanting (Carodenuto, 2019). These improved farm management practices have a strong influence on environmental impacts but also require investments in farm training and enabling policy environments (Blaser et al., 2018; Costa et al., 2020; Erb et al., 2017; Kleppel, 2020; Schulze et al., 2019).

Companies could benefit from the inclusion of land use dynamics in the assessment of impacts by showing that business goals, if managed properly in the landscape, do not necessarily contradict sustainability goals. By making more contextualized assessments of impacts, companies can not only anticipate future changes caused by sourcing strategies but can also help to strengthen the very much needed trust of consumers (Gardner et al., 2018; Lambin et al., 2018). Such assessments could also help companies to have more accurate information about the extent of their negative impacts and improve the scope of sustainability strategies.

Our results suggest that corporate decisions on cocoa sourcing (volumes and locations) may have much larger impacts than those usually accounted for by non-spatially explicit methods that do not account for fine-scale land use dynamics. Therefore, companies might be not only making decisions based on incomplete information but might be also missing the opportunity to demonstrate environmental gains in the landscape due to sustainable initiatives. Companies could reduce impacts by fostering investments in activities that drive positive impacts in the entire landscape, such as sustainable yield increases or more sustainable farming systems.

To effectively minimize negative impacts, the close and transparent coordination of private and public actors is necessary for the assessment, management, and monitoring stages of sustainability actions (Folke et al., 2019; Lambin et al., 2018). Isolated initiatives, either from the private or public sector, are insufficient to tackle sustainability challenges of forest-risk commodities like cocoa. On the one hand, clear land use planning and regulatory policies are needed to guide companies' business goals and sourcing strategies. At the same time, companies need to assess the landscape-level implications of future business strategies.

The jurisdictional approach is an increasingly promoted strategy to govern the impacts of farming systems beyond the farm-level. By engaging multiple stakeholders in the planning of sustainability interventions at the landscape-level, the jurisdictional approach aims at minimizing the risk of displacing negative outcomes of cocoa farming into other parts of the landscape (Boshoven et al., 2021; von Essen et al., 2021) . In support of these initiatives, the LCA research community is increasingly promoting the landscape approach with the aim of better capturing the effect that landscape configurations have on the impacts caused by agricultural systems. By capturing the impacts that expand beyond farming units in space and time (e.g., biodiversity loss, soil degradation, indirect land use change), this approach also helps to prevent LCA studies from being bias towards highly-intensive farming systems by default (van der Werf et al., 2020; Wu et al., 2021). Jurisdictional approaches can benefit from the inclusion of land use dynamics in the assessment of impacts of cocoa production.

4.3 Challenges for the inclusion of land use change impacts beyond the farm-level

Although the importance of accounting for land use change impacts on biodiversity and carbon emissions has been widely acknowledged in the LCA community, the inclusion of these indicators remains limited in practice (Knudsen et al., 2020; Winter et al., 2017). LCA remains a very useful tool to account for the toxicity impacts of agricultural production on humans and ecosystems. However, sustainability practitioners in the corporate sector should seek to complement LCA assessments with tools able to impacts beyond the farm-level (Crenna et al., 2020; McManus and Taylor, 2015; Parra Paitan and Verburg, 2019; Raschio et al., 2018). One complication is that in practice, due to the high complexity and fragmentation of value chains, companies usually do not know the exact origin of the products they use. Due to the high cost and logistic complications of achieving full traceability, companies mostly rely on volume data to assess the impacts caused by value chains. Therefore, achieving full traceability of agricultural commodities is one of the first challenges to complete. Traceability and transparency efforts of recent years show that multiple industry sectors are moving in that direction (Gardner et al., 2018; Ingram et al., 2018b). As more of these initiatives emerge in different value chains, multi-stakeholder platforms become necessary to ensure that they are regulated to collectively maximize synergies and minimize trade-offs (Folke et al., 2019). This would require setting adequate open and independent monitoring and reporting systems alongside corporate sustainability strategies (Lambin et al., 2018), which could benefit from a close collaboration with organizations holding information about local landscapes (e.g., government for providing land use maps or scoping future regulatory policies).

Consequential LCA (CLCA) is an LCA tool that integrates economic modeling to assess the consequences of value chain decisions on physical flows and impacts (Earles and Halog, 2011; Prox and Curran, 2017). This tool could have also been used to evaluate impacts beyond the farm-level. However, CLCA would have done so from a global economic perspective and defining coarser units of analysis, while our goal was to address fine-scale land use dynamics. Our land use modeling approach also accounts for broad scale economic dynamics by defining demand shifts according to the outputs of computable general equilibrium models (e.g., IMAGE). Although our study area only covers a small part of the world, it is second most important cocoa production area and thus, the analysis, has importance even from a global perspective.

4.4 Limitations and ways forward

We used a life cycle impact assessment method with high geographic differentiation (IMPACT World+). However, in some cases, the geographic resolution of this approach was very coarse, so continental or global averages had to be used as characterization factors (see Table 3 from Appendix B). When these were not available for the substances reported in our case study, we used factors from equivalent substances (e.g., for the case of some pesticides in the PestLCI 2.0 model). The selection of these equivalent values strictly followed the literature and scientific advice, so this might only affect slightly the accuracy of our results. The life cycle inventory data and the characterization factors for biodiversity and carbon changes used did not provide with variability ranges reflecting the actual variability in yields, agrochemical inputs, biodiversity composition and carbon stocks in cocoa farms. However, it is important to keep in mind that these factors vary greatly (and might even overlap) depending on soil type, tree age, phenology stage, cocoa variety, farm management practices, and local climatic conditions (Blaser et al., 2018). If available, cocoa value chain decisions regarding sustainability would need to complement our findings with information on specific locations, farming types and phenology stage. Additionally, it is important to mention that although, due to our data sources, we used average characterization factors, the biodiversity composition and carbon stocks in cocoa agroforestry and full-sun systems vary greatly.

The land use model used allows to account for potential indirect impacts caused by cocoa demand and production within the Ghanaian high forest zone, however, it does not capture spillovers beyond it. This means that we cannot assess the impacts that sustainability strategies in this area could cause in other cocoa-producing landscapes, countries, or markets. Because land resources are limited, spillovers and leakages may emerge in different locations. Therefore, the conclusions made in this study are only valid in the given context. The integration of other modeling methods may help to address this challenge (e.g., computable general equilibrium models) (Cucurachi et al., 2019; Hellweg and Canals, 2014; Parra Paitan and Verburg, 2019). In this study, the Volta region was not included due to the low quantities of cocoa produced nowadays (Forestry Commission, 2017). Although this would not strongly affect our results, the Volta region could be used to complement landscape restoration initiatives.

The land use model considers cocoa yield increases that require changes in farm management practices. However, we only accounted for changes in carbon and biodiversity due to yield increases in the LCA analysis. Due to lack of documentation, we did not assess the impacts that the new farm management practices would bring due to changing agrochemical usage. The land use model did not account for lag-times in the production of perennial crops and due to the data limitations explained, the effect of price fluctuation on rubber demand was not considered when defining future rubber demand.

It is important to emphasize that the method chosen to account for carbon emissions from land use change in LCA aims to exemplify the situation in which a company or practitioner conducts an assessment relying solely on cocoa volumes due to lack of information on the origin of cocoa and the land use dynamics in the production area. Spatially explicit characterization factors could be used within LCA when the necessary information is available.

The land use model was designed to reflect plausible demand shifts rather than hypothetical experimental conditions. Our approach prioritizes reality over comparative capacity by changing not cocoa demands alongside other demands (e.g., rubber, forest cover) between scenarios. This was, our results are easier to apply to reality but, at the same time, they did not allow us to completely isolate the effects of cocoa production. Because cocoa production is dominant in the landscape and one of the strongest drivers of land use change, the risk of false impact attribution is minimal. Moreover, cocoa is embedded in a socioeconomic system that also changes when cocoa demand change. Therefore, it is important to keep consistency in all other socioeconomic factors linked to cocoa production. Impacts of changing rubber demands remained constrained to the southern non-cocoa producing area due to land suitability. Therefore, minimally affecting the spatial allocation of cocoa farms. Oil palm is another cash crop present in the landscape however, due to lack of spatial data, we could not include it in the analysis.

Indirect nitrous oxide emissions (N_2O) due to the mineralization of organic matter were not accounted because of the lack of characterization factors differentiating cocoa agroforestry and full-sun systems under our study conditions. Land use change can generate nitrous oxide emissions but in the long term they are mainly determined by nitrogen input rates (Corré, 2002; Veldkamp et al., 2008; Verchot et al., 2020). Therefore, this omission might have limited implications giving the absence of nitrogen fertilizers in our case study.

Finally, we acknowledge that this study mainly addresses environmental impacts and does not address the socioeconomic trade-offs that could arise as a result of sustainability initiatives. Worrisome problems linked to cocoa production such as poverty and child labor need to be assessed alongside to balance the suggestions taken based on environmental assessments (De Rosa, 2018; Onat et al., 2017; Ruf, 2011; Sala et al., 2013).

5. Conclusions

This study shows that the impacts of cocoa production can only be accurately accounted for when the land use dynamics in the original production context are taken into account. Impact assessments of value chains involving an agricultural phase need to complement farm-level accounting methods with tools able to capture the land use change impacts that farming causes beyond the farm-level. Land use modeling and fine-scale spatial assessments can help the assessment of these context-specific land use dynamics. Due to its lower yields, most impact indicators of cocoa agroforestry perform worse than those of cocoa full-sun except for biodiversity and human toxicity. Nevertheless, increasing cocoa demand can deliver positive impacts for biodiversity and carbon stocks if cocoa agroforestry, sustainable intensification, and forest protection policies are implemented. The impacts on biodiversity and carbon stocks at the landscape level can be worse than those at the farm-level or even show contrary trends. Due to the entangled nature of drivers and impacts of cocoa production, close cooperation between private and public actors is needed to solve sustainability issues in cocoa value-chains.

4. Large gaps in voluntary sustainability commitments covering the global cocoa trade

Abstract

The production and trade of agricultural commodities, such as cocoa, have important impacts on farmer livelihoods and the environment, prompting a growing number of companies to adopt public commitments to address sustainability issues in their value chains. Though trading companies, who handle the procurement and export of these commodities, are key actors in corporate sustainability efforts, cross-country data on their identity, market share, and adoption of sustainability commitments is lacking. Here, we address this gap for the cocoa sector by compiling detailed shipping data from eight countries responsible for 80% of global cocoa exports, developing a typology of trader types, and assessing their adoption of sustainability commitments. We find that cocoa trading is a highly concentrated market: seven transnational companies handled 62% of the global cocoa trade, with even larger shares in individual cocoa producing countries. The remaining 38% of exports were handled by domestic trading companies and farmer cooperatives. Overall, the adoption of public sustainability commitments is low. We estimated that just over one quarter (26%) of cocoa is traded under some form of sustainability commitment, with gaps arising from their exclusion of indirect sourcing, low adoption rates by domestic traders, and commitment blind spots, notably on forest degradation and farmer incomes. Low rates of traceability and transparency pose a further barrier to the broadscale implementation and monitoring of these commitments: one quarter of traders report being able to trace at least some of their cocoa back to farmer cooperatives and only half of them openly disclose the identity of their suppliers. We discuss the opportunities and limitations of voluntary sustainability initiatives and argue that, to realize visions of sustainable trade, the gaps in commitment coverage must be closed by extending current efforts to smaller traders and indirect suppliers. However, companies must support, coordinate, and align with government efforts so that voluntary initiatives are ultimately rendered more transparent and accountable.

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1. Introduction

Global value chains that connect geographically dispersed production activities have become the centerpiece of the world economy, with fundamental repercussions for societies, economies, and the environment (Kano et al., 2020; OECD, 2013; Ponte et al., 2019). In particular, agrifood value chains play a key role in global food security and the livelihoods of billions of rural laborers, while also being a driver of environmental degradation (Clapp, 2021).

Cocoa (*Theobroma cocoa)* is one of the agrifood commodities raising sustainability concerns due to issues such as persistent poverty and child labor among cocoa farmers, and deforestation due to the expansion of cocoa farming (Abdullah et al., 2022; Fountain and Huetz-Adams, 2020; Sadhu et al., 2020). Cocoa, originating from the Amazon rainforest, is now planted across the tropics and its consumption, although still dominated by Europe and North America, is rapidly increasing in emerging economies of Asia, Latin America, and the Middle East (Fountain and Huetz-Adams, 2020; KPMG, 2014; Neilson et al., 2018). The global cocoa sector was worth 44 billion US dollars in 2019 and cocoa bean production has doubled in the last thirty years (Fortune Business Insights, 2019), which has contributed to make it one of the top ten deforestation-risk agricultural commodities globally (Goldman et al., 2020; Ordway et al., 2017; Pendrill et al., 2022).

In recent decades, the sustainability governance of commodity production, including of cocoa, has shifted from being state led to become polycentric, with an expansion of the influence of market actors. Governance efforts are increasingly oriented around global value chains, implemented through a combination of voluntary, self-regulatory, market-led initiatives (Meemken et al., 2021; Ostrom, 2010; Thorlakson, 2018). These efforts include multi-stakeholder initiatives (e.g. the Cocoa and Forests Initiative-CFI) (Carodenuto and Buluran, 2021; ICI, 2021; Thorlakson, 2018; Vellema and Van Wijk, 2015; World Cocoa Foundation, 2017), third-party certification schemes (e.g. Fairtrade, Rainforest Alliance, UTZ, Organic) (Grabs and Carodenuto, 2021; Ingram et al., 2018b), own-firm sustainability standards (e.g. Forever Chocolate, Cocoa Compass) (Grabs and Carodenuto, 2021), and national publicly-led initiatives (e.g. Beyond Chocolate in Belgium, GISCO in Germany, DISCO in the Netherlands) (Wahba and Higonnet, 2020). In each of these governance structures, companies have taken a lead role in the definition and implementation of sustainability (Ponte, 2019; Thorlakson, 2018). Among companies, international traders, defined in this study as companies in charge of exporting cocoa from producing countries, are keystone actors who, because of their position in the value chain, often carry the responsibility of translating industry sustainability signals into ground-level action (Figure 1) (Grabs and Carodenuto, 2021; Thorlakson, 2018). In addition to industry-led initiatives, legislative efforts are also expanding, such as the upcoming European due diligence legislation, which intends to hold trading companies legally accountable for impacts embedded in their value chains (European Commission, 2021).

Within the frame of this article, we use the term 'value chain sustainability initiatives' to include both voluntary, publicly made corporate commitments (made either by individual companies or collectively by companies participating in multi-stakeholder initiatives) and third-party certification. Commitments notably differ from third-party certification in their self-reported nature and the lack of third-party verification or auditing mechanisms to guarantee implementation. We also differentiate between the adoption of commitments - the self-reported promise to implement a concrete sustainability action or program - and implementation, which is the concrete execution of such commitments. Further, there may be a gap between implementation and impact, the measurable accomplishment of the promised commitments. Third-party certification can be used as an implementation mechanism of commitments, however, the information made available by companies does not allow to differentiate them from the commitments adopted.

Multiple studies have tried to understand why some companies adopt sustainability commitments and others do not. According to global value chain theory, the organization of value chains has a fundamental impact on how sustainability is steered by a company (Gereffi, 2018; Gereffi et al., 2006; Lebaron et al., 2019). Complementarily, agency theory explains how principal actors (i.e., larger companies with more extended trade networks) utilize their power on agents (i.e., smaller companies or suppliers of principals) to lead the implementation of sustainability standards. The principal-agent relation seeks to ensure favorable agent's behavior and it is modulated by power, information, and goal asymmetries between the two (Beal Partyka, 2022; Matinheikki et al., 2022). In the context of global value chains, power is understood as the capacity of actors to dictate or influence behavior of other actors or strategic market factors, and it is often used to increase value, gain competitive advantage, and achieve desired market outcomes (Dallas et al., 2019). Agency theory also explains how principal actors foster collaborative initiatives with industry partners to improve their own performance and protect their own interests (Delbufalo, 2018; Mason, 2019). However, the asymmetric nature of the principal-agent relation can lead to opportunistic agent behavior and the failure of a sector to deliver the sustainability outcomes (Wiese and Toporowski, 2013). Studies on various commodities found that, due to the stronger pressure received from civil society, larger companies are more likely to adopt sustainability commitments than smaller ones (Bager and Lambin, 2020; Dauvergne and Lister, 2012; Garrett et al., 2019). In addition, the higher visibility of companies closer to the consumer end and the involvement of companies in other commodities facing similar sustainability issues, have been identified as factors contributing to a higher adoption of commitments (Bager and Lambin, 2020; Grabs and Carodenuto, 2021).

Evidence also shows that companies utilize different implementation strategies and prioritize only certain sustainability issues. Over the recent years, large companies have increasingly shifted from relying primarily on third-party certification labels towards developing their own in-house sustainability commitments, programs, and standards (Grabs and Carodenuto, 2021; Ingram et al., 2018b). In contrast, smaller companies typically lack the resources to develop such in-house schemes and continue to rely more on third-party certification (Bager and Lambin, 2020; Lambin and Thorlakson, 2018; Thorlakson, 2018). Further, commitments are mostly framed around problems receiving high media attention, such as deforestation and child-labor. Often, these topics are not always aligned with the priorities identified in producing countries, such as poverty, living incomes, low market prices, or the need to favor domestic processing and export of processed products (such as cocoa butter and powder) instead of raw product exports (Carodenuto, 2019; Neilson, 2007; Oomes et al., 2016).

Recent studies have documented sustainability commitments in the cocoa sector (Carodenuto, 2019; Grabs and Carodenuto, 2021; Ingram et al., 2018a; Thorlakson, 2018). Others have studied the factors driving commitment implementation and have analyzed the factors influencing commitment effectiveness (Garrett et al., 2019; Gereffi and Lee, 2012; Ingram et al., 2017; Nelson and Phillips, 2018; Tayleur et al., 2017). Despite these research advances, four main gaps remain in the knowledge: First, most of the studies have focused essentially on large traders, which represent a large share of the cocoa volumes, yet little is known about the non-negligible shares of cocoa traded by a myriad of smaller companies. Second, no study has yet analyzed the heterogeneity in the adoption of sustainability commitments between types of traders in the cocoa sector. Third, no study has properly analyzed whether these commitments cover the various sustainability issues. Fourth, no study has quantified the uptake of different implementation approaches for sustainability initiatives in the cocoa sector at a global scale.

In this study, our objective is to identify coverage and gaps in the adoption of sustainability commitments among cocoa traders and compare choices in implementation strategies and sustainability priorities. In contrast to previous studies, we address traders regardless of their market dominance. We address this through four questions:

1. How is the cocoa trading market structured? Following Clapp (2021), here our first hypothesis is that the downstream market concentration extends also to cocoa trading. To test this, we described the market share, and degree of vertical and horizontal integration of traders, both globally and within each country of production.
2. Which traders adopt sustainable sourcing commitments? Here, our second hypothesis is that larger, more vertically and horizontally integrated companies are likely to adopt more commitments. To test this, we compared the sustainability commitments made by cocoa traders with different market coverage and market integration profiles.

3. What are the gaps in commitment adoption coverage? Here, our third hypothesis is that gaps exist in the coverage of sustainability commitments due to the limited involvement of small traders, the selective application of commitments to direct suppliers, and the prioritization of specific sustainability topics. To test this, we analyzed the global coverage of commitments and the topics engaged with by traders.
4. What strategies do companies use to implement sustainable value chain initiatives? Here, our fourth hypothesis is that smaller companies prioritize externalizing sustainability action (i.e., third-party certification and ecolabels) while larger companies prioritize in-house sustainability programs (i.e., own schemes). To test this, we compared sustainability initiatives adopted by different traders.

To address these questions, we compiled shipping data of the eight largest cocoa exporting countries and documented the sustainability initiatives adopted by companies exporting cocoa from these countries. We used a combination of descriptive statistics and generalized linear models to evaluate our hypotheses. Following the literature on the effectiveness of voluntary sustainability commitments, we discussed the potential implications of the limited commitment coverage and the limited involvement of small companies on resolving sustainability issues in the global cocoa value chain. For this, we elaborate on the role of market coverage as a key enabling condition for the effectiveness of voluntary sustainability commitments, and as a key factor for mainstreaming market action and reducing opportunities for leakage (Garrett et al., 2019; Gollnow et al., 2022; Meemken et al., 2021). Here, we do not go so far as to evaluate the impact of these value chain sustainability initiatives, though we discuss the potential risks of sustainability agency concentration and the need to address known limitations of voluntary schemes to migrate from commitment implementation to impact. Using a key commodity as a case study case, our research contributes to deepening the understanding of the role of private voluntary sustainability mechanisms in addressing sustainability issues in one of the largest sectors contributing to global environmental change, the agrifood business.

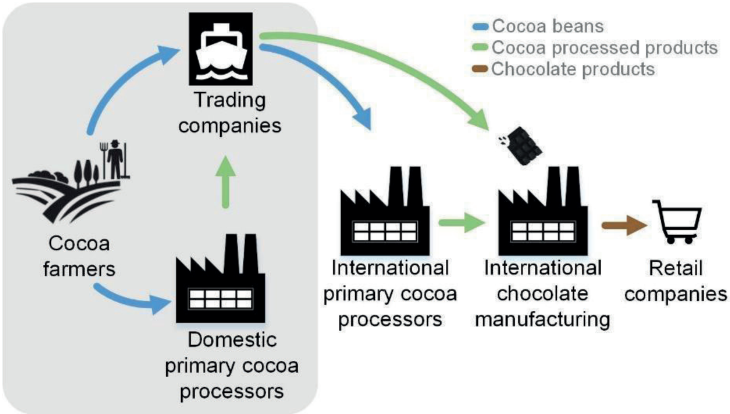


Figure 1. Global cocoa value chain and boundaries of the study (in gray).

2. Methods

2.1 Data collection and classification

We compiled shipping data of exports of cocoa beans and cocoa derivatives (cocoa butter, paste, powder, and waste) from eight of the world's leading cocoa-producing countries (Côte d'Ivoire, Ghana, Cameroon, Indonesia, Ecuador, Peru, Colombia, and Brazil). We obtained this data from the Transparency for Sustainable Economies (Trase) initiative (www.trase.earth) and contains information on the cocoa volumes traded per company, country of origin, country of destination, type of cocoa product traded (e.g., cocoa beans, butter, paste or waste) and the free on-board price (FOB). This data covers 80% of global cocoa exports (ICCO, 2021). The data available corresponds to records for 2018 for all countries except Brazil, for which only the records of 2017 were available. We validated this data against trade volumes reported by the United Nations International Trade Statistics Database and International Cocoa Organization (ICCO) (Figure 7 from Appendix). When aggregating traded volumes of different cocoa products, we converted all products into 'cocoa bean equivalents' using standard conversion coefficients (see Table 1 from Appendix C). We used data from the eight largest cocoa producers, though our data do not account for re-exports of cocoa that may be exported from one country (e.g., Ghana) and processed in another (e.g., Brazil, Malaysia) before re-export. In these cases, we may double-count cocoa if processing and re-export occurs within the same year, though three-quarters of global cocoa grinding takes place in Africa, Europe, or the United States and so this is unlikely to dramatically alter our results (ICCO, 2021).

Shipping records commonly refer to both the “exporter” and “importer” of a commodity. In this study, we focused on the “exporter” (henceforth the “trader”), except in Ghana, where we selected the importing company as the trader. We chose this because in Ghana the Cocoa Marketing Company (CMC) is listed as the only exporter of cocoa beans. The CMC is part of The Ghana Cocoa Board, the government-owned cocoa marketing institution that controls the Ghanaian cocoa market by setting prices and coordinating the purchase of all cocoa from farmers through licensed buying companies. The CMC is the institution responsible for mediating the trade between national producers and international traders (Bymolt et al., 2018). The CMC sells to trading companies such as Cargill or Olam, listed as the “importer” in customs records – hence the selection of the importer as the “trader” in Ghana for our analysis. This approach best captures the trade relations of Ghana with international cocoa markets in a manner consistent with our representation from other countries. However, we present how selecting the “exporter” data for Ghana would affect our analysis in the Appendix (Figure 3 from Appendix C).

We grouped together the records with different trader names corresponding to subsidiaries of the same company, as is often the case of transnational companies (see Table 2 from Appendix C). For these trader groups (to which we simply refer as “traders”) we first recorded general company information, including ownership status (i.e., whether they are publicly listed or privately owned), their legal country address, horizontal integration (i.e., whether they trade other agricultural commodities as well), and vertical integration (i.e., the level of involvement in other cocoa business besides trading). We classified the degree of vertical integration through four binary variables, depending on whether companies reported being engaged in subnational sourcing (i.e., purchase from farmers or farmer groups, rather than indirectly sourcing from intermediates), primary cocoa processing (i.e., transformation of cocoa beans into butter, paste, powder, liquor, etc.), chocolate preprocessing (i.e., manufacturing of non-finished forms of chocolate), and chocolate manufacturing (i.e., production of finished chocolate products for direct consumption) (Table 1). Secondly, we recorded the sustainability initiatives self-reported by each company. These initiatives included: 1) sustainability commitments related to deforestation, forest degradation, child labor, poverty alleviation, climate change adaptation, agroforestry, traceability, and transparency; 2) third-party certification labels: UTZ, Rainforest Alliance, Fairtrade and Organic. UTZ and Rainforest Alliance were kept separated because the documentation of initiatives was collected for the period when these labels were not yet operationally merged.

We recorded information on cooperative-level traceability and transparency since this is an important step to determining the origin and impact of cocoa. Traceability refers to the capacity of a company to trace a product to its origins and transparency refers to the public disclosure of this information (Gardner et al., 2018). We recorded all sustainability initiatives as binary variables, with 0 for lack of reported initiative, 1 for a reported initiative on a given topic. Because we focused on self-reported initiatives, lack of information was always recorded as zero (e.g., in case of the lack of company website or lack of reported sustainability initiative).

These two types of company data collection followed an online search of official websites, official social media accounts, and official reports disclosed by companies or their partner organizations (e.g., NGOs or the World Cocoa Foundation). We assessed all traders covering the top 80% of exports from each country (67 companies), plus a random sample of 10% of the companies handling the remaining 20% in each country (another 80 companies). The complete list of traders in the full dataset comprises 968 traders and our final sample comprises 147 including: 33 traders from Ecuador, 24 from Indonesia, 24 from Ghana, 23 from Peru, 19 from Côte d'Ivoire, 9 from Brazil, 8 from Cameroon, and 7 from Colombia. This range reflects the diversity in the number of small companies in each producing country.

Next, we designed a decision tree to classify our sample of traders based on the volume of cocoa beans traded, the number of sourcing countries, and the level of participation within national markets (for domestic traders) (Figure 2). We did not include the number of destinations as a classification criterion because our dataset did not account for re-exports and, therefore, did not have information on final destinations. The type of consumer demands of different market destinations influences the pressure exerted on value chains so this might be an important factor to consider in future research. Due to the special role of farmer cooperatives in the cocoa market, we separated these into a specific category. We used this typology of traders as a reference for the subsequent analysis of sustainability initiatives.

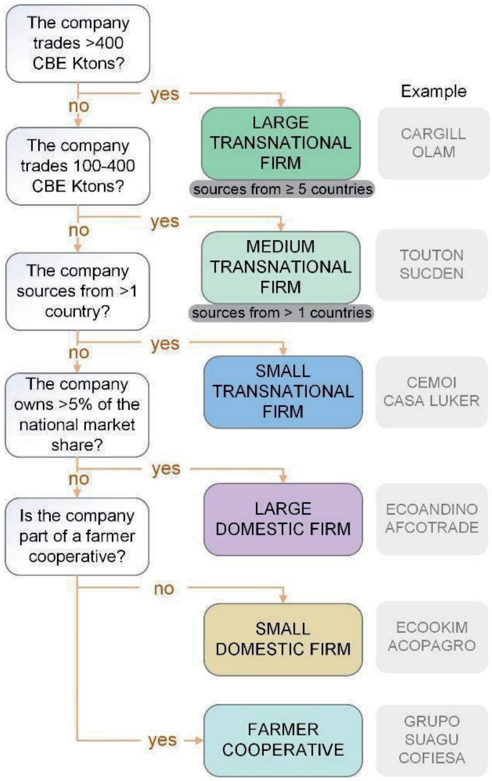


Figure 2. Criteria used to classify cocoa traders. CBE stands for cocoa bean equivalent.

2.2 Descriptive analysis of company types

We provide a descriptive analysis of the market shares of traders and trader's types at the global level and per producing country. We used the four-firm Concentration Ratio as an indicator of market concentration per producing country (OECD, 2018). By summing the market shares of the four largest cocoa traders in each producing country, this indicator distinguishes markets as competitive (<50%), oligopolistic (≥50%), monopolistic (where a single company concentrates most of the market share), and pure monopoly (a single company holds 100%). This index sheds light on potential market asymmetries and the responsibilities and opportunities of traders in moving the sustainability agenda forward (Folke et al., 2019). Next, we analyzed the involvement of traders in subnational sourcing of cocoa beans and the levels of vertical integration, horizontal integration, and industrialization. Additionally, we characterized each type of trader in terms of the number of cocoa origin countries and the number of destination countries, using the Shannon-Weaver diversity index, which balances the number of trading partners (i.e., "richness") with the homogeneity of this exchange (i.e., "evenness") (according to the volume traded with each partner) (Magurran, 2004). This index usually varies between 0-5 with lower values indicating little to no richness and evenness, and higher values indicating companies with richer and more even trade relations. We used trade data from 2017/2018 to describe these patterns. We acknowledge that sourcing can change year on year, yet there is evidence that national-level sourcing is relatively consistent, as seen by small changes in sourcing reported by companies during the COVID-19 pandemic (Nestlé, 2021). Even so, we suggest future research to evaluate the stability of trade relationships over time if data is available (Reis et al., 2020).

Table 1. Information on general characteristics and sustainability initiatives recorded per traded company. All variables except "country name" were coded as binary variables. More information on definitions used and methods to record the information are in Appendix C.

Variable category	Description	Variables
General company characteristics		
Company origin	Country where the company is legally registered.	Country name
Cocoa quality traded	Whether the company trades fine-flavor or bulk cocoa beans or both. Fine-flavor cocoa comprises beans with special aromatic and flavor profiles that are sold at higher prices.	Cocoa bulk Cocoa fine-flavor
Ownership	Legal ownership of the company between publicly listed and privately owned.	Publicly listed Privately own
Vertical integration	Company involvement in different sourcing and industrial activities along the cocoa value chain.	Subnational sourcing Primary cocoa processing Chocolate preprocessing Chocolate manufacturing
Horizontal integration	Company involvement in the trade of other agricultural commodities (e.g., coffee, soybeans, oil palm, etc.).	Horizontal integration
Sustainability initiatives		
Traceability	Company traceability capacity to the cooperative or farm-level. Interpreted as the maximum traceability level achieved by a company.	Traceability to cooperative
Transparency	Company transparent disclosure of cooperatives or farms supplying cocoa beans. Interpreted as the maximum transparency level achieved by a company.	Transparency to cooperative
Certification	Certifications a company has adopted any third-party certification scheme between UTZ, Rainforest Alliance, Fairtrade, and Organic.	UTZ Rainforest Alliance Fairtrade Organic
CFI signatory	The company is a signatory of the Cocoa and Forest Initiative (CFI).	CFI
Zero deforestation	Company commitment to zero deforestation.	Zero deforestation
Forest degradation	Company commitment to avoid forest degradation.	Forest degradation
Climate change	Company commitment to support farmers in adapting to climate change by using climate smart agriculture.	Climate smart agriculture

Variable category	Description	Variables
Agroforestry	Company commitment to promoting agroforestry systems.	Agroforestry
Living income	Company commitment to provide a fair price and living income to farmers.	Living income
Child labor	Company commitment to end child labor in cocoa farms. Child labor follows the International Labor Organization's definition: activities that harm or compromise the physical, mental, social or moral integrity of children, and compromise schooling. Child labor, therefore, is differentiated from child work in this paper, and it can include child slavery as its worst form (Abdullah et al., 2022; ILO, 2020).	Child labor
CLMRS	Company implements a Child Labor Monitoring and Remediation System (CLMRS) in its cocoa value chain.	CLMRS

2.3 Analysis of sustainability initiatives between company types

To understand how voluntary sustainability initiatives were adopted by different types of traders, we aggregated and compared the market shares of companies engaged in each of these initiatives. When reporting the coverage of sustainability initiatives of smaller traders, we extrapolated the data from our random sample of these smaller companies. For example, if for the traders handling the top 80% of cocoa exports in a country, they traded 90% of this under a sustainability initiative, and for the remaining 20% of exports, our sample of companies had 5% of their volume covered by an initiative, then the overall percentage was 73% (i.e., 80*0.9 + 20*0.05). When a company reported a sustainability initiative, we assigned the market share linked to that initiative to the direct supply share managed by that company, as reported by (Fountain and Huetz-Adams, 2020). We calculated this by multiplying the direct value chain share of that company by its global market share. We did this because large traders source an important share of cocoa beans (between 30-100%) through indirect suppliers. In indirect sourcing, cocoa beans are bought to intermediate suppliers who operate independently from company policies, with companies therefore lacking oversight or leverage on the production conditions (Fountain and Huetz-Adams, 2020; Zu Ermgassen et al., 2022). As a result, most of the initiatives of these companies are exclusively targeted to their direct suppliers. In the Appendix (Figure 4 from Appendix C) we provide results using the full market shares of companies as this represents, in principle, the market share over which they can be considered accountable. We document sustainability initiatives as reported by companies in 2021, while our trade data is from 2017-2018. Given the growing awareness of sustainability, our results may over-report the share of cocoa that was traded with initiatives in 2017/2018. However, given the limited transparency and verification systems, this is the best available information (Thorlakson, 2018). We based our search on digital material, which has the risk of underreporting the initiatives of, often smaller, companies that do not have websites or do not update them regularly.

Nevertheless, we make explicit our focus on "openly reported" initiatives. In addition, there may be some noise in our numbers for market share and sustainable initiative coverage, caused by transactions between traders. For example, in Côte d'Ivoire, transnational companies are required to source 20% of their cocoa through local traders (Reuters, 2021) - it is ambiguous whether this exchange is recorded within country (i.e., contributing to their indirect sourcing), or whether it is recorded after export, with transnational traders acting as 'importers' - in the latter case, our estimates of transnationals' market share would be lower than if we were analyzing import data.

To test whether the level of adoption of sustainability initiatives was influenced by the type of trading company, we built generalized linear models (GLM) with these reported adoptions as response variables, and company types and company characteristics as explanatory variables. We first assessed the correlations among our variables to guide the final selection of variables and minimize the risk of collinearity in the models, using the Spearman correlation index (Crawley, 2013). If two variables showed strong correlation (<-0.8 or >0.8), we included the variable with the most important theoretical meaning in the statistical models. The explanatory variables comprised all the types of companies as dummy variables, and the following company characteristics that were not captured by the typology: number of destination countries, company ownership, horizontal integration, subnational sourcing, and level of vertical integration. The response variables were of two types: i) summary variables describing the overall level of engagement of a company, i.e., the number of initiatives (commitments and third-party certifications) adopted, and ii) binary variables on specific initiatives. Because of the different nature of explanatory variables, we used two types of regression models. GLM with Poisson errors was used for the cases of count data as response variables (number of commitments and certifications). Our models showed little over-dispersion, justifying the selection of GLMs with Poisson errors instead of Negative Binomial errors. GLM with binomial errors (logistic regression) was used for the remaining binary response variables. We included the same set of explanatory variables in each initial model, except for variables causing perfect separation in the model. We then automatized the simplification and selection of the best-fitted model by using stepwise deletion based on Akaike's information criterion (AIC). To facilitate interpretation, we report the odds ratios (OR) for the logistic regression models (Table 5 from Appendix C) and 95% confidence intervals (CI). Odds ratios represent the odds of an outcome (dependent variable) to occur in the presence of a particular condition (independent variable), if all other conditions remain constant, compared to the odds of the outcome occurring in the absence of that condition. To correct for multiple comparisons, we used the false discovery rate (Benjamini–Hochberg method) to calculate adjusted p-values (Crawley, 2013).

3. Results

3.1 The market coverage of cocoa trader types

At the global level, transnational traders handled 62% of the cocoa bean trade, with 40%, 18%, and 4% being handled by large, medium, and small transnational traders, respectively (Figure 3). Among large transnational traders, Olam had the highest share, handling 17% of the cocoa trade, followed by Cargill with 12%, and Barry Callebaut with 11% (Figure 4). Medium transnational companies included Ecom, which had 5% of the global market share, Touton with 6%, Sucden with 4%, and Guan Chong Bhd with 3%. The remaining 38% of the global cocoa market was handled by domestic traders, from which 27% was handled by small domestic traders, 8% by large domestic traders, and 2% by farmer cooperatives (Figure 3). Almost all medium and large transnational traders are headquartered in high-income countries: Olam in Singapore, Cargill in the USA, Barry Callebaut and Ecom in Switzerland, and Touton and Sucden in France, with one headquartered in a middle-income country (Guan Chong Bhd in Malaysia).

Even though cocoa production has expanded to many countries and that most of them are increasing production volumes, the global market remains strongly dependent on Ivorian and Ghanaian bulk cocoa supplies (Figure 3). Over 60% of the supply of the six largest cocoa trading companies depended on Côte d'Ivoire and Ghana, with the three largest companies (Olam, Cargill, and Barry Callebaut) also sourcing importantly from Indonesia and Brazil. The four-firm concentration ratio indicated that the cocoa bean export markets are oligopolies in all countries, except Côte d'Ivoire and Ecuador (Figure 4). These results support our first hypothesis on the high market concentration extended to traders, however, it provides important nuance on the context-specific occurrence of market concentration, as it does not apply to all top exporters nor globally. Most countries with oligopolies had a market dominated by the three largest transnational companies: Olam, Cargill, and Barry Callebaut. Countries where these companies did not dominate the market (Ecuador, Peru, and Colombia) had a more balanced competition between domestic traders. Transnational companies handled between 59-97% of the market in most cocoa producing countries except Ecuador, Peru, and Cameroon, where domestic traders handled more than 50% of exports (Figure 3). A special case is Colombia, where 64% of the exports were handled by the small transnational companies "Casa Luker" and "Grupo Nutresa", which are domestic traders that have started to expand into other Latin-American countries in the last decade. Additionally, farmer cooperatives had a particularly strong presence in Colombia and Peru (21% and 13% of the market share, respectively). The presence of domestic traders was among the lowest in the two main global cocoa suppliers Côte d'Ivoire and Ghana (with 42% and 23% of the market shares, respectively).

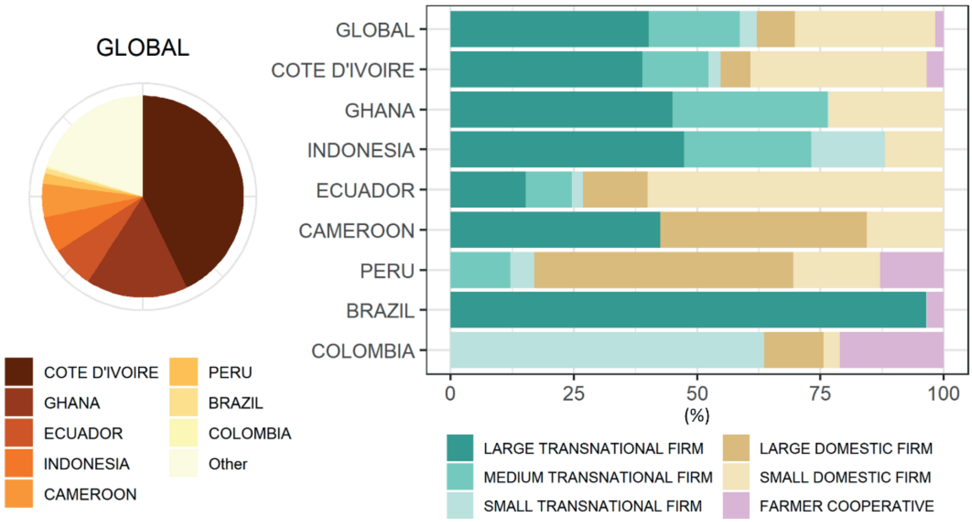


Figure 3. Market coverage per country (left panel), and per type of trader within each producing country (right panel).

3.2 Market differentiation between types of traders

Overall, transnational traders were more commonly engaged in subnational sourcing, cocoa processing, and the export of other non-cocoa commodities (i.e., horizontal integration), than in downstream activities (i.e., chocolate pre-processing and manufacture), but with important variations (Figure 5). For example, the only transnational traders involved in chocolate manufacturing were the Colombian small transnational traders Grupo Nutresa and Casa Luker, which also produce non-chocolate finished food products. Domestic traders and farmer cooperatives mainly exported untransformed cocoa beans, with about a third involved in cocoa processing and less than a quarter in further cocoa industrial transformation. All farmer cooperatives and medium-to-large transnational traders were involved in subnational sourcing activities, while only half of domestic traders reported doing so. Horizontal integration into other agricultural commodities was the highest among farmer cooperatives and transnational traders while domestic traders tended to focus exclusively on cocoa beans.

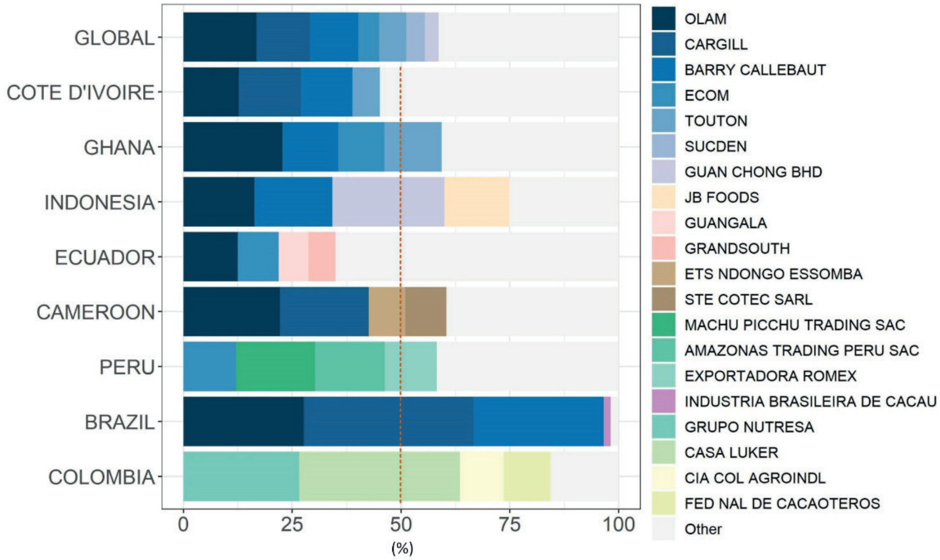


Figure 4. Market shares of the four largest traders in each producing country, except in "Global" where the seven largest traders are displayed. The dashed line indicates where the Concentration Ratio is 50%, depicting a threshold between competitive markets and oligopolies.

The diversity of countries that each trader sourced from and sold to varied greatly among types of traders (Figure 6). Large transnational traders had a more diverse country portfolio and evenly distributed volume (higher diversity index), followed by medium and small transnational companies. Guan Chong Bhd is the only transnational firm with a low diversity because it sources almost entirely from Indonesia. The number of destination countries showed less differentiation between types of traders (Figure 6 and 7). Large transnational traders exported to more than 45 countries while other companies exported to ~30 or fewer countries. The diversity index of export countries for large transnational companies was lowered by Cargill whose exports are unevenly targeted to the Netherlands, which is both a major hub for re-exports and the site of four of their processing plants (Cargill, 2022). Domestic traders and cooperatives supplied cocoa to multiple international markets, either evenly or strongly focusing on a few countries, which explains the high dispersion of diversity index values (Figure 6a).

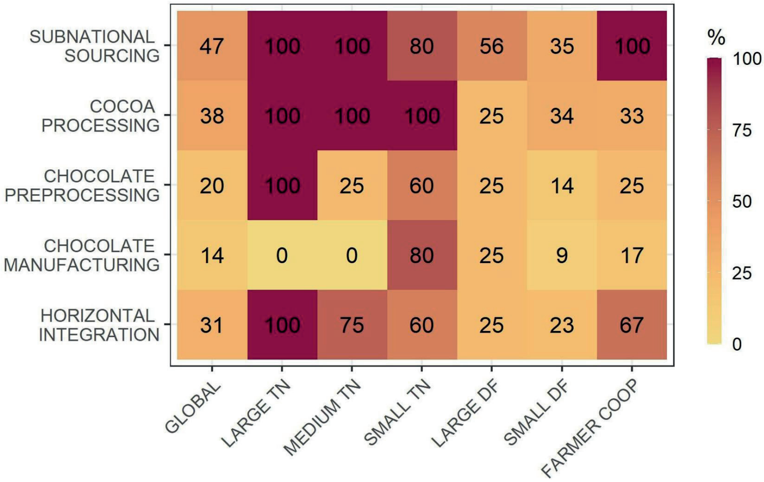


Figure 5. Share of companies that are vertically and horizontally integrated. Because each company can do multiple activities, each row must be interpreted independently, e.g., 60% of small transnational traders are involved in industrial manufacturing and 60% in horizontal integration, yet these might be the same or a different set of companies. COOP= Cooperative, DF= Domestic firm, TN= Transnational company.

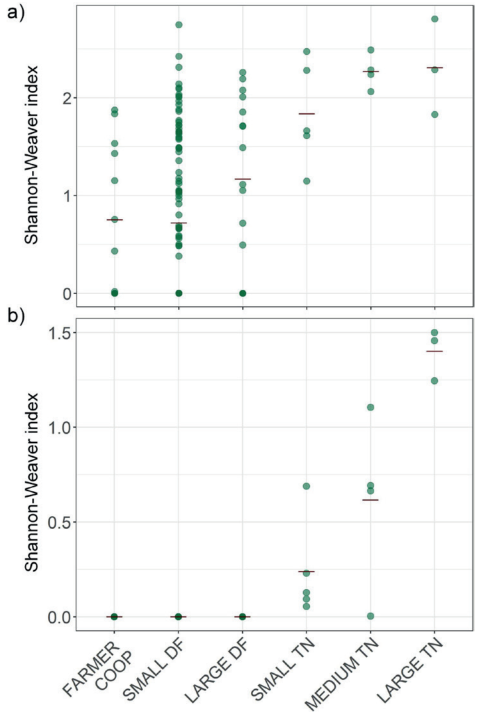


Figure 6. Diversity and evenness of trade relations per type of trader as calculated with the Shannon-Weaver diversity index for a) sourcing countries and b) destination countries. Horizontal lines indicate mean values. Higher values indicate higher diversity in sourcing or destination countries. See numeric values in the Appendix (Table 3 from Appendix C).

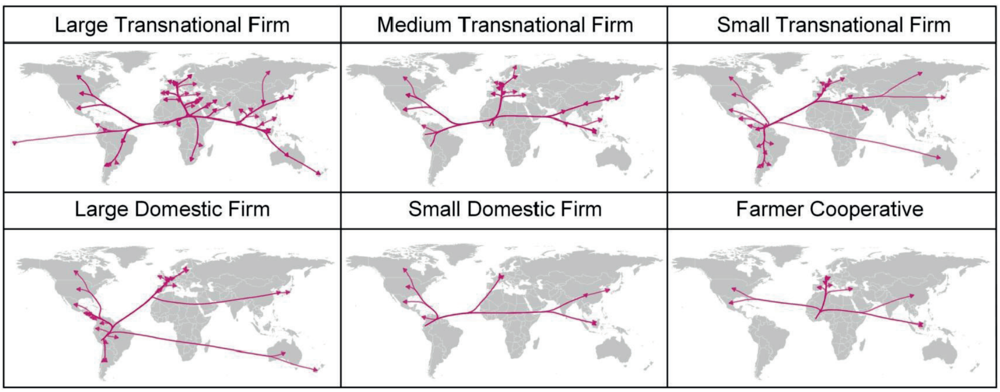


Figure 7. Example trade networks for each type of trading company. Edges connect all the sourcing and destination countries of a representative company in each group. Selected companies are depicted as examples for each case: Olam (large transnational firm), Ecom (medium transnational firm), Casa Luker (small transnational firm), Machu Picchu Trading (big domestic firm), Sanchez Group (small domestic firm), and Ecookim (farmer cooperative).

3.3 Sustainability commitments

In line with our second hypothesis, public sustainability commitments were more commonly adopted by large, transnational traders. Of the reviewed cocoa trading companies, only 14% made one or more public sustainability commitments. Half of these public commitments were made by transnational traders, a quarter by large domestic traders and the other quarter by farmer cooperatives. Though domestic traders and farmer cooperatives handled 38% of the global market share, they rarely made public sustainability commitments. Only two large domestic traders publicly committed to address child-labor and most farmer cooperatives had no commitments or focused only on one particular topic (with climate change and CLMRS rarely included). In general, companies adopting public commitments tended to adopt more than one (see Figure 5 from Appendix C), while transnational companies were likely to adopt most of them.

We also find large gaps in the market coverage and the imbalanced engagement on certain sustainability topics, in line with our third hypothesis. In terms of traded volumes, only 26% of global cocoa was traded under any commitment (Figure 8). Yet, if commitments would also cover the indirect sourcing shares of companies, more than 60% of the whole cocoa value chain would be reached by sustainability commitments (Figure 4 from Appendix C). A key mechanism through which commitments were adopted is membership of the CFI, to which all transnational companies are signatories. The CFI sets targets for deforestation, forest restoration, agroforestry, and income diversification, but has been criticized for excluding forest degradation from corporate action plans - a notable blind spot (Carodenuto and Buluran, 2021; World Cocoa Foundation, 2017). Only three companies, covering 10% of the traded volume, committed to address forest degradation: Nestle, Touton, Guan Chong Bhd, as well as the Peruvian cooperative Cooperativa Agraria Naranjillo. In contrast with other commitments, fewer transnational companies adopted child labor, CLMRS and living income commitments.

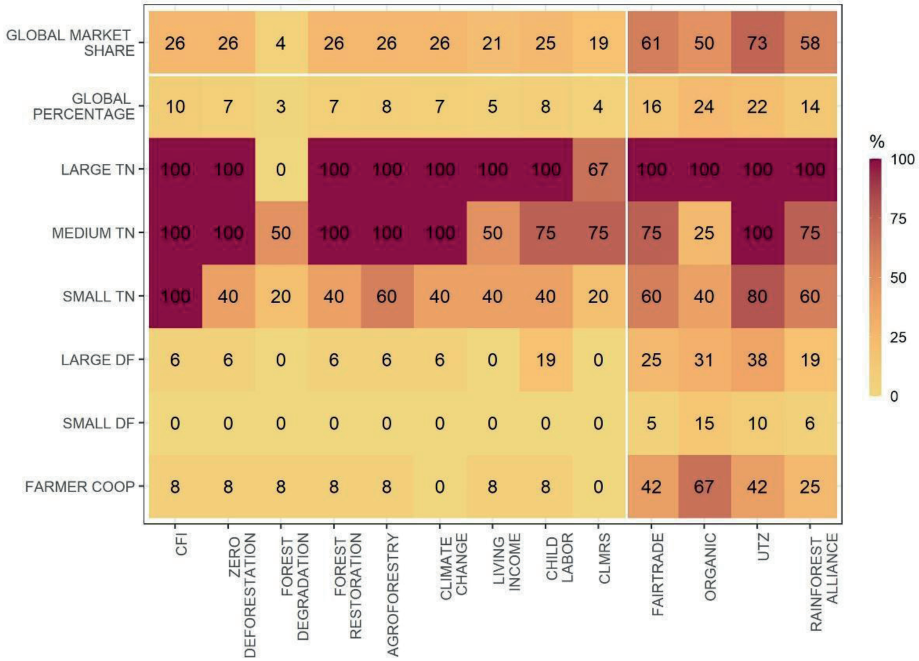


Figure 8. Percentage of companies and shares of cocoa beans traded by companies adopting sustainability commitments (first nine columns) and trading cocoa under certification labels (last four columns). The first row depicts the total market share of companies engaged in each initiative and the remaining rows depict the percentage of companies involved.

3.4 Third-party certification labels

In line with our fourth hypothesis, we found that small companies were more likely to trade third-party certified cocoa than to adopt sustainability commitments (Figure 8). We found, however, that although large transnational traders increasingly adopted their own sustainability commitments, they also continued to trade cocoa certified under multiple labels. An important nuance is that our findings only refer to the number of initiatives of traders and not to the volume traded, since the data did not allow us to make this distinction. Overall, transnational companies and farmer cooperatives were the largest users of certification labels; 75-100% of transnational traders and 25-67% of farmer cooperatives traded cocoa with at least one certification (favoring UTZ and Organic, respectively). However, this does not mean that all these companies' exports were certified: in Côte d'Ivoire, for example, it is estimated that less than 40% of exports by the transnational traders Cargill, Barry Callebaut, and Olam come from certified cooperatives (Renier et al., 2023). Fewer than 40% of large domestic traders traded some certified cocoa, among which most traded cocoa with more than one certification, especially UTZ. The larger market penetration of UTZ is generally explained by its relatively lower requirements compared to other standards (Krauss and Barrientos, 2021). Domestic traders and farmer cooperatives adopting certifications were mostly based in Latin America (mainly Peru and Ecuador) and favored organic labels probably due to the larger government support to organic farmers in this region (Meemken et al., 2021; Raynolds, 2004).

3.5 Traceability and transparency

Only 22% of all companies, handling 32% of cocoa exports, reported being able to trace their directly sourced cocoa back to farmer cooperatives, and only 8% of companies (handling 23% of cocoa volumes) were transparent about the identity or location of their direct suppliers (Figure 9). The information disclosed varied, but most companies disclosed either the jurisdiction of origin and/or name of farmer cooperatives, with some also including the number of farmers, the certifications adopted, and the volumes traded. All medium and large transnational traders traced at least some of the cocoa they source to the cooperative level. Among medium transnational companies, only one in four, Touton, openly disclosed this information. Only 60% of small transnational companies, 38% of large and domestic traders and 5% of small domestic companies reported tracing some of the cocoa traded to the cooperative level - in line with their lower engagement in subnational sourcing. It is important to clarify that traceability to cooperative level does not necessarily imply full traceability to the farm-level, not even for farmer cooperatives. Currently disclosed information is scattered, not constantly updated, and does not allow to verify whether traceability to farm-level is achieved by any company (Renier et al., 2023).

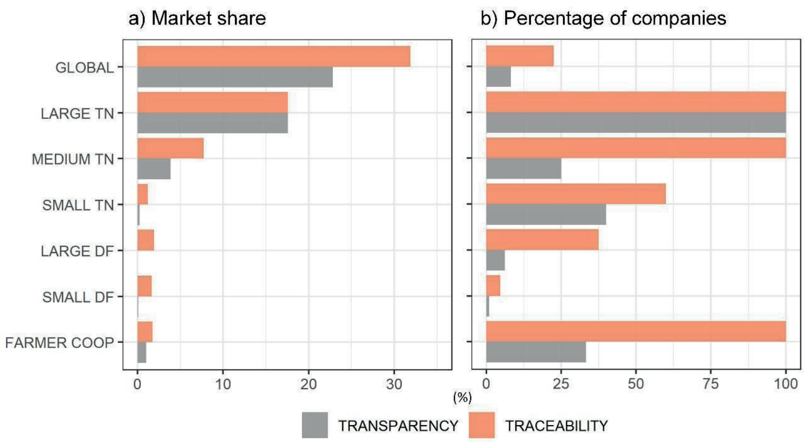


Figure 9. Share of traded cocoa (a) and percentage of companies (b) reportedly having traceability and transparency systems up to the cooperative level for at least some of the cocoa beans traded.

3.6 Correlates of sustainability initiatives adoption

Our statistical modeling confirmed the above-mentioned results and hypothesis (Table 2). In general, the adoption of sustainability commitments was low. Transnational companies adopted significantly more sustainability commitments ($ß>2.1$, $p<0.01$), and small domestic traders significantly fewer ($ß=-3.96$, $p<0.01$). Small domestic traders were also significantly less likely to report traceability information (OR 0.20, $p<0.01$) or be transparent about their sourcing (OR 9E-03, $p<0.01$) (Table 4 from Appendix C). Companies engaging in subnational sourcing acquired a significantly higher number of certification labels ($ß=1.74$, $p<0.01$) and were more likely to report sourcing traceable cocoa (OR 31, $p<0.01$). Large domestic traders were more likely to adopt child labor commitments (OR 17, $p<0.05$). Publicly listed companies were significantly more likely to adopt deforestation (OR 18.5, $p<0.01$) or child labor commitments (OR 19.4, $p<0.05$). Vertically integrated companies were more likely to adopt traceability commitments (OR 2.2, $p<0.1$) and horizontally integrated companies were more likely to adopt transparency commitments (OR 5.4, $p<0.1$), which may reflect a “spillover” from transparency commitments set for other agricultural commodities. We also found that traders involved in cocoa processing that are horizontally integrated adopted ten times as many commitments as traders engaged in chocolate manufacturing (Figure 6 from Appendix C).

Table 2. Results of statistical modeling indicating regression coefficients (ß). 95% Confidence intervals are shown in brackets for logistic models. "-" indicates variables that were not included in the initial model due to perfect separation or collinearity; "~" indicates variables that were included in the initial model but were not retained in the final model due to automatized stepwise model selection based on AIC values.

Explanatory variables	Nº Commitments	Nº Certifications	Traceability	Transparency	Zero deforestation	Agroforestry	Child labor
Large TN	2.84** (2, 3.8)	-1.03 (-2.1, 0)	-	-	-	-	-
Medium TN	2.44** (1.8, 3.1)	~	-	-1.78 (-5.1, 0.9)	-	-	~
Small TN	2.19** (1.4, 3.2)	~	-2.11 (-5.03, 0.9)	-	~	3.32* (0.6, 6.6)	3.03 (-0.1, 6.8)
Large DF	~	~	-	-2.68 (-5.9, 0.33)	~	-	2.85* (0.6, 5.7)
Small DF	-3.96** (-6.9, -2.4)	-0.65** (-1.1, -0.2)	-4.17** (-6.1, -2.7)	-4.64** (-7.8, -2.4)	-	-	-
Farmer cooperative	~	~	-	-1.22 (-3.4, 0.7)	2.34 (-0.9, 5.2)	~	~
Public company	~	~	-	~	2.92** (1.1, 5.1)	~	2.24* (0.3, 4.5)
Nº country destinations	~	0.04** (0, 0.1)	~	~	0.17** (0.1, 0.3)	0.21* (0.1, 0.4)	0.24* (0.1, 0.5)
Subnational sourcing	~	1.74** (1.1, 2.5)	3.44** (1.6, 6.6)	~	~	2.13 (-0.4, 6)	2.03 (-0.4, 5.5)
Vertical integration	0.2 (-0.3, 0.6)	~	0.78 * (0.1, 1.6)	~	~	-0.85 (-2.2, 0.1)	-1.96* (-3.8, -0.6)
Horizontal integration	1.47** (0.6, 2.4)	0.35 (0, 0.8)	~	1.69 (0, 3.8)	~	2.4* (0.6, 4.8)	1.89 (-0.2, 4.6)
Vertical integration: Horizontal integration	-0.75** (-1.2, -0.2)	~	-	-	-	-	-
Intercept	-1.18 (-2.1, -0.4)	-1.76** (-2.6, -1)	-2.16 (-5.1, 0.5)	-0.72 (-3, 1.3)	-5.76** (-8.8, 4)	-7.45** (-12.6, -4.6)	-7.93** (13.9, -4.7)
Akaike Inf. Crit. (AIC)	141.73	271.43	67.77	57.32	44.97	46.36	48.48

*p<0.05; **p<0.01

4. Discussion

In the following sections we discuss the importance of market concentration in the prevalence, distribution, focus and potential effectiveness of value chain sustainability commitments; the factors that may explain such market concentration in the cocoa sector; the current gaps in sustainability commitments and strategies; and end with broader implications for commitment implementation, effectiveness, and accountability for addressing global environmental challenges.

4.1 Market concentration - a double-edged sword

Previous studies have demonstrated that cocoa processing and chocolate manufacturing is concentrated in the hands of a few transnational companies (Oomes et al., 2016). Here, we show that this concentration also extends to cocoa trading in which transnational traders handle around two thirds of global cocoa exports. Often presented as an opportunity for sustainability (Folke et al., 2019; Ponte, 2019), market concentration presents a double-edged sword.

On the one hand, high market coverage can be seen as a prerequisite for corporate sustainability initiatives to be effective (Garrett et al., 2019). It has been argued that sustainability upgrading is more likely when power is exercised by a group of (concentrated) lead firms than in value chains with a more balanced power distribution (Ponte, 2019). Similarly, the "hourglass" theory of change posits that market concentration offers an opportunity for sustainability impact, as the actions of a small number of companies active in the middle of value chains can improve sustainability outcomes across large sourcing regions (Folke et al., 2019; Gollnow et al., 2022; Grabs et al., 2021; Lyons-White and Knight, 2018). For this reason, and their position as suppliers to global brands, traders have been identified as key actors in sustainable global value chains (Grabs and Carodenuto, 2021; Zu Ermgassen et al., 2022). In line with agency theory, the leadership of large companies in sustainability commitments could, therefore, be advantageous if the accumulated agency of these actors is used as an opportunity to create leverage points for sustainability initiatives in the entire sector (Folke et al., 2019). This opportunity could apply to transnational traders that are horizontally integrated into trading other agricultural commodities and that face similar social and environmental challenges (e.g., Cargill, Olam and Ecom). These companies adopt similar commitments across different commodities, which is facilitated by the lower costs of expanding commitment portfolios to commodities with similar strategic requirements (Fountain and Hütz-Adams, 2017; KPMG, 2014; Oomes et al., 2016).

On the other hand, market concentration allows leading companies (principals) to exert uneven pressure on less powerful actors (agents) to obtain strategic market and sustainability outcomes

(Dallas et al., 2019). Concentration, for instance, increases the agency of larger companies in priority-setting of policy agendas and can exacerbate the unequal representation of smaller actors in sustainability governance structures. Arguably, the greater focus that transnational companies and multi-stakeholder initiatives like the CFI place on forests, rather than poverty or living income, partially reflects this power over agenda-setting (Clapp, 2021; Schneider et al., 2020). Larger traders have more resources to set up commitments and can attract more investment from sustainability-oriented downstream companies. Therefore, voluntary sustainability markets indirectly provide an unequal competitive advantage to large traders, which creates a self-reinforcing process of ever deepening market concentration (Mcdermott et al., 2022; Smith et al., 2019). Lead companies also push sustainability costs and risks upstream onto less powerful actors, the local traders or farmers supplying multinational traders, thus raising the entry barrier, and leading to their own consolidation (Ponte, 2020, 2019). Despite achieving some improvements, claimed sustainability solutions might be reinforcing the underlying drivers of sustainability issues while providing a false sense of security to consumers (LeBaron and Lister, 2021). In addition, market concentration can lead to a softening or delay of government sustainability agendas by generating a deterring effect on policy makers who fear that more stringent regulation would incentivize divestment or, even worse, the relocation of trade (Clapp, 2021). This can be of particular concern when private companies are part of multistakeholder partnerships with governments, in which the efforts to implement more stringent policy regulations are at risk to be delayed or weakened (Ponte, 2019).

4.2 Factors explaining market concentration

Concentration is partly driven by efforts to benefit from economies of scale, of particular concern in low-margin businesses, as commodity trading is typically characterized (Bonfiglioli et al., 2021; Oomes et al., 2016). It is estimated that traders only capture 3-5% of the net margins associated with a typical chocolate bar (FAO and BASIC, 2020). Market concentration between cocoa traders has occurred through a series of company mergers (Oomes et al., 2016). In Côte d'Ivoire for example, the USA trader Archer Daniels Midland exited the cocoa sector in 2013, citing low margins (Reuters, 2013). Its cocoa branch was then purchased by its transnational rival Cargill (Cargill, 2015).

The pattern of market concentration differs between producer countries. Transnational companies handle most exports in Côte d'Ivoire, Ghana, Indonesia, Brazil, and Colombia, but not in Peru, Colombia, and Ecuador. The latter markets are major producers of fine flavor cocoa (ICCO, 2020), which has a more heterogeneous and complex aromatic and flavor profile and is rarely traded in bulk volumes typical of transnational companies (Daniels et al., 2012; ICCO, 2021; Leissle, 2013; Oomes et al., 2016). The high market penetration of domestic traders in these

countries is also a consequence of longstanding national incentives to national entrepreneurs (Meliciani and Savona, 2015; Neilson et al., 2020; Purcell, 2018; Scott et al., 2015). The apparent market differentiation between fine and bulk cocoa might dissipate in the future, however, as with the growth of the market for fine flavor cocoa, transnational traders have increasingly invested in in-house fine-cocoa trading divisions (Confectionery News, 2021b, 2021a).
In addition, farmer cooperatives buffered market concentration in Brazil and Peru, which are countries with long-term technical support, infrastructure, and financial assistance for rural community enterprises through government and NGO programs (Donovan et al., 2008; Neilson, 2007; Scott et al., 2015). In West Africa, cooperatives had an important but lesser participation, and have been supported by private companies seeking high quality products and stable and predictable supplies in return (Donovan et al., 2017, 2008). Other countries, such as Indonesia, have given more emphasis to trade and taxation policies and have discouraged the organization of cooperatives as they gathered agency and were seen as politicized institutions (Neilson, 2007). Varying degrees of market concentration thus stem from factors related to the cocoa value chain itself (e.g., the focus of some countries on fine flavor versus bulk cocoa) as well as factors related to countries' socio-political contexts.

4.3 Gaps in sustainability commitments

Despite the existing market concentration and the leadership of large companies in commitment setting, we identified large gaps in sustainability commitments - through the partial adoption of commitments, non-signatory traders, and commitment blind spots. First, our estimate that only 26% of cocoa is traded under some form of sustainability commitment accounts for the fact that traders only apply commitments to their so-called 'direct' value chains, where they purchase cocoa directly from known farmer groups or cooperatives. The inclusion of indirect sourcing through intermediary local traders in sustainability monitoring and reporting is essential to the success of corporate sustainability efforts (Zu Ermgassen et al., 2022). If transnational traders were to apply commitments to volumes sourced through local intermediaries and through international spot markets, the coverage of sustainability commitments would more than double, to cover 60% of global trade.

Second, the exclusion of smaller traders is also an important contributor to the gaps in sustainability commitments. Domestic traders and farmers cooperatives represent an important 'missing link' in sustainable cocoa initiatives. These companies were responsible for 38% of the global trade, with only 7% of traders adopting at least one sustainability commitment, and just 28% using certification labels. One positive step would be for multi-stakeholder initiatives, such as the CFI, to bring domestic traders into the fold. However, these companies would still face important challenges in implementing sustainable procurement initiatives due to the high entry barriers favored by the existing power asymmetry. Domestic companies inevitably have less agency and fewer financial resources than their larger, transnational rivals to establish, for instance, costly traceability of child-labor monitoring and remediation systems (CLMRS) systems, and satellite-based deforestation monitoring systems (Carodenuto, 2019; Fountain and Huetz-Adams, 2020). This is one reason why they more commonly rely on certification labels than setting up their own independent commitments. Further, traceability is a very important requirement for commitment implementation, and we found that domestic traders have a business model that limits the visibility of the value chain and complicates traceability even more. Domestic traders were less likely to engage in subnational sourcing: rather than buying cocoa from specific farmer groups, they were more likely to source through local aggregators and intermediaries (Grabs and Carodenuto, 2021; Zu Ermgassen et al., 2022).

Third, in terms of sustainability topic gaps and alignment, the type of information disclosed in commitments reports focused on only a few issues, was variable, and rarely aligned with reporting norms such as the Accountability Framework Initiative. Even among transnational trading companies, some issues received more attention than others without acknowledging that the range of sustainability issues in the cocoa sector encompasses many additional dimensions, such as forest degradation, biodiversity loss, soil degradation, climate vulnerability, etc. (Tennhardt et al., 2022). Agency seems to be used to adopt commitments on factors driving reputation gains and increased value creation rather than addressing systemic issues. We found that traders more commonly adopted forest-related commitments than they adopted commitments to ensure a living income, or address child labor through the implementation of CLMRS systems. This focus also is a missed opportunity, as deforestation cannot be addressed without addressing poverty and farmer incomes as underlying drivers (Meyfroidt et al., 2022; Pendrill et al., 2022; Southworth, 2009). Even so, only three traders made explicit commitments to address forest degradation, which can rival deforestation as a source of carbon emissions and biodiversity loss and can contribute to the expansion of the cocoa frontier (Barlow et al., 2016; Matricardi et al., 2020; Renier et al., 2023). Agroforestry was actively promoted as a 'win-win' option for combining cocoa production with biodiversity protection and carbon storage. However, in most cases companies did not provide definitions about the actual practices promoted. In addition, there is a lack of recognition that the benefits of agroforestry systems are likely to be context-specific due to land use dynamics and potential leakage effects across producing landscapes (Meyfroidt et al., 2014). Where it replaces sun grown cocoa, agroforestry can indeed benefit biodiversity, carbon storage, and soil fertility (Blaser et al., 2018; Martin and Raveloaritiana, 2022; Parra-Paitan and Verburg, 2022). But where shade-grown cocoa encroaches into old-growth forest, it is likely to erode these services too, which is a process that is not actively detected and acknowledged by sustainability initiatives (Renier et al., 2023; Wurz et al., 2022). Therefore, corporate efforts to promote agroforestry should be guided by land use planning to navigate these trade-offs.

In addition, by having narrow geographic units of intervention (i.e., some farmers in some areas) these commitments and certification labels fail to address the systemic problems that emerge at the landscape level due to the telecoupled nature of land-based issues. The competing interests that arise at larger scales need to be addressed to avoid leakage and compromising other environmental and development agendas. Therefore, sustainable value chain initiatives can be more effective if they are aligned to and complement efforts addressing issues at wider scales and dimensions (Mcdermott et al., 2022; Pendrill et al., 2022; Smith et al., 2019).

Overall, this imbalanced distribution of commitments scope and coverage can lead to the abandonment of important sustainability dimensions and to the displacement of negative practices into smaller non-committed companies or other sectors (LeBaron and Lister, 2021). This can lead to market bifurcation where traders from high-demanding consumer markets prefer sourcing from cocoa origins with less social and environmental challenges, while traders from less-demanding markets source from countries with more challenges and less stringent regulations (Lambin et al., 2018; Meyfroidt et al., 2020). To avoid leakage and scale up the impact of own-company sustainability commitments, government interventions at multiple levels are needed to create a legally-binding, level playing field where all companies are requested to fulfill sustainability criteria (Gollnow et al., 2022; Grabs and Carodenuto, 2021; Mayer and Gereffi, 2010). Yet, to avoid further marginalization of smaller traders, it is necessary to also support the bottom-up inclusion of all types of traders in the sustainability market, notwithstanding their market share, in all parts of the value chain (direct and indirect) (Gardner et al., 2018; Lambin et al., 2018; Pedersen et al., 2021).

4.4 Commitment implementation, effectiveness, and accountability

So far, we have discussed what sustainability commitments trading companies preach, which are not necessarily the same as what they practice. Though corporate sustainability commitments have been shown to improve sustainability outcomes in several commodity contexts (Chen et al., 2019; Gollnow et al., 2022; Heilmayr et al., 2020; Heilmayr and Lambin, 2016), there are also many examples of companies not living up to their sustainability ideals (Hofmeister et al., 2022; Mighty Earth, 2022; Ponte, 2020). Specifically in the cocoa sector, child labor (Krauss and Barrientos, 2021; Sadhu et al., 2020), poverty (DeFries et al., 2017; Guzmán and Chire Fajardo, 2019), deforestation (Goldman et al., 2020; Oomes et al., 2016; van der Ven et al., 2018a), and environmental degradation (Barnett et al., 2021; Clapp, 2021) persist, despite the proliferation of sustainability commitments.

The factors that make voluntary sustainability governance arrangements attractive for participating companies are arguably also what potentially limits their impact. When sustainability is voluntary, it can be used strategically for product differentiation and value capture by lead firms – sometimes referred to as 'green capital accumulation' (Ponte, 2019). Besides new market opportunities, voluntary commitments offer companies flexibility in goal-setting and progress reporting, with low bureaucratic cost and no legal risks when targets are not met. As a result, voluntary sustainability commitments are not enforceable, and generally lack external auditing, reporting and verification mechanisms, cross-sectoral benchmarks, and standardized definitions around sustainability issues (e.g., of deforestation, risk, agroforestry) (Clapp, 2021; Garrett et al., 2019; Meemken et al., 2021; Tayleur et al., 2017). Though some companies issue annual reports documenting the implementation of their commitments, such as the Cocoa Compass from Olam, Cocoa Promise report from Cargill, Cocoa Horizons report from Barry Callebaut, the statements contained are not third-party verified and often do not allow distinguishing the contribution of certification labels and voluntary commitments. Altogether, the incentive for sustainability value creation, the lack of minimum standards, transparency, accountability, and the risk of softened regulation creates an enabling environment for potential corporate greenwashing (Ponte, 2019; Wu et al., 2020).

Though certification schemes are third-party audited, which in principle provides them higher accountability than voluntary sustainability commitments, the capacity of auditing bodies is questioned (Greenpeace, 2021; Ruf et al., 2019) and even certification shows limited evidence of efficacy, with heterogeneous impacts on farm worker incomes and deforestation (Dietz and Grabs, 2021; Meemken et al., 2021; Oberlack et al., 2023; Tayleur et al., 2018). Moreover, certifications focus on an even narrower set of sustainability topics than commitments, and their benefits have been reported to not match with the implementation costs (Ingram et al., 2018a; Mcdermott et al., 2022; Thorlakson, 2018; van der Ven et al., 2018) . Other bottom-up initiatives complementary to certification can help navigate these challenges by enhancing the agency and representativeness of farmer organizations in global value chains. Some studies have documented positive outcomes of solidarity economy, inclusive business, and participatory guarantee schemes in sustainability outcomes and inclusive value creation. These bottom-up schemes use participatory tools to build trust-based schemes for the definition, measurement, and assessment of sustainability (Loconto and Hatanaka, 2018; Oberlack et al., 2023).

A prerequisite for the implementation of sustainability commitments, however, is knowing where the products come from. It is therefore concerning that only 32% of cocoa trading was handled by traders who reported being able to trace directly sourced cocoa back to specific farmer cooperatives or groups. Ultimately, accountability for and monitoring the impact of corporate sustainability efforts requires that companies are transparent about their sourcing practices and publish independent audits of their sustainability activities. Despite annual reporting under initiatives such as the CFI, few companies (cumulatively handling 23% of cocoa trade) disclose information about the identity and location of their suppliers according to the Accountability Framework (AFI, 2019). Traceability and transparency often require costly up-front investments for GPS farm mapping, digitalization, and online transparency portals that are less available to smaller traders (Carodenuto, 2019). The need for traceability will become even more acute with proposed due-diligence legislation from the European Union and other importing markets. These laws require trading companies to geolocate the origin of deforestation-risk products, including cocoa, and provide evidence that products do not originate from recently deforested land nor are associated with human rights abuses.

Multi-level initiatives are needed to balance competition in the sustainability market and create an enabling environment for achieving sustainability upgrading (Furumo and Lambin, 2021). In addition to the bottom-up initiatives cited above, national, and subnational governments can play a variety of 'orchestrating roles' to address the shortfalls of sustainable value chain initiatives and deliver improved sustainability outcomes (Ponte, 2019; Zu Ermgassen et al., 2022). Governments in producer countries can facilitate traceability for all companies, regardless of their financial resources (Zu Ermgassen et al., 2022). The governments of Côte d'Ivoire and Ghana, for instance, are setting up farm-level traceability systems to support sustainability accountability efforts. Similarly, governments can set minimum standards, reporting norms, or transparency requirements - arguably, the European Union's proposed due-diligence legislation is an effort to provide this for the European market, though side-effects of such policies are also likely (Sellare et al., 2022). At subnational level, jurisdictional sourcing approaches are initiatives that can help addressing the lack of oversight in indirect sourcing volumes, in which actors (e.g., companies, local governments, and civil society organizations) operating in a common jurisdiction or landscape establish targets for production, incomes, and conservation through a multi-stakeholder process (Boshoven et al., 2021; Zu Ermgassen et al., 2022). Recent studies have documented the potential holistic benefits of this approach (Torralba et al., 2023) and the CFI has started to implement this approach by identifying a number of priority landscapes in Ghana and Côte d'Ivoire (WCF, 2023), though these remain in the pilot stage. In order to make sustainability standards enforceable, governments can move to internalize market-led or multi-stakeholder standards into regulation (Ponte, 2019). For example, in the Brazilian cattle sector, more than 100 slaughterhouses in the Amazon have voluntarily entered legally-binding sustainable procurement commitments, coordinated by the Federal Public Prosecutor's Office. It is important to stress, however, that for improved sustainability outcomes in polycentric governance arrangements, it is not simply a case of governments creating an enabling environment for market-led initiatives, but it is also necessary for companies to support government initiatives.

5. Conclusion

The current paradigm of market-led governance arguably emerged as a response to weak national and international regulation of environmental and social issues arising in value chains (Bernstein and Cashore, 2007; Ponte, 2019). Now, more than two decades since the emergence of these initiatives, there is growing frustration at the perceived lack of progress on sustainability goals, and even their unintended consequences (LeBaron and Lister, 2021; Ponte, 2020). For the case of global cocoa trading, this study found high levels of market concentration among traders and an imbalanced representation of large companies in the adoption of sustainability commitments. Only seven companies trade most of the cocoa volumes and have the largest adoption of sustainability commitments. Despite this dominance, we identified large gaps in the adoption, framing, and implementation of these commitments which conspire to undermine their potential effectiveness: less than 30% of cocoa is traded under some form of sustainability commitment due to the selective focus of these commitments on direct cocoa supplies. Smaller companies, domestic traders and farm cooperatives hold an important market (38%) share but rarely adopt commitments. The agency derived from market concentration could support sustainability efforts only if it creates leverage points for upgrading in the entire sector. However, the power asymmetry from concentrated markets also creates high entry barriers to smaller traders in the sustainability market. Government interventions can help level the playing field by promoting the representation of smaller traders in sustainability agenda-setting, leading cross-sectoral initiatives to set up standards, and providing the infrastructure for traceability and transparency systems.

Further, commitment does not equal implementation or impact, and voluntary sustainability initiatives have known limitations regarding these. Voluntary mechanisms can improve on certain sustainability outcomes but are insufficient to fully address sustainability issues in global value chains, as they often lack external verification, follow non-standardized definitions, cover only some sustainability topics, have limited coverage, are not enforceable, and do not address the root causes of sustainability issues that include poverty, inequality, tenure insecurity, lack of regulation enforcement, and power asymmetries. Several other interventions are needed. Jurisdictional approaches can support addressing the lack of commitments covering indirect sourcing, bottom-up initiatives can enhance the agency and representativeness of farmer organizations, national initiatives and international initiatives can help minimizing spillovers across locations and sectors. Without coordinated corporate and government efforts to make sustainable value chain initiatives transparent, monitorable, and enforceable, the cocoa sector will not succeed in closing the gap between sustainability rhetoric and reality.

5. Deforestation and climate risk hotspots in the global cocoa value chain

Abstract

Climate change and deforestation are two of the most pressing environmental issues of the global cocoa value chain. Deforestation that often precedes cocoa farm establishment releases large amounts of greenhouse gases contributing to global warming. At the same time, cocoa production is highly vulnerable to the impacts of climate change. 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, and thus may bring failures in supply and severe socio-economic impacts if it remains 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 relying heavily on West African supplies, and even more the regionally based exporting farmer cooperatives and domestic firms, will be affected by the increased climate risk in that region. With regional exceptions, traders operating in Latin America and Southeast Asia might only face a modest increase in climate risk. Together, these results question the soundness of sustainability commitments made by companies and other sector initiatives, which focus on single commodities and do not integrate the diversity of actors adding pressure on landscapes. Tackling these issues requires a joint effort of diverse sectors and stakeholders linked to land use decisions to avoid geographical displacement of negative impacts, prioritize urgent action, and implement these in an efficient and coordinated manner. Further, sustainability commitments rarely target climate change adaptation, with agroforestry and climate smart agriculture action focused mostly on carbon reductions and increased farmer income, giving much less attention to farm practices that reduce cocoa vulnerability.

In review as: Parra-Paitan, C., Meyfroidt, P., Verburg, P.H., zu Ermgassen, E.K.H.J. Deforestation and climate risk in the global cocoa value chain.

1. Introduction

Cocoa production is both a driver of climate change and is highly vulnerable to its impacts. Cocoa production releases greenhouse gases (GHG) mainly through the removal of tropical forests that precedes 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 more than 5 million farmers, the majority of which 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 set up to worsen 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.

Besides the urgency to act upon these challenges, coming regulatory initiatives are increasingly mandating governments and companies to act. 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 recently approved 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 expense of natural forests cleared after December 2020 (European Commission, 2021) Complementarily, the proposed European Due Diligence legislation will, if approved, 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 consuming markets such as the USA and the UK. Cocoa producing countries and cocoa value chain actors need to quickly build robust and transparent systems to account, monitor, and remediate sustainability issues linked to their operations, among which 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 key to inform 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 adds a new level of detail by analyzing jointly two of the most pressing environmental risks in the cocoa sector, in a spatially explicit manner, breaking these risks down 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 on 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 (per commodity including 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)

To characterize the future climate risk of cocoa, 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 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 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 through 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 low increase in a climate risk, values >1.2 and <1.5 represent moderate levels, and values >1.5 indicate high future climate risk. 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), although it can have a stronger effect when combined with heat stress (Malek et al., 2022; Schroth et al., 2016). We provide results using the RCP 2.6 scenario in Figures 2-4 from Appendix D, 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.

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 selection of countries and traders 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 detailed the traders' market share in each country and provided 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 a 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 (Figure 1 from Appendix D). We sampled pixels randomly, with replacement, weighting 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 Figure 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 Figures 1, 2, and 3. The overall deforestation driven by agri-commodities (%) was calculated by dividing the area (ha) of deforestation driven by agri-commodities by the cocoa producing landscape area (pixel area in ha), see Figure 4b.

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 modeled 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)

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 (Figure 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 (Figure 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.

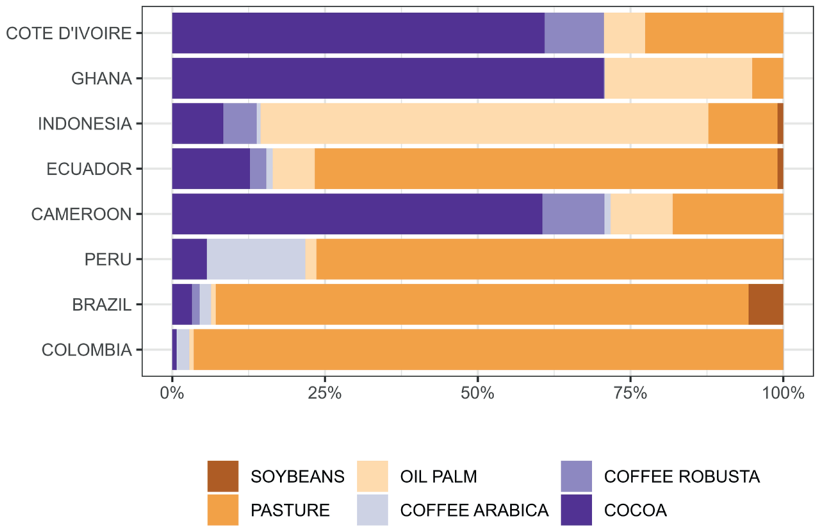


Figure 1. Deforestation driven by agri-commodities in cocoa producing landscapes of top 8 cocoa exporters.

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-commodities (Figure 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 (Figure 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 less climate risks (Figure 3). More than 66% of cocoa in Cote d'Ivoire is produced in areas that will experience a modest increase in drought severity, with a further 14% in areas that will experience a moderate increase, and ~1% of cocoa produced in areas facing a sharp increase in drought severity in 2050. 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 and <1.5), and modest (>1 and <1.2) increased climate risk, respectively.

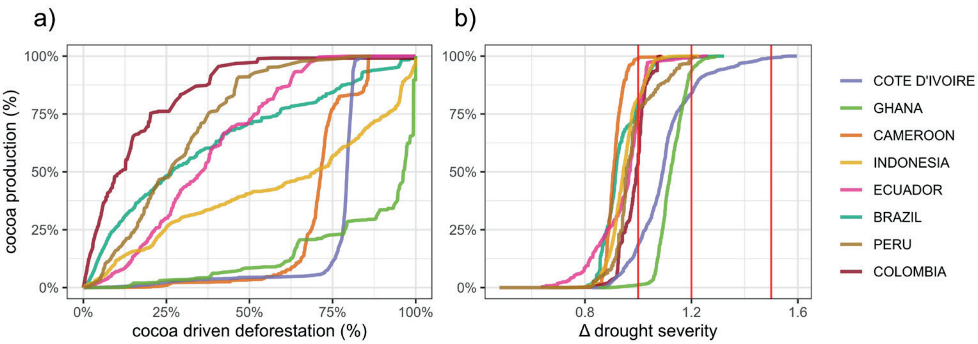


Figure 2. (a) Cumulative cocoa production (%) affected by agri-commodity deforestation attributed to cocoa (%), and (b) future drought severity in cocoa producing landscapes of top 8 cocoa exporters. In (b), the red vertical lines indicate the thresholds for reduced (<1), modest (>1 and <1.2), moderate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

3.3 Where do climate risk and deforestation hotspots converge?

As Figure 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* 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.

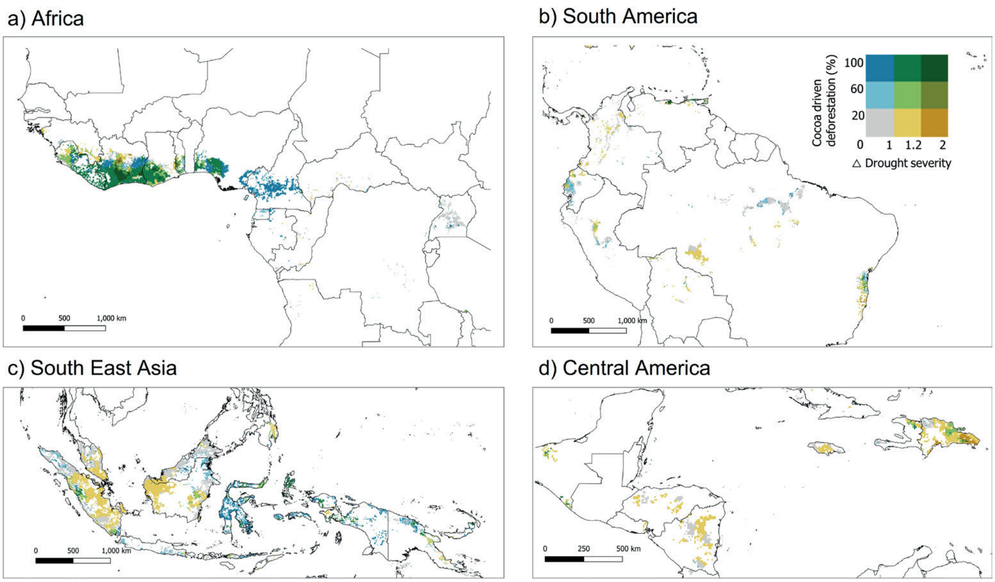


Figure 3. Combined levels of drought severity change and agri-commodity deforestation attributed to cocoa (%) in cocoa producing landscapes.

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 (Figure 4a) and where deforestation driven by agri-commodities is about the same in cocoa producing landscapes (Figure 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 because they are strongly present in Cote d'Ivoire.

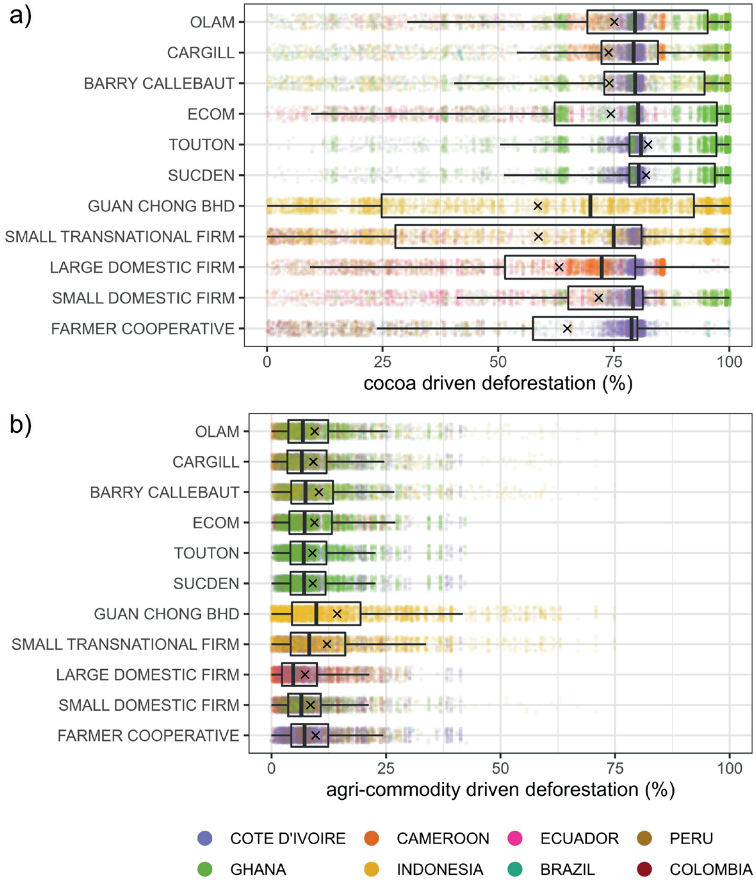


Figure 4. (a) Agri-commodity deforestation attributed to cocoa (%), and b) overall deforestation driven by agri-commodities in cocoa producing landscapes (%) in the value chain of global cocoa traders. "X" indicates the mean.

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

Regarding climate change, small domestic firms and farmer cooperatives will be the most affected with moderate to highly increased future climate risk (Figure 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 risk (~9% of supplies exposed to moderated 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.

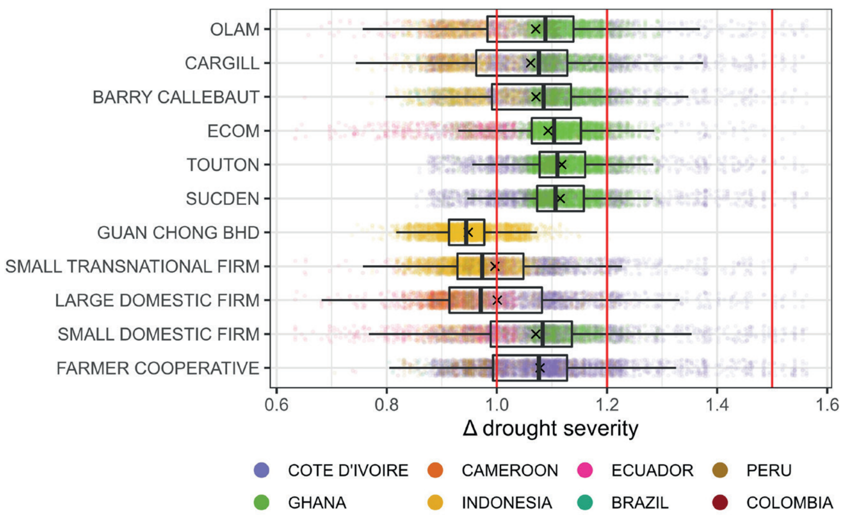


Figure 5. Change in drought severity risk in cocoa producing landscapes in the value chain of global cocoa traders. "X" indicates the mean. The red vertical lines indicate the thresholds for reduced (<1), modest (>1 and <1.2), moderate (>1.2 and <1.5), and high (>1.5) drought severity.

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 of 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 (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 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 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 have limited involvement of value chain actors (Carodenuto, 2019; von Essen et al., 2021)

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 excluding responsibility 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 will require early policy interventions to organize the use of the 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 a few exporting countries that will experience increased risks. Traders relying strongly on Cote d'Ivoire and Ghana supplies, such as Touton, Sucden, Barry Callebaut, Cargill, and Olam, will be severely affected if they do not help implement adaptation measures among cocoa farmers. Besides being a priority for these traders, climate adaptation in these countries should be of global concern due to the current dependence on global supplies of 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 that are more prominent 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 scrap the benefits of future reduced climate risks in certain locations, which could reinforce current patterns of high market concentration and power accumulation by large companies (Parra-Paitan et al., 2023). Besides 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 in 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). 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 (Figure 5 from Appendix D). 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 2001-2018; however, deforestation is not, static, therefore making new cocoa frontiers possible. This means that companies must be continually vigilant to land use changes in their sourcing landscapes. 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).

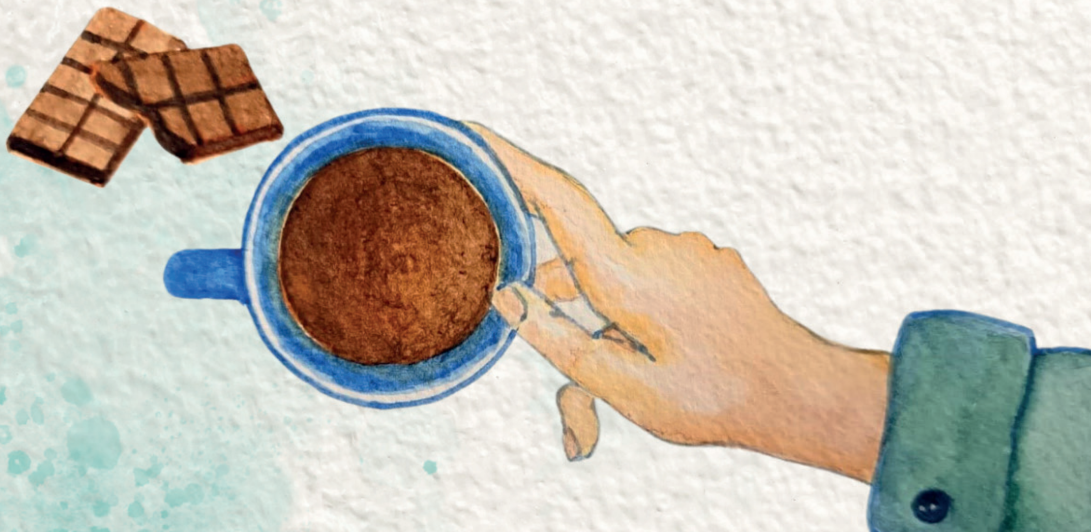
Regarding climate risk data, the drought severity index should be combined with other climatic factors affecting cocoa physiology, such as heat stress, flooding, and the effect of increased carbon dioxide levels (Lahive et al., 2018; Schroth et al., 2016). This is important to have a complete understanding 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.

6. Synthesis



The overall objective of this thesis was to better understand the role of agricultural value chains in triggering telecoupled sustainability impacts. It also aimed to understand how these impacts can be strategically mitigated to achieve net sustainability gains that benefit nature and people. The cocoa value chain was used to explore our initial research questions. In this chapter, the research questions presented in Chapter 1 will be revisited to explore the extent to which they have been answered and to identify future research avenues that will help to advance this field of research. Finally, the broader social implications of this thesis will be discussed at the end of this chapter.

1. How can we evaluate the telecoupled sustainability impacts of agricultural GVCs, such as those involving cocoa?

Given that agricultural value chains are embedded in socioecological systems, they have a reciprocal relation with the environment; they impact the environment and are impacted by environmental dynamics. Multidirectional dynamics can arise as a direct or indirect consequence of GVC's operations, (e.g., feedbacks on poor production performance due to soil erosion, or reduced pollination due to excessive use of agrochemicals) and can be distantly linked to GVC's direct operations (e.g., climate change, and ozone depletion). At the same time, these environmental dynamics can be modulated by socioeconomic factors influencing GVCs, such as policies, regulations, and market dynamics (e.g., subsidies to increase agrochemical use efficiency, shifts in demand preferences, and carbon taxes). In that sense, to grasp the complete array of telecoupled impacts, it is important to consider all the feedback loops arising from the socioeconomic and environmental dynamics playing at multiple scales. Chapter 2 discussed how telecoupled impacts can be accounted for with the integration of multiple impact assessment methods, while Chapters 3 and 5 explored this question quantitatively through empirical case studies.

The diverse and complex nature of environmental dynamics linked to agricultural production and the several impact pathways that arise complicate the identification and quantification of impacts caused by agricultural GVCs on multiple systems, such as on human health, water bodies, biodiversity, and air quality. Chapters 2 and 3 showed that capturing these dynamics and quantifying impacts require: 1) the integration of assessment tools approaching the different aspects of these dynamics, 2) clear causality attribution, and 3) granular and consistent data.

Environmental impact pathways are not yet fully understood individually and in interaction with other factors. This complicates causality attribution and impact accounting exercises and suggests the need to improve available impact assessment factors (e.g., GHG emission factors). For instance, it is known that increasing CO_2 atmospheric concentration can accelerate photosynthesis, but it is not yet clear how this can interact with other factors limiting plant physiology, such as water, nutrient mineralization, and increasing temperatures, and the differential effect that these changes can have on species with different photosynthetic cycles in the long term (Hovenden and Newton, 2018; Wang et al., 2020). In addition, impact assessments could benefit from more granular analysis using spatially explicit impact factors (Chapter 3), which also require improved traceability and transparency in GVCs to be operationalized (Chapter 4). As shown in Chapter 3, besides the progress made in impact accounting methods, the most widely used impact factors simplify cause-effect dynamics and are provided at coarse units of analysis (e.g., countries, regions).

Complicating this picture, the dynamics playing at the local level (e.g., farm-level) interact with socioeconomic dynamics (e.g., market and policy dynamics) from nearby and distant systems, which can lead to the bifurcation of impacts in ways difficult to predict. For instance, environmental economists have shown that increased farming efficiency - through agronomic yield improvements - can lead to further nature conversion instead of reducing it (exemplifying the Jevons paradox) due to the incentives created by the improved efficiency achieved. This points out the need for contextualizing small-scale scientific findings (e.g., plant science research) with market and policy dynamics proper of socioecological telecoupled systems (Hamant, 2020), as it was done in Chapter 3 and Chapter 5. In agricultural value chains, since the outcomes of socioecological dynamics are ultimately translated on the land, the land use approach helps to connect these cross-scale impacts. However, several limitations in the land research field need to be overcome to make this possible, such as better identifying land use trajectories, quantifying spatially-explicit impacts, and attribute responsibility (Baumann et al., 2022; Meyfroidt et al., 2022).

This thesis provided a detailed description of the pros and cons of available impact assessment methods, concluding that no method is sufficient in isolation to capture impacts of agriculture value chains across scales and that, instead, a combination of available methods is needed to bridge the gaps between them (as shown in Chapter 2 and 3). For instance, economic modeling techniques can help capture the impacts triggered by global-local market dynamics, agent-based modeling can help capture the factors influencing local decision making, and more granular impact characterization factors can help capture context-specific impacts. Using the land use approach, Chapter 2 stressed the need for capturing the telecoupled impacts triggered beyond the agricultural unit of production due to the interconnectedness of global land systems and the importance of doing so spatially explicitly. Using a combination of life cycle assessment, land use modeling, and spatial analysis, Chapter 3 accounted for the land use impacts triggered by telecoupled dynamics beyond the farm-level by considering economic dynamics linked to future demand scenarios. However, it did not go as far as to capture the telecoupled impacts that extend beyond the Ghanaian cocoa producing region. This would require the use of more advanced economic techniques such as computable equilibrium models or input-output analysis (Leijten et al., 2023). Chapter 5 helped to grasp the global heterogeneity of climate risk and deforestation exposure of cocoa producing regions so that sustainability decisions can consider the potential telecoupled effects of local actions. However, this thesis did not account for feedback loops triggered by climate change or other broader environmental factors, which would have required updating the future land suitability maps used in the iterative and dynamic land use model of Chapter 3.

2. How do the environmental impacts triggered by the cocoa GVC at different scales compare to each other?

Chapter 2 concluded that a mix of methods is needed to capture the telecoupled impacts driven by agricultural value chains across geographic and temporal scales. Using the land use approach, Chapter 3 confirmed this by concluding that when broader dynamics are considered, the impacts on biodiversity and carbon caused by cocoa-driven land conversion at the landscape level can be opposite to those caused by cocoa production within the farm. Because of environmental gains at the farm-level, agroforestry is largely promoted by state and private actors against full-sun cocoa monocrops. However, our study found that while the promotion of cocoa full-sun causes larger negative impacts on biodiversity and carbon stocks at the farm-level, by requiring less land to produce the same yield as agroforestry systems, at landscape scale cocoa full-sun could help to spare land and generate net biodiversity and carbon gains through higher yield outcomes, if environmental protection policies are in place (to avoid the Jevons paradox). Promoting agroforestry at the farm scale might seem more beneficial but it can trigger larger biodiversity losses as it requires more land to produce the same cocoa volume than cocoa full-sun systems. Chapter 3 suggests that, due to telecoupled dynamics, developing state or private policies that are based on the extrapolation of conclusions from farm-level assessments can risk causing large net negative impacts on carbon and biodiversity.

Chapter 3 focused on identifying the displacement of impacts at the landscape scale which, although larger than the farm scale, is still limited in geographic scope. The cocoa GVC expands across multiple countries from the African, Asian, South, and North American continents and the telecoupled feedback loops therefore operate at a global scale. Consequently, quantifying the indirect impacts caused by the telecoupled cocoa GVC requires dynamic assessments, like Chapter 3, to be applied at the global scale. This would require large sets of data with the necessary granularity and comparability, and it would require an improved understanding of large-scale telecoupled dynamics for causality attribution. Globally consistent land use maps differentiating cocoa farming systems and with sufficiently detailed land cover classes would be required (i.e., differentiating industrial vs. smallholder intercropping systems, instead of just setting an agricultural land over class), together with the integration of economic and policy dynamics and the use of spatially explicit impact factors covering these regions. Currently, several studies have attempted to map cocoa farms using high-resolution satellite images and improved remote sensing algorithms, however, these efforts are mostly focused on Cote d'Ivoire and Ghana and have difficulties in differentiating types of cocoa farming systems (e.g., full-sun, agroforestry) (Abu et al., 2021; Kalischek et al., 2022). Limitations also exist regarding mapping natural ecosystems and land cover classes across time to understand historical land use trajectories, which is needed for accurate causality attribution (Baumann et al., 2022; Pendrill et al., 2022; Vancutsem et al., 2021). Chapter 3 quantified impacts based on modeled land conversion, however, the deforestation dataset used in Chapter 5 assumed a much more generalized impact attribution approach by assuming that most current cocoa and other crop areas have directly replaced forest, which dismisses land use dynamics causing indirect deforestation and other potential land use trajectories. This discrepancy in methods was accepted on the ground of the limited data availability faced by Goldman et al. (2020), however, we encourage the refinement of causality attribution with more accurate information on land use trajectories. Finally, incorporating socioecological telecoupled dynamics at a global scale and modeling spatially explicit impacts is computationally and data intensive, however, it could be replicated following recent studies that used a combination of land use models and multi-commodity and multiregional computable general equilibrium models (Leijten et al., 2023).

Chapter 5 provided a spatially explicit assessment of another dimension of impacts triggering telecoupled dynamics, those of future climate risks and historical deforestation associated with the main producing countries and traders of the cocoa GVC. Although this analysis had a static approach and, as such, did not identify the telecoupled climate change and deforestation dynamics across cocoa production regions, it provided a spatially explicit overview of areas that might experience future land use changes due to future climate risk and deforestation pressures. It also provided a spatially explicit overview of the interconnected deforestation drivers present in cocoa producing areas, suggesting research avenues to better understand the drivers of land use change, such as other commodities (e.g., other agri and non-agri-commodities), availability of resources (e.g., fertile forest soils), and infrastructure (i.e., accessibility). The findings of Chapter 5 can be used to identify landscapes of concern where dynamic assessments, such as those provided by Chapter 3, should be prioritized. Complementarily, identifying the main cocoa value chain actors affected by telecoupled dynamics, such as climate risk and deforestation (Chapter 5), and identifying the sustainability commitments taken by them (Chapter 4) can inform the definition of policy dynamics in assessment models that try to capture telecoupled dynamics.

This thesis showed that to capture the telecoupled impacts of cocoa and agricultural GVCs, assessments need to account for context-specific factors and consider the dynamics playing at larger scales, such as market, land use, and climate dynamics. Chapter 3 showed that industrial rubber plantations and food crop systems are important sectors competing for land in cocoa producing landscapes of Ghana, however, Chapter 5 showed that coffee, oil palm, and pastureland for beef production are important competing sectors in other countries, suggesting that multi-commodity assessments are needed to capture telecoupled global land dynamics even when the focus is just on a single crop. The findings of Chapter 4 showed that the strong focus of dominant traders on zero deforestation commitments in Cote d'Ivoire and Ghana might modulate these land dynamics differently than in other regions where these commitments are lacking (e.g., South America). It could be argued that the consolidated cocoa sector in West Africa has helped other cocoa-suitable regions to spare land from cocoa farming, has minimized the pressure of cocoa on forests, and might have favored the establishment of other agricultural commodities. However, as shown in Chapter 5, climate change might alter this equilibrium, as the low-yielding regions in West Africa will be exposed to increased climate risks through increased future drought severity. This might transform the landscape depending on the adaptation measures implemented, the local land use dynamics (within and beyond the agricultural sector), and, as shown in Chapter 3, the environmental regulations enforced. Ivorian and Ghanaian cocoa farmers might be put out of business and land be replaced by other more suitable crops that are not yet targeted by stringent regulations (e.g., EU legislation on imported deforestation), while displacing the pressure to other producing regions. However, the outcome could be different if the strong dependency of the cocoa GVCs on Ivorian and Ghanaian cocoa triggers investments on climate-smart agriculture to support smallholder farmers, further consolidating the dominance of this region and allowing other crops to consolidate in other regions.

3. How can cocoa GVC actors mitigate environmental risks at different scales?

Understanding the agency of value chain actors is key to understanding how sustainability can be leveraged in a sector. The dominance of private actors in the local and global markets determines their agency to steer sustainability and business agendas both in sourcing and destination markets. Following this logic, Chapter 4 characterized the interplay of cocoa value chain actors at global and national scales, showing that the management decisions of transnational corporations can trigger inter-continental (telecoupled) impacts due to their strong market dominance across regions and their geographically extended sourcing network. On the contrary, smaller companies mostly act at a domestic scale or, at most, at a subregional scale (i.e., sourcing from 2-3 nearby countries), and have therefore less agency to influence global market dynamics and sustainability agendas. The market dominance of domestic and transnational companies differs in cocoa producing countries, with domestic companies present in all countries but dominating the local market only in some countries (e.g., Peru and Ecuador). Sustainability commitments to address deforestation, poverty, child labor, etc., are mostly issued by transnational corporations and are mostly exclusively targeted to the two largest producing countries, Cote d'Ivoire, and Ghana, leaving other countries unattended. The imbalanced coverage of sustainability commitments can incentivize the displacement of negative impacts (i.e., spillovers) from committed to non-committed regions and from committed to non-committed companies (often smaller domestic companies). Therefore, to achieve net global sustainability gains, value chain initiatives need to integrate the entire ecosystem of value chain actors regardless of their market size, which is particularly relevant given that 38% of exports are handled by small domestic trading companies and farmer cooperatives that rarely issue sustainability commitments. In addition, as shown in Chapter 5, there is the need to expand the single-commodity focus of most sustainability initiatives to a multi-commodity one as, for instance, cocoa traders are connected through the landscape with actors from other land competing sectors (agriculture or not) whose activities (e.g., land expansion) can lead to indirect impacts in the cocoa value chain. Dynamic modeling techniques as those discussed in Chapters 2 and 3 showed how these telecoupled dynamics could be quantified. Current voluntary sustainability mechanisms are ill-equipped in their current design to achieve effective and long-term sustainability upgrading in the cocoa GVC.

Although voluntary sustainability commitments are just one of the existing sustainability governance mechanisms, they are currently widely extended as, under the strong influence of large companies, value chain actions have shifted from state regulation to voluntary private mechanisms in the last few years. As shown in Chapter 4, the high market concentration exhibited by the cocoa GVC could play a positive role if dominant actors commit and implement sustainability commitments aligned to global standards and are open to external verification systems. However, market concentration translates to unequal competitiveness against smaller market actors because larger companies have more resources to invest in sustainability action and, as such, can benefit from product differentiation, which can deepen market concentration and lead to the domination of sustainability agendas by the lobbying of large companies (Clapp, 2021; Ponte, 2019). Government action is needed to create a level playing field and balance these dynamics. Such initiatives can be informed by the identification of sustainability risk hotspot areas described in Chapter 5 and the knowledge of land use dynamics described in Chapter 3. Legally binding regulations, supporting bottom-up participation schemes, and setting up jurisdictional approaches that include multi-stakeholder coalitions are some of the potential options to help voluntary initiatives achieve net sustainability gains. However, research has shown that any single sustainability governance intervention is unlikely to match the scale of the environmental and social problems generated by telecoupled systems, such as the cocoa GVC (Coenen et al., 2023; Newig, 2018). Therefore, a combination of governance approaches is needed to address these scale mismatches. Currently, the importance of cross-sectoral and cross-scale organized action is not yet fully understood let alone operationalized in the value chains.

4. Broader implications of this research

This thesis has helped to expand the understanding of the dynamics determining the telecoupled impacts of global agricultural value chains, has provided advice on the use of multiple methods to capture these impacts, and has provided concrete examples on how to capture telecoupled dynamics in sustainability impact assessments. Given the complexity and interdisciplinarity of the factors at play, research in this field is in constant need to integrate additional factors proper of socioecological systems into the sustainability equation. This thesis has contributed with concrete and quantitative examples to the debate about land extensification and intensification (land sharing and land sparing) using different farm management systems (agroforestry and full-sun in the case of cocoa), and the impacts of promoting these beyond the farm-level. It has provided concrete guidance on this polarized topic by looking beyond farm-level impacts and modeling other socioeconomic factors influencing real-life situations. In this regard, this thesis has also shown that it is important to look beyond the land-sharing and land-sparing dichotomy and integrate a deeper understanding of the market dynamics, the agency of actors in driving sustainability action, and the spatially explicit and context-specific nature of the sustainability problems affecting the cocoa sector. This thesis has also suggested topics for a future research agenda to improve the accountability of telecoupled impacts caused by agricultural GVCs, such as the improvement of spatially explicit datasets (e.g., land use maps, impact factors), improved causality attribution, identification of land use trajectories, the integration of different impact modeling approaches, modeling of cross-scale indirect impacts and feedback loops and increasing value chain transparency and traceability.

Drawing on the cocoa case, this thesis has provided a benchmark on how to analyze the value chain configuration of agricultural GVCs to understand the role of market dominance and power-relations on sustainability outcomes. This thesis can help guide decision makers to design tailored strategies, prioritize action, and tackle the most vulnerable hotspots while being aware of global teleconnections to avoide shifting burdens across scales, sectors, and actors (spillovers). It can also be used by committed private actors to direct resources to the most needed areas, implement tailored sustainability strategies, and guide the engagement with other actors competing for land resources and influencing sustainability outcomes in their operating landscapes. This comes particularly at hand with the current legislative initiatives in the sector that will grant licenses to operate in exclusive cocoa markets only to companies able to demonstrate sustainability compliance (EU legislation on deforestation and coming due diligence legislation). In that sense, this thesis has shown how this initiative that helped level the playing field still has a way to go to include small and medium enterprises into the fold to avoid negative unintended consequences that jeopardize the achievement of sustainability ambitions in the entire sector. The telecoupled nature of GVCs impacts requires the integration of multiple governance approaches that bridge the mismatches between current governance approaches and the scale of the social and environmental problems caused by telecoupled systems.

Overall, this thesis has shown that the assessment of the telecoupled impacts caused by agricultural value chains can be largely improved with the integration of diverse assessment methods and information on value chain configurations. Besides the knowledge gaps that are still to be addressed, this thesis has shown that the nuanced insights generated by this combination of methods and data can already be actionable to better inform and guide the sustainability governance initiatives coming from multiple stakeholders in the agriculture sector.

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Appendix A

Table 1. Additional information of input-output databases mentioned in the main text.

Abbreviation	Full name	General description	Main references
EoRA	EoRA (no abbreviation)	Global database of high-resolution multi-region input-output tables coupling economic data with environmental and social data. Considers 190 countries and 15909 industrial sectors. Time series for 1990-2015.	(Lenzen et al., 2013) (Inomata and Owen, 2014; Moran and Wood, 2014)*
GTAP	Global Trade Analysis Project (GTAP)	Global input-output database to represent consumption, production and international trade for 140 countries and 57 industrial sectors for the years 2004, 2007, 2011 and 2014. Earlier years available but with variable amount of data and detail. It couples environmental data.	(Aguiar et al., 2016) (Inomata and Owen, 2014)*
EXIOBASE	EXIOBASE (no abbreviation)	Global environmentally extended multiregional input-output database for 43 countries and 163 industrial sectors for the years 2000 and 2007.	(Wood et al., 2015) (Inomata and Owen, 2014; Moran and Wood, 2014)*
WIOD	World Input-Output Database	Global database of inter-country input-output tables covering 56 industrial sectors from 43 countries. Yearly data for 1995-2014. It incorporates socio-economic and environmental accounts	(Dietzenbacher et al., 2013) (Inomata and Owen, 2014; Moran and Wood, 2014)*

Table 2. Additional information of land use models mentioned in the main text.

Abbreviation	Full name	General description	Main references
CLUMondo	Conversion of Land Use on Mondial Scale	Spatially explicit land system change model to simulate future changes to land use, land cover, and land management. Based on land systems approach. Makes emphasis on land use intensity and livestock systems.	(Van Asselen and Verburg, 2013a) (Alexander et al., 2017; Nelson et al., 2014; Schmitz et al., 2014)*
GLOBIOM	Global Biosphere Management Model	Global dynamic partial equilibrium model that simulates the competition between the largest land-based production sectors (agriculture, bioenergy, and forestry) for land in a spatial explicit manner.	(Havlik et al., 2014) (Alexander et al., 2017; Nelson et al., 2014; Schmitz et al., 2014)*
IMAGE	Integrated Model to Assess the Global Environment	Spatially explicit global dynamic integrated assessment model to simulate changes generated by the interaction of social, economic and environmental factors.	(Stehfest, E., van Vuuren, D., Kram, T., Bouwman, L., Alkemade, R., Bakkenes, M., Biemans, H., Bouwman, A., den Elzen, M., Janse, J., Lucas, P., van Minnen, J., Müller, C., Prins, 2014) (Alexander et al., 2017; Nelson et al., 2014; Schmitz et al., 2014)*
MagPIE	Model of Agricultural Production and its Impact on the Environment	Global spatially explicit land use optimization model that combines economic and biophysical data to simulate land use change scenarios.	(Popp et al., 2014) (Alexander et al., 2017; Nelson et al., 2014; Schmitz et al., 2014)*

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Appendix B

A. Inventory of inputs for life cycle assessment

Table 1. Total inventory of inputs to produce 1 kg of cocoa beans with cocoa agroforestry and full-sun systems.

Inputs	Unit	Cocoa full-sun	Cocoa agroforestry
Water	kg	4.7059	4.7059
Land occupation	m2/year	0.6346	0.7979
Land transformation	m2	19.0388	23.9382
Petrol (for sprayers)	l	0.0198	0.0249
Fertilizers			
N	kg		
P (P2O5) 22%	kg	0.0690	0.0345
K (K2O) 18%	kg	0.0565	0.0282
S (S) 7%	kg	0.0220	0.0110
MgO (MgO) 6%	kg	0.0188	0.0094
CaO (CaO) 9%	kg	0.0282	0.0141
Insecticides			
Confidor 200 SL (Imidacloprid)	kg	0.0011	0.0014
Akate master (Bifenthrim)	kg	0.0011	0.0014
Carbamult (Promecarb)	kg	0.0107	0.0134
Fungicides			
Champion (77% cupric hydroxide)	kg	0.0034	0.0043
Ridomil 72 (12%metalaxyl, 60% Cu2O)	kg	0.0017	0.0022
Kocide 101	kg	0.0034	0.0043
Nordox 75 (85% Cu2O, 14%inert)	kg	0.0034	0.0043

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B. Inventory of outputs for life cycle assessment

The calculation of emissions caused by pesticides was done based on the PestLCI 2.0 model. Some choices had to be made to apply this model to our case. The pesticides Bifenthrim and Promecarb were replaced by Esfenvalerate and Methiocarb because the model did not include data for those pesticides. The replacing pesticides were chosen based on their similarity in terms of chemical family group and other physicochemical properties such as molecular weight, vapor pressure and solubility. We chose physical and climatic conditions based on similarity as well: olives in fruit development, soil type 1 and Mediterranean climate in August.

Table 2. Total inventory of outputs and emissions created to produce 1 kg of cocoa beans with cocoa agroforestry (AF) and full-sun (FS) systems.

Outputs-emissions	Unit	Cocoa full-sun	Cocoa agroforestry
To air			
Imidacloprid to air	kg	1.57544E-05	1.98086E-05
Bifenthrim to air	kg	1.76319E-06	2.21693E-06
Promecarb to air	kg	0.002501054	0.003144671
HC (hydrocarbon)	kg	1.33271E-05	1.67567E-05
NOx	kg	0.000150597	0.000189351
CO (carbon monoxide)	kg	1.8658E-05	2.34594E-05
Carbon dioxide CO2	kg	0.044110216	0.055461476
Sulphur dioxide SO2	kg	1.05865E-06	1.33108E-06
Lead Pb	kg	2.1467E-06	2.69913E-06
Methane CH4	kg	4.29339E-05	5.39825E-05
Benzene C6H6	kg	0.000139388	0.000175258
Cadmium Cd	kg	1.47034E-10	1.84872E-10
Chromium Cr (IV)	kg	7.3517E-10	9.24358E-10
Copper Cu	kg	2.49958E-08	3.14282E-08
Dinitrogen monoxide/ oxide N2O	kg	1.91144E-06	2.40333E-06
Nickel Ni	kg	1.02924E-09	1.2941E-09
Zinc Zn	kg	1.47034E-08	1.84872E-08
Benzo(a)pyrene C20H12	kg	5.88136E-10	7.39486E-10
Ammonia NH3	kg	5.88136E-07	7.39486E-07
Selenium Se	kg	1.47034E-10	1.84872E-10
Benz(a)-Anthracene	kg	1.10276E-09	1.38654E-09
Benzo(b)-Fluor -anthracene	kg	5.88136E-10	7.39486E-10
Chrysene	kg	1.47034E-10	1.84872E-10
Dibenzo(a, h)-Anthracene	kg	2.20551E-09	2.77307E-09
Fluoranthene	kg	6.61653E-09	8.31922E-09
Phenanthene	kg	1.76441E-08	2.21846E-08

Outputs-emissions	Unit	Cocoa full-sun	Cocoa agroforestry
To surface water			
Imidacloprid to surface water	kg	2.03638E-07	2.56042E-07
Bifenthrim to surface water	kg	1.83085E-10	2.30199E-10
Promecarb to surface water	kg	3.26158E-13	4.10091E-13
PO4 to freshwater	kg	0.000295925	0.000385084
Cd to surface water (ions)	kg	6.40906E-08	5.39057E-08
Cu to surface water	kg	4.13042E-06	3.24201E-06
Zn to surface water	kg	1.62706E-05	9.63885E-06
Pb to surface water	kg	1.39275E-07	7.51572E-08
Cr to surface water (IV)	kg	3.41528E-05	3.48264E-05
Hg to surface water	kg	4.90521E-10	2.78507E-10
To groundwater			
Imidacloprid to ground water	kg	2.16872E-06	2.72681E-06
Bifenthrim to ground water	kg	6.66101E-08	8.37514E-08
Promecarb to ground water	kg	3.05498E-12	3.84115E-12
PO4 to ground water	kg	0.00011837	0.000154034
Cd to groundwater (ions)	kg	6.40906E-08	5.39057E-08
Cu to groundwater	kg	4.13042E-06	3.24201E-06
Zn to groundwater	kg	1.62706E-05	9.63885E-06
Pb to groundwater	kg	1.39275E-07	7.51572E-08
Cr to groundwater (IV)	kg	3.41528E-05	3.48264E-05
Hg to groundwater	kg	4.90521E-10	2.78507E-10

C. Life cycle impact assessment

Table 3. Impact categories and details of characterization factors used in life cycle assessment impact assessment.

Method	Author	Scope	Name	Unit	Spatial resolution
IMPACT World + (midpoint)	(Bulle et al., 2019)	midpoint	Acidification potential (freshwater and terrestrial)	kg SO_2eq	2x2.5-degree pixel average
			Freshwater eutrophication	kg PO_4 P-lim eq	0.5x0.5-degree pixel average
			Freshwater ecotoxicity	CTU (comparative toxic units)	North Africa
			Global warming potential	kg CO_2eq	Global average
			Human toxicity, cancer and non-cancer	CTU (comparative toxic units)	North Africa
			Land occupation, biodiversity	m^2 arable land eq per yr	Biome and land use type
			Land transformation, biodiversity	m^2 arable land eq	Biome and land use type
		damage	Disability-adjusted life years	DALY	Diverse. As in each +midpoint category
Biodiversity loss	(Chaudhary et al., 2015)	damage	Potential species loss (PSL)	PDF. m^2.yr	Ecoregion and land uses

D. Land use modeling settings

D.1. Provision of goods and services per land use type: The provision of services per pixel of each land use is calculated based on statistical data. These services include built-up area (ha), tree cover (ha), rubber (kg), food crops (including cassava, plantain and maize in kg) and cocoa beans (kg). This is calculated based on the area occupied by each land use and subnational statistics reported by FAO for the year 2015.

Table 4. Land use matrix detailing the provision of services and goods per pixel from each land use.

	Built-up (ha)	Tree cover (ha)	Rubber (kg)	Food crops (kg)	Cocoa beans (kg)
Built-up	3.2	0.2	0.0	6750.1	0.0
Mining	0.0	0.0	0.0	0.0	0.0
Vegetation regularly flooded	0.0	0.4	0.0	9584.5	0.0
Rubber	0.0	0.6	515.1	1056.9	0.0
Closed Forest	0.0	4.1	0.0	728.0	0.0
Cocoa agroforestry	0.0	2.3	0.0	907.4	1308.2
Mixed forest with agriculture	0.0	2.3	8.3	14508.3	0.0
Open forest	0.0	1.6	2.2	1248.7	37.9
Agriculture. sparse tree cover	0.0	0.2	16.0	32550.8	0.0
Cocoa full-sun	0.0	0.5	0.0	195.0	1787.0

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D.2. Productivity increases in the provision of good and services: The supply of services by each pixel changes in each scenario along the years. The ratio of this change is obtained based on linear projections of FAO data for 10 years (2005-2015) (for rubber), scenario projections made for the Shared Socioeconomic Pathways (SSP Database) developed by (IIASA, 2020; Riahi et al., 2017) (for built up areas) and IFPRI (for food crops and cocoa beans) (IFPRI, 2017; Sulser et al., 2015).

Table 5. Total productivity increases (%) in the provision of goods and services for each scenario. AF= cocoa agroforestry; FS= cocoa full-sun.

Scenario	Built-up	Tree cover	Rubber	Food crops	Cocoa beans
Green Development	3%	0%	0%	19%	139%
Intensive Agriculture Development	0	0%	26%	19%	90%
Regulated Investments	3%	0%	26%	19%	139% (AF) 90% (FS)

D.3. Future demand of goods and services per scenario: Future demands were fixed according to the country level quantification of Shared Socioeconomic Pathways (SSP Database) developed by (IIASA, 2020; Riahi et al., 2017) for built up areas and developed by IFPRI for food crops and cocoa (IFPRI, 2017; Sulser et al., 2015). To define the future demand of tree crop we used the targets set by official national policy documents related to restoration and forest plantation targets (Dave et al., 2019b; Forestry Commission, 2016; IUCN, n.d.; Republic of Ghana, 2017).

Table 6. Demand changes in each scenario.

Scenario	Built-up	Tree cover	Rubber	Food crops	Cocoa beans
Green Development	20%	31%	-20%	35%	27%
Intensive Agriculture Development	29%	-20%	72%	23%	40%
Regulated Investments	20%	18%	72%	23%	33%

D.4. Driving factors and regression functions of each land use

The driving factors were selected based on literature and their importance to determine the distribution of each land use was calculated with logistic regressions. The explanatory variables are detailed for each land use together with the area under the curve (AUC) indicating their accuracy in predicting the occurrence of each land use.

Table 7. Explanatory variables contributing to predicting the occurrence of each land use, and the area under the curve (AUC) for each combination of explanatory variables. Direction of interaction is indicated with + and – for positive and negative interactions, respectively.

Explanatory variable	Description	Built up	Rubber	Closed forest	Cocoa agroforestry	Mixed forest with agriculture	Open forest	Agriculture with sparse tree cover	Cocoa full sun
Clay content	Clay mass in % in depth of 30cm			+		-	+		-
SoilPH	Measured in KCl (30cm)		-	-	-	+	+	+	-
Cation Exchange Capacity (CEC)	cmol/kg in depth of 30cm			-	+		+	-	
Haplic (undetermined) Acrisols	Predicted most probable class	-	+		+	-	+	-	+
Coarse fragments	Volumic in % top 30cm	-	-	+		-			
Depth of topsoil		+		+	-			-	
Soil organic carbon content (fine earth fraction)	g/kg in the top 60 cm		+	+	-	+	-		-
Available water capacity	(volume %) of the fine earth	-	+	-	+	-	+	-	+
Elevation	m above sea level		-		-				
Precipitation*	annual precipitation (sum of monthly means) in mm	+	+	-	-	+	+	-	-
Accessibility to high-density urban centers	measured though travel time, based on roads, water and terrain		-		-	-	-	-	-

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Explanatory variable	Description	Built up	Rubber	Closed forest	Cocoa agroforestry	Mixed forest with agriculture	Open forest	Agriculture with sparse tree cover	Cocoa full sun
Accessibility to major cities	measured though travel time, based on roads, water and terrain	-					+	+	
Accessibility to district centers	measured though travel time, based on roads, water and terrain					+			
Population density	People/km^2	+	-	-	-	-	-	-	-
Distance to roads	Euclidean distance	-	-	+		-		-	+
Distance to major rivers	Euclidean distance		-		-	+		+	
Accessibility to ports	Measured though travel time	-	-						
Temperature	temp. mean of monthly means in Celsius degree			-	-	+	-		+
AUC		0.87	0.93	0.84	0.74	0.65	0.66	0.72	0.71

D.5. Land use conversion resistance in each scenario

Table 8. Conversion resistance values for each land use in each scenario. 1 indicates full resistance and 0 indicates low resistance to change.

	Green Development	Intensive Agriculture Development	Regulated Investments
Built-up	1	1	1
Mining	0.8	0.8	0.8
Vegetation regularly flooded	1	1	1
Rubber	0.3	0.5	0.5
Closed Forest	1	0.2	0.8
Cocoa agroforestry	0.8	0.3	0.6
Mixed forest with agriculture	0.8	0.3	0.4
Open forest	0.3	0.3	0.3
Agriculture, sparse tree cover	0.7	0.4	0.4
Cocoa full-sun	0.4	0.7	0.5

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D.6. Allowed land use conversions per scenario

Table 9. Table of allowed land use conversions in each scenario. 1 means conversion, 0 means no conversion.

	Built-up	Mining	Vegetation regularly flooded	Rubber	Closed Forest	Cocoa agroforestry	Mixed forest with agriculture	Open forest	Agriculture, sparse tree cover	Cocoa full-sun
Green Development										
Built-up	1	0	0	0	0	0	0	0	0	0
Mining	0	1	1	1	0	1	1	1	1	1
Vegetation regularly flooded	1	1	1	1	1	1	1	1	1	1
Rubber	1	0	0	1	1	1	1	1	0	0
Closed Forest	1	0	0	0	1	0	0	0	0	0
Cocoa agroforestry	1	0	0	0	1	1	0	0	0	0
Mixed forest with agriculture	1	0	0	1	1	1	1	1	0	0
Open forest	1	0	0	1	1	1	1	1	1	0
Agriculture, sparse tree cover	1	0	0	1	1	1	1	1	1	0
Cocoa full-sun	1	0	0	1	1	1	1	1	1	1
Intensive Agriculture Development										
Built-up	1	0	0	0	0	0	0	0	0	0
Mining	0	1	1	1	0	0	1	1	1	1
Vegetation regularly flooded	1	1	1	1	1	1	1	1	1	1
Rubber	1	0	0	1	0	1	1	1	1	1
Closed Forest	1	0	0	1	1	1	1	1	1	1
Cocoa agroforestry	1	0	0	1	0	1	1	1	1	1
Mixed forest with agriculture	1	0	0	1	0	1	1	1	1	1
Open forest	1	0	0	1	0	1	1	1	1	1
Agriculture, sparse tree cover	1	0	0	1	0	1	1	1	1	1
Cocoa full-sun	1	0	0	1	0	1	1	1	1	1
Regulated Investments										

	Built-up	Mining	Vegetation regularly flooded	Rubber	Closed Forest	Cocoa agroforestry	Mixed forest with agriculture	Open forest	Agriculture, sparse tree cover	Cocoa full-sun
Built-up	1	0	0	0	0	0	0	0	0	0
Mining	0	1	1	0	0	1	1	1	1	1
Vegetation regularly flooded	1	1	1	1	1	1	1	1	1	1
Rubber	1	0	0	1	1	1	1	1	1	1
Closed Forest	1	0	0	0	1	0	0	0	0	0
Cocoa agroforestry	1	0	0	1	1	1	1	1	1	1
Mixed forest with agriculture	1	0	0	1	1	1	1	1	1	1
Open forest	1	0	0	1	1	1	1	1	1	1
Agriculture, sparse tree cover	1	0	0	1	1	1	1	1	1	1
Cocoa full-sun	1	0	0	1	1	1	1	1	1	1

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E. Spatial analysis – carbon storage

E.1. Emission factors for carbon accounting

Table 10. Emission factors per vegetation zone due to the transformation of closed forest and open forest to new land uses (tCO_2eq).

Forest carbon stratus	**Forest type**	**Built-up**	**Mining**	**Vegetation regularly flooded**	**Rubber**	**Closed forest**	**Cocoa agroforestry**	**Mixed forest with agriculture**	**Open forest**	**Agriculture sparse tree cover**	**Cocoa full-sun**
Wet evergreen	Closed forest	589.50	698.60	0.00	191.30	0.00	318.90	464.76	381.70	584.10	409.53
Moist Evergreen	Closed forest	704.60	808.30	0.00	309.80	0.00	437.40	554.83	464.20	650.90	527.96
Moist Semidecidious SE	Closed forest	608.60	656.90	0.00	248.40	0.00	376.00	429.41	390.50	473.10	457.19
Moist Semidecidious NW	Closed forest	255.90	341.60	0.00	-105.23	0.00	22.70	133.14	112.93	223.50	112.89
Upland Evergreen	Closed forest	431.90	521.20	0.00	46.20	0.00	173.70	291.07	220.37	387.10	264.33
Dry Semideciduous inner zone	Closed forest	234.80	360.90	0.00	-172.88	0.00	-44.55	132.69	50.05	277.70	45.24
Dry Semideciduous fire zone	Closed forest	113.60	182.40	0.00	-270.64	0.00	-142.30	0.81	-25.34	117.90	-52.51
Savannah	Closed forest	137.70	221.10	68.90	-261.10	0.00	-132.77	28.75	-6.97	160.90	-42.98
Southern Marginal	Closed forest	157.40	224.30	0.00	-214.54	0.00	-86.20	55.37	52.62	171.20	3.59
Forest carbon stratus	Forest type	Built-up	Mining	Vegetation regularly flooded	Rubber	Closed forest	Cocoa agroforestry	Mixed forest with agriculture	Open forest	Agriculture sparse tree cover	Cocoa full-sun
Wet evergreen	Open Forest	208.10	317.20	0.00	-190.30	-381.70	-61.97	83.55	0.00	202.60	27.83
Moist Evergreen	Open Forest	210.50	265.60	0.00	-154.37	-464.20	-26.03	53.85	0.00	119.20	63.76

Forest carbon stratus	Forest type	Built-up	Mining	Vegetation regularly flooded	Rubber	Closed forest	Cocoa agroforestry	Mixed forest with agriculture	Open forest	Agriculture sparse tree cover	Cocoa full-sun
Moist Semidecidious SE	Open Forest	198.00	236.70	0.00	-151.43	-390.50	-23.10	19.86	0.00	55.00	66.69
Moist Semidecidious NW	Open Forest	138.00	216.00	0.00	-218.17	-112.93	-89.83	14.36	0.00	99.60	-0.04
Upland Evergreen	Open Forest	190.50	245.90	0.00	-174.17	-220.37	173.70	143.84	0.00	119.40	43.96
Dry Semideciduous inner zone	Open Forest	160.00	246.40	0.00	-222.93	-50.05	-94.60	52.14	0.00	172.20	-4.81
Dry Semideciduous fire zone	Open Forest	127.80	229.90	0.00	-245.30	25.34	-116.97	20.02	0.00	132.10	-27.17
Savannah	Open Forest	131.80	221.10	0.00	-254.14	6.97	-125.80	29.68	0.00	156.90	-36.01
Southern Marginal	Open Forest	106.40	175.90	0.00	-267.15	-52.62	-138.82	4.80	0.00	122.30	-49.03

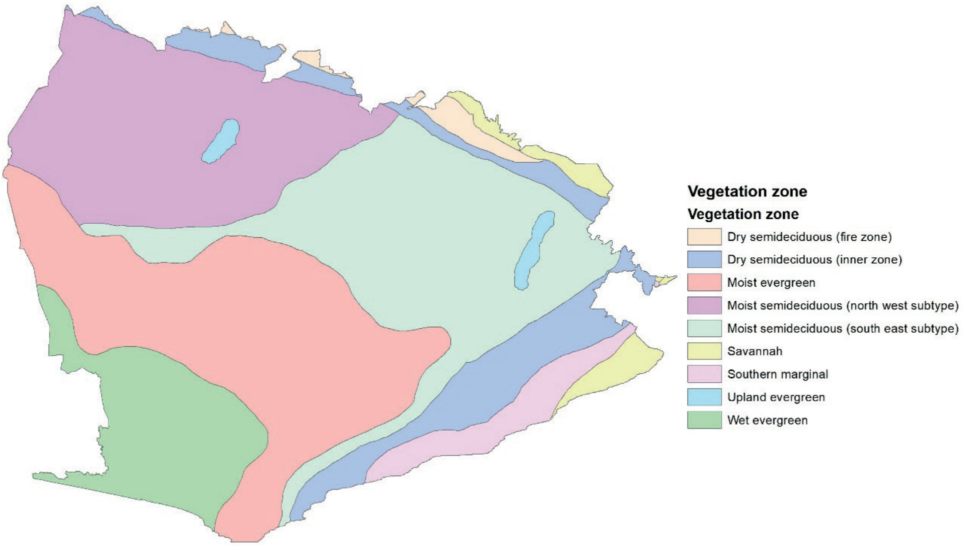

Figure E1. Vegetation zones in study area.

F. Spatial assessment - biodiversity

F.1. GLOBIO settings

Table 11. Land cover equivalences for the GLOBIO model.

Original land use	GLOBIO land use equivalent	GLOBIO Land use code
Built-up	Built-up	10
Mining	Built-up	10
Vegetation regularly flooded	Built-up	10
Rubber	Plantation forest	4
Closed forest	Primary vegetation	1
Cocoa agroforestry	Agroforestry	7
Mixed forest with agriculture	Low input agriculture	8
Open forest	Secondary vegetation	3
Agriculture sparse tree cover	Low input agriculture	8
Cocoa full-sun	Low input agriculture	8

Table 12. MSA values for land use (msa_lu), distance to infrastructure (msa_i) and fragmentation (msa_f). FFQI means a Fragmented Forest Quality Index.

MSA_type	Measurement	Value	MSA_x	SE
msa_i_tropical forest	Distance(m)	<1000	0.4	0.22
msa_i_tropical forest	Distance(m)	1000-4000	0.8	0.13
msa_i_tropical forest	Distance(m)	4000-14000	0.9	0.06
msa_i_tropical forest	Distance(m)	>14000	1	0.02
msa_i_grassland and cropland	Distance(m)	<500	0.4	0.22
msa_i_grassland and cropland	Distance(m)	500-2000	0.8	0.13
msa_i_grassland and cropland	Distance(m)	2000-7000	0.9	0.06
msa_i_grassland and cropland	Distance(m)	>7000	1	0.02
msa_f	FFQI	<0.43	0.3	0.15
msa_f	FFQI	0.43-0.58	0.6	0.19
msa_f	FFQI	0.58-0.90	0.7	0.19
msa_f	FFQI	0.90-0.98	0.9	0.2
msa_f	FFQI	0.98-0.99	0.95	0.2
msa_f	FFQI	0.99-1	1	0.2
msa_lu	LandCoverClass	0	0	
msa_lu	LandCoverClass	1	1	<0.01
msa_lu	LandCoverClass	2	0.7	0.07
msa_lu	LandCoverClass	3	0.5	0.03
msa_lu	LandCoverClass	4	0.2	0.04
msa_lu	LandCoverClass	5	0.7	0.05

MSA_type	Measurement	Value	MSA_x	SE
msa_lu	LandCoverClass	6	0.1	0.07
msa_lu	LandCoverClass	7	0.5	0.06
msa_lu	LandCoverClass	8	0.3	0.12
msa_lu	LandCoverClass	9	0.1	0.08
msa_lu	LandCoverClass	10	0.05	na

G. Life cycle assessment results

Table 13. Complete results for LCA per kg and ha for cocoa beans produced via agroforestry (AF) and full-sun (FS) systems.

Method	Impact category	Explanation	Unit	CF spatial detail	Per kg		Per ha	
					FS	AF	FS	AF
	AcidFW	Freshwater acidification	kg SO_2eq	2x2.5degree pixel average	5.67E-12	7.12E-12	2.98E-09	2.98E-09
	AcidTerr	Terrestrial acidification	kg SO_2eq	2x2.5degree pixel average	3.18E-08	3.99E-08	1.67E-05	1.67E-05
	EcotoxFW	Freshwater ecotoxicity	CTUe (comparative toxic units)	North Africa	30.68234	34.4623	16115.71	14396.37
	EutroFW	Freshwater eutrophication	kg PO4 P-lim eq	0.5x0.5-degree pixel average	4.71E-05	5.92E-05	0.024725	0.024723
	HumaToxCancer	Human toxicity cancer	CTUh	North Africa	5.09E-08	5.81E-08	2.67E-05	2.43E-05
IMPACT World +	HumaToxNonCancer	Human toxicity non cancer	CTUh	North Africa	4.26E-06	3.28E-06	0.002238	0.001369
	GWP 100	Global warming potential	kg CO_2-equiv/DALY	Global average	0.046255	0.058158	24.29501	24.29501
	LandOcc, biodiversity	Land occupation, biodiversity	m^2 arable land eq. yr/m^2 yr	Biome/LU	0.405013	0.509239	212.7308	212.7308
	LandTrans, biodiversity	Land transformation, biodiversity	m^2 arable land eq /m^2 yr	Biome/LU	4.984977	6.267804	2618.328	2618.328
	DALY	Disability-adjusted life years-DALY. Damage to human health	DALY/kg	Same as before	1.21E-05	9.53E-06	0.006356	0.003982
Chaudhary	PDF	Potential Disappeared Fraction-PDF (marginal)	PDF	Ecoregion/LU	1.7E-10	5.93E-11	9.03E-08	2.51E-08
PAS 2050-1	Carbon emissions from land use change	Carbon emissions due to land use change	kg CO_2-equiv/DALY	Ghana	13.70792	17.2355	7200	7200

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H. Spatial analysis results

Table 14. Impacts due to cocoa farming in the entire landscape in each scenario.

	Spatial analysis			LCA
	GHG emissions (tCO2eq)	**MSA loss**	**PDF**	**GHG emissions (tCO2eq)**
Regulated Investments	-13740683	-0.039598	0.00197	365493
Intensive Agriculture Development	5.2E+07	0.0803	0.041472	4.9E+07
Green Development	-61505447	-0.030012	0.213869	6.2E+07

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Appendix C

A. Supplementary data

Table 1. HS codes and conversion coefficients for cocoa beans and cocoa processed products.

PRODUCT	CONVERSION COEFFICIENT	HS6 CODE
Cocoa beans	1	180100
Cocoa butter	1.72	180400
Cocoa paste	1.14	180310, 180320
Cocoa powder	0.63	180500
Cocoa waste	1	180200

Table 2. Trader names and corresponding subsidiary and/or alternative names used as equivalents in the analysis.

SUBSIDIARY AND/OR ALTERNATIVE NAMES	TRADER	SUBSIDIARY AND/OR ALTERNATIVE NAMES	TRADER
GOKALDAS	AARISH GOKALDAS	GCB SPECIALTY CHOCOLATE SDN BHD	GUAN CHONG BHD
ABCO SA DE CV	ABCOTEX SA DE CV	GUAN CHONG COCOA MANUFACTURER SDN BHD	GUAN CHONG BHD
AYD SANCHEZ ADSANCOCOA S A	AD SANCHEZ ADSANCOCOA	GUANG CHONG COCOA MANUFACTURER SDN BHD	GUAN CHONG BHD
ADELCOCOA S A	ADELCOCOA	PT ASIA COCOA INDONESIA	GUAN CHONG BHD
ADRIANA CIOCAN	ADRIAN CIOCAN	GUAN CHONG COCOA MANUFACTURER	GUAN CHONG BHD
ADU MARX ENTERPRISES LIMITED	ADU MARX ENTERPRISES	GUAN CHONG COCOA MANUFACTURER SDNBHD	GUAN CHONG BHD
AFROTROPIC COCOA PROCESSING COMPANY	AFROTROPIC COCOA PROCESSING CO	GUAN CHONG COCOA MANUFACTURER SDN	GUAN CHONG BHD
AGP ALSERVICE BUSINESS S A C	AGP ALSERVICE BUSINESS	GUANG ZHOU SUKE FOOD CO	GUANG ZHOU SUKE FOOD
AGRICOLA CONDURU LTDA	AGRâˆšâ‰ COLA CONDURU	INMOBILIARIA GUANGALA S A	GUANGALA
AGRICOLA BEAN AND CO LA MEJOR BEANMEJOR S	AGRICOLA BEAN AND CO LA MEJOR BEANMEJOR	AGRICOLA GUANGALA SA	GUANGALA
AGRICOLA RIVAS PLATA S A C	AGRICOLA RIVAS PLATA	AGRIGUANGALA	GUANGALA
AGRITRADE S A C	AGRITRADE	GUANGZHOU CITY JI CHEN TRADE CO LT	GUANGZHOU CHI CHEN TRADE CO
AGRO AMERICANO S A C	AGRO AMERICANO	GUANGZHOU CITY JI CHEN TRADE CO	GUANGZHOU CHI CHEN TRADE CO
AGRO INDL FRUTA DE LA PASION C	AGRO INDL FRUTA DE LA PASION	GUANGZHOU CITY JI CHEN TRADE COLTD	GUANGZHOU CITY JI CHEN TRADE CO

SUBSIDIARY AND/OR ALTERNATIVE NAMES	TRADER	SUBSIDIARY AND/OR ALTERNATIVE NAMES	TRADER
AGRO INDUSTRIAS PUMA REAL S R L	AGRO INDUSTRIAS PUMA REAL	GUANGZHOU CITY JI CHEN TRADE CO L	GUANGZHOU CITY JI CHEN TRADE CO
AGRO MI PERU FOODS S A C	AGRO MI PERU FOODS	GUANGZHOU COCOA COMMODITIES LIMITED	GUANGZHOU COCOA COMMODITIES
AGROALAVA S A	AGROALAVA	HARALD INDUSTRIA E COMERCIO DE ALIMENTOS SA	HARALD INDUSTRIA E COMERCIO DE ALIMENTOS
AGROCAVA SL	AGROCAVA	HARD DISCOUNT PANAMA S A	HARD DISCOUNT PANAMA
AGROCONDOR SRL	AGROCONDOR	NEO INDUSTRY	HAWTHORNE PARTNERS
AGROFILIAL S A S	AGROFILIAL	HD COTTEREL	HD COTTERELL
AGROFINO FOODS S A C	AGROFINO FOODS	HD COTTERELL B V	HD COTTERELL
AGROGHANA LIMITED	AGROGHANA	HD COTTERELL GMBH	HD COTTERELL
LLC AGROIMPEKS TRADE	AGROIMPEKS TREID	HD COTTERELL HAMBURG GMBH	HD COTTERELL HAMBURG
AGROINDL SALAZAR MOLINA AGROSAMEX S A	AGROINDL SALAZAR MOLINA AGROSAMEX	HD COTTERELL GMBH CO KG	HDCOTTERELL GMBH
AGROINDUSTRIA DE ALIMENTOS BRANGGI S A C	AGROINDUSTRIA DE ALIMENTOS BRANGGI	HEDBLOM CACAO PERU S A C	HEDBLOM CACAO PERU
AGROLAYA S A	AGROLAYA	HENACENT LIMITED	HENACENT
AGRO MANOBANDA HNOS S A AGROMABAN	AGROMANOBANDA HNOS	HERITAGE FRESH FOOD VENTURES	HERITAGE FRESH FOOD
AGROMER PROCESOS DEL PERU E I R L	AGROMER PROCESOS DEL PERU	HERSHEY TRADING G	HERSHEY TRADING
AGROMIX INDUSTRIAL S A C	AGROMIX INDUSTRIAL	HERSHEY TRADING GMB	HERSHEY TRADING
AGROPECUARIA SEMPRE FIRME LTDA	AGROPECUARIA SEMPRE FIRME	WAWEL SA	HOSTA INTERNATIONAL
AGROSANCHEZ COCOA EXPORT S A	AGROSANCHEZ COCOA EXPORT	DROSTE	HOSTA INTERNATIONAL
AGS CORP COLOMBIA S A S	AGS CORP COLOMBIA	HOTEL CHOCOLATE	HOTEL CHOCOLAT GROUP PLC
MOLENBERGNATIE ESPANA	AKIRA HOLDING FOUNDATION	HOTEL CHOCOLAT	HOTEL CHOCOLAT GROUP PLC
MOLENBERGNATIE ESPANA S L	AKIRA HOLDING FOUNDATION	IAB GROUP S A S	IAB GROUP
ALBRECHT DILL TRADING GMB	ALBRECHT DILL TRADING	IAS GHANA LIMITED	IAS GHANA
ALBRECHT AND DILL TRADING	ALBRECHT DILL TRADING	IVOIRE COMMODITIES SOURCING	ICS-SA
ALBRECHT DILL TRADING GMBH BALLIN	ALBRECHT DILL TRADING	IKE IKE S R L	IKE IKE
ALBRECHT AND DILL	ALBRECHT DILL TRADING	IMPORTADORA CAPRILE LIMITADA	IMPORTADORA CAPRILE

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SUBSIDIARY AND/OR ALTERNATIVE NAMES	TRADER	SUBSIDIARY AND/OR ALTERNATIVE NAMES	TRADER
ALECON COMERCIAL EXPORTADORA E REPRESENTACAO LTDA	ALECON COMERCIAL EXPORTADORA E REPRESENTACAO	IMPORTADORA CAPRILE LTDA	IMPORTADORA CAPRILE
SANDRA HECHT	ALEXANDRA HECHT	IMPORTADORA Y EXPORTADORA DONA ISABEL E	IMPORTADORA Y EXPORTADORA DONA ISABEL
ALGARROBOS ORGANICOS DEL PERU SOCIEDAD A	ALGARROBOS ORGANICOS DEL PERU SAC	IMPORTADORA Y EXPORTADORA EL PICAFLOR E	IMPORTADORA Y EXPORTADORA EL PICAFLOR
ALIGOOD S A C	ALIGOOD	IMPORTADORAYEXPORTA-DORA PAIS DEL CACAO E	IMPORTADORAYEX-PORTADORA PAIS DEL CACAO
ALIMENTOS ANDINO S	ALIMENTOS ANDINO	INCA INVEST E I R L	INCA INVEST
ALIMENTOS ZAELI LTDA	ALIMENTOS ZAELI	INCADEX S R L	INCADEX
ALIMPROS S L	ALIMPROS S	INDCRESA	INDCRE
ALMIGHTY FOODS LIMITED	ALMIGHTY FOODS	INDCREASA	INDCRE
AMANDAU S A	AMANDAU	INDUSTRIA BRASILEIRA DE CACAU E GENEROS ALIMENTICIOS LTDA	INDUSTRIA BRASILEIRA DE CACAU E GENEROS ALIMENTICIOS
AMAZON BASIN TREASURES S R L	AMAZON BASIN TREASURES	INDUSTRIA DE PRODUTOS ALIMENTICIOS MAVALERIO LTDA	INDUSTRIA DE PRODUTOS ALIMENTICIOS MAVALERIO
AMAZONAS TRADING PERU S A C	AMAZONAS TRADING PERU SAC	INDUSTRIA E COMERCIO DE CACAU FINO MAGALHAES LTDA ME	INDUSTRIA E COMERCIO DE CACAU FINO MAGALHAES
AMAZONIA NATURALS LTDA	AMAZONIA NATURALS	INDUSTRIA E COMERCIO DE COSMETICOS NATURA LTDA	INDUSTRIA E COMERCIO DE COSMETICOS NATURA
AMMA TODOS OS SANTHOS DIVISAO BRASIL INDUSTRIA E COMERCIO LT	AMMA TODOS OS SANTHOS DIVISAO BRASIL INDUSTRIA E COMERCIO	INDUSTRIALYJM SOCIEDAD ANONIMA CERRADA	INDUSTRIALYJM
AMP LOGISTICS GHANA LIMITED	AMP LOGISTICS GHANA	INDUSTRIAS ALIMENTICIAS CUSCO S A	INDUSTRIAS ALIMENTICIAS CUSCO
DAARNHOUWER CO	AMTRADA HOLDING	INDUSTRIAS EL SINAI S A C	INDUSTRIAS EL SINAI
DAARNHOUWER CO BVKO	AMTRADA HOLDING	INDUSTRIAS T INKIY S A C	INDUSTRIAS T INKIY
DAARNHOUWER CO BV	AMTRADA HOLDING	CJSC INFORUM PROM	INFORUM PROM
DAARNHOUWER COBV	AMTRADA HOLDING	ING BELGIUM BRUSSELS GENEVA BRANCH	ING GROEP NV
DAARNHOUWER AND CO B V	AMTRADA HOLDING	ING BELGIUM GENEVA BRANCH	ING GROEP NV
ANDINA FOODS EXPORT EMPRESA INDIVIDUAL D	ANDINA FOODS EXPORT EMPRESA INDIVIDUAL	INKA FRESH S A C	INKA FRESH
ANDY CONCEPT CO	ANDY CONCEPT	INKA S COMMODITIES TRADING S A C	INKA S COMMODITIES TRADING

SUBSIDIARY AND/OR ALTERNATIVE NAMES	TRADER	SUBSIDIARY AND/OR ALTERNATIVE NAMES	TRADER
ANHUI IMPORT EXPORT CO LTD	ANHUI IMPORT EXPORT CO	INNOVA LTDA	INNOVADA
ANHUI IMPORT AND EXPORT CO LTD	ANHUI IMPORT EXPORT CO	INSUQUIM S R L	INSUQUIM
ANHUI IMPORT AND EXPORT C	ANHUI IMPORT EXPORT CO	INTERAMSA AGROINDUSTRIAL S A C	INTERAMSA AGROINDUSTRIAL
ANHUI IMPORT AND EXPORT CO	ANHUI IMPORT EXPORT CO	INTERCAMBIO MEXICANO DE COMERCIO S A DE C V	INTERCAMBIO MEXICANO DE COMERCIO SA DE CV
ANIFFER TRADING CO	ANIFFER TRADING	INVERSIONES LA MINGA E I R L	INVERSIONES LA MINGA
AOG FOODS S A	AOG FOODS	INVESMENTS PACIFICO SUR S A C	INVESMENTS PACIFICO SUR
APTI ALIMENTOS LTDA	APTI ALIMENTOS	NATRA CACAO SL	INVESTINDUSTRIAL
AQIA QUIMICA INDUSTRIAL LTDA	AQIA QUIMICA INDUSTRIAL	NATRA CACAO	INVESTINDUSTRIAL
ARASA INVESTMENTS LIMITED	ARASA INVESTMENTS	ITOCHU CORPORATION	ITOCHU CORP
ARASCO FOOD BV	ARASCO HOLDING	ITOCHU EUROPE PLC	ITOCHU CORP
ARASCO FOOD	ARASCO HOLDING	ITOCHU FOODSALES AND MARKETING CO	ITOCHU CORP
ARCO IRIS BRASIL IND COM DE PRODUTOS ALIMENTICIOS LTDA	ARCO IRIS BRASIL IND COM DE PRODUTOS ALIMENTICIOS	ITOCHU FOOD SALES AND MARKETING CO	ITOCHU CORP
ARCOR S A I C	ARCOR S A I	ITOCHUINTERNATIONAL	ITOCHU CORP
ARGIA SARL	ARGIA	IVCOM	IVCO
ASCOLI HFD S R L	ASCOLI HFD	JAMES ASANTE MACLEAN	JAMES MACLEAN
ASCOT	ASCOT AMSTERDAM	NANA ZIMMERMANN	JANA ZIMMERMANN
ASCOT AMSTERDAM BV	ASCOT AMSTERDAM	JB COCOA SDN BHD	JB FOODS
ASKINOSIE CHOCOLATE LL	ASKINOSIE CHOCOLATE	PT JEBE KOKO	JB FOODS
ASOC DE ORGANIZACIONES PRODUCTORAS DE CACAO DEL NUDO D	ASOC DE ORGANIZACIONES PRODUCTORAS DE CACAO DEL NUDO	JEBE KOKO	JB FOODS
ASOCIACIN DE PRODUCTORES CACAOTEROS Y C	ASOCIACIN DE PRODUCTORES CACAOTEROS Y	JB COCOA	JB FOODS
ATLANTIC COCOA	ATLANTIC COCOA CO	GRIFFINS FOODS LIMITED	JG SUMMIT HOLDINGS
KAOKA	ATLAS FOOD HOLDING	GRIFFINS FOODS	JG SUMMIT HOLDINGS
AVALMARTI S A AVALMARTI S A	AVALMARTI S A AVALMARTI	JOAQUIN CUTCHET E HIJOS S R L	JOAQUIN CUTCHET E HIJOS
PACORINI GLOBAL SERVICES	B PACORINI SPA	JPM COMERCIO E EXPORTACAO LTDA	JPM COMERCIO E EXPORTACAO
BAKEPLUS CO	BAKEPLUS	JS COCOA	JS COCOA HOLDING

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SUBSIDIARY AND/OR ALTERNATIVE NAMES	TRADER	SUBSIDIARY AND/OR ALTERNATIVE NAMES	TRADER
BAKER PERKINS	BAKER PERKINS HOLDINGS	JUAN A CIBERT S A	JUAN A CIBERT
BANCO SANTANDER CHILE	BANCO SANTANDER	KALLAS PAPADOPOULOS SA	KALLAS PAPADOPOULOS
BARRY CALLEBAUT NEGOCE B C N	BARRY CALLEBAUT	KALLASPAPADOPOULOS	KALLAS PAPADOPOULOS
BARRY CALLEBAUT BRASIL INDUSTRIA E COMERCIO DE PRODUTOS ALIM	BARRY CALLEBAUT	KAOKA S A S	KAOKA
BARRY CALLEBAUT ECUADOR S A	BARRY CALLEBAUT	KARGHER CORPORATION	KARGHER CORP
BARRY CALLEBAUT NORD CACAO	BARRY CALLEBAUT	HUYSER	KEVIN HUYSER
BARRY CALLEBAUT NORD CACAO SAS	BARRY CALLEBAUT	KINGBEE DUNAMIS LIMITED	KINGBEE DUNAMIS
BARRY CALLEBAUT MFG UK BANBURY	BARRY CALLEBAUT	KOKOA DEL ISTMO S A	KOKOA DEL ISTMO
BARRY CALLEBAUT NORD COCOA	BARRY CALLEBAUT	KONTROL TRADING E TRANSPORTE LTDA ME	KONTROL TRADING E TRANSPORTE
BARRY CALLEBAUT NORD COCAO	BARRY CALLEBAUT	KORPERSHOEK WAREHOUSING Y FOWARDING	KORPERSHOEK WAREHOUSING FORWARDING
BARRY CALLEBAUT COCAO	BARRY CALLEBAUT	AB MARKET	KREMLIN TRADE INTERNATIONAL
BARRY CALLEBAUT COCOA GERMANY	BARRY CALLEBAUT	LABORATORIOS PORTUGAL S R L	LABORATORIOS PORTUGAL
BARRY CALLEBAUT GHANA LIMITED	BARRY CALLEBAUT	LALA GUATEMALA S A	LALA GUATEMALA
BARRY CALLEBAUT USA	BARRY CALLEBAUT	LALA NICARAGUA S A	LALA NICARAGUA
BARRY CALLEBAUT COCOA AG	BARRY CALLEBAUT	LANONEXPORT S A	LANONEXPORT
BARRY CALLEBAUT MANUFACTURING	BARRY CALLEBAUT	LAZZARO ZONA LIBRE COLON S A	LAZZARO ZONA LIBRE COLON
BARRY CALLEBAUT SOURCING	BARRY CALLEBAUT	LAZZARO ZONA LIBRE DE COLON S A	LAZZARO ZONA LIBRE DE COLON
BARRY CALLEBAUT COCOA	BARRY CALLEBAUT	LEI CORPORATION E I R L	LEI CORPORATION
BARRY CALLEBAUT MFG UK	BARRY CALLEBAUT	CIA LEVAPAN PANAMA S A	LEVAPAN DE PANAMA
BARRY CALLEBAUT SUZHOU CHOCOLATE	BARRY CALLEBAUT	LFG COMERCIO ASSESSORIA IMPORTACAO E EXPORTACAO LTDA	LFG COMERCIO ASSESSORIA IMPORTACAO E EXPORTACAO
BARRY CALLEBAUT BELGIUM NV	BARRY CALLEBAUT	LIBEROMONDO SCS	LIBEROMONDO SC
PT PAPANDAYAN COCOA INDUSTRIES	BARRY CALLEBAUT	LINYI KALEFU FOOD CO	LINYI KALEFU FOOD

SUBSIDIARY AND/OR ALTERNATIVE NAMES	TRADER	SUBSIDIARY AND/OR ALTERNATIVE NAMES	TRADER
BARRY CALLEBAUT MANUFACTURING MALAY	BARRY CALLEBAUT	LM ENVIOS PERU E I R L	LM ENVIOS PERU
BARRY CALLEBAUR	BARRY CALLEBAUT	LODISER SA	LODISER
BARRRY CALLEBAUT SOURCING	BARRY CALLEBAUT	LOK FOODS S A S	LOK FOODS
BARRY CALLEBEAUT SOURCING	BARRY CALLEBAUT	LOTTE CONFECTIONERY	LOTTE CONFECTIONERY CO
BARRY CALLEBAUT MEXICO S DE RL D	BARRY CALLEBAUT	LOUISE HINES	LOUISE HINDS
BARRY CALLEBAUT FRANCE	BARRY CALLEBAUT	LOVECHOCK B V	LOVECHOCK
BARRY CALLEBAUT AG HEAD OFFICE	BARRY CALLEBAUT	LUA CACAO Y CHOCOLATE LUATE CIA LTDA	LUA CACAO Y CHOCOLATE LUATE CIA
BARRY CALLEBAUT CHOCOLATE ASIA PACI	BARRY CALLEBAUT	LUDWIG WEINRICH GMBH CO KG	LUDWIG WEINRICH GMBH
BARRY CALLEBAUT MFG UK LTD	BARRY CALLEBAUT	LUIS GARRATON	LUIS GARRATâˆšâ‰¥N
BARRY CALLEBAUT MANUFACTURING POLSK	BARRY CALLEBAUT	M J TROPICAL LIMITED	M J TROPICAL
BARRY CALLEBAUT MEXICO S DE RL C	BARRY CALLEBAUT	M LIBANIO AGRICOLA S A	M LIBANIOAGRICOLA
BARRY CALLEBAUT ASIA PACIFIC PTE LT	BARRY CALLEBAUT	M Y M TRADING S A S	M Y M TRADING
BARRY CALLEBAUT MEXICO S DE RL DE	BARRY CALLEBAUT	SUPERFOOD	M80 PARTNERS NV
PT PAPANDAYAN COCOA INDS	BARRY CALLEBAUT	MACHU PICCHU FOODS S A C	MACHU PICCHU FOODS
BARRY CALLEBAUT SOURCING A G	BARRY CALLEBAUT	MACHU PICCHU FOOD SAC	MACHU PICCHU FOODS
BARRY CALLEBAUT NORD CACAO S A S	BARRY CALLEBAUT	MACHU PICCHU COFFEE TRADING SAC	MACHU PICCHU FOODS
BARRY CALLEBAUT MALAYSIA SDN BHD	BARRY CALLEBAUT	MAGLIO ARTE DOLCIARIA S R L	MAGLIO ARTE DOLCIARIA
BARRY CALLEBANT USA	BARRY CALLEBAUT	MAGOREXPORT DEL ECUADOR S A	MAGOREXPORT DEL ECUADOR
SACO	BARRY CALLEBAUT	MAHAMADOU MOUSTAPHA	MAMADOU MOUSTAPHA
BARRY CALLEBAUT BELG	BARRY CALLEBAUT	MAMUSCHKA S R L	MAMUSCHKA
PT PAPANAYAN COCOA	BARRY CALLEBAUT	MANACAO S A	MANACAO
PAPANDAYAN COCOA INDUSTRIES	BARRY CALLEBAUT	MANDINA HOLDINGS S A C	MANDINA HOLDINGS
PT BARRY CALLEBAUT COMEXTRA INDONESIA	BARRY CALLEBAUT	MANJIMEXPORT S A	MANJIMEXPORT
BD ASSOCIARES UKLTD	BD ASSOCIARES UK	MARANON CACAO S R L	MARANON CACAO
BD ASSOCIATES UK LTD	BD ASSOCIATES UK	MAREMI S A C	MAREMI

SUBSIDIARY AND/OR ALTERNATIVE NAMES	TRADER	SUBSIDIARY AND/OR ALTERNATIVE NAMES	TRADER
BEIJING ZHONG TIAN XU TENG FOOD CO	BEIJING ZHONG TIAN XU TENG FOOD	MARIANA COCOA EXPORT LTDA	MARIANA COCOA EXPORT
BELTRAN MARIN INVS AGROPS S A S	BELTRAN MARIN INVS AGROPS	MARKA TRADING S A S	MARKA TRADING
BERYLS CHOCOLATE AND CONFECTIONARY	BERYLS CHOCOLATE CONFECTIONERY SDN BHD	GYAMARS AFRICAN FOOD PTY	MARS
BERYLS CHOCOLATE CONFECTIONERY S	BERYLS CHOCOLATE CONFECTIONERY SDN BHD	MARS FOODS JIAXING CO	MARS
BERYLS CHOCOLATE AND CONFECTIONERY	BERYLS CHOCOLATE CONFECTIONERY SDN BHD	MARS FOODS CHINA CO	MARS
BANCO BICE	BICECORP	MASSAMIRI FOR TRADE AND INDUSTRY LT	MASSAMIRI FOR TRADE AND INDUSTRY
BLUE PACIFIC OILS SA	BLUE PACIFIC	MAXLY FOOD CO	MAXLY FOOD
BOFAS COMPANY LIMITED	BOFAS COMPANY	MAZAPAN DE LA ROSA SA DE C V	MAZAPAN DE LA ROSA SA DE CV
BOHNKAF KOLONIAL GMBH AND CO KG	BOHNKAFKOLONIAL GMBH	MAZEX FOR EXPORT IMPORT	MAZEX IMPORTEXPORT
BOHNKAF KOLONIAL GMBH CO KG	BOHNKAFKOLONIAL GMBH	MC AGRI ALLIANCE LTD	MC AGRI ALLIANCE
BRACAU TRADING CACAU LTDA	BRACAU TRADING CACAU	MC AGRI ALLIANCE LTD COFFEE COCOA	MC AGRI ALLIANCE
NUTKAO USA	BRAIDA FAMILY	MC AGRIALLIANCE	MC AGRI ALLIANCE
BRAZILCOA COM DE PRODALIM LTDA	BRAZILCOA COM DE PRODALIM	MCDAN SHIPPING COMPANY LIMITED	MCDAN SHIPPING COMPANY
SOUZA CRUZ LTDA	BRITISH AMERICAN TOBACCO PLC	MEDCO GROUP COMPANY LIMITED	MEDCO GROUP COMPANY
BRYTEMEDIA LIMITED	BRYTEMEDIA	MEGA INTERNATIONAL COMMERCIAL BANK	MEGA FINANCIAL HOLDING CO
BUCHBINDEREI BREMEN	BUCHBINDER	MELAR S A	MELAR
BVR TRADING IMPORTACAO E EXPORTACAO LTDA EPP	BVR TRADING IMPORTACAO E EXPORTACAO	MEMEX SOCIEDAD ANONIMA CERRADA	MEMEX
C I COLFOOD S A	C I COLFOOD	MERCONTROL ESTUDIOS DE DISTRIBUCION S L	MERCONTROL ESTUDIOS DE DISTRIBUCION
C I FRUTOS DE LOS ANDES FRUANDES S A S	C I FRUTOS DE LOS ANDES FRUANDES	MERIDIAN CACAO	MERIDIAN CACAO CO
C STEINWEG HANDELSVEEM B V	C STEINWEG HANDELSVEEM BV MANAGEMENT	MERRILL INTERNACIONAL S A C	MERRILL INTERNACIONAL
C STEINWEG	C STEINWEG HANDELSVEEM BV MANAGEMENT	MG AGRO SOCIEDAD ANONIMA CERRADA MG	MG AGRO MG

SUBSIDIARY AND/OR ALTERNATIVE NAMES	TRADER	SUBSIDIARY AND/OR ALTERNATIVE NAMES	TRADER
CACAO DE COLOMBIA S A S	CACAO DE COLOMBIA	MICHOC SA	MICHOC
CACAO DE ORIGEN CACAOSOURCE S A S	CACAO DE ORIGEN CACAOSOURCE	MIGRATE AUSTRALIA IMPORT Y EXPORT S A S	MIGRATE AUSTRALIA IMPORT Y EXPORT
CACAO DEL ORIENTE S A C	CACAO DEL ORIENTE	MIHEHUA COMPANY LIMITED	MIHEHUA COMPANY
CACAO HUNTERS JAPAN CO	CACAO HUNTERS JAPAN	MIRAL SA	MIRAL
CACAO JUNTOS S A C	CACAO JUNTOS	MIRANDA ENTERPRISE LIMITED	MIRANDA ENTERPRISE
CACAO PACIFICO S A	CACAO PACIFICO	MITSUI CO	MITSUI
CACAOFRUITEC S A	CACAOFRUITEC	MITSUI CO EUROPE PLC	MITSUI CO
CACAU FOODS DO BRASIL ALIMENTOS LTDA	CACAU FOODS DO BRASIL ALIMENTOS	MITSUI CO INDIA PVT LTD	MITSUI CO
CAFE TRES CORACOES SA	CAFE TRES CORACOES	HASHIM SULIMAN MOHAMED ALI	MOHAMED ALI HASHIM
CARGILL GHANA LIMITED	CARGILL	MONDELEZ INDIA FOODS PVT	MONDELEZ
CARGILL AGRICOLA S A	CARGILL	MONDELEZ EGYPT FOODS	MONDELEZ
CARGILL DEL ECUADOR CARGILLECUADOR CIA	CARGILL	MONDELEZ PAKISTAN LIMITED	MONDELEZ
CARGILL CO	CARGILL	MONDELEZ RUS	MONDELEZ
CARGILL COCOA SARL	CARGILL	MONDELEZ SOUTH AFRICA PTY	MONDELEZ
STE TELCAR COCOA LIMITED	CARGILL	MONDELEZ SOUTH AFFRICA PTY	MONDELEZ
CARGIL WEST AFRICA	CARGILL	MONDELE	MONDELEZ
CARGILL BV CARGILL COCOA AND CHOCOL	CARGILL	MONDO IMPRENDITORE S A C	MONDO IMPRENDITORE
CARGILL JAPAN LIMITED	CARGILL	MOOD FOODS LIMITED	MOOD FOODS
CARGILL JAPAN	CARGILL	CHRISTIAN AMELN	MORTEN CHRISTIAN AMELN
CARGILL COCOA CHOCOLATE	CARGILL	MULTIDIRECTION S A C	MULTIDIRECTION
TOSHOKU SINGAPORE PTE LTD	CARGILL	MULTINGENIOS MAKARIZA S A	MULTINGENIOS MAKARIZA
CARGILL COCOA AND CHOCOLATE	CARGILL	NAIKE E I R L	NAIKE
CARGILL JAPAN LTD	CARGILL	NAKAYAMA CO LTDA	NAKAYAMA CO
CARGIL JAPAN	CARGILL	NATIGOLD S A	NATIGOLD
CARGILL BV CARGILL COCOA AND CHOCO	CARGILL	NATRA CAMAÂ¬Ã§ DE TORRENT SN	NATRA CAMAA DE TORRENT SN
CARGILL INVESTMENTS CHINA	CARGILL	NATRA	NATRAHUDSON EUROPE

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SUBSIDIARY AND/OR ALTERNATIVE NAMES	TRADER	SUBSIDIARY AND/OR ALTERNATIVE NAMES	TRADER
CARGILL B V CARGILL COCOA CHOCOLATE	CARGILL	AVON COLOMBIA S A S	NATURA CO HOLDING
CARGILL B V CARGILL COCOA AND CHOCOLATE	CARGILL	NATURAL HEALTH FOODS S A C	NATURAL HEALTH FOODS
CARGILL BV CARGILL COCOA	CARGILL	NELLO COMERCIO ATACADISTA DE ALIMENTOS LTDA EPP	NELLO COMERCIO ATACADISTA DE ALIMENTOS
CARGILL BV CARGILL COCOA CHOCOLATE	CARGILL	NESTLE AUSTRALIA	NESTLE
CARGILL B V CARGILL COCOA Y	CARGILL	NESTLE MEXICO S A DE C V	NESTLE
CARGILL JAPN	CARGILL	NESTLE DE MEXICO S A DE C V	NESTLE
CARGILL LIMITED	CARGILL	NESTLE BRASIL LTDA	NESTLE
PT CARGILL INDONESIA	CARGILL	CHOCOLATES GAROTO	NESTLE
TELCA	CARGILL	NESTLE ECUADOR S A	NESTLE
TECLAR	CARGILL	NESTLE CAMEROUN	NESTLE
CARIF JAPON CO	CARIF JAPON	NESTLE DE COLOMBIA S A	NESTLE
CASALUKER EUROPE BVBA	CASA LUKER	NESTRADE S A	NESTLE
CASA LUKER EUROPE BVBA	CASA LUKER	NESTLE ESPAA S A	NESTLE
PRODS ALIMENTICIOS PASCUAL S A	CASA LUKER	NESTLE CHILE S A	NESTLE
CASA LUKER DEL PERU S A C	CASA LUKER	NESTLE PERU S A	NESTLE
SUCESORES DE JOSE JESUS RESTREPO Y CIA S A	CASA LUKER	NESTLE USA	NESTLE
HOSTA	CEGEDIM	NESTLE ESPA A S A	NESTLE
PPC GRYF S A	CEMOI	NESTLE AUSTRALIA	NESTLE
PPC GRYF	CEMOI	NESTLE ESPAAA S A	NESTLE
CEMOI TRADING SA	CEMOI	NESTL	NESTLE
CEMOICI	CEMOI	INDS NEUCHATEL S A	NEUCHATEL
CEMOI CHOCOLATIER	CEMOI	NEVSKIY KONDITERLTD	NEVSKIY KONDITER
CEMOI TRADING	CEMOI	NEXT CO	NEXT
CENCOSUD RETAIL	CENCOSUD	NICHE COCOA INDUSTRY LIMITED	NICHE COCOA INDUSTRY LTD
PURDYS CHOCOLATES	CHARLES FLAVELLE INVESTMENTS	NICHE COCOA SHANGHAI CO	NICHE COCOA SHANGHAI
FUSION FOODS S A C	CHAROEN POKPHAND FOODS PUBLIC CO	NICHE FOOD SHANGHAI CO	NICHE FOOD SHANGHAI
CHIZANDY COMPANY LIMITED	CHIZANDY COMPANY	NUTRY BODY SOCIEDAD ANONIMA CERRADA	NUTRY BODY

SUBSIDIARY AND/OR ALTERNATIVE NAMES	TRADER	SUBSIDIARY AND/OR ALTERNATIVE NAMES	TRADER
CHOCOLAR S R L	CHOCOLAR	OLAM COCOA PROCESSING GHANA LIMITED	OLAM
CHOCOLATE COLONIAL S A	CHOCOLATE COLONIAL	OLAM COCOA PROCESSING COTE DIVOIRE	OLAM
CHOCOLATERA DE JALISCO S A DE C V	CHOCOLATERA DE JALISCO SA DE CV	UNICAO	OLAM
CHOCOLATERIE DE BEUSSENT LACHELLE	CHOCOLATERIE DE BEUSSENT LACHELLE SARL	OLAM CAMEROUN	OLAM
CHOCOLATES BEST DE GUATEMALA S A	CHOCOLATES BEST DE GUATEMALA	OLAM COCOA PTE	OLAM
CHOCOLATES FINOS NALS COFINA S A	CHOCOLATES FINOS NALS COFINA	OLAM AGRO INDIA PRIVATE LIMITED	OLAM
CHOCOLATES INDLS S A	CHOCOLATES INDLS	OLAM INTERNATIONAL LIMITED OIL PR	OLAM
CHOCOLATES INDUSTRIALES S A	CHOCOLATES INDUSTRIALES	OLAM INTERNATIONAL LIMITEDOIL PROD	OLAM
CHOCOLATES INDUATRIALES S A	CHOCOLATES INDUSTRIALES	OLAM COCOA	OLAM
CHOCOLATES LACASA ARGENTINA S A	CHOCOLATES LACASA ARGENTINA	OUTSPAN IVOIRE SA	OLAM
CHOCOMAC GHANA LIMITED	CHOCOMAC GHANA	OLAM AGRICOLA LTDA	OLAM
CHOCOMUSEO SOCIEDAD ANONIMA CERRADA CH	CHOCOMUSEO	OUTSPAN ECUADOR S A	OLAM
CHOCONO S A	CHOCONO	OLAM INTERNATIONAL	OLAM
CIA AGROCOMERCIAL PANCHANA Y ZAMBRANO S A	CIA AGROCOMERCIAL PANCHANA Y ZAMBRANO	OLAM INTERNATIONAL LIMITED	OLAM
CIA COL AGROINDL S A S	CIA COL AGROINDL	OALM INTERNATIONAL	OLAM
COMPANIA DE ALIMENTOS LTDA	CIA DE ALIMENTOS	OLAM INTERNATIONAL LTD	OLAM
CIA FRU Y VER MADRID S L	CIA FRU Y VER MADRID S	OLAM FOOD INGREDIENTS SPAIN SLU	OLAM
CIA FRUVER MADRID S L	CIA FRUVER MADRID S	QUEENSLAND COTTON CORP PTY	OLAM
CIA NAL DE CHOCOLATES DCR S A	CIA NACIONAL DE CHOCOLATES DCR	OLAM AMERICAS OLAM AMERICAS	OLAM
COMPANIA NAL DE CHOCOLATES DCR S A	CIA NACIONAL DE CHOCOLATES DCR	OLAM FOOD INGREDIENTS SPAIN S L	OLAM
CIAL H MORALES S L	CIAL H MORALES S	OLAM STORAGE AND DISTRIBUTION	OLAM
CIAL POZUELO DE PANAMA S A	CIAL POZUELO DE PANAMA	PT BUMITANGERANG MESINDOTAMA	OLAM

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SUBSIDIARY AND/OR ALTERNATIVE NAMES	TRADER	SUBSIDIARY AND/OR ALTERNATIVE NAMES	TRADER
CIALZDORA CLOUDFORESTCOCOA CIA L	CIALZDORA CLOUDFORESTCOCOA CIA	OLAM AMERICAS	OLAM
CIALZDORA DE PRODS AGRICOLAS ZAMBRANO VELEZ AGROZAMVELSA S A	CIALZDORA DE PRODS AGRICOLAS ZAMBRANO VELEZ AGROZAMVELSA	OLAM INT	OLAM
COOPERATIVE NOUVEL ESPRIT DE K	CNEK	PT BUMITANGERANG MESINDOTAMA JL	OLAM
ESPRIT	CNEK	OLAM INTERNTIONAL	OLAM
COCOA PROCESSING COMPANY LIMITED	COCOA PROCESSING CO	OLAM INTERNATIONAL LIMITED OIL PRO	OLAM
COINPAL SR LTDA	COINPAL SR	OLAM INTERNATIONL LIMITED	OLAM
COLCOCOA S A S	COLCOCOA	SAM YAS SEBZE MEYVE GIDA DEPOLAMA	OLAM
COLOMBIAN BUSINESS S A S	COLOMBIAN BUSINESS	ORECAO S A	ORECAO
COMAS ROYAL COMPANY LIMITED	COMAS ROYAL COMPANY	ORGANIC HARVEST S A C	ORGANIC HARVEST
COMERCIAL INDUSTRIAL DEL CACAO S A C	COMERCIAL INDUSTRIAL DEL CACAO	ORGANIC RAINFOREST S A C	ORGANIC RAINFOREST
COMERCIAL LIBORIO E I R L	COMERCIAL LIBORIO	ORIGEN PIURA E I R L	ORIGEN PIURA
COMERCIALIZADORA EL GRANERO E I R L	COMERCIALIZADORA EL GRANERO	ORIGIN PARTNER S A C	ORIGIN PARTNERS
COMERCIO E DISTRIBUICAO DE PRODUTOS BR LTDA EPP	COMERCIO E DISTRIBUICAO DE PRODUTOS BR	ORKILA SENEGAL SA	ORKILA SENEGAL
COMESTIBLES ITALO S A	COMESTIBLES ITALO	OSELLA S A	OSELLA
JUS INTERNATIONAL	COMPAL ELECTRONICS	OVERSEAS COMPANY FOR FOOD PRODUCTS	OVER SEAS CO FOR FOOD PRODUCTS SAE
COMPANIA DE GALLETAS POZUELO DCR S A	COMPANIA DE GALLETEAS POZUELO DCR	OVER SEAS COMPANY FOR FOOD PRODUCTS	OVER SEAS CO FOR FOOD PRODUCTS SAE
CONFITECA C A	CONFITECA CA	PACHAKUTEQ S A C	PACHAKUTEQ
CONFITECA S A	CONFITECA CA	PANIRIS S A	PANIRIS
CONFITECA C A CONFITES ECUATORIANOS	CONFITECA CA	PAULISTA S A	PAULISTA
CONFITERA CO LTD	CONFITERA CO	PEORIA S A	PEORIA
CONGRUPO S A	CONGRUPO	PERU Y SUS REGIONES S A C	PERU Y SUS REGIONES
CONSERVAS Y ALIMENTOS SA	CONSERVAS Y ALIMENTOS	PERUVIAN ORGANIC GARDEN S A C	PERUVIAN ORGANIC GARDEN
CONTATO COMERCIO IMPORTADORA E EXPORTADORA EIRELI ME	CONTATO COMERCIO IMPORTADORA E EXPORTADORA EIRELI	PERUVIAN SUPERFOOD CORPORATION E I R L	PERUVIAN SUPERFOOD CORPORATION
COOP AGRAR CAFETALERA ORO VERDE LTDA	COOP AGRAR CAFETALERA ORO VERDE	PETROFORCE TRADING AND SHIPPING	PETROFORCE TRADING SHIPPING

SUBSIDIARY AND/OR ALTERNATIVE NAMES	TRADER	SUBSIDIARY AND/OR ALTERNATIVE NAMES	TRADER
COOP AGRARIA CAFETALERA SATIPO LTDA	COOP AGRARIA CAFETALERA SATIPO	PETROFOERCE TRADING AND SHIPPING	PETROFORCE TRADING SHIPPING
COOPERATIVA AGRICOLA MISTA DE TOME ACU	COOPERATIVA AGRâˆšâ‰ COLA MISTA DE TOMâˆšAâˆšSSU	PIETER BON WAREHOUSING BV	PIETER BON WAREHOUSING
COOPERATIVA AGRARIA ALLIMA CACAO LTDA	COOPERATIVA AGRARIA ALLIMA CACAO	PLOT ENTERPRISE GHANA LIMITED	PLOT ENTERPRISE GHANA
COOPERATIVA AGRARIA CAFETALERA PANGOA LT	COOPERATIVA AGRARIA CAFETALERA PANGOA	PLURY QUIMICA LTDA	PLURY QUIMICA
COOPERATIVA AGRARIA CAFETERA DIVISORIA L	COOPERATIVA AGRARIA CAFETERA DIVISORIA	PRAC AGRIBUSINESS TRADING S A C	PRAC AGRIBUSINESS SAC
COOPERATIVA AGRARIA DE CACAO AROMATICO C	COOPERATIVA AGRARIA DE CACAO AROMATICO	DISTRIBUIDORA NACIONAL COOPERATIVA	PRECOOPERATIVA DISTRIBUIDORA NACIONAL
COOPERATIVA AGRARIA EL GRAN SAPOSOA LTDA	COOPERATIVA AGRARIA EL GRAN SAPOSOA	PREDILECTA ALIMENTOS LTDA	PREDILECTA ALIMENTOS
COOPERATIVA AGRARIA INDUSTRIAL NARANJILL	COOPERATIVA AGRARIA INDUSTRIAL NARANJILLO	EMPRESAS CAROZZI S A	PRINCIPADO DE ASTURIAS
COOPERATIVA AGRARIA MONTE AZUL MONTE A	COOPERATIVA AGRARIA MONTE AZUL	MOLITALIA S A	PRINCIPADO DE ASTURIAS
COOPERATIVA AGROINDUSTRIAL SONOMORO LTDA	COOPERATIVA AGROINDUSTRIAL SONOMORO	PROCOLCACAO CI S A S	PROCOLCACAO CI
COOPERATIVA AGROINDUSTRIAL TOCACHE LTDA	COOPERATIVA AGROINDUSTRIAL TOCACHE	PRODS CHOCOLA S A	PRODS CHOCOLA
CHOCOLATS HALBA	COOPGRUPPE GENOSSENSCHAFT	PROMOT DE CAFE COL S A	PROMOT DE CAFE COL
CORACAN S A	CORACAN	PROQUIMSA S A	PROQUIMSA
CORALAC S A	CORALAC	PROYECTO CHAZUTA S A C	PROYECTO CHAZUTA
CORDIS SA	CORDIS	TENDA ATACADO LTDA	PSN COMERCIAL
CORP DIST DE ALIMENTOS S A	CORP DIST DE ALIMENTOS	PYMA LIMITED	PYMA
IBERCACAO SA	CORPORACION CHOCOLATES LACASA	PYMA STAR LIMITED	PYMA STAR
CHOCOLATES DEL NORTE S A	CORPORACION CHOCOLATES LACASA	QCS QUICK CARGO SERVICE	QCSQUICK CARGO SERVICE
INDUSTRIAS DEL ESPINO SA	CORPORACION DE SERVICIOS GR	QINGDAO NICK BROTHERS TRADE CO	QINGDAO NICK BROTHERS TRADE
CORPORACION EXPORTADORA ESTAPLES FOODS S	CORPORACION EXPORTADORA ESTAPLES FOODS	QORI PRODUCTS S A C	QORI PRODUCTS
CORPORACION GERONIMO S A C	CORPORACION GERONIMO	QUAST CONS GMBH CO KG	QUAST CONS GMBH
COSMO INGREDIENTS S A C	COSMO INGREDIENTS	QUECHUA FOODS S A C	QUECHUA FOODS

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SUBSIDIARY AND/OR ALTERNATIVE NAMES	TRADER	SUBSIDIARY AND/OR ALTERNATIVE NAMES	TRADER
COSTA RICAN COCOA PRODUCTS COMPANY S A	COSTA RICAN COCOA PRODUCTS	QUEVEXPORT S A	QUEVEXPORT
CREATION FOOD CO	CREATION FOODS	BOSCH PACKAGING SYSTEMS	R O B E R T B O S C H S T I F T U N G
OM FOODS	CREATIVE CAFES	RABOBANK INTL	RABOBANK
CULTIVAGRO S A	CULTIVAGRO	RABOBANK TRADE COMMODITY FINANCE	RABOBANK
CWT COMMODITIES ANTWERP N V	CWT INTERNATIONAL	RAYMISA S A	RAYMISA
CYMART INVESTMENTS LIMITED	CYMART INVESTMENTS	REBECCA AMOAH	REBECCA AMOAH CO
D ORIGENN S A S	D ORIGENN	RESIGHA LIMITED	RESIGHA
DAARNHOUWER 7 CO	DAARNHOUWER 7	RESOLT SOCIEDAD ANONIMA CERRADA RESOLT S	RESOLT RESOLT
DALAMY S A	DALAMY	RETAIL Y MARKETING S A S	RETAIL Y MARKETING
DAMOA CORPORATION S A C	DAMOA CORPORATION	DS FREIGHT LOGISTICS LIMITED	RHENUS AIR OCEAN NV
DE AROMAS Y SABORES FINOS DASAFI S A	DE AROMAS Y SABORES FINOS DASAFI	RIJA IMPORTACAO E EXPORTACAO LTDA EPP	RIJA IMPORTACAO E EXPORTACAO
DE GUSTE GROUP S A C	DE GUSTE GROUP SAC	RISTOKCACAO S A	RISTOKCACAO
STE DELTA INDUSTRIES INT	DELTA INDUSTRIES	BANQUE INTERNATIONALE	RUE LA BOÉTIE
DENGO DO BRASIL LTDA ME	DENSO CORP	RUVICOA CIA LTDA	RUVICOA CIA
DEPENDABLE DITRIBUTION SERVICES	DEPENDABLE DISTRIBUTION SERVICES	S 3 C	S 3
DESARROLLADORA CONDORCANQUI S A C	DESARROLLADORA CONDORCANQUI	SADIMEX S R L	SADIMEX
DINAS DISTRIB CORP	DINAS DISTRIBUTION CORP	SALEMOK GHANA LIMITED	SALEMOK GHANA
DIPEVIRE S A	DIPEVIRE	SAMUEL ATTA MENSAH	SAMUEL ATTAMENSAH
DISAR S A	DISAR	SAMUEL K MENSAH	SAMUEL MENSAH
ALMACENADORA MERCADER S A	DISEÑO Y DESARROLLO DE ALMACENADORA MERCADER	AROMATIC COCOA EXPORT S A AROMAEXCO	SANCHEZ GROUP
DOMORI S R L	DOMORI	SINODIS SHANGHAI CO	SAVENCIA HOLDING SCA
DOSIS S R L	DOSIS	SAVORY PACK	SAVORY
DP CHOCOLATES	DP CHOCOLATES PVT	NOVA TRAFFIC	SCHNEIDER CIE
DR OETKER BRASIL LTDA	DR AUGUST OETKER KG	SD TRADE OU	SD TRADE CO
DUAS RODAS INDUSTRIAL LTDA	DUAS RODAS INDUSTRIAL	SEA OLIMPIC IMPORTACAO E EXPORTACAO EIRELI EPP	SEA OLIMPIC IMPORTACAO E EXPORTACAO EIRELI

SUBSIDIARY AND/OR ALTERNATIVE NAMES	TRADER	SUBSIDIARY AND/OR ALTERNATIVE NAMES	TRADER
DUFRY DFAAS COLOMBIA S A S	DUFRY	ORION	SEDKO GROUP
DULFIX S A	DULFIX	SELVACACAO SOCIEDAD ANONIMA CERRADA	SELVACACAO
E COMMERCE LOGISTICS SERVICE S A	E COMMERCE LOGISTICS SERVICE	SERVICIOS INTEGRALES AGROEXPORTACION S R	SERVICIOS INTEGRALES AGROEXPORTACION
HUYSERMOLLER BV	E WESTERWEEL BEHEER	SEVEN LOGISTICS GHANA LIMITED	SEVEN LOGISTICS GHANA
EAFF S A	EAFF	SEVILLE PRODUCTS	SEVILLE PRODUCTS LTD
ECO OLA S A C	ECO OLA	SEVILLE PRODUCTS LLC	SEVILLE PRODUCTS LTD
ECO KAKAO S A	ECOKAKAO	SEVILLE PRODUCT LLC BR	SEVILLE PRODUCTS LTD
AGROINDUSTRIAS ARRIBA DEL ECUADOR AGROARRIBA S A	ECOM	SEVILLE PRODUCTS BR	SEVILLE PRODUCTS LTD
ECOM AGROTRADE	ECOM	SHANANTINA S A C	SHANANTINA
ECOM AGROTRADE LIMITED	ECOM	SHANDONG MAOBANG TRADING CO	SHANDONG MAOBANG TRADING
ECOM AROTRADE	ECOM	SHANDONG MAOBANG TRAGING CO	SHANDONG MAOBANG TRAGING
ECOM AGROTRADE LTD	ECOM	SHANGHAI WIN WIN INTL CO	SHANGHAI WIN WIN INTL
ECOM AGOTRADE	ECOM	SHANGHAI YULI IMPORT EXPORT CO L	SHANGHAI YULI IMPORT EXPORT CO
ECOM AGTROTRADE	ECOM	SHOEI FOODS CORPORATION	SHOEI FOODS CORP
THEOBROMA INVERSIONES S A C	ECOM	SHOPBRAS COMERCIO E DISTRIBUICAO EIRELI EPP	SHOPBRAS COMERCIO E DISTRIBUICAO EIRELI
THEOBROMA	ECOM	SILCOM S A	SILCOM
THEOBROMA BV	ECOM	SITRAPAL SA	SITRAPAL
THEOBROMA BV ECOM COCOA	ECOM	SLOW WATER CAFE LTDA	SLOW WATER CAFE
THEOBROMA B V	ECOM	SMART ORGANIC AD EOOD BG	SMART ORGANIC AD
ECOM AGROTRADE LTDOLD BROAD STR	ECOM	SMC FOOD THAILAND COLTD	SMC FOOD THAILAND CO
ZAMACOM SA	ECOM	SMC FOOD THILAND COLTD	SMC FOOD THAILAND CO
AGROINDUSTRY UNIDAS DE CACAO SA DE	ECOM	SMC FOOD THAILAND CO LTDLAEM C	SMC FOOD THAILAND CO
AGROINDUSTRIAS UNIDAS DE CACAO S A DE C V	ECOM	SMC FOOD 21 MALAYSIA SDN BHD	SMC FOOD21 MALAYSIA SDN BHD
AGROINDS UNIDAS DE CACAO S A DE C V	ECOM	ENRICH MIX SDN BHD	SMC FOOD21 MALAYSIA SDN BHD

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SUBSIDIARY AND/OR ALTERNATIVE NAMES	TRADER	SUBSIDIARY AND/OR ALTERNATIVE NAMES	TRADER
AGROINDUSTRIAS UNIDAS DE CACAO S A	ECOM	SMC FOOD21MALAYSIA SDN BHD	SMC FOOD21 MALAYSIA SDN BHD
AGROINDUSTRIAS UNIDAS DE MEXICO S A DE C V	ECOM	SOC COM IMP EXP SOGANOL LTDA	SOC COM IMP EXP SOGANOL
AGROINDUSTRIAS UNIDAS DE CACAO SA DE CV	ECOM	SOCIEDAD DE ALIMENTOS PROCESADOS SANTIAGO S R L	SOCIEDAD DE ALIMENTOS PROCESADOS SANTIAGO
AGROINDUSTRIAS UNIDAS DE CACAO	ECOM	SOCIEDAD INDUSTRIAL DE YURIMAGUAS S A	SOCIEDAD INDUSTRIAL DE YURIMAGUAS
AGROINDUSTRIAL UNIDAS DE CACAO SA DE CV	ECOM	SOJITZ FOODS CORPORATION	SOJITZ CORP
ECOMMODITIES SOCIEDAD ANONIMA CERRADA	ECOM	SOLLAS HOLLAND B V	SOLLAS HOLLAND
AFRICA SOURCING	ECOM	NATURE VISIONS	SOOUM CORP
ZAMACOM	ECOM	CIMPA	SOPRA STERIA GROUP
AGROINDUSTRIAS ARRIBA DEL ECUADOR AGROARRIBA S A	ECOM	SPIDERONIC TECHNOLOGY CO	SPIDERONIC TECHNOLOGY
CAFETALERA AMAZONICA SAC	ECOM	BANQUE CANTONALE VAUDOISE LAUSANNE	STATE OF VAUD
ENTREPRISE COOPERATIVE KIMBE	ECOOKIM	SOCIETE COOPERATIVE AGRICOLE D	STE COOPERATIVE AGRICOLE
ECPAD	ECPAT	STE D USIN TPOR ET EXPT DE C C	STE D USIN TPOR ET EXPT DE C
ECUADOR COCOA Y COFFEE ECUACOFFEE S A	ECUADOR COCOA COFFEE ECUACOFFEE	STELLA S A	STELLA
ECUADOR KAKAO PROCESSING PROECUAKAO S A	ECUADOR KAKAO PROCESSING PROECUAKAO	STEVIAFARMA INDUSTRIAL SA	STEVIAFARMA INDUSTRIAL
ECUAMAGIC ECUADOR MAGIC FLOWERS S A	ECUAMAGIC ECUADOR MAGIC FLOWERS	DEKKER TRANSPORT TANKOPSLAG	STICHTING ADMIN-ISTRATIEKANTOOR HA DEKKER GROEP HOLDING
ECUATORIANA DE CHOCOLATES ECUACHOCOLATES S A	ECUATORIANA DE CHOCOLATES ECUACHOCOLATES	DEKKER TRANSPORT TANKOSPLAG	STICHTING ADMIN-ISTRATIEKANTOOR HA DEKKER GROEP HOLDING
EDANREY S A	EDANREY	STLS LIMITED	STLS
EL CAFETAL CO	EL CAFETAL	FCSTONE	STONEX GROUP
EL COLABORATORIO S A S	EL COLABORATORIO	FCSTONE MERCHANT SERVICESLLC	STONEX GROUP
ELAH DUFOUR S P A	ELAH DUFOUR SPA	SUCDEN COTE DIVOIRE	SUCDEN
ELIT CIKOLATA VE SEKL SAN AS	ELIT CIKOLATA VE SEKL SAN	SUCRES ET DENREES	SUCDEN

SUBSIDIARY AND/OR ALTERNATIVE NAMES	TRADER	SUBSIDIARY AND/OR ALTERNATIVE NAMES	TRADER
ELSSY KESS COMPANY LIMITED	ELSSY KESS COMPANY	SUCFES ET DENREES	SUCDEN
ELVANTE LIMITED	ELVANTE	SUCREE ET DENREES	SUCDEN
ENSINCRO S R L	ENSINCRO	SUCRES ET DENREES	SUCDEN
ERISLER YEM SANAYI VE TICARET AS	ERISLER YEM SANAYI VE TICARET	GENERAL COCOA CO	SUCDEN
ESCOFFEE S A	ESCOFFEE	GENERA COCOA CO	SUCDEN
ESPECIERA DEL SUR LTDA	ESPECIERA DEL SUR	GENERAL COCOA COMPANY	SUCDEN
ESPECIES PERUANAS S A C	ESPECIES PERUANAS	GENERAL COCOA	SUCDEN
ESPIRITO CACAU INDUSTRIA E COMERCIO LTDA EPP	ESPIRITO CACAU INDUSTRIA E COMERCIO	SUCRET ET DENREES	SUCDEN
COCOANECT B V	ETG	SUCRES ET DENEES	SUCDEN
EXPORT TRADING CORPORATION	ETG	SUCRES DENREES	SUCDEN
COCOANECT	ETG	GENERAL COCOA CO N Y	SUCDEN
EUR CACAO CIA LTDA	EUR CACAO CIA	SUCRES ET DENREES PARIS	SUCDEN
EXIGRANOS S A	EXIGRANOS	SUCESORES DE JOSE SALGADO S A I C	SUCESORES DE JOSE SALGADO S A I
EXPDORA IMPDORA INDL EXPORCAFE C	EXPDORA IMPDORA INDL EXPORCAFE	SUMAQAO SOCIEDAD ANONIMA CERRADA	SUMAQAO
EXPDORA MANABI EXPORTMANABI S A	EXPDORA MANABI EXPORTMANABI	ISLA BONITA TROPICAL FRUIT S A	SUMITOMO CORP
EXPERTOS EN CAFE PERU S A C	EXPERTOS EN CAFE PERU	INTERNATIONALE FRUCHTIMPORT GESELLSCHAFT WEICHERT GMBH CO KG	SUMITOMO CORP
EXPO COSURCA S A C I	EXPO COSURCA	SMC FOOD MALAYSIA SDN BHD	SUMITOMO MITSUI CONSTRUCTION CO
EXPOCOLMENAREZ S A	EXPOCOLMENAREZ	BTL SERVICES	SUMMIT REAL ESTATE HOLDINGS
EXPORGANIC S A	EXPORGANIC	SURCACAO S A S	SURCACAO
EXPORSELL COMERCIAL EXPORTADORA E IMPORTADORA LTDA EPP	EXPORSELL COMERCIAL EXPORTADORA E IMPORTADORA	TACHIBANA CO	TACHIBANA
EXPORT IMPORT BETZALEL E I R L	EXPORT IMPORT BETZALEL	TACHIBANA COLTD	TACHIBANA
EXPORT IMPORT GRUPO MEGA DE JESUS S A C	EXPORT IMPORT GRUPO MEGA DE JESUS	TACHIBANA CO LIMITED	TACHIBANA CO
EXPORT IMPORT MEGA PERU S A C	EXPORT IMPORT MEGA PERU	TACHITBANA CO LTD	TACHITBANA CO
EXPORTACIONES LIBERTENOS HJ S A C	EXPORTACIONES LIBERTENOS HJ	TAIBA FOOD INDUSTRIES CO	TAIBA FOOD INDUSTRIES

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SUBSIDIARY AND/OR ALTERNATIVE NAMES	TRADER	SUBSIDIARY AND/OR ALTERNATIVE NAMES	TRADER
EXPORTADORA CAMINOS ALTOS DEL PERU S A C	EXPORTADORA CAMINOS ALTOS DEL PERU	TASTYCHOCO FOODSTUFF CO LTD	TASTYCHOCO FOODSTUFF CO
EXPORTADORA E IMPORTADORA GLOBO LTDA	EXPORTADORA E IMPORTADORA GLOBO	TERRA AZUL S A C	TERRA AZUL
EXPORTADORA E IMPORTADORA PANAMBI LTDA EPP	EXPORTADORA E IMPORTADORA PANAMBI	THE ALEXANDRIA CONFECTIONERY CHOC	THE ALEXANDRIA CONFECTIONERY CHOCOLATE
EXPORTADORA ROMEX S A	EXPORTADORA ROMEX	THE BAKING PRODUCT W L L	THE BAKING PRODUCT W L
F LP LATINOAMERICAN PERISHABLES DEL ECUADOR S A	F LP LATINOAMERICAN PERISHABLES DEL ECUADOR	PROSECCO SOURCE	THE GARFIELD WESTON FOUNDATION
F PACHE DO BRASIL IMPORTACAO E EXPORTACAO LTDA	F PACHE DO BRASIL IMPORTACAO E EXPORTACAO	THE LORD HEALS COMPANY LIMITED	THE LORD HEALS COMPANY
F Y D INVS S A C	F Y D INVS	THE MANSA GROUPE LIMITED	THE MANSA GROUPE
FACTA INT	FACTA	THE NEW HORIZONTE CORP D B A LA CEN	THE NEW HORIZONTE CORP
FACTA INTERNATIONAL BV	FACTA INTERNATIONAL	THE SUPERFOOD COMPANY SOCIEDAD ANONIMA C	THE SUPERFOOD COMPANY SOCIEDAD ANONIMA
FACTA INTERNATIONAL B V	FACTA INTERNATIONAL	TORONTO ON THOMSON TERMINALS	THOMSON TERMINALS
FACTORES MERCADEO S A	FACTORES Y MERCADEO	TIANJIN HAIYUN INTERNATIONAL TRADE	TIANJIN INTERNATIONAL TRADE CO
FECOLOGICAL S A C	FECOLOGICAL	TIERRA ORGANICA S A C	TIERRA ORGANICA
FENIX SUCESORES DE JOSE SALGADO S A I C	FENIX SUCESORES DE JOSE SALGADO S A I	ROYAL STAR FOODS LIMITED	TIGNISH FISHERIES COOPERATIVE ASSOCIATION
FERRERO TRADING LUX S A	FERRERO FAMILY	TIRYAKI AGOR GIDA SAN VE TIC AS	TIRYAKI AGOR GIDA SAN VE TIC
SOREMARTEC ITALIA S R L	FERRERO FAMILY	TIRYAKI AGRO GIDA SAN VE TIC AS	TIRYAKI AGRO GIDA SANAYI VE TICARET
SOREMARTEC ITALIA SRL GRUPO FERRERO	FERRERO FAMILY	TIRYAKI AGRO GIDA SAN VE TICAS	TIRYAKI AGRO GIDA SANAYI VE TICARET
FINCA SANTA ESTELA SOCIEDAD ANONIMA CERR	FINCA SANTA ESTELA	TIRYAKI AGRO GIDA SAN VE TIC A5	TIRYAKI AGRO GIDA SANAYI VE TICARET
FINO DE AROMA CO	FINO DE AROMA	TIRYAKI AGRO GIDA SANVETIC AS	TIRYAKI AGRO GIDA SANVETIC
FLAVIO ALEXANDRE BARRETO DA SILVA ME	FLAVIO ALEXANDRE BARRETO DA SILVA	TM AGL INSTALLER CO	TM AGL INSTALLER
FLO TRADING S A C	FLO TRADING	TOREN GIDA SANAYI VE TICARET A S	TOREN GIDA SANAYI VE TICARET

SUBSIDIARY AND/OR ALTERNATIVE NAMES	TRADER	SUBSIDIARY AND/OR ALTERNATIVE NAMES	TRADER
FLORDHARI S A	FLORDHARI	TOUTON NEGOCE CI TNCI	TOUTON
FLORES ALLPA CHILE LTDA	FLORES ALLPA CHILE	COCOA TOUTON PROCESSING COMPANY GHA	TOUTON
FLORIDA NATUMENTOS S R L	FLORIDA NATUMENTOS	COCOA TOUTON PROCESSING COMP GH	TOUTON
FOOD LINKS	FOOD LINK	TOUTON SA	TOUTON
BLOMMER CHOCOLATE COMPANY	FUJI OIL HOLDINGS	TOUTON FAR EAST PTE LTD	TOUTON
BLOMMER CHOCOLATE	FUJI OIL HOLDINGS	TOUTON FAR EAST PTE LTD CO	TOUTON
GAMBIT LOGISTICS SOCIEDAD ANONIMA CERRAD	GAMBIT LOGISTICS AD	TOUTOU FAR EAST PTE LTD	TOUTON
MO GANDOUR SONS SAL	GANDOUR MALAYSIA SDN BHD	TOUTON FAR EAST PTE	TOUTON
GARANTIBANK	GARANTIBANK NV	TOUTO	TOUTON
GATYFAX LOGISTICS LIMITED	GATYFAX LOGISTICS	MONER COCOA SA	TRADE TRADE
GENERTEC INTERNATIONAL CORP	GENERTEC INTERNATIONAL GROUP	MONER COCCOA SA	TRADE TRADE
GEORGALOS HNOS S A I C A	GEORGALOS HNOS SAICA	NEDERLAND S A	TRADE TRADE
GIM	GIM CO	MONER COCOA S A	TRADE TRADE
GIRONES S A	GIRONES	TRADER JOE S	TRADER JOE
GLINT S A C	GLINT	ASSOCIATED BRANDS INDS	TREEHOUSE FOODS
GOLDCOCOA EXPORT S A	GOLDCOCOA EXPORT	TRES CORACOES ALIMENTOS SA	TRES CORACOES ALIMENTOS
PT GOLDEN HARVEST COCOA INDONESIA	GOLDEN HARVEST COCOA	TRINITY TRADE	TRINITY TRADE CORP
GOLDEN LEAVES GHANA LIMITED	GOLDEN LEAVES GHANA	TROPICAL FOREST PERU S A C	TROPICAL FOREST PERU
GOLOSINAS O E N P S A	GOLOSINAS O E N P	COCOA HOUSE SDN BHD	TSH RESOURCES BHD
GOOD PRICE CORP S A S	GOOD PRICE CORP	TULICORP S A	TULICORP
GOURMET IMPORTS DCR S A	GOURMET IMPORTS DCR	GARANTIBANK INTERNATIONAL	TURKIYE GARANTI BANKASI
BANCO DEL ESTADO DE CHILE	GOVERNMENT OF CHILE	GARANTIBANK INTERNATIONAL NV	TURKIYE GARANTI BANKASI
ALIMPORT	GOVERNMENT OF CUBA	UCAYALI RIVER CACAO S A C	UCAYALI RIVER CACAO
GEODIS	GOVERNMENT OF FRANCE	UNIKA	UNIKA CO
SCHENKER DEUTSCHLAND	GOVERNMENT OF GERMANY	UNILIVER ISRAEL FOODS	UNILEVER
COCOA MARKETING COMPANY GHANA	GOVERNMENT OF GHANA	UNILIVER ISRARL FOODS	UNILEVER

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SUBSIDIARY AND/OR ALTERNATIVE NAMES	TRADER	SUBSIDIARY AND/OR ALTERNATIVE NAMES	TRADER
COCOA MARKETING COMPANY GHANA LIM	GOVERNMENT OF GHANA	UNILIVER	UNILEVER
COCOA MARKETING COMPANY	GOVERNMENT OF GHANA	UNIVERSAL SWEET INDS S A	UNIVERSAL SWEET INDS
GRANCACAO EXPORT S A	GRANCACAO EXPORT	URBAN FLOWER S L	URBAN FLOWER S
GRANDSOUTH S A	GRANDSOUTH	VALLEY CARGO S A S	VALLEY CARGO
GRANOS AGRICOLAS DEL PERU S A C	GRANOS AGRICOLAS DEL PERU	VALLEY CARGO S A	VALLEY CARGO
GREEN ANDINA COLOMBIA LTDA	GREEN ANDINA COLOMBIA	VALRHONA S A	VALRHONA
GREEN EXPRESS S A GREEN EXPRESA	GREEN EXPRESS	VANDELIS BVBA	VANDELIS
GREENBOX SOCIEDAD ANONIMA CERRADA GREE	GREENBOX GREE	VILLA ANDINA SOCIEDAD ANONIMA CERRADA	VILLA ANDINA
GREENLINE LOGISTICS LIMITED	GREENLINE LOGISTICS	VVR GLOBAL ANDINO S A C	VVR GLOBAL ANDINO
GRIFFINS FOOD LIMITED	GRIFFINS FOOD	WALTER MATTER SA G	WALTER MATTER
SOPEX COCOA	GROUP SOPEX	WALTER MATTER S A	WALTER MATTER
OF SOPEX COCOA	GROUP SOPEX	WALTER MATTER SA	WALTER MATTER
GROUPMOTMOT S A	GROUPMOTMOT	WAYCOLOMBIA CAFE S A S	WAYCOLOMBIA CAFE
ARCOR SAIC	GRUPO ARCOR	WCS DISTRIB	WCS DISTRIBUTING
GRUPO BIZ COL S A S	GRUPO BIZ COL	AALST CHOCOLATE PTE LID	WILMAR INTERNATIONAL
CAFE BRITT COSTA RICA S A	GRUPO BRITT NV	AALST CHOCOLATE RTE	WILMAR INTERNATIONAL
COMPANIA NACIONAL DE CHOCOLATES DE PERU	GRUPO NUTRESA	AALST CHOCOLATE PTE	WILMAR INTERNATIONAL
COMPANIA NAL DE CHOCOLATES DE PERU S A	GRUPO NUTRESA	XIAMEN C D COMMODITY TRADING CO	XIAMEN CD
COMPANIA NACIONAL DE CHOCOLATES	GRUPO NUTRESA	YANAP PERU SOCIEDAD ANONIMA CERRADA YA	YANAP PERU YA
GRUPO SUAGU S A S	GRUPO SUAGU	YELLOW HORSE INTERNATIONAL	YELLOW HORSE
GCB SPECIALIOTY CHOCOLATE SDN BHD	GUAN CHONG BHD	YEM CORPORATION S A	YEM CORPORATION
		ZARAHEMLA LTDA	ZARAHEMLA

B. Destination markets

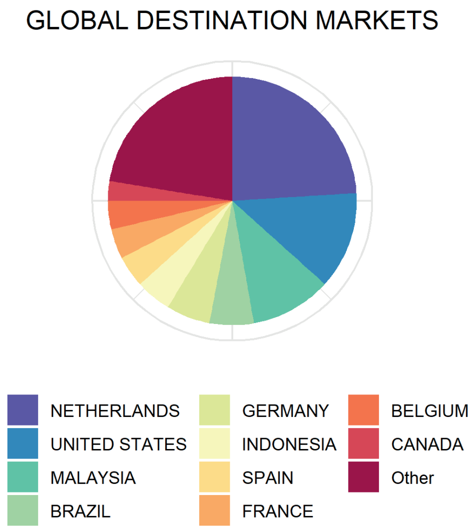

Figure 1. Global market share of major cocoa importing countries.

C. Trade flows

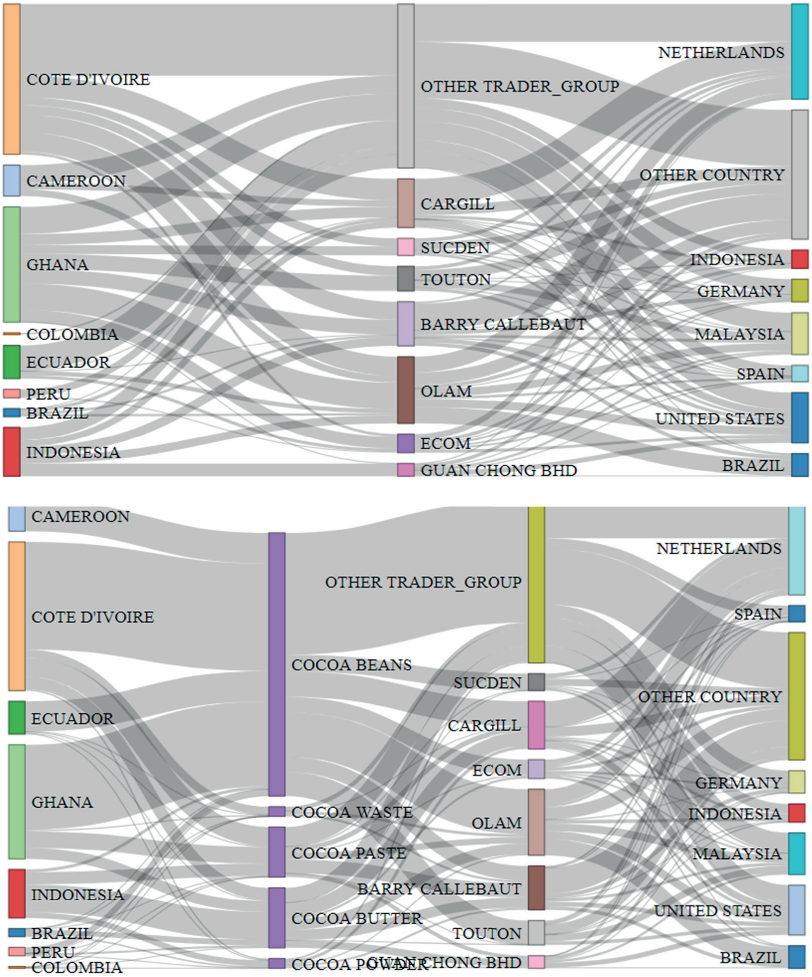

Figure 2. Flow graphs of cocoa exports country-trader-country (upper figure) and country-cocoa type-trader-country (lower figure).

D. Market concentration considering "exporter" as trader in Ghana.

When the Cocoa Marketing Company (CMC) is considered as an exporter in Ghana, transnational corporations handled only ~17%, other domestic firms 9% and CMC ~ 74% of national exports. When the Cocoa Marketing Company is considered as an exporter in Ghana, the four-firm concentration ratio (CR4) in that country rises further from 59 to 87% (Figure 3 from Appendix C).

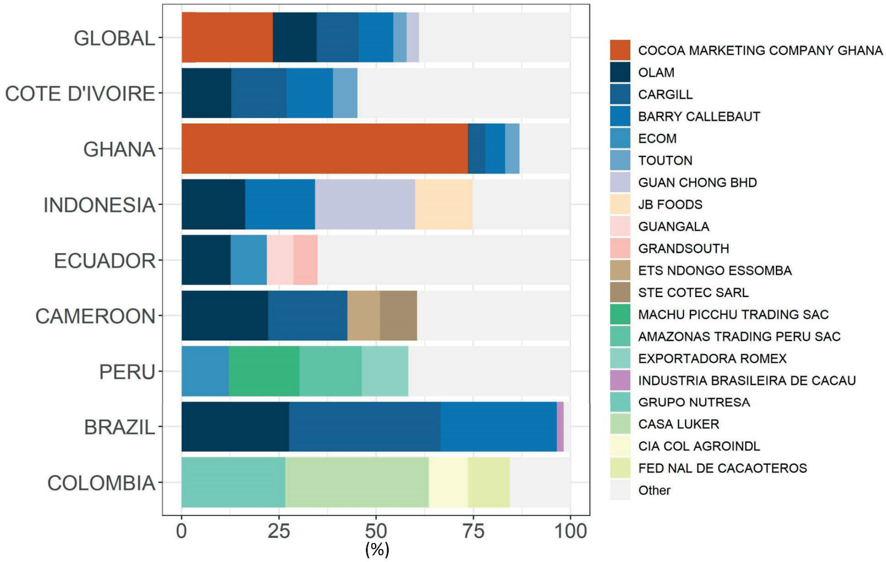

Figure 3. Market shares of 4 largest traders per country (except at global level where the 7 largest are displayed), considering the Cocoa Marketing Company of Ghana (CMC).

E. Shannon-Weaver index results per type of company

Table 3. Results of Diversity Index per type of company for sourcing and destination countries.

TYPOLOGY	SOURCING COUNTRIES		DESTINATION COUNTRIES	
	MEAN	SD	MEAN	SD
Large transnational firm	1.400847	0.136168	2.307087	0.489496
Medium transnational firm	0.616239	0.455461	2.269032	0.175551
Small transnational firm	0.238889	0.259758	1.835576	0.538276
Large domestic firm	0	0	1.167403	0.858899
Small domestic firm	0	0	0.719033	0.805204
Farmer cooperative	0	0	0.752185	0.772361

F. Sustainability initiatives considering direct and indirect shares

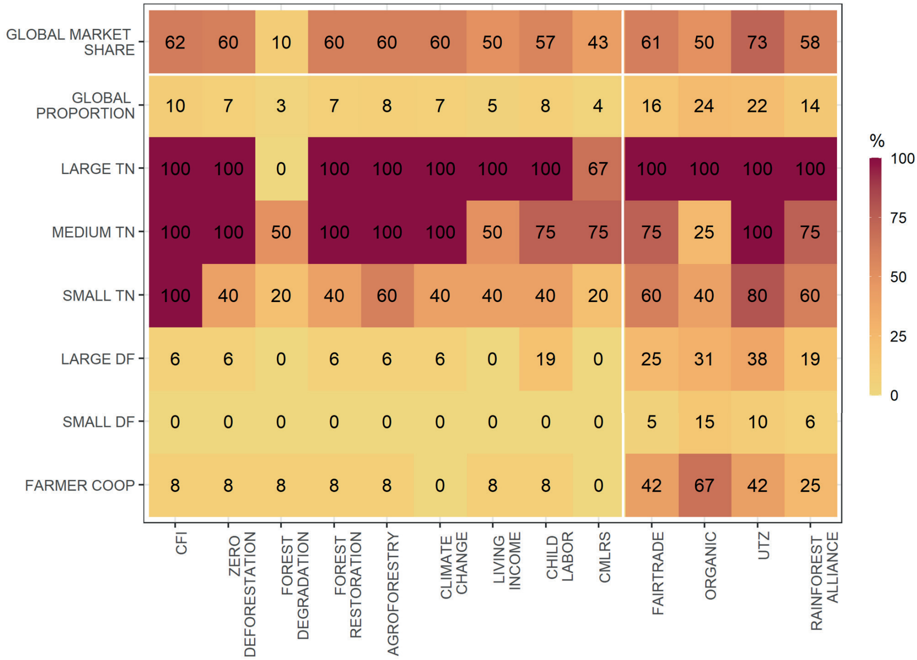

Figure 4. Proportion of companies (bottom seven rows) and market share (top row) of adoption of sustainability commitments and certifications without considering direct and indirect market shares.

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G. Spearman

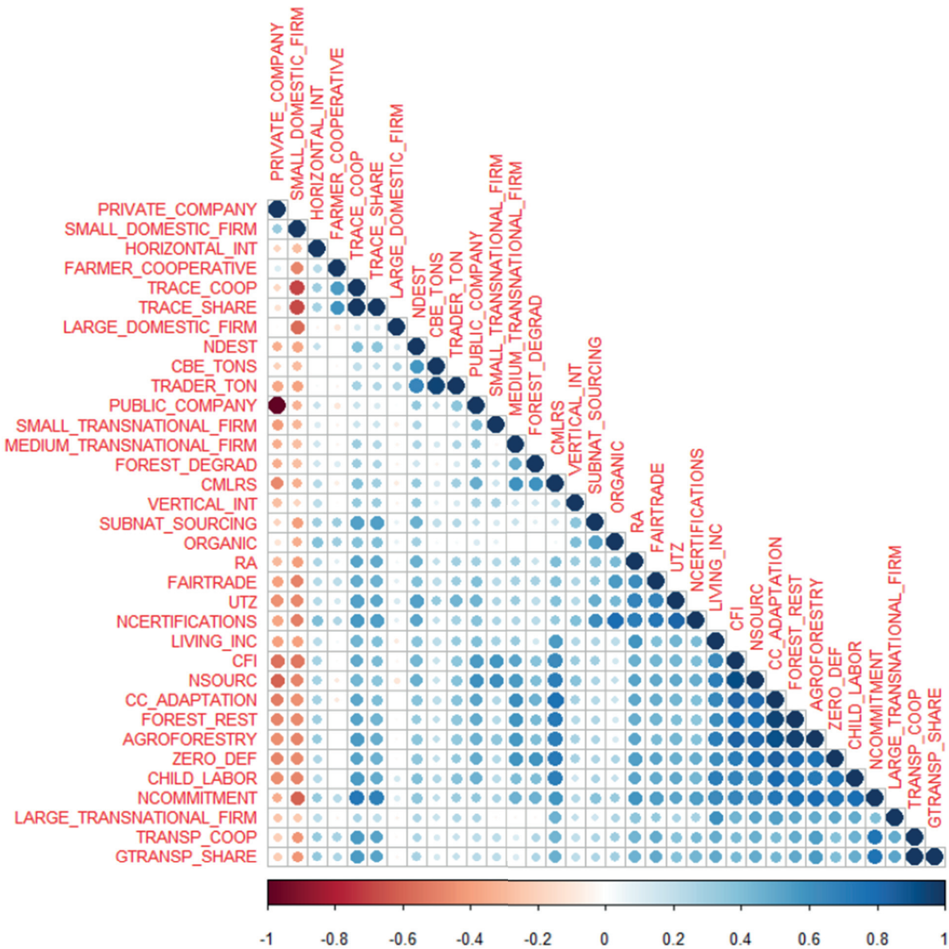

Figure 5. Correlogram of variables using the Spearman index.

H. Statistical modeling

Table 4. Standard errors of statistical modeling results. TN= Transnational company; D = Domestic firm.

EXPLANATORY VARIABLES	Nº COM	Nº CERT	TRACEABILITY	TRANSPARENCY	ZERO DEFORESTATION	AGROFORESTRY	CHILD LABOR
Large TN	0.44	0.52					
Medium TN	0.34			1.43			
Small TN	0.47		1.43			1.46	1.68
Large DF				1.32			1.24
Small DF	1.03	0.23	0.84	1.28			
Farmer cooperative				1.02	1.41		
Public company					0.99		1.02
Nº country destinations		0.01			0.05	0.07	0.09
Subnational sourcing		0.35	1.14			1.52	1.41
Vertical integration	0.21		0.36			0.58	0.79
Horizontal integration	0.46	0.21		0.92		1.05	1.16
Vertical integration: Horizontal integration	0.26						
(Intercept)	0.42	0.39	1.06	1.03	1.18	1.97	2.22

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Table 5. Results of statistical modeling indicating regression coefficients (ß). *Odds ratios are shown in brackets for logistic models.* "-" indicates variables that were not included in the initial model due to perfect separation or collinearity; "~" indicates variables that were included in the initial model but were not retained in the final model due to automatized stepwise model selection based on AIC. values. Com= Commitments; Cert= Certifications; TN= Transnational company; DF= Domestic firm.

EXPLANATORY VARIABLES	Nº COM	Nº CERT	TRACEABILITY	TRANSPARENCY	ZERO DEFORESTATION	AGROFORESTRY	CHILD LABOR
Large TN	2.84**	-1.03	-	-	-	-	-
Medium TN	2.44**	~	-	-1.78 (0.2)	-	-	~
Small TN	2.19**	~	-2.11 (0.1)	-	~	3.32* (27.6)	3.03 (20.7)
Large DF	~	~	-	-2.68 (0.1)	~	-	2.85* (17.3)
Small DF	-3.96**	-0.65**	-4.17** (0.02)	-4.64** (9E-03)	-	-	-
Farmer cooperative	~	~	-	-1.22 (0.3)	2.34 (10.4)	~	~
Public company	~	~	-	~	2.92** (18.5)	~	2.24* (9.4)
Nº country destinations	~	0.04**	~	~	0.17** (1.2)	0.21* (1.2)	0.24* (1.3)
Subnational sourcing	~	1.74**	3.44** (31)	~	~	2.13 (8.5)	2.03 (7.6)
Vertical integration	0.2	~	0.78 (2.2)	~	~	-0.85 (0.4)	-1.96* (0.1)
Horizontal integration	1.47**	0.35	~	1.69 (5.4)	~	2.4* (10.9)	1.89 (6.7)
Vertical integration: Horizontal integration	-0.75**	~	-	-	-	-	-
Intercept	-1.18	-1.76**	-2.16 (0.1)	-0.72 (0.5)	-5.76** (3E-03)	-7.45** (5E-04)	-7.93**(3E-04)
Akaike Inf. Crit. (AIC)	141.73	271.43	67.77	57.32	44.97	46.36	48.48

p<0.05*, p<0.01**

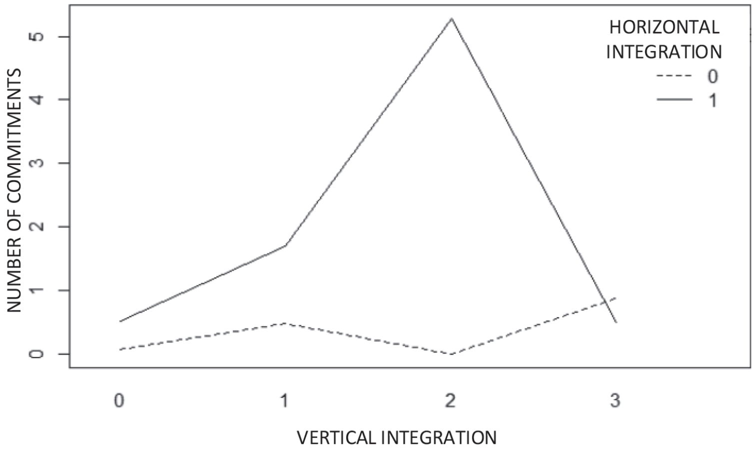

Figure 6. Effect of the interaction between horizontally and vertically integrated companies.

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I. Validation of trade data

We used shipping data for cocoa beans and processed cocoa products, validated against trade data published by the ICCO and UN Comtrade.

ICCO export data were available for the 2017-18 season. Comtrade is the UN's source of international trade statistics and publishes data on an annual basis. There was good agreement between data sources: all Trase data had less than 20% of difference from Comtrade and ICCO statistics except for cocoa paste and butter in Côte d'Ivoire, and cocoa paste from Peru (Figure 7 from Appendix C).

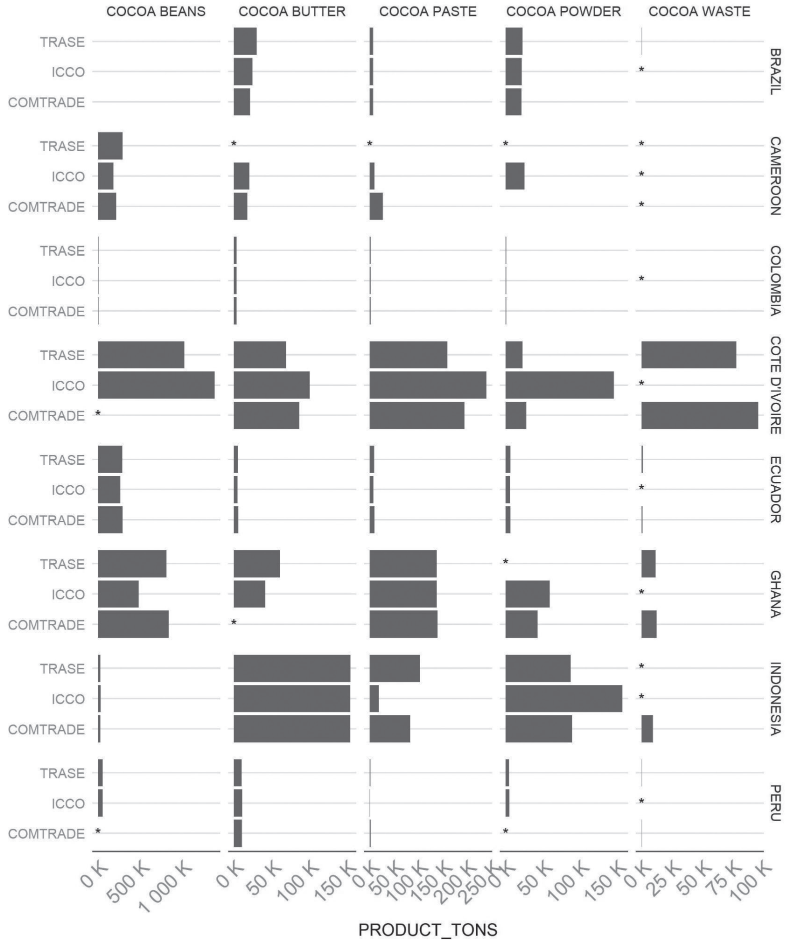

Figure 7. Volumes reported per product/country in Trase ICCO, and Comtrade. Missing data are marked by a *.

Appendix D

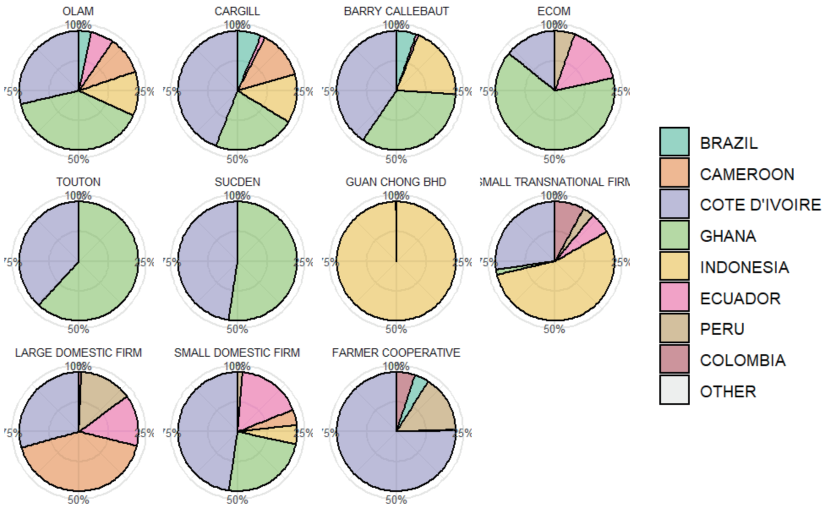

Figure 1. Contribution of each country to sourcing volumes (%) of each trader.

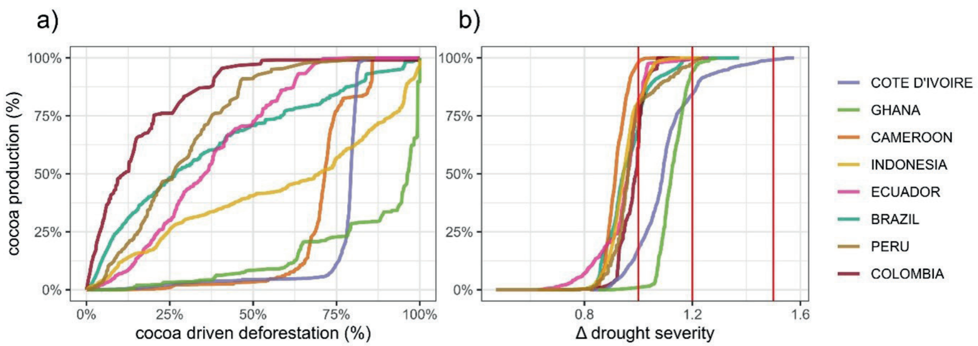

Figure 2. (a) Cumulative cocoa production (%) affected by agri-commodity deforestation attributed to cocoa (%), and (b) future drought severity in cocoa producing landscapes of top 8 cocoa exporters under *RCP 2.6*. In (b), the red vertical lines indicate the thresholds for reduced (<1), modest (>1 and <1.2), moderate (>1.2 and <1.5), and high (>1.5) drought severity.

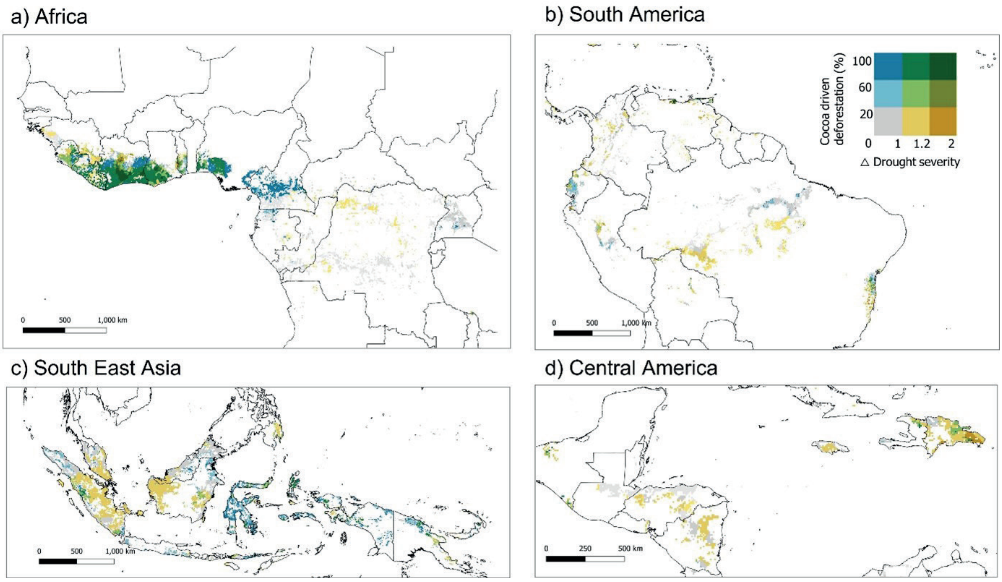

Figure 3. Combined levels of drought severity change under *RCP 2.6*, and agri-commodity deforestation attributed to cocoa (%) in cocoa producing landscapes.

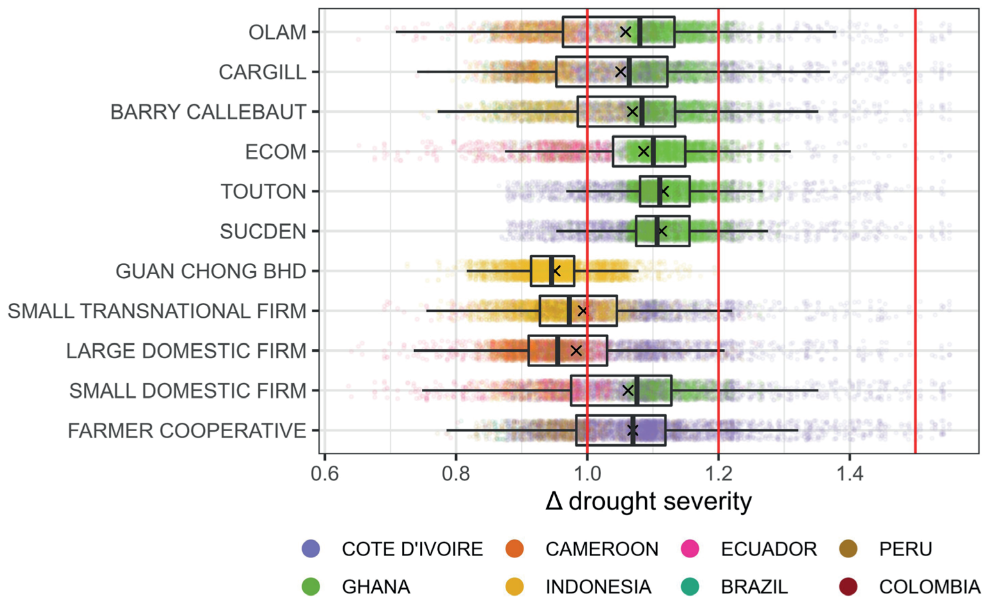

Figure 4. Change in drought severity risk in cocoa producing landscapes in the value chain of global cocoa traders under *RCP 2.6*. "X" indicates the mean. The red vertical lines indicate the thresholds for reduced (<1), modest (>1 and <1.2), moderate (>1.2 and <1.5), and high (>1.5) drought severity.

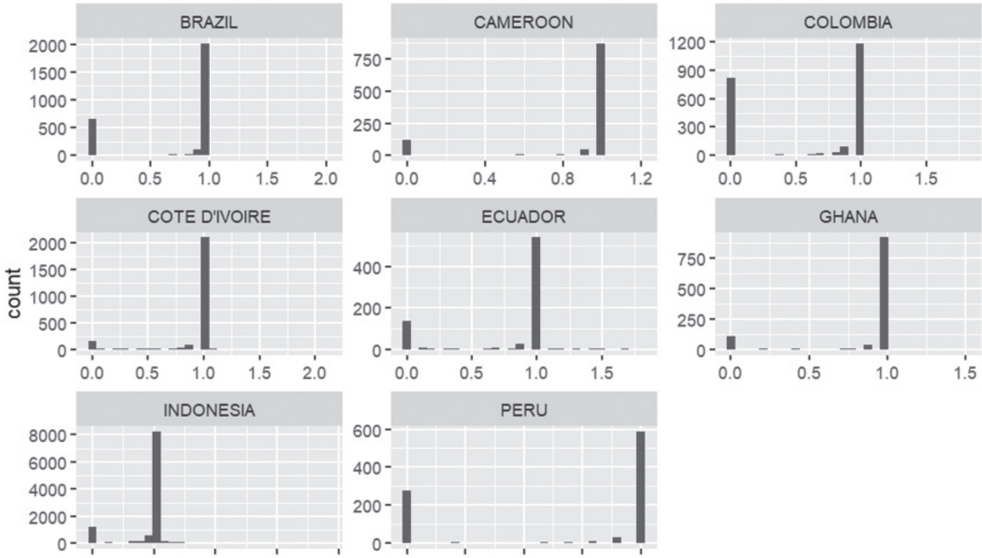

Figure 5. Histogram of the proportion of cocoa area linked to cocoa-driven deforestation. The pixel values [cocoa-driven deforestation (ha)/ cocoa area (ha)] are ~1 in 78% of pixels, showing that the attribution of deforestation to cocoa area is mostly 1:1, while only 18% of pixels have value 0, denoting areas where deforestation occurred before 2000 or had another driver.

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Acknowledgments

This thesis is the final product of a dream that started in 2017 when I stumbled upon a fascinating position online. Having completed my master's thesis on the ex-post impacts of the largest project of the United National Development Program (UNDP) in Peru at the time, I was unsatisfied with my understanding of the challenges faced by smallholder farmers and the way different institutions tried to help them fight poverty and adapt to climate change. After looking at local scale dynamics for some years, I knew there was a piece missing. Larger forces were influencing these farming systems and I was eager to know more about them to make my contribution meaningful. This Ph.D. position offered me the possibility to expand my understanding of the interconnections between global and local dynamics, from a fascinating interdisciplinary perspective. This was a Ph.D. in geography with a significant load on quantitative analytics. At that time, I had a basic knowledge of GIS and, though I was always fond of statistics, I had never applied it to big and complex datasets. Moreover, I had limited knowledge of programming languages. Therefore, I must thank first prof.dr.ir. Peter Verburg for believing in me, trusting my passion, and allowing me to learn all this almost from scratch while applying it to my dream topic. My Ph.D. journey has been full of excitement for science, perseverance in learning new skills, stubbornness to get results, concentration to write, and many passionate scientific debates. It has also been full of challenging moments where I had to learn to take care of my mental health and accept that learning has its own pace. There are many things I'd do differently, but I'd choose to do this Ph.D. again.

Peter, thank you for your guidance, your always accurate feedback, your honest opinions, and your patience in this journey. Thank you, dr. Patrick Meyfroidt, for accepting me as your Ph.D. student and teaching me how to do science, your always constructive feedback, your bright ideas, and your mentoring were critical in my Ph.D. journey. Thank you dr. Erasmus zu Ermgassen for involving yourself so deeply in two of my favorite chapters and guiding me from very close. Working with you allowed me to learn an exciting new skill (coding) and learn from the fascinating field of global value chains. It was a completely new journey for me, thank you for your patience. Dr. Jean Hugè and prof. dr. Marjolein Visser, deep thanks for encouraging me to pursue a Ph.D. and for giving me your trust, this thesis would not exist without the support you gave me.

Thanks also to the company of brilliant colleagues who always triggered fascinating intellectual debates about global politics, trade, economics, justice, inequality, history, nature, lifestyles, and much more. Special thanks to all my COUPLED project fellows for the great moments shared, all of you continue to be a source of intellectual inspiration. Special thanks to those I was lucky to have closer: Perrine, Siyu, Finn, Floris, Johanna, and Tiago. Thanks to prof.dr. Jonas Østergaard Nielsen for leading with such greatness the COUPLED project, Kathrin for always providing support, and all other research leaders for your guidance. It was an honor to share so many sessions with such brilliant minds, I have learned to appreciate deeply each of your fields of research. Thanks also to my EG colleagues, all the fun and intellectual activities that you organized really made a difference. Special thanks to Sarah, Cecilia, Jonas, Žiga, Katharina, Mengmeng, and Bep. My Ph.D. journey brought many new friendships that I now treasure, thank you Emilia, Francoise, Elvia, Alphonse, Sahar, Mirna, and Jules for always being there for me when I needed it and for sharing your lovely energy to cheer me up. Thank you also Marine for being my favorite colleague-friend and for sharing so many special moments during the last push of my Ph.D. journey.

The distance was never an obstacle to feeling my sister Celeste close to me. Thank you for being the most stable support and the best sister-friend I could ever wish for, without you my difficult moments would have been much harder to overcome. Collin, for being the closest and most understanding spectator of this work and the most loving and patient presence in my life. Thanks to my family for always trusting that I could finish this, I carry with pride our Andean roots. Thanks also to the many dear friends spread across all continents, all of you remain close to me despite the distance. To many more years of intellectual curiosity, research partnerships, and transformational changes for our planet Earth.

About the author

Claudia Parra Paitan was born on the 11th of April 1990 in Lima, Peru. In 2007 she enrolled in a five-year bachelor's program in Biology at the Universidad Nacional Agraria La Molina (Lima, Peru). She completed her bachelor's degree in 2011, specializing in Ecology. During her studies, Claudia volunteered as a park ranger in three National Parks in the Peruvian Amazon rainforest, the Andean mountains, and South-Pacific mangroves, where she gained experience in conservation biology and sustainable resource management. For her bachelor thesis, she worked with the Geophysical Institute of Peru and the Centro de Datos para la Conservación (CDC) to research the impacts of climate change on Peruvian mangroves.

After graduation, Claudia worked for four years as an advisor on climate change adaptation and sustainable land management in smallholder farming systems for various organizations, including the United Nations Development Program, the United Nations Environment Program, the Peruvian Ministry of Environment, the German Cooperation, and the Belgian Cooperation. From 2015 to 2017 she pursued her master's degree in Human Ecology at the Vrije Universiteit Brussel (VUB), Belgium, supported by a full scholarship granted by the Flemish Inter-University Council (VLIR-UOS). For her master's thesis, she made an ex-post impact assessment of the UNDP program "Manejo Sostenible de la Tierra (MST)", to evaluate its impact on the livelihoods and sustainable farming practices of Andean communities guarding agro-biodiversity.

Between 2018 and 2021, Claudia was hired as a Ph.D. researcher at the Environmental Geography Department of the Institute for Environmental Studies (IVM) of the Vrije Universiteit Amsterdam (VU), after being selected as one of 15 EU Marie Skłodowska-Curie Ph.D. fellows of the COUPLED project. She focused her research on the sustainability impacts of global agricultural value chains, using the land use change and telecoupling theories as main foundations. She completed a research exchange at the Centre for Development and Environment (CDE) of the University of Bern and was part of the IGS North-South – International Graduate School North-South hosted by the Centre Suisse de Recherches Scientifiques (CSRS) in Côte d'Ivoire. For her research, she collaborated closely with the Université Catholique de Louvain in Belgium, the Trase Initiative of the Stockholm Environment Institute (SEI), and the European Forest Institute (EFI).

Since 2022, Claudia has been working for Olam Food Ingredients. She is the Ecosystems & Biodiversity Manager and is part of the Corporate Responsibility & Sustainability team and the Global Cocoa Sustainability team. At Olam, Claudia leads the design, implementation, monitoring, and evaluation of sustainability initiatives aimed at reducing deforestation risk, scaling up sustainable landscape initiatives, and improving farming practices across the cocoa, coffee, nuts, spices, and dairy business units.