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Determining greenhouse gas emissions hotspots and potential abatement strategies: the rice sector in India and the cacao beans sector in Ivory Coast

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Master thesis report

submitted to obtain the degrees of

- Master in biology AgroSciences (BAS) of the University of Reims Champagne-Ardenne
- Master of Science in Engineering of Tallinn University of Technology
- Master in Bioengineering: Chemistry and Bioindustries of the University of Liège

Determining greenhouse gas emissions hotspots and potential abatement strategies: the rice sector in India and the cacao beans sector in Ivory Coast

Presented by: QUIENG, Shery Rose Domingo

Defended the: 27/06/24

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Confidentiality: No

TALLINN UNIVERSITY OF TECHNOLOGY
SCHOOL OF ENGINEERING
Department's title

DETERMINING GREENHOUSE GAS EMISSIONS HOTSPOTS AND POTENTIAL ABATEMENT STRATEGIES: THE RICE SECTOR IN INDIA AND THE CACAO BEANS SECTOR IN IVORY COAST

KASVUHOONEGAASIDE HEITKOGUSTE LEVIALADE JA VÕIMALIKE VÄHENDAMISE STRATEEGIATE KINDLAKSMÄÄRAMINE: INDIA RIISISEKTOR JA ELEVANDILUURANNIKU KAKAOUBADE SEKTOR

MASTER THESIS

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Tallinn 2024

AUTHOR’S DECLARATION

Hereby I declare that I have written this thesis independently.
No academic degree has been applied for based on this material. All works, major viewpoints and data of the other authors used in this thesis have been referenced.

16 June 2024

Author: Shery Rose Domingo QUIENG
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Thesis is in accordance with terms and requirements

16 June 2024

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Accepted for defence

June 2024

Chairman of theses defence commission: Prof. Sophie Landaud
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16 June 2024

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Department of Materials and Environmental Technology

THESIS TASK

Student: Shery Rose Domingo Quieng, 241394KVEM

Study programme: KVEM12/21 Technology of Wood, Plastic and Textiles; Bioceb European Master in Biological and Chemical Engineering for a Sustainable Bioeconomy

Supervisors: Niina Dulova, Senior Research Scientist, +372 620 2854
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Thesis topic:

(in English) *Determining greenhouse gas emissions hotspots and potential abatement strategies: the rice sector in India and the cacao beans sector in Ivory Coast*

(in Estonian) Kasvuhoonegaaside heitkoguste levialade ja võimalike vähendamise strateegiate kindlaksmääramine: India riisisektor ja Elevandiluuranniku kakaoubade sektor

Thesis main objectives:

1. To comprehensively assess current greenhouse gas (GHG) emissions determine the emission hotspots in the two sectors

2. To identify agricultural interventions with high GHG abatement potential for the selected sectors

3. To evaluate the costs and barriers associated to the implementation of the interventions.

Thesis tasks and time schedule:

No	Task description	Deadline
1.	Familiarization with relevant literature and documentation	05.2024
2.	Data collection, analysis and interpretation of results	05.2024
3.	Writing and formatting the thesis	06.2024

Language: English **Deadline for submission of thesis:**16 June 2024

Student: Shery Rose Domingo Quieng .... 27 March 2024
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PREFACE

This thesis is the culmination of my studies under the Biological and Chemical Engineering for a Sustainable Bioeconomy (Bioceb) program, undertaken to fulfill the requirements for the following triple master's degree:

- Master in Biology and AgroSciences (BAS) of the University of Reims Champagne-Ardenne
- Master of Science in Engineering of Tallinn University of Technology
- Master in Bioengineering: Chemistry and Bioindustries of the University of Liège

The topic, "Determining greenhouse gas emissions hotspots and potential abatement strategies: the rice sector in India and the cacao beans sector in Ivory Coast," was initiated in collaboration with Quantis, where I had the opportunity to work under the guidance of various analysts. Most of all, I am deeply grateful to Tetyana Pecherska, my internship company supervisor, for her invaluable support, guidance and feedback throughout this process.

I would also like to extend my heartfelt thanks to my academic supervisors, Dr. Niina Dulova from Tallinn University of Technology and Dr. Manon Genava from the University of Liege Agro-Biotech Gembloux. Their expertise, insightful feedback, and constant encouragement have been instrumental in shaping this thesis.

Finally, I would like to acknowledge all the colleagues and friends who assisted and inspired me during this journey. Their contributions and encouragement have helped me complete this work.

This thesis explores critical issues in greenhouse gas emissions and mitigation strategies in the agricultural sectors of India and Ivory Coast. It aims to identify emissions hotspots and propose effective strategies for reducing greenhouse gas emissions in these key agricultural sectors.

Key words: greenhouse gas emissions, abatement strategies, rice sector, cacao beans sector, master thesis

List of abbreviations and symbols

+ greenhouse gas (GHG)
+ land use, land-use change and forestry (LULUCF)
+ emission factors (EF)
+ CO_2e – carbon dioxide equivalents
+ land-use change (LUC)
+ Biomass energy with carbon capture and storage (BECCS
+ Food and Agriculture Organization of the United Nations (FAO)
+ biological nitrogen fixation (BNF)
+ Cocoa Swollen Shoot Virus (CSSV)
+ World Food LCA Database (WFLDB)
+ paddy rice-wheat (PW)
+ paddy rice-potato-fallow (PP)
+ alternate wetting and drying (AWD)
+ dry direct rice seeding (DDRS)
+ global warming potential (GWP)
+ transplanted rice (TPR)
+ Cool Farm Tool (CFT)
+ good agricultural practices (GAP)
+ World Wildlife Fund (WWF)
+ soil organic carbon (SOC)
+ integrated pest management (IPM)

ABSTRACT

The urgency to mitigate greenhouse gas (GHG) emissions, particularly in the agricultural sector, has become paramount in the wake of escalating climate change. This urgency is underscored by the Paris Agreement's ambitious goal of limiting the temperature rise to 1.5°C above pre-industrial levels. Agriculture, Forestry, and Other Land Use (AFOLU) sectors, accountable for 22% of total global emissions, have been identified as significant contributors. This paper addresses the imperative need for strategic and comprehensive actions within agriculture to align with the 1.5°C pathway.

Focusing on two critical crops essential to the modern diet – rice and cocoa – this master's thesis aims to assess GHG emissions comprehensively, identify principal sources of emissions, and propose agricultural interventions with high GHG abatement potential. The research considers India as a major rice producer and exporter and Ivory Coast as the largest cacao bean producer and exporter globally.

Challenges in achieving emission reduction targets include the immense scale and heterogeneity of agricultural production systems. Each production system, influenced by factors such as geography, type of production, and farming practices, exhibits different emission sources and magnitudes. Moreover, farmers lack adequate incentives to adopt novel methods and technologies crucial for climate change mitigation.

The results reveal that direct emissions dominate in rice cultivation, primarily methane and nitrous oxide emissions from flooded paddy rice fields. In contrast, land use changes due to massive deforestation to accommodate the growing demand for cacao accounts for most of the emissions in this agricultural sector. The paper identifies interventions such as alternate wetting and drying in rice cultivation and agroforestry in cacao production as effective strategies for climate mitigation.

However, significant knowledge gaps exist regarding the applicability, costs, and barriers to implementing these interventions. Enhanced research and development efforts are necessary to address these gaps and foster adoption by farmers. Transparent methodologies and accurate estimations of GHG abatement are crucial for guiding strategies towards achieving net-zero emissions by 2050 and aligning with the goals of the Paris Agreement.

In conclusion, while challenges remain, agriculture holds the potential to achieve net-zero emissions with sufficient support, motivation, and concerted efforts across stakeholders. Enhanced research, development, and adoption of sustainable practices

are essential for realizing this potential and mitigating the impacts of climate change on global food security.

1. INTRODUCTION

In the face of escalating climate change matters, the requisite to mitigate greenhouse gas (GHG) emissions has been more pressing than ever. The ambition of the Paris Agreement (PA) to limit the temperature-rise to 1.5°C above pre-industrial levels compels strategic and comprehensive actions across all sectors, including agriculture. In 2019, Agriculture, Forestry and Other Land Use (AFOLU) was accountable for 22% of total global emissions according to the IPCC report in 2023 (Calvin et al., 2023). Excluding land use, land use change and forestry, the European Union estimates that 11% of its emissions in 2021 are from agriculture (French Ministry of the Energy Transition, 2023). Likewise, the US reported a 10% contribution of agriculture to its total emissions (US EPA, 2015). Global emissions are predicted to increase as the world's population continues to rise and the demand for food along with it. By 2050, the food sector must reduce its absolute emissions by 80% despite the increase in demand for production (WWF, 2024). On the other hand, the IPCC urges for the implementation of strategies to reach net zero emissions globally by 2050 in order to limit global warming to an additional 1.5°C (Calvin et al., 2023). Faced with these challenges, the agricultural sector must transform its practices and systems at a substantial and rapid scale to be aligned with the 1.5°C pathway.

However, barriers, such as immense scale and heterogeneity of agricultural production systems, must first be overcome to achieve emission abatement targets. Thousands of different species of plants, fungi and animals (including breeds) are cultivated, raised or caught for food while hundreds of millions of farmers work on the field. Each production system has different sources of greenhouse gases and to different extents. For instance, enteric fermentation is the leading source of cattle GHG emissions whereas nitrous oxide emissions during fertilizer application is the primary source in row crops. Moreover, the heterogeneity mentioned is compounded by the dependency of emissions on geography (soil, climate, water, etc.), type of production system and more leading to a ten- to hundred-fold differences (WWF, 2024). On top of those higher-level constraints, farmers who are pivotal to the sustainability transition of agriculture currently lack adequate incentives to embrace novel methods and technologies (McKinsey & Company, 2023).

Besides climate change and decarbonization matters, agriculture cannot be disconnected from its impact to nature and society when discussing sustainability (McKinsey & Company, 2023). Ritchie and Roser (2024) report that agricultural land spans half of all inhabitable areas and accounts for 70% of freshwater extraction.

Furthermore, Benton et al. (2021) pinpoint that current food production systems are the main cause of global biodiversity decline, with escalating impacts on biosphere health, human well-being, and food availability. Six out of the nine planetary boundaries have already surpassed the tipping point where irreversible consequences may be experienced as outlined by the Stockholm Resilience Centre (Stockholm Resilience Centre, 2023). The ones crossed include climate change, biosphere integrity, land system change (i.e., land use change), biogeochemical flows (i.e., phosphorus and nitrogen cycles), freshwater change and novel entities. The remaining three are ocean acidification, atmospheric aerosol landing and stratospheric ozone depletion. Therefore, it is also imperative to discuss trade-offs along with benefits related to decarbonization actions.

As there are only 26 years remaining before 2050, individual producers, farms and companies cannot work in silos, squandering time and resource on the same mistakes. In contrast, knowledge should be shared so that mitigation strategies can be applied to where they are pertinent and can be successfully applied based on geography, type of operations and scale (WWF, 2024). By examining the factors behind variations in emissions and identifying pivotal interventions for each commodity, key production systems, geographic areas, sources of emissions for intervention and motivations can be pinpointed to accelerate change for climate mitigation. Therefore, this master’s thesis aims to contribute by comprehensively assessing GHG emissions, determining the principal sources of emissions, and identifying agricultural interventions with high GHG abatement potential, all of which are commodity-specific and focused on crucial crops to the modern human diet, such as rice and cocoa.

2. STATE OF THE ART (Literature Review)

2.1. Current agricultural emissions landscape

According to the report entitled "The agricultural transition: Building a sustainable future" published recently by McKinsey & Company (2023), the agricultural and LULUCF sector must cut down its overall emissions by approximately 80% from 14.4 to 3.1 Gt carbon dioxide equivalents (CO_2e) by 2050 (Figure 1) to be on track with the 1.5°C pathway. As this paper focuses on commodity-based climate roadmaps, only two levers identified above are tackled: (1) sustainable food production and (2) land conservation, including natural carbon sinks. Nevertheless, these two levers still comprise 9 Gt CO_2e or 82% of the total emission reduction target.

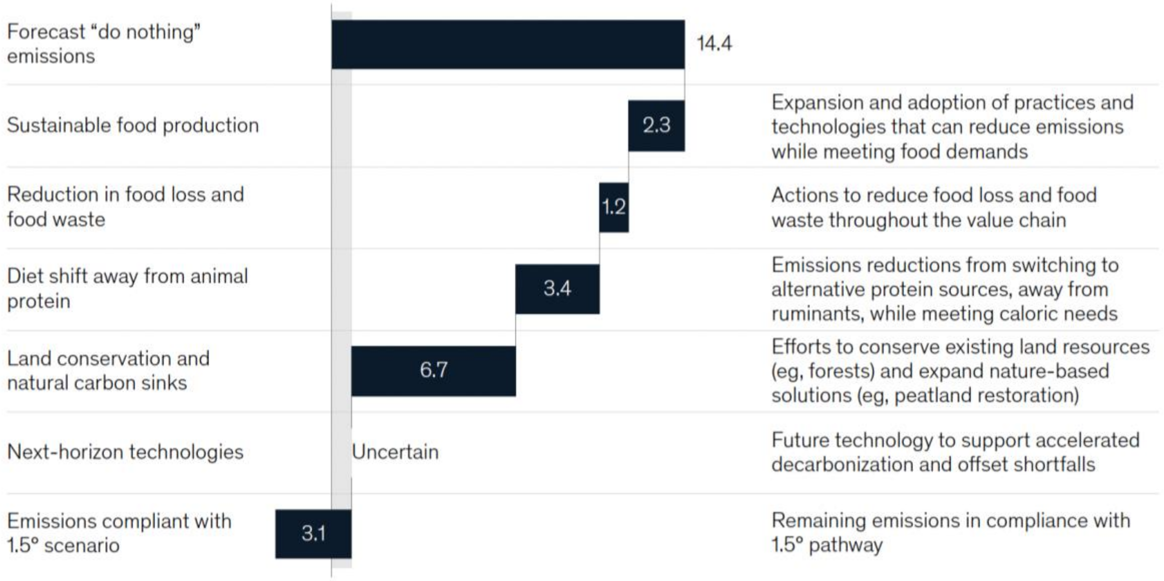

Figure 1. Levers to abate forecasted emissions of the agricultural and land use, land-use change and forestry (LULUCF) in 2050 expressed in $GtCO_2e$[1] according to GWP AR6 100Y[2] conforming to the 1.5°C pathway (McKinsey & Company, 2023).

[1] *Metric gigatons of carbon dioxide equivalent*

[2] *Global warming potential as summarized in the 100-year scenario of the IPCC Sixth Assessment Report.*

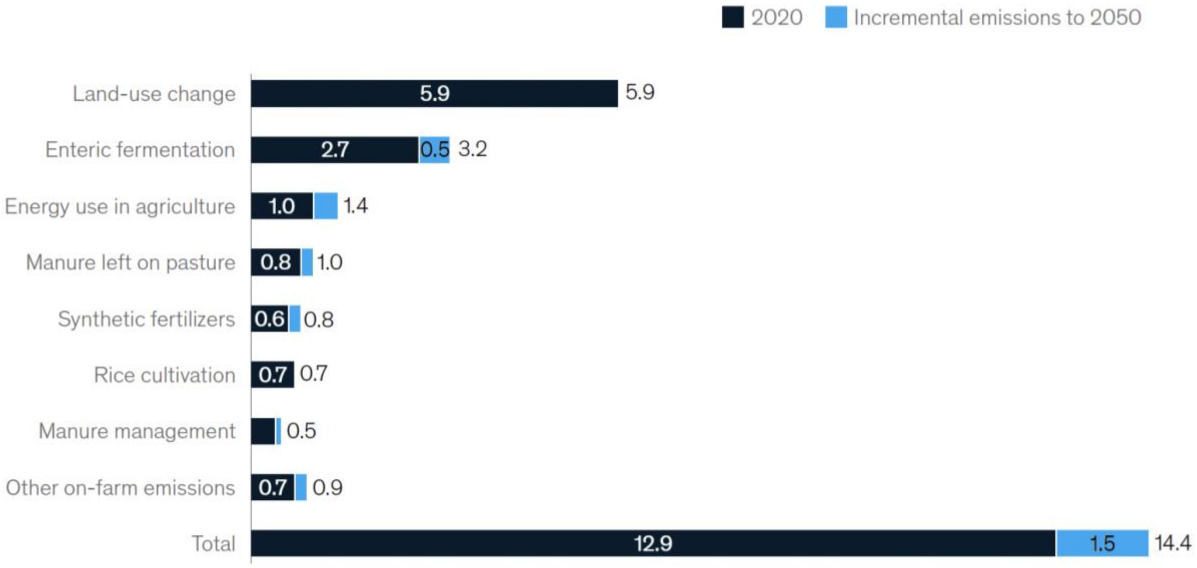

Figure 2. Projected global greenhouse gas emissions from agricultural activities per emission source in 2050 expressed in $GtCO_2e$ according to GWP AR6 100Y(McKinsey & Company, 2023).

McKinsey & Company (2023) reported 3 main sources of emissions, accounting for an estimated 74% of the total emissions. Thus, targeting these 3 main areas has great potential for significant reductions. With 5.9 Gt CO_2e in 2020, the primary source of emissions is land-use change (LUC) which are those associated with the conversion of land for agricultural purposes. Forests have been cleared to pave way for more row crops, livestock and feed production. Other LUC examples include peatland and grassland conversion into agricultural fields. It is noted that 33% of the Earth's ice-free land is currently employed for feed production while 26% is for livestock grazing (FAO, 2013). To be in line with the 1.5°C pathway, LUC, particularly deforestation should be monitored closely and halted immediately.

Enteric fermentation with a forecasted 3.2 Gt CO_2e emissions in 2050 comes second. It is defined as the methane emitted by ruminants such as cattle, goats, and sheep during their digestion process. Methane significantly augments the carbon footprint of ruminants compared to other sources of protein, e.g., poultry, seafood, and plant-based proteins. Third is energy utilised in agriculture with an estimated 1.4 Gt CO_2e emissions in 2050. It refers to on-farm emissions linked to energy production, mainly fuel combustion as well as electricity generation. Synthetic fertilizers from production to application also contribute significantly to the total emissions with 0.6 Gt CO_2e emissions in 2020 and an additional 0.2 Gt CO_2e emissions by 2050 (McKinsey & Company, 2023).

2.2. Net zero emissions in agriculture

Several studies aimed to investigate how net zero emissions can be achieved in the agricultural sector and to what extent can it be attained.

Rees et al. (2020) reported that in contrast to other sectors, agriculture cannot entirely reach net zero emissions alone through on-farm interventions that reduce mainly methane and nitrous oxide missions. They highlighted the crucial role of land use sector, (i.e., afforestation, reforestation, conversion of degraded land into silvopasture, etc.) in mitigating residual emissions. "Biomass energy with carbon capture and storage (BECCS)" presents the greatest potential for CO_2 capture, while other methods like enhanced soil carbon sequestration, mineral weathering, biochar application, and direct air capture are also being investigated. Similarly, Teske & Nagrath (2022) who examined global net zero targets in "agriculture, forestry and harvested products" concluded the improbability of the agriculture sector to achieve net zero by 2050, whereas the forest sector can transform into carbon sinks (i.e., carbon negative).

A more recent study by Rosa & Gabrielli (2023) reviewed the current available technologies and innovations to diminish GHG emissions in the agricultural sector. They considered decarbonization of on-farm energy consumption, adaptation of nitrogen fertilizer management measures, implementation of alternative rice farming methods, and application of breeding and feeding technologies to decrease enteric methane emissions. Combining all these measures resulted in a 42% abatement of GHG emissions according to their model. The remaining 3.8 Gt CO_2e/year must be offset using carbon removal technologies. They underscored that although technologies are available, the elevated costs and low scalability hinder its implementation.

Conversely, WWF (2024) and McKinsey & Company (2023) indicate that agricultural production could reduce its emissions by 80% (from 14.4 Gt CO2e to 3.1 Gt CO2e) by 2050. The remaining 20% of emissions can be mitigated by shifting diets away from animal protein, decreasing food loss and waste, and adopting nature-based solutions such as afforestation, wetland restoration, and agroforestry.

Overall, the literature indicates that achieving net zero in the agricultural sector requires the implementation of carbon removal strategies such as BECCS, enhanced soil carbon sequestration (e.g., agroforestry, no tillage, cover cropping, etc., biochar application), nature-based solutions, in addition to greenhouse gas reduction methods across the entire value chain.

2.3. Selection of crops and countries for the study

This study not only aims to develop climate roadmaps but also focuses on investigating the similarities and differences in the agricultural interventions that can be applied to annuals and perennials.

In agriculture, crops can be categorized into two main types: annuals and perennials, depending on the duration of their life cycles (Friedman, 2020). Annual plants live for a single season, during which they grow, produce seeds, begin senescence, and die (Poppenwimer et al., 2023). These plants are associated with seed dormancy traits, implying that in stressful environmental conditions, the seeds enter the soil seed bank and remain dormant until conditions improve; hence, enabling annuals to have a brief juvenile phase and quickly produce seeds, aiding species survival (Lundgren and Des Marais, 2020). According to FAO (2023), cereals were the most produced group of crops globally in 2022, with a total output of 3.1 billion tonnes. In this group, maize (*Zea mays*), wheat (*Triticum aestivum*), and rice (*Oryza sativa*) were the three most significant crops in terms of production volume (FAO, 2023). Despite their high yields, annual crops demand significant field preparation, tilling, crop management, and frequent agrichemical use to achieve optimal results (Chapman et al., 2022). These intensive agricultural practices contribute to soil degradation, loss of biodiversity, and increased carbon emissions, exacerbating the threats posed by climate change (Lal, 2012).

In contrast, perennial plants continue to live for over two years and often regrow from the same roots. The ability to flower and produce seeds numerous times over their lifespan are what mainly sets perennials apart from annuals. (Mauseth, 2011; Pimentel et al., 2012). In agriculture, perennialism offers numerous environmental advantages. Once perennial crops are planted, they can be cultivated and harvested over several seasons, thus, minimizing tillage requirements. In addition, their deep roots contribute to increasing soil organic carbon over time (Paustian et al., 2016; Peixoto et al., 2022). Compared to annuals, perennials tend to exhibit superior nutrient uptake, weed suppression, reduced nutrient leaching, and enhance soil microbial biomass (Glover et al., 2007; Audu et al., 2022). Sugar cane (*Saccharum spp.*), palm fruit (*Elaeis spp.*), coffee (*Coffea arabica*) and cacao (*Theobroma cacao*) are among the most produced perennial crops based on global area harvested in 2017 (Migicovsky & Myles, 2017). While perennials require less intensive management, they are as threatened by climate change as annuals, i.e., via heat and water stress, extreme temperatures, etc. (Hatfield & Walthall, 2014).

2.3.1. Annual crop: paddy rice

Rice (*Oryza sativa* L.) is the third most produced crop in the world with 777 million tons produced in 2022 according to FAO (FAOSTAT, 2023). The world trade was valued at $32.1 billion in 2022 (OEC, 2022b). It is a 32% increase since the beginning of the century (2000). It is a staple food crop for approximately half of the global population. Furthermore, rice serves as a vital food staple, supplying over 70% of the caloric intake for populations in numerous developing nations (Fukagawa & Ziska, 2019).

Asia is the leading producer of rice with China (27%), India (25%) and Bangladesh (7%) being the top producers (CIRAD, 2022; FAO, 2022) as shown in Figure 3. Approximately 91% of global paddy rice production and 90% of area cultivated for rice are located in Asia (Fukagawa & Ziska, 2019). The top three rice exporters to the global market in 2022 were India (35%), Thailand (13%) and Vietnam (10%) (OEC, 2022b). While the percentage share varied slightly in comparison to 2021 (Figure 3) (FAOSTAT, 2023), the major key players remained the same. In contrast, the top three rice importers were China (8%), Philippines (5%) and Saudi Arabia (4%) in 2022 (OEC, 2022b). **As a major rice producer and exporter to the global market, the analyses related to rice will be focusing on India.**

Rice cultivation occupies 11% of the world's arable land and accounts for 10.1% of overall agricultural emissions, along with approximately 1.3%–1.8% of anthropogenic greenhouse gas emissions globally (Meijide et al., 2017; FAO, 2022). The primary source of these emissions is methane released during rice cultivation (US EPA, 2012). Annual methane emissions from rice fields worldwide are estimated to range from 25 to 100 metric ton (t), constituting 48% of total greenhouse gas emissions from croplands worldwide (Carlson et al., 2017; Wang et al., 2023).

Therefore, rice was selected as the annual crop for this study for three principal reasons: (1) its critical role in global food security (especially in Asia, Latin America and Africa), (2) its environmental impact, and (3) vulnerability to climate change. FAO, IPCC AR6, Friedlingstein et al. (2020) identified rice cultivation as an individual, significant source of emissions with 0.7 Gt CO_2e in 2020 as illustrated in Figure 2 (McKinsey & Company, 2023). Additionally, the researcher is originally from the Philippines, where rice holds significant economic value as a cash crop – accounting roughly 23% of total agricultural production value (PhilRice, 2023). Therefore, rice emerges as a pertinent crop for this study on multiple levels.

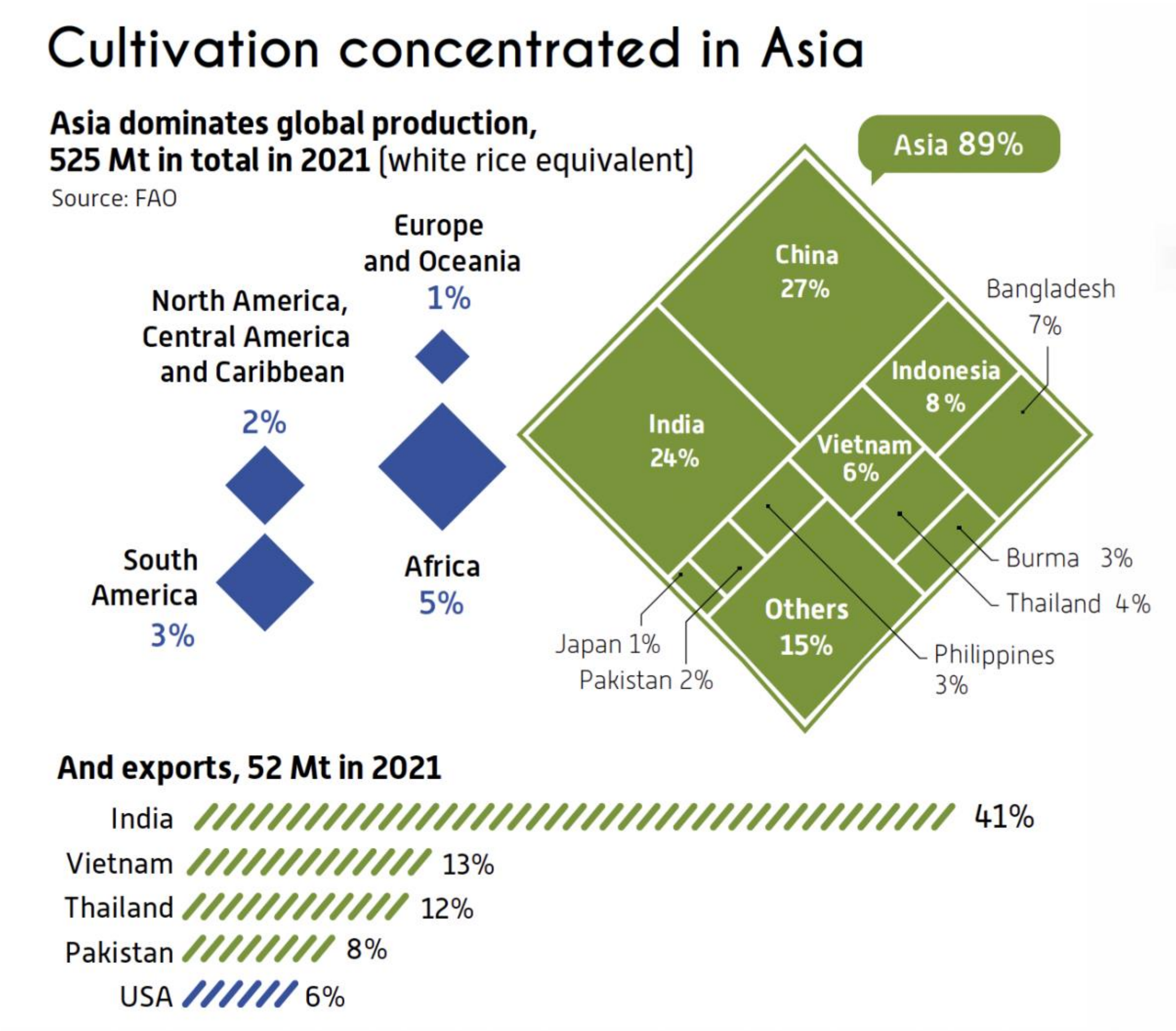

Figure 3. Infographic on the production and exportation of rice in the global market (CIRAD, 2022).

2.3.2. Rice production systems

A synoptic review by Asian Development Bank Institute (Reddy & Rahut, 2023) on the multifunctionality of rice underscores the adaptability of the crop to diverse agroclimatic conditions worldwide. These conditions span from exceptionally wet regions to exceedingly arid deserts. For example, Myanmar's Arakan coast experiences an average precipitation exceeding 5,100 millimeters (mm) during the growing season, whereas Saudi Arabia's Al-Ahsa Oasis receives less than 100 mm of rainfall. Furthermore, rice demonstrates resilience across a broad spectrum of temperatures, ranging from 17°C in Otaru, Japan, to 33°C in Sindh, Pakistan. It thrives under solar radiation levels ranging from 25% in Myanmar, Thailand, and India to 95% in Egypt and Sudan, as well as at altitudes of up to 2,600 meters above sea level in Nepal (Neue & Sass, 1994; Sass & Fisher, 1997; Global Rice Science Partnership, 2013).

A classification of rice production systems was created based on water regimes, temperature and landscape of the region, i.e., rainfed lowland, upland, irrigated and flood prone (Greenland, 1997). These four categories are widely used such as by the International Rice Research Institute. Over half of the rice-growing land utilizes irrigation, while the rest relies on rainfall, particularly in lowland regions. Across Africa and Latin America, rice cultivation predominantly occurs in upland areas, with less than 20% benefiting from irrigation (Reddy & Rahut, 2023). Conversely, in Europe, the United States, and Australia, rice cultivation takes place exclusively in irrigated regions (Papademetriou et al., 2000). An illustration of various rice cropping systems is provided in Figure 4.

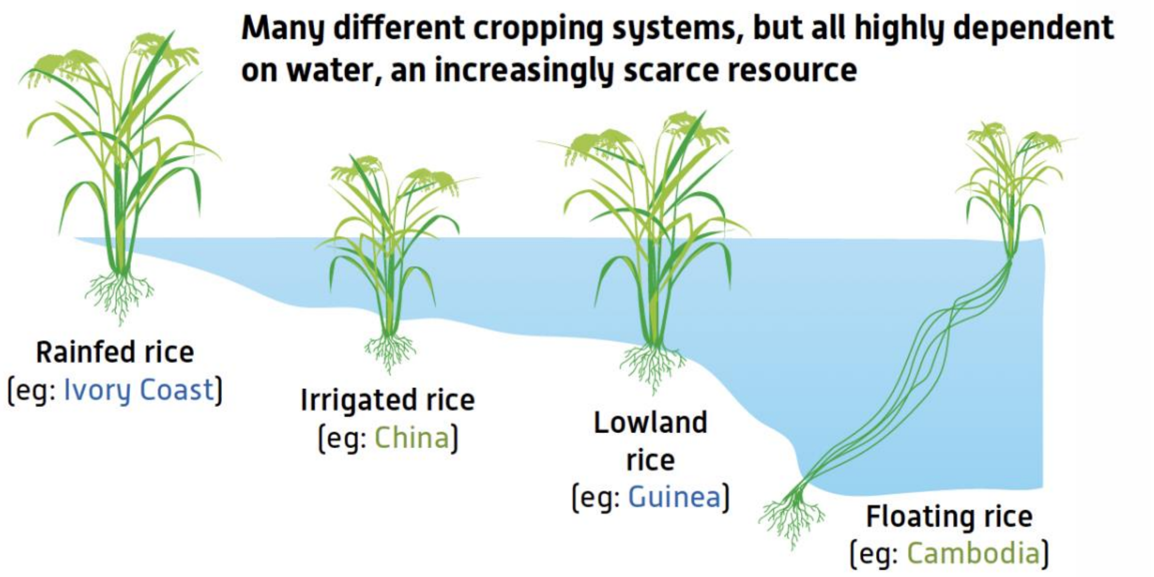

Figure 4. Rice cropping systems (CIRAD, 2023).

2.3.3. Yield: Paddy Rice

Although rice production surged after the Green Revolution, there remains a gap between its actual and potential yields. Rice can yield between 10 metric tons per hectare (t/ha) under tropical conditions and 13 t/ha under temperate conditions, however, actual farm-level yields typically fall below 5 t/ha as reported by (Papademetriou et al., 2000). Scientific research efforts are ongoing to decrease the yield gap through the development of higher yielding cultivars. Modifications in agronomic practices are also taking place to boost yields while reducing pressures on natural resources like water. For instance, Bangladesh substituted deep water rice with Boro rice that can be cultivated during dry season in South Asia (Reddy & Rahut, 2023). Approaches such as system of rice intensification (SRI) (where irrigation is tailored to meet the specific water needs of the crop without flooding), direct seeding and aerobic rice are also being developed to address the mentioned issues. However, their lower yields and higher costs render them non-competitive still compared to other systems (Riaz et al., 2020).

2.3.4. Environmental Challenges: Paddy Rice

Rice production face challenges such as monocropping, water intensity, decreasing number of farmers, climate change and overapplication of nitrogen fertilizers. Rice monocropping has been a practice for decades as the conversion of rice fields to cultivate other crops are costly and arduous (Adusumilli et al., 2017; Reddy & Rahut, 2023). Not only does the soil have poor drainage, but it has also undergone field levelling and bunding (Figure 5). Consequently, farmers persist with cultivating rice on the same plots for extended periods and the modest yield enhancements are only brought by elevated fertilizer application. However, this approach not only escalate expenses but also exacerbates soil deterioration and water pollution (Papademetriou et al., 2000).

Figure 5. Rice field leveling with animals (A); field leveling with tractor (B); bund construction (C) (Rice Knowledge Bank, n.d.).

Furthermore, rice is one of the most water-intensive crops. Water-use efficiency remains low in this sector as indicated by the ratio of water to rice (5000 L/kg of rice) whereas available water in Asia has declined by 40 to 60% (Papademetriou et al., 2000). Meanwhile, the diminishing profits and rising age of farmers impact the rates of technology adoptions alongside efficient resource utilization (Deshpande & Prabhu, 2005). Climate change is also expected to disturb water resources available for rice production (Mushtaq et al., 2013).

Another problem in the rice sector is the overapplication of nitrogen fertilizers. Extensive studies conducted at the International Rice Research Institute revealed that significant rice yields can be achieved without relying on nitrogen fertilizers, owing to rice's considerable biological nitrogen fixation (BNF) capacity (Ladha et al., 2016; Adusumilli et al., 2017). Ladha et al. (2016) estimated that rice cultivation provides 40 kg of nitrogen/ha/season from BNF, atmospheric deposition and irrigation water. It is attributed to paddy soils minimizing water percolation combined with flooding irrigation averting nutrient leaching downward to deeper soil horizons (Chivenge et al., 2020). Chivenge et al. (2020) supported the idea and reported the flooded soil conditions is conducive to biological nutrient cycling in the context of rice production. An analysis of the top three major cereal crops based on quantity (i.e., maize, rice and wheat) by ADBI (2023) revealed that only rice exhibits a positive nitrogen balance. This can be attributed to the lower nitrogen content in harvested rice grain compared to the other two cereal crops in addition to BNF (Reddy & Rahut, 2023). Nevertheless, farmers in Asia continue to apply increasing amounts of nitrogen since 1970s, leading to eutrophication and other forms of soil and water contamination (Ladha et al., 2016; Adusumilli et al., 2017).

2.3.5. Impact of Rice on Climate Change

Flooded rice fields are significant sources of methane emissions, and the application of nitrogen fertilizers releases nitrous oxide, both of which are greenhouse gases contributing to global warming (FAO, 2024). The mechanisms contributing to methane release from submerged rice fields into the atmosphere comprise methane generation within the soil by methane-producing microorganisms (methanogens), methane consumption within oxygen-rich regions of the soil and flooded areas by methane-consuming microorganisms (methanotrophs), and the upward movement of the gas from the soil into the atmosphere. Methane emerges as the final byproduct in various anaerobic microbial decomposition pathways (Holzapfel-Pschorn & Seiler, 1986). The main process facilitating methane release from rice paddies is plant-mediated transport, wherein up to 90% of methane is conveyed to the atmosphere via the aerenchymal system of rice plants (Cicerone & Shetter, 1981).

The type of rice cropping system has an impact on its emissions (Wassmannu et al., 2001). According to a paper under the "Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories" of the IPCC (2006), the emission per square meter and season is arranged as follows: irrigated rice surpasses continuously flooded rice, which exceeds flood-prone rainfed rice, deepwater rice, drought-prone rainfed rice, and tidal rice in terms of emissions. Upland rice, which is cultivated in aerated soils and are not flooded for extended periods of time (Neue &

Sass, 1994). Nevertheless, this hierarchy merely offers an initial evaluation of emission potentials that may be overridden at the local level by crop management practices that either enhance or reduce actual emission rates (Wassmann et al., 2001).

Although there are many factors that can affect emissions of a paddy rice field, the greatest methane emissions occur in fields where organic amendments are applied. In contrast, the lowest methane emissions are detected in fields characterized by minimal residue recycling, frequent aeration intervals, impoverished soils, and limited fertilizer application, leading to suboptimal rice growth and reduced yields (Neue & Sass, 1994).

2.3.6. Perennial crop: cacao

Similar to rice, cacao (*Theobroma cacao*) was chosen as the perennial crop for this study due to its economic importance, role in global food supply, environmental impact and susceptibility to climate change phenomena. In the first quarter of 2024, it has been reported that the price cacao skyrocketed 136% between July 2022 and February 2024, which is attributed to high market demand while the supply is low. Western Africa, where more than 70% of cacao are cultivated, has been significantly impacted by adverse climate-related event (Carodenuto, 2019). For instance, excessive, abrupt rainfall in Ivory Coast and Ghana prompted an outburst of black pod disease, a condition causing cacao pods to rot and toughen, and swollen shoot virus (UNCTAD, 2024). This shows how cacao yields have been negatively impacted by climate-related events, i.e., intense heatwaves (heat stress), shifting rainfalls (water stress) and pest and diseases.

Cultivated across the humid tropics, cacao involves approximately 5-6 million farmers, predominantly smallholders. Latest data from FAOSTAT (2022) indicates that cacao production spans 61 countries, yet nearly 90% originates from only seven, notably Ivory Coastand Ghana, which contributed over 60% over the period 2021/2022. The majority of cacao cultivation occurs in West Africa, accounting for 77.3% of the 2020/2021 season's output (ICCO, 2021). Latin America and South/Southeast Asia also yield significant cacao volumes (Daymond et al., 2022).

The global trading of cacao beans is valued at $8.29 billion in 2022. Cote d'Ivoire (40%), Ghana (12%) and Ecuador (11%) were the top exporters, whereas the Netherlands (20%), Malaysia (12%), Germany (8%) and Belgium (8%) were the top importers in the mentioned year (OEC, 2022a). **As the largest producer and exporter of cacao beans in the world, the cacao climate roadmap will be focused on Ivory Coast.**

While cacao and cocoa are used interchangeably in English, they refer to different things. Cacao is the raw material, i.e., the cacao beans harvested from the tree, whereas cocoa is the product that has been powdered, roasted, and ready for direct consumption. Since this paper centralizes on the farm level cultivation of cacao and its unroasted beans, the terminology cacao will be maintained (Lindt & Sprungli, 2021; Merriam-Webster, 2024).

2.3.7. Cacao production systems

WWF Netherlands reported_that over 90% of the world's cocoa output are cultivated on plots ranging from 2 to 5 hectares, i.e., by small-scale farmers (Jennings et al., 2022). Cacao plantations can be managed in a variety of ways, from traditional low-input agroforestry systems to highly intensive monocultures (Recanati et al., 2018). Each production system comes with its own farm management practices. This consequently influences the emissions associated to the production of cacao, particularly the quantity of shade trees and the handling of residues based on the study conducted by (Vervuurt et al., 2022).

Management practices in cacao plantations entail the application of pruning, shade regulation, fertilizers and waste management. Common examples of shade trees include timber species like *Cordia alliodora*, leguminous species such as *Erythrina poeppigiana*, and fruit trees like mango, orange and avocado. Shade trees make up a significant portion of the plantation's total aboveground biomass (Dawoe et al., 2016). Pruning waste, along with pod husks and other field residues, are typically either burned or composted (van Vliet & Giller, 2017).

In their report “A Global Review of Cocoa Farming Systems”, the International Cocoa Organization (ICCO) describes 5 major categories which is further divided into 11 systems of cacao farming (Daymond et al., 2022).

Table 1. Five major categories of cacao beans farming systems according to Daymond et al. (2022).

Category	Farm Size	Farming System	Irrigation	Yield (t/ha)	Pesticide Use	Fertilization	Management Practices	Market Type	Locations
Large Plantation	>100 ha	**Fertigated**	Yes	1.5 - 2.5	Bulk	High use for pest control	High, through fertigation	Bulk	West Coast of Ecuador, Brazil, Dominican Republic
		Non-irrigated	No	>1	Bulk, Fine Flavor	Moderate to high use depending on pests	High, synthetic fertilizers	Bulk, Fine Flavor	Java, Indonesia
Medium Plantation Mixed Cropping	20 - 100 ha	**Mixed Crop with Cocoa**	No	0.6 - 1	1	Bulk	Moderate use, integrated pest management (IPM)	Bulk	Ivory Coast, Brazil, Ecuador
		Intercropped Cocoa	No	0.6 - 1.2	1.2	Bulk	Moderate use, often IPM practices	Bulk	Ivory Coast, Brazil, Ecuador
Structured Intercrop Small Holding	~1 ha	**Well-managed Intercrop, non-irrigated**	No	1 - 1.5	1	1.5	Bulk (Unfermented/Fermented)	Bulk (Unfermented/Fermented)	Indonesia, Peru
		Irrigated Intercrop	Yes	0.525 - 0.95	Bulk Fermentation	Low to moderate, IPM	Moderate, often organic	Bulk Fermentation	India
Well-managed Small Holding	1 - 5 ha	**Full-sun Farms (CCN 51)**	No	>1	No	>1	Bulk (Fermented)	Bulk (Fermented)	Ecuador
		Light shade	No	0.8 - 1.2	0.8	1.2	Bulk Fermented	Bulk Fermented	Ghana, Ivory Coast
Traditional Small Holding	Small to Medium	**Cabruca-biodiverse shade**	No	0.12 - 0.18	0.18	Bulk (Fermented/Unfermented)	Low, due to natural biodiversity	Bulk (Fermented/Unfermented)	Brazil (Bahia), Costa Rica, Cameroon
		Fine flavor producing	No	0.1 - 0.5	Fine Flavor	Low, minimal pesticide use	Low to none, minimal inputs	Fine Flavor	Ecuador
		Rustic-limited management	No	0.2 - 0.4	0.4	Bulk Fermented	Low, minimal pesticide use	Bulk Fermented	Ghana, Ivory Coast

While precise estimation of the global distribution of cacao bean production across different production systems remains challenging, FAO provides comprehensive data on the leading cacao-producing countries (Table 2).

Table 2. Top ten countries producing cacao beans in 2022 based on production quantities with corresponding area harvested and yield (FAOSTAT, 2023).

Ranking (Production)	Row Labels	Production (t)	Area harvested (ha)	Yield (t/ha)
1	Ivory Coast	2230000	4397047	0.5072
2	Ghana	1108662.93	2007417	0.5523
3	Indonesia	667296	1442403	0.4626
4	Ecuador	337149.41	509179	0.6621
5	Cameroon	300000	621611	0.4826
6	Nigeria	280000	1020906	0.2743
7	Brazil	273873	590232	0.464
8	Peru	171176.75	177350	0.9652
9	Dominican Republic	75900	2945	25.7764
10	Colombia	62158	185459	0.3352

2.3.8. Yield: Cacao Beans

Cacao productivity, measured by yield per unit area, exhibits significant variability across farms and from year to year. Six primary factors influencing on-farm productivity include the cultivated variety, soil quality, farming practices, farm age, abiotic elements (such as climate), and biotic elements (such as pests, diseases, weeds, and parasitic plants) (Deheuvels et al., 2012). These factors are interconnected. For instance, an improved variety may only achieve optimal yield in fertile soil and favorable climatic conditions, while effective control methods and farming practices can mitigate the impact of pests and diseases, especially when combined with the adoption of disease-resistant varieties (Daymond et al., 2022).

2.3.9. Environmental Challenges: Cacao Beans

The cacao sector faces several challenges such as high yield losses due to pests and diseases, escalating deforestation, soil degradation and reduced water availability. Monocropping renders cacao trees vulnerable to pests such as Cocoa Swollen Shoot Virus (CSSV) and mirids. An estimated 30-40% of crops are lost to these infestations and diseases (Aikpokpodion, 2019). To combat this issue, farmers employ numerous pesticides, detrimental to both the environment and their health. For instance, the government of Ghana provides fungal and pesticide application to the farmers through the COCOBOD board (Daymond et al., 2022). This practice adversely affects biodiversity, which is rapidly diminishing in numerous cocoa-producing areas. This poses a threat to cocoa production, as cocoa relies on insects for pollination (Arnold et al., 2018).

Kroeger et al. (2017) account that cacao cultivation is responsible for 1% of deforestation in the world from 1998 to 2008, amounting to 2 to 3 million hectares deforested. World Resources Institute (2019) also reports that Ivory Coast and Ghana, major cacao producers, reported 26% and 60% percent increase of primary forest loss over the period 2017 to 2018 (Figure 6). Expanding cacao farms and illegal mining were identified as significant contributors to massive primary forest loss in these countries (Weisse & Goldman, 2019). Within the cacao sector, it is reported that aging cacao trees (which produce lower yields), increasing market demand and insufficient investment in smallholder farmers (skills, finance and management related) are driving deforestation (Jennings et al., 2022).

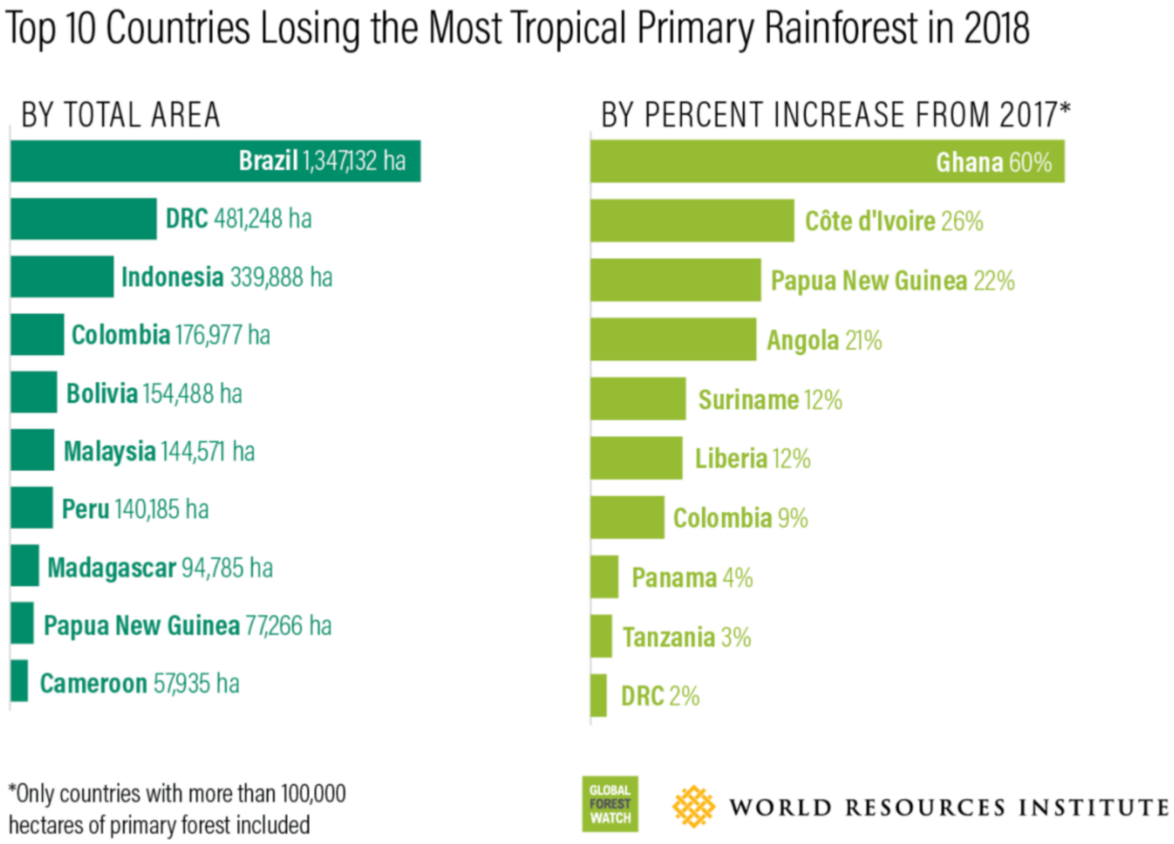

Figure 6. Top 10 countries with highest deforestation of tropical primary rainforest in 2018 (Weisse & Goldman, 2019).

Soil degradation is another reported issue in the sector. Without healthy soil, plants are unable to bear fruits abundantly and have weakened immune system (Kibblewhite et al., 2007). Subsequently, farmers are becoming more and more reliant on chemical inputs such as fertilizers to boost or maintain their yields while minimizing loss due to pests and diseases. Moreover, water is also becoming a pressing matter for cacao farmers. It is forecasted that some regions in West Africa will no longer be able to grow cacao due to less water availability (Schroth et al., 2016).

2.3.10. Impact of Cacao Production on Climate Change

A study conducted by scientists from Wageningen University in the Netherlands estimated that the production of 1 kg of cacao beans in Ivory Coast produces 1.47 kg CO_2e. Deforestation significantly contributed to greenhouse gas emissions, whereas tree biomass and residue management primarily facilitated carbon storage. The climate impact of cacao production is closely linked to farm management practices, particularly the number of shade trees and how residues are handled. Emissions calculated for good agricultural practices were 2.29 kg CO_2e per kg of cacao beans. The increased emissions resulting from the use of additional agro-inputs and residue management practices, like burning residues for sanitary purposes, were not offset by higher yields (Vervuurt et al., 2022).

Conversion of forests to cacao farms, the burning of organic material (a prevalent practice in current cacao production), and the application of fertilizers are linked to greenhouse gas emissions (Ledo et al., 2018). In contrast, perennial crops like cacao have the ability to sequester carbon in their aboveground biomass (Dawoe et al., 2016; Schroth et al., 2016) and contribute to soil carbon through plant roots and litter, which decompose and later becomes soil organic carbon (Ledo et al., 2018).

2.3.11. Potential Impact of Climate Change on Paddy Rice and Cacao Production

Climate change affects agriculture by altering precipitation patterns as well as rainfall intensity and distribution. Farmers are compelled to adjust cropping patterns due to delayed monsoons, heightened drought frequency, and increased pest and disease occurrences (Mushtaq et al., 2013).

The primary impact of climate change on rice production is evident in shifts in water resources (Adusumilli et al., 2017). Subtropical regions are anticipated to experience decreased precipitation, with a potential increase in extreme events, thus diminishing water availability for rice farming. Concrete measures are imperative to conserve water and enhance water utilization efficiency (Schroth et al., 2016). Moreover, changes in temperature and ocean levels can profoundly impact rice cultivation. Raised temperatures may diminish rice yields in tropical regions, while altered rainfall patterns could increase the frequency and severity of floods and droughts (Toriyama et al., 2005). On the other hand, increasing sea levels may expand the areas affected by tidal surges, particularly in low-lying floodplains and river deltas where various rice cultivation methods are prevalent, notably in East Asia, Southeast Asia, and South Asia. To ensure sustainable rice production amidst climate change, ongoing advancements in rice varieties will likely be essential in addition to the mentioned strategies (FAO, 2024).

Similar to the rice sector, cacao cultivation is also expected to be negatively impacted by rising temperatures and decreasing precipitation, particularly in West Africa (Ofori-Boateng & Insah, 2014).

Schroth et al. (2016) reports that climate change may lead to a substantial reduction in the regions suitable for cocoa farming in West Africa, which currently accounts for 65% of global production. This decline is expected to be caused to a higher extent by drying conditions than a temperature rise of approximately 2°C by 2050 (Schroth et al., 2016). With less suitable land for cocoa cultivation due to drying phenomena, the West African region is expected to encounter challenges in establishing new plantations while facing high mortality rates of young trees (Wessel & Quist-Wessel, 2015). On top of these, there are also risks of increased occurrence of pests and diseases as warmer temperatures and altered precipitation can promote black pod disease, cocoa pod borer and frosty pod rot (Walters, 2021). Consequently, farmers would have to enhance their pest and disease management strategies (Cilas & Bastide, 2020). This is particularly relevant as cacao farmers today lose approximately 30 to 40% of their yield to pests and diseases according to "A Global Review of Cacao Farming Systems" (Daymond et al., 2022).

2.3.12. Agricultural Interventions

Agricultural interventions are specific actions or strategies that target particular challenges and aim achieve specific goals in agricultural systems (Westermann et al., 2018). In this paper, interventions refer to actions targeted to attain climate mitigation or decarbonization goals. McKinsey & Company (2023) identified several agricultural interventions for crops such as paddy rice and cacao beans (Figure 7). Despite a wide array of proposed agricultural interventions in literature, selecting and applying the most suitable interventions while minimizing costs and increasing adoption rates are key to the effectiveness of the applied interventions in reducing emissions and adverse effects on the environment (Moore & Boldero, 2017). Factors such as type of crop, climate, soil, water requirements and availability amongst others must be carefully considered (McKinsey & Company, 2023).

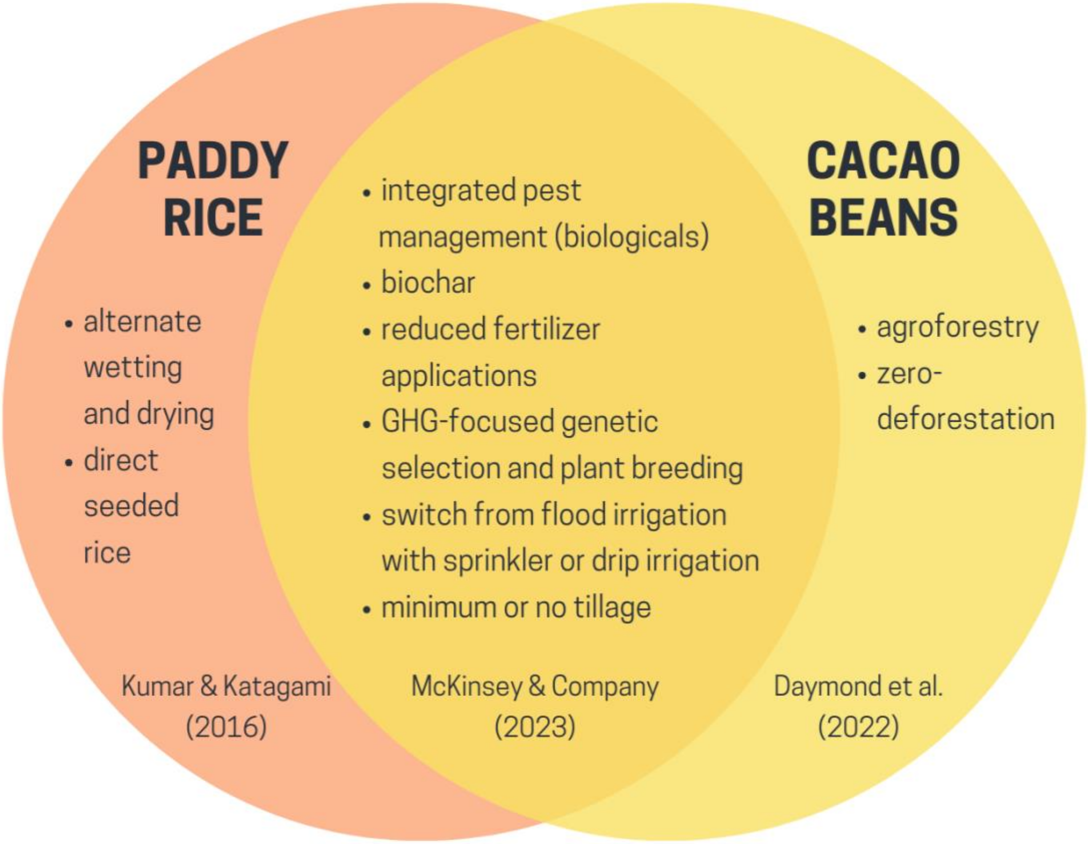

Figure 7. Venn diagram of agricultural interventions available for paddy rice and cacao beans sector.

2.3.13. Significance of the Study

With agriculture contributing substantially to global emissions through the procurement of goods for various industries (particularly for food and beverage sectors), targeted strategies are essential to meet emission reduction goals while ensuring sustainable food production. By identifying emission hotspots and proposing specific mitigation measures tailored to rice and cocoa production in major producing countries, this master’s thesis aims to inform effective interventions that reconcile food security with environmental sustainability.

Furthermore, this study offers valuable insights for climate roadmaps that are commodity- and/or country-specific. A climate roadmap is a quantitative and visual tool demonstrating the impact reduction potential of various interventions for a specific sector or organization (e.g., company) to address targets, such as net zero emissions by 2050 (Loboguerrero Rodriguez et al., 2018). Therefore, this research study contributes to urgent climate change concerns through emphasizing the significance of integrated, sector-specific solutions in achieving global climate mitigation targets by 2050.

2.3.14. Objectives

As of today, there is a lack of insights on how specific commodity or crop sectors can achieve net-zero emissions by 2050 to be in line with the 1.5°C pathway. By evaluating the main sources of emissions on farm level, agricultural interventions that are most relevant, economically feasible and have high GHG abatement potential can be determined to help reduce emissions on the path to net zero. Moreover, this master's thesis seeks to fill in the knowledge gap regarding climate concerns within two critical agricultural sectors: paddy rice (annual crop) in India and cacao (perennial crop) in Ivory Coast. Therefore, this paper aims to (1) thoroughly evaluate GHG emissions and determine the main sources (hotspots) of these emissions, (2) and identify agricultural interventions with significant GHG reduction potential, (3) and evaluate the costs and barriers associated to the implementation of the interventions. Through these objectives, the paper aims to offer actionable insights for fostering resilient and sustainable agricultural practices while assessing the feasibility of each action, thereby illuminating the reduction potentials and priorities for 2050 in the face of climate change.

3. METHODOLOGY

3.1. System boundary

Fundamentally, this study employs a Life Cycle Assessment (LCA) approach to systematically analyze the principal sources of emissions from the two selected sectors and identify pertinent and effective mitigation strategies. The system boundary of this study is **cradle–to–farm gate**, which includes the evaluation of the climate impacts associated with the procurement of agricultural commodities – from the extraction of raw materials and inputs (cradle) up to the point where the commodity leaves the farm (farm gate). This approach assesses all stages included in the agricultural production, i.e., soil preparation, sowing, cultivation, fertilization, irrigation, pest control and harvesting. However, it does not encompass subsequent phases of processing (e.g., milling of paddy rice to remove the hull and transformation of cacao beans into chocolate), packaging, distribution, or use. Thus, this study provides an analysis of the climate impact of rice production in India and cacao production in Ivory Coast up to the stage where the agricultural commodities are ready to be moved for processing or distribution.

Furthermore, unlike life cycle assessments which includes many other indicators, this paper focuses exclusively on climate change impact (i.e., EF 3.1). In LCA, this impact category (climate change) assesses the potential GHG emissions (usually measured in CO_2 equivalents) and their contribution to global warming potential (GWP). It is not part of the scope to include other impact categories such as water depletion, fossil depletion, ecotoxicity and so on. Hence, the discussion is centered on greenhouse gas emissions. Nevertheless, co-benefits and tradeoffs with nature will be discussed.

3.2. Data collection

According to the IPCC’s 4th assessment report, an emission factor (EF) refers to the emission rate per unit of activity, output, or input. It is a coefficient quantifying the ratio between the amount of pollution generated and a measure of activity linked to the pollutant released. For instance, a specific fossil fuel power plant has a CO_2e emission factor of 0.568 kilograms per kilowatt-hour produced (IPCC, 2007b). In this study, EFs were expressed in CO_2e per kilogram of the agricultural commodity produced, i.e., 1 kg of paddy rice (with a standard water content necessary for storage: 13.1%) or 1 kg of cacao beans (with a standard water content of 5.6 %). The EFs of paddy rice were based on data from 2016 to 2022, whereas those of cacao beans are from 2007 to 2017.

Emission factor data including production methods, energy inputs, land use, fertilizer application and other relevant contributors to the emissions were collected from Quantis's World Food Land and Agriculture Database (WFLDB v3.9). It is their most up to date database dedicated to food, land and agriculture. Over a span of more than 12 years, this database has been collaboratively developed in partnership with leading companies in the food and beverage industry. The methodology employed to generate these emission factors is elaborated in the "WFLDB Methodological Guidelines for the Life Cycle Inventory of Agricultural Products" (Nemecek et al., 2023).

To specify, the data collected for this study encompass secondary emission factors (EF) for agricultural and food-related products. While primary emission factors are based on specific activities in the value chain of a company, secondary emission factors are not specific to the company's value chain (Barrow et al., 2013). The study only focused on datasets specific to agricultural commodities, such as paddy rice grain and sun-dried cacao beans. Other components of the plants, such as straws, shells, and husks, were not included as they were beyond the study's scope.

3.3. Identification of key drivers of emissions

After importing the EF datasets, the exchanges (input and outputs occurring within or between the system) comprising the EF that were relevant to agricultural (on-farm) emissions were selected and categorized as contributors (e.g., tillage, machinery, seeds, direct emissions, land use change, etc.) as shown in Table 4 in the appendix. In this paper seeking to analyze emissions factors, contributors are defined as any activity, source or factor that contributes to the total emissions of a specific greenhouse gas or pollutant.

The principal contributors to the emissions within cacao and rice production systems were identified using contribution plots. For example, these plots can show what percentage share of paddy rice emissions at farm level are due to irrigation or methane field emissions. The emission factors were broken down into contributors, e.g., field emissions, land use change, fertilizers production, etc.

The rice EF exclusively considers flooded paddy rice production systems, i.e. assumes 100% paddy rice fields. In the case of India, the second-largest rice producer in the world, another consulting firm estimated that 80% of rice fields practice continuous flooding resulting in high methane emissions (McKinsey & Company, 2022).

Due to copyrights concerns, the absolute EF of each country available in the database could not be revealed, except for the EF of paddy rice cultivation in India and the EF of cacao beans production in Ivory Coast.

3.4. Identification of most relevant agricultural interventions

Based on the findings of the preceding step, several agricultural interventions were established for each crop. Their GHG abatement potential were based on extensive literature review. Criteria for selecting agricultural interventions are GHG abatement potential, applicability and economic feasibility. Barriers to implementation of each intervention was also considered.

4. RESULTS

This section of the paper is dedicated to analyzing and comparing emissions factors (EF) within the paddy rice and cacao beans sectors according to the available data. Examining EFs not only provides insights about the intensity of emissions of a production system (e.g., agroforestry vs non-agroforestry in cacao beans) but also an understanding of the main contributors to the emission from cradle-to-farm gate. Through the identification of the hotspots or main contributors in rice and cacao beans production, it is possible to determine the agricultural interventions that has higher GHG abatement potential at the farm level.

4.1. Paddy rice

4.1.1. Overview and contribution analysis of paddy rice EF

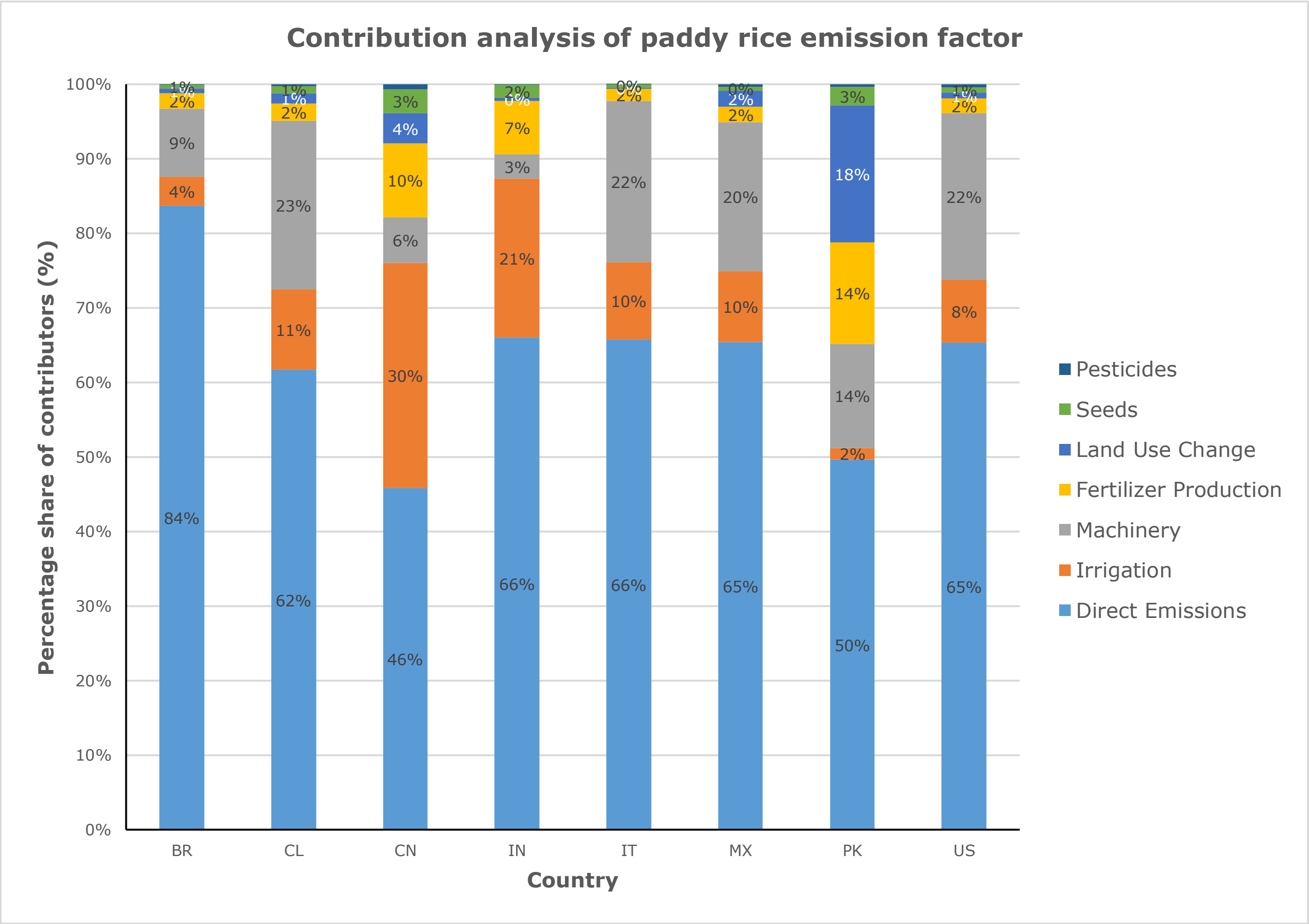

Figure 8. Contributors to paddy rice emission factors (EF) in Brazil (BR), Chile (CL), China (CN), India (IN), Italy (IT), Mexico (MX), Pakistan (PK) and the United Sates (US) expressed in percentage share of the EF (%).

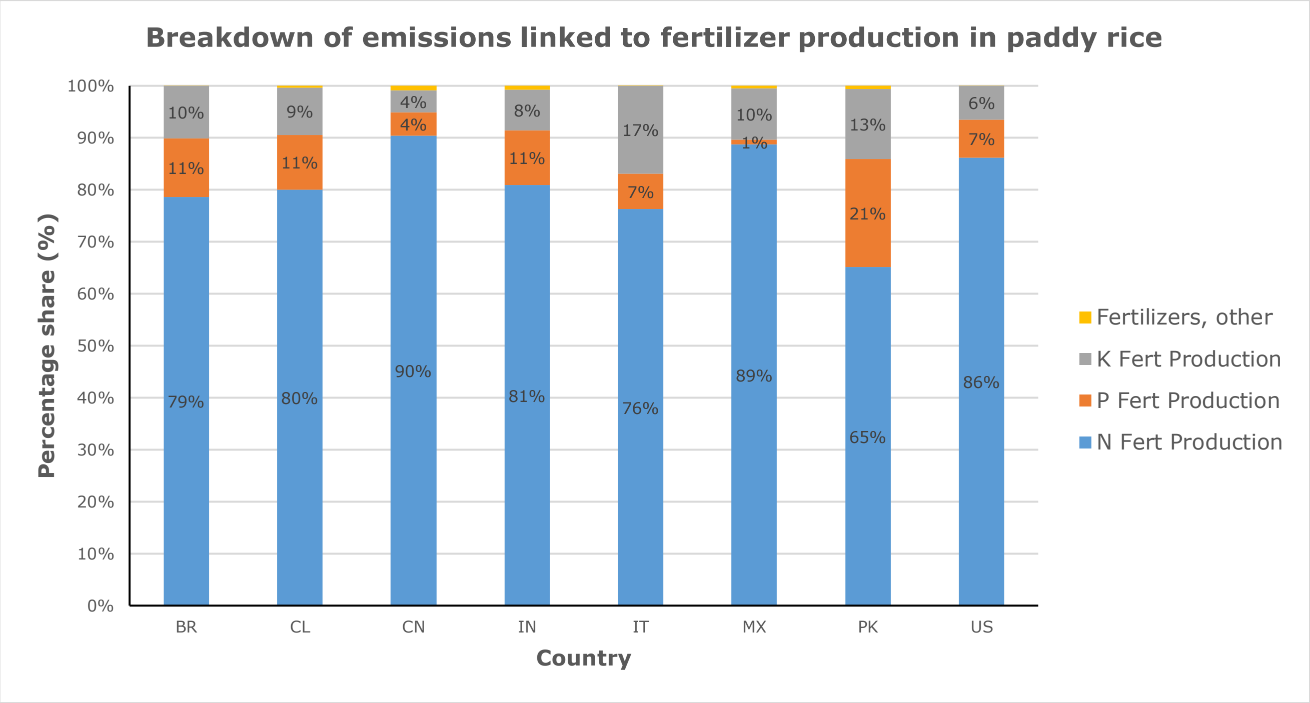

Figure 9. Breakdown of the emissions related to fertilizer production in paddy rice cultivation in Brazil (BR), Chile (CL), China (CN), India (IN), Italy (IT), Mexico (MX), Pakistan (PK) and the United Sates (US) expressed in percentage share (%).

With an average of **63%** share of the total EF value across the eight countries in the dataset, the main contributor to paddy rice cultivation emissions is **direct emissions** from the field (Figure 8). China had the lowest share coming from direct emissions at 46% while Brazil had the highest share at 84%. India is closer to the average at around 66%. Direct emissions associated with rice farming are methane and nitrous oxides. Flooded (paddy) rice fields are conducive to anaerobic microbial pathways, leading to emissions (Holzapfel-Pschorn & Seiler, 1986). On the other hand, the application of nitrogen fertilizers increases the availability of substrates for both nitrification and denitrification, thus, leading to higher production of nitrous oxide in flooded paddy fields (Pittelkow et al., 2013).

The second main contributor is **machinery** with an average of **15%**. Countries that had significantly higher share of their emissions attributed to machinery – with at least 20% share – include Chile, Italy, US and Mexico. In contrast, Brazil (9%), China (5%) and India (3%) had much lower shares from machinery, indicating that rice farming in these countries relies more on human labor and less on machinery. In rice cultivation, machineries are typically used for field preparation, sowing, fertilization, harvesting and irrigation (Nemecek et al., 2023). According to the WFLDB methodology for modeling emission factors (EFs), greater use of machinery is linked to increased productivity and higher yields (Nemecek et al., 2023). For instance, the US yields more than 10 000 kg/ha of rice while India yields around 6 000 kg/ha. Regarding WFLDB rice EFs, carbon footprint of machineries is predominantly due to combustion of fossil fuel (i.e., diesel) and only marginally due to the production of the machinery itself. For soil preparation, sowing, fertilization, harvesting.

At third rank is **irrigation** with an average of **12%**. India and China had higher shares of their emissions linked to irrigation, at 21% and 30% respectively. Meanwhile, Pakistan and Brazil had the lowest shares at 2% and 4% respectively. Italy, Mexico and Chile were closer to the average with 10 to 11% share. The inclusion of irrigation among the top three hotspots in rice cultivation underscores the elevated water demands of rice production. The International Rice Research Institute (IRRI) reports an average of 2 500 L of water to grow 1 kg paddy rice. The reported variability in their studies is high, ranging from a minimum of 800 L to a maximum of 5000 L consumed by rice farming systems (IRRI, 2009). Schreier (2014) reported a narrower threshold for the water requirements of rice: 1900 to 4000 L of water per kg of paddy rice. Bouman (2002) reported that 1 kg of rice cultivated under a system that transplants rice seedlings in puddled soil requires between 3000 and 5000 L of water. Rice requires a lot of water because traditional cultivation systems involve flooding the fields, i.e., paddy fields. Additionally, rice plants have high transpiration rates and need substantial water input at different growth stages (Bouman, 2009).

Fertilizer production is a contributor that is closely tied to direct emissions, particularly due to nitrous oxides emissions following N fertilization. It is shown as a separate category to demonstrate impact of the upstream (manufacturing) side of fertilizers to climate change. With an average of **5%**, (nitrogen, potassium and phosphorus or N-P-K) fertilizer production emerges as fourth major contributor to paddy rice emissions. In India, fertilizer production (7%) is a more significant contributor than machinery.

Despite the higher percentage share of fertilizer production in Asian countries, e.g., India, China and Pakistan (7 to 14%) compared to American and European nations (~ 2%), it does not necessarily imply that they use more fertilizers per kg of paddy rice. However, it can be deduced from Figures 9 that the contribution of N fertilizers to the emissions is significantly higher than that of P and K fertilizers in paddy rice.

This finding that N is the greatest sources of emissions among various types of fertilizers is not unexpected as it is the main fertilizer used to boost crop production (Frink et al., 1999). In rice farming, it has been a common practice to incorporate high quantities of fertilizers, especially N-based ones, to boost yields since the green revolution (Kumar & Katagami, 2016). Although P and K fertilization (direct emissions and production) contributes less to GHG emissions, they also negatively impact the environment through surface and groundwater pollution and soil pollution (Ladha et al., 2016; Adusumilli et al., 2017; Khan et al., 2018).

LUC with **4%** comes at fifth ranking. It considers emissions associated with the conversion of forests and peatland to paddy rice fields. However, the indicated average of LUC was primarily influenced by Pakistan, as LUC was not a significant contributor for most other countries in the dataset (Figure 8). The remaining contributors include seed production and pesticides application.

Overall, the main contributors to paddy rice field production are (1) direct emissions, driven by methane and nitrous oxides; (2) machinery, particularly in mechanized countries like Chile and the US; and (3) irrigation.

As for India, its top three contributors are **direct emissions (66%), irrigation (21%) and fertilizer production (7%**). The EF of paddy rice production in India is approximately 1.5 kg CO_2e/ kg paddy rice. It implies that direct emissions are linked to 0.98 kg CO_2e/ kg paddy rice, while irrigation and fertilizer production are associated with 0.32 and 0.11 kg CO_2e/ kg paddy rice, respectively.

While these areas represent the primary emission hotspots in paddy rice cultivation, they also offer significant opportunities for mitigation of GHG emissions. For instance, there are alternative water management techniques targeting the reduction of direct emissions from the paddy fields.

4.1.2. Gas split of paddy rice EF

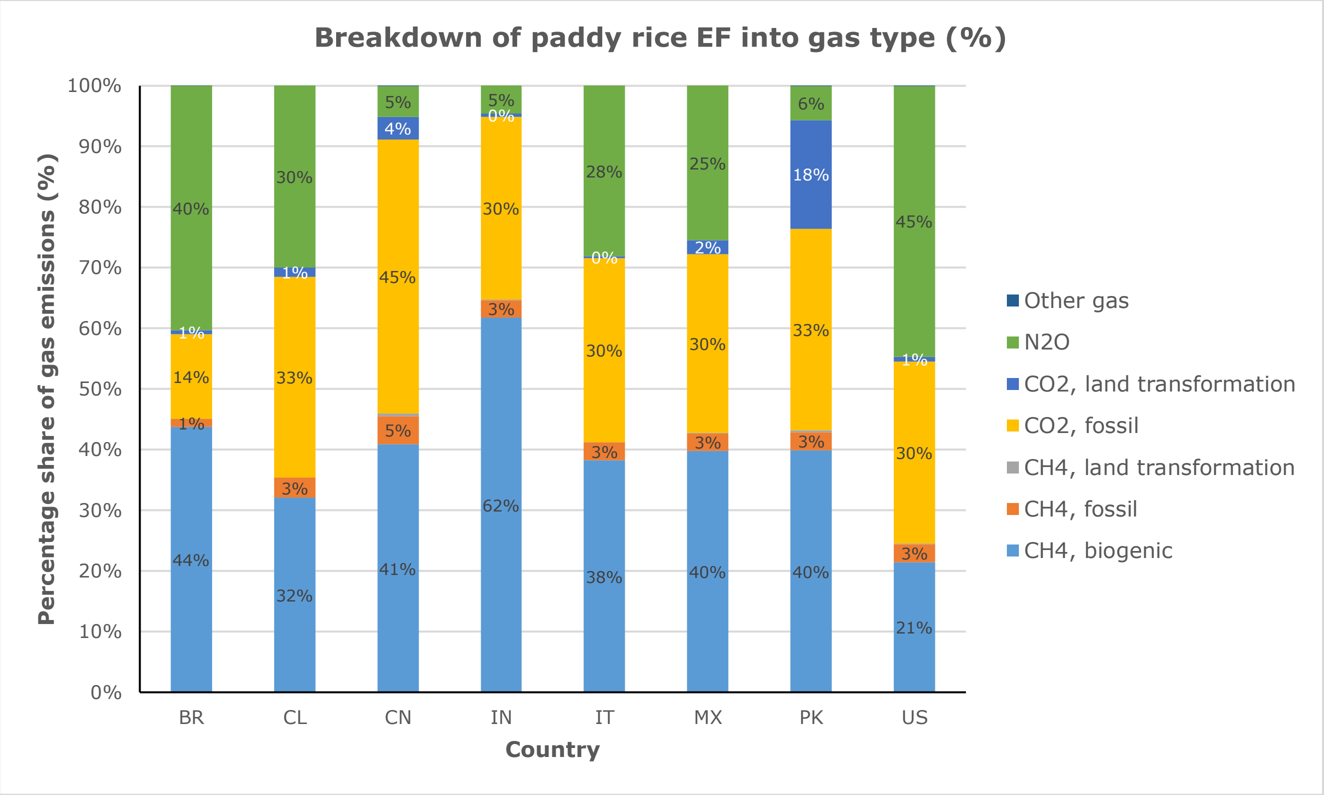

Figure 10. Breakdown of paddy rice emission factors into various types of gases in the following countries: Brazil (BR), Chile (CL), China (CN), India (IN), Italy (IT), Mexico (MX), Pakistan (PK) and the United Sates (US) expressed in percentage share of the EF (%). Other gas category includes HFCs, PFCs, SF6 and NF3.

The quantitative composition and main contributing GHG emitted to the atmosphere by rice farming varies depending according to the country. However, the top 3 most significant gases in terms of share are methane (biogenic), nitrous oxide and carbon dioxide (fossil fuel) as demonstrated in Figure 10.

According to the Ministry of Environment of New Zealand, biogenic methane is generated by biological sources (e.g., plant, animal and microorganisms), and is emitted by wetlands, waste treatment and livestock. In contrast, fossil methane emissions releases back into the atmosphere the geological carbon stored below ground for millions of years. Since rice paddy fields are wetlands, they are sources of biogenic methane emissions (Neue & Sass, 1994).

In India, methane (biogenic) comes first at 62% of its total EF value. Carbon dioxide (fossil fuel) comes second at 30% share while nitrous oxide comes third at 5%. After analyzing the exchanges (input and outputs occurring within or between the system) comprising rice EFs, it was found biogenic CH_4 emissions are primarily driven by the sowing, growth and development of rice seeds in flooded paddy rice fields (i.e., seeds category). On the other hand, the key drivers of CO_2 fossil emissions are the diesel-powered surface and sprinkler irrigation, production of N-P-K fertilizers (particularly, urea, diammonium phosphate and ammonium nitrate phosphate) in the plant, machinery, pesticides and so on. Similarly, N_2O emissions were propelled mainly by N fertilizer production, diesel-powered irrigation, sowing, growth and development of rice seeds in flooded paddy rice fields. This aligns with the findings that N_2O emissions peak during early growth stages of the rice crop, especially right after fertilization (Sass, 2007). Although at a lower extent, machinery also contributes to N_2O emissions. This could help explain why western countries (e.g., such as the US, Brazil and Chile) that use more machineries to cultivate rice had higher share of nitrous oxides compared to India and China. In contrast, the high quantities of rice seeds planted, and the subsequent water and chemical input requirements drive the shares of biogenic methane and fossil carbon in India and China.

Identifying which types of gases primarily contribute to rice EF is crucial since not all gases are created equal. Based on the global warming potential spanning 100 years (GWP_{100}), CH_4 and N_2O are 25 and 298 times more potent as a greenhouse gas than carbon dioxide (IPCC, 2007a). This helps decision-makers and policymakers prioritize and focus efforts on maximizing emission abatement, especially when time and budget are limited.

4.2. Cacao beans

There are several cacao beans EFs modelled according to following production systems:

- Agroforestry is broadly defined, with a portion of shade trees being native forest species and others, like Gliricidia, being planted. In the "agroforestry" cocoa farming model described here, most of these trees are not valued economically but instead offer various ecosystem services.
- Extreme high input farms are typically larger cocoa farms that incorporate irrigation, use advanced planting materials, and apply one tonne or more of fertilizer per hectare. These farms also practice mechanical pruning and achieve yields of 1.5 tonnes or more of cocoa beans per hectare. It is estimated that 10-15% of South America's cocoa production comes from these high input farms, while in Indonesia, they account for only about 5% of total production.
- Improved farms are defined as those that adhere to the official recommendations by the government for the quantities of fertilizers and pesticides applied, leading to a yield increase of approximately 150 kg/ha.

- Low input farms have minimal to moderate shade that lack substantial organization. Many of these farmers apply little to no fertilizers and pesticides, with the modeled scenario reflecting an average condition.
- Medium input, intercropping farms represents typical cocoa farms in South America and Indonesia. These farms utilize higher amounts of fertilizer compared to those in West Africa and cultivate additional crops like fruits, coconut, or rubber trees alongside cocoa. These intercropped trees, which provide light to medium shade, have economic value either for the farmer's use or for sale.
- **Production mix** represents the mix of production systems present in each country based on weighted average cacao market, i.e., considering the total production shares from cacao farming systems utilizing agroforestry, low/medium/extremely high input methods and improved agricultural practices.

For the analyses of cacao beans EF, the focus is on production mix datasets.

It should be noted that none of these datasets (including agroforestry) from WFLDB took into account carbon removal in contrast to the those presented earlier in literature review. This is because WFLDB is meant to be used for corporate inventory accounting, and secondary EF (i.e., not specific to the company’s value chain) are insufficient to meet Greenhouse Gas Protocol (GHGP)’s reporting criteria for removals of the. GHGP is a global framework for measuring, accounting and managing GHG emissions from public and private sector value chains, operations, and mitigation actions (GHGP, 2024).

Moreover, it is difficult to accurately estimate the amount of carbon captured at country level since agroforestry is defined broadly and the sequestration depends on so many factors such as species, age or size, lifespan of the shade tree (Ramachandran Nair et al., 2010).

4.2.1. Overview and contribution analysis of cacao beans EF

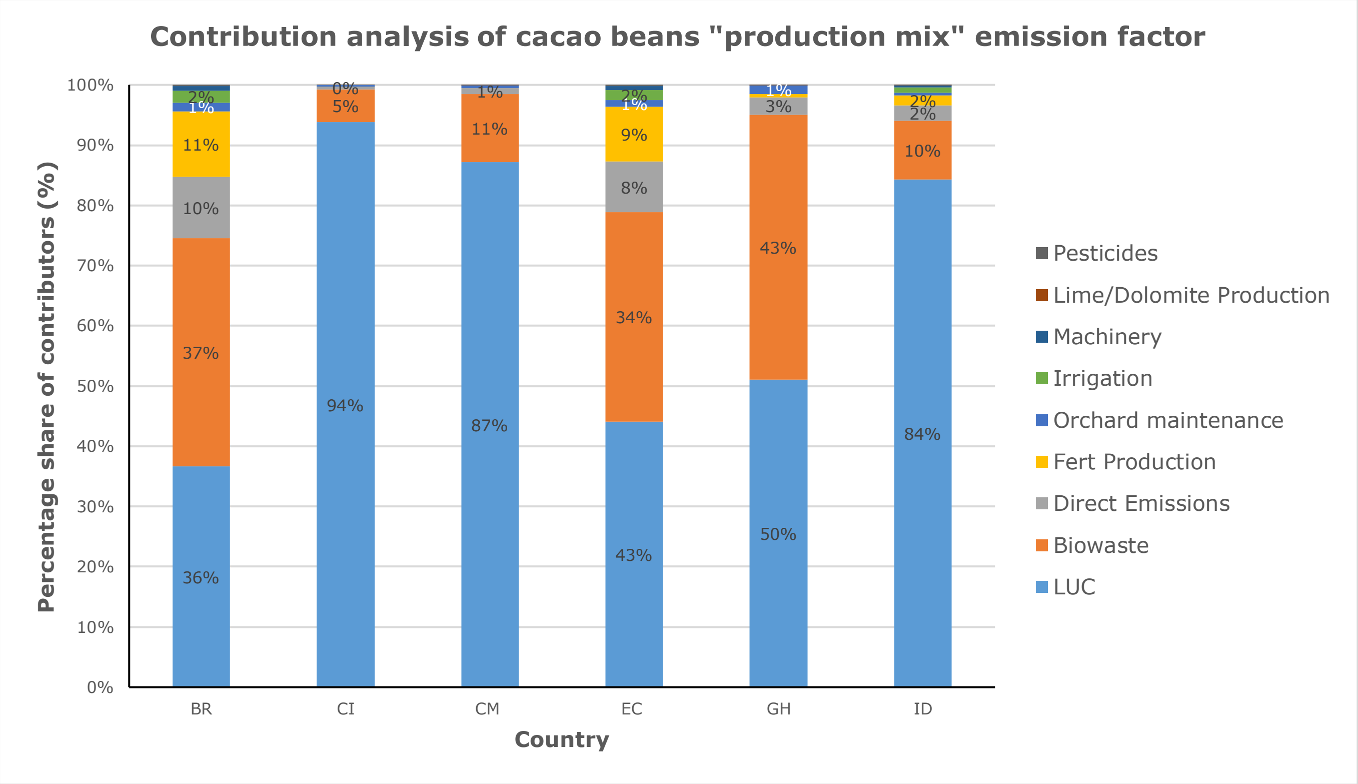

Figure 11. Contribution analysis of the cacao beans production mix emission factor (EF) of Brazil (BR), Ivory Coast (CI), Cameroon (CM), Ecuador (EC), Ghana (GH), Indonesia (ID) expressed in percentage share of the EF (%).

Analyzing the production mix datasets from Figure 11, the top contributor to the GHG emissions of cacao beans is **land use change (LUC)** with an average of **66%**. Ivory Coast with 94% represents the maximum share while Brazil with 36% shows the lowest share in the dataset.

Biowaste management is the second main driver of emissions with an average of **23%**. Even though the biowaste management share appears to vary between countries, the absolute value was constant (~1.9 kg CO_2e/kg cacao beans) across the countries. Only approximately 5% of Ivory Coast’s cacao beans EF can be traced back to this contributor due to the massive impact of LUC in this country.

Direct emissions (4%) and **fertilizer production (4%)** emerge as third main contributors to cacao beans farm-level emissions. The share of these two contributors were higher in Brazil and Ecuador due to lower rates of LUC or deforestation. In contrast, these contributors along with others are dwarfed by LUC in countries with high rates of LUC such as Ivory Coast. Moreover, it should be noted that the relationship between direct field emissions (via fertilizer application), and upstream fertilizer production emissions is interdependent. An increase in nitrogen fertilizer application results in higher field emissions and necessitates greater fertilizer production, consequently elevating upstream production emissions.

Orchard maintenance (corresponding to the emissions associated with the procurement of cacao tree seedling) and **irrigation** each contribute **1%** to the average emissions of production mix systems across the countries in the dataset.

It was also observed in Figure 12 that while land use change refers to deforestation in most of the cacao-producing countries, there is also some peatland degradation and conversion in Cameroon (1%), Brazil (2%), Ecuador (2%) and particularly Indonesia (65%) where there are more peatlands (Osaki et al., 2016).

4.2.2. Impact of land use change (LUC) on cacao beans EF

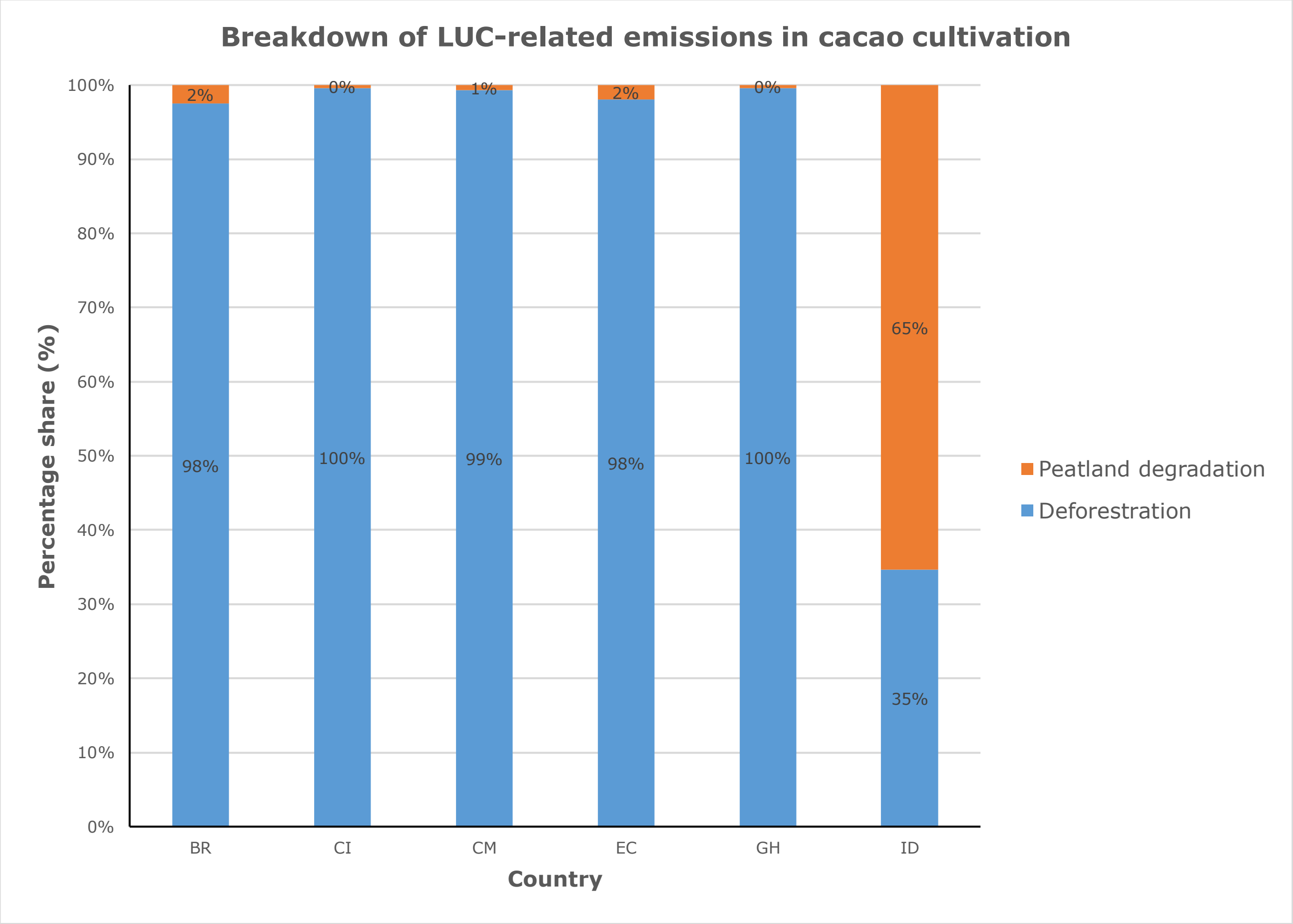

Figure 12. Breakdown of land use change-related emissions of production mix emission factors of cacao cultivation in Brazil (BR), Ivory Coast (CI), Cameroon (CM), Ecuador (EC), Ghana (GH), Indonesia (ID) expressed in percentage share (%).

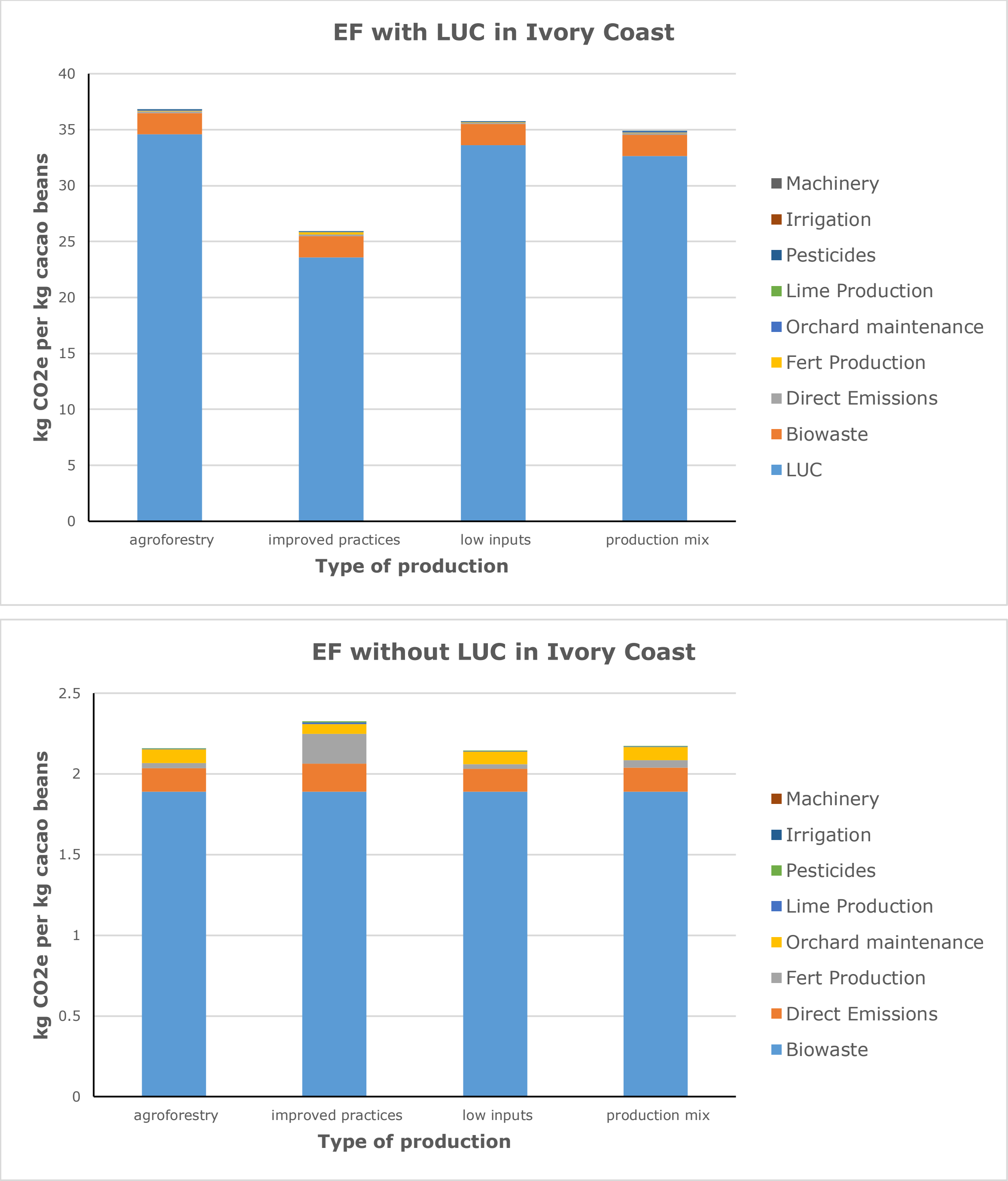

Figure 13. Emission factors of various types of cacao beans production systems in Ivory Coast (a) with and (b) without land use change. Cacao EFs are based on data from 2007 to 2017.

Among all the countries presented in Figure 11, Ivory Coast production systems have the highest land use change share and the highest EF value. For example, the highest EF value in the dataset is 36.8 kg CO_2e/ kg cacao beans (agroforestry system in Ivory Coast) whereas the lowest EF values are around 4.0 to 4.5 kg CO_2e/ kg cacao beans.

Based on Figures 11 and 13a, Ivory Coast's main contributor is land use change (LUC), accounting for an estimated 91% to 94% of its total EF depending on the production system. Due to this contributor's significant impact, the variation (approximately 11 kg CO_2e/ kg cacao beans) among the production systems is determined solely by the amount of LUC considered per production system. Hence, it is not possible to distinguish the impact of production system and its associated agricultural practices on the emissions due to overwhelming impact of LUC the EF of cacao in Ivory Coast.

The impact of LUC on cacao beans production in Ivory Coast is further highlighted in Figure 13. Without LUC, the EF of the production systems drops from double-digit-values to single digits. For example, an agroforestry system has an average of 37 kg CO_2e/kg cacao beans with land use drops to around 2 kg CO_2e/kg cacao beans without it. Therefore, efforts must be focused on eradicating deforestation in cacao production, particularly in Ivory Coast.

LUC refers to the transformation of natural land, particularly carbon-rich areas such as forests in Western Africa, into agricultural land for cocoa production. Due to high demand for cocoa, deforestation pressure is significant, leading to substantial carbon loss as these forests are converted into cocoa farms (Ruf et al., 2015; Asubonteng et al., 2018; Acheampong et al., 2019; Hawkins et al., 2024). A similar situation occurs with the conversion of peatlands in specific regions like Indonesia (Osaki et al., 2016).

Figure 13b illustrates that without LUC, biowaste is the second largest contributor to the EFs of Ivory Coast. Biowaste treatment is associated to 5% to 7% of the total EF of Ivory Coast as shown in Figure 10. In cacao datasets, biowaste emissions stem from waste management practices. In contrast to rice, this contributor is particularly significant in cacao production due to the decomposition of husks and shells left in the fields after harvest. There are two types of biowaste management incorporated into the emission factors: (1) via non-aerated heap, husks, wet tropical conditions and (2) via spreading on field, pulp, wet tropical conditions. The climate change impact of the non-aerated biowaste management is 8 times the value of that under aerobic conditions. This highlights the impact of waste management practices on overall emissions and suggests that adopting more efficient methods could reduce the environmental footprint of cocoa production. Other methods that could lower emissions of biowaste management in cacao production include aerated composting of heaps, husks, etc. as well as transforming the agricultural by-products into biochar (Ferry et al., 2022).

4.2.3. Fertilizer-related emissions of cacao beans cultivation

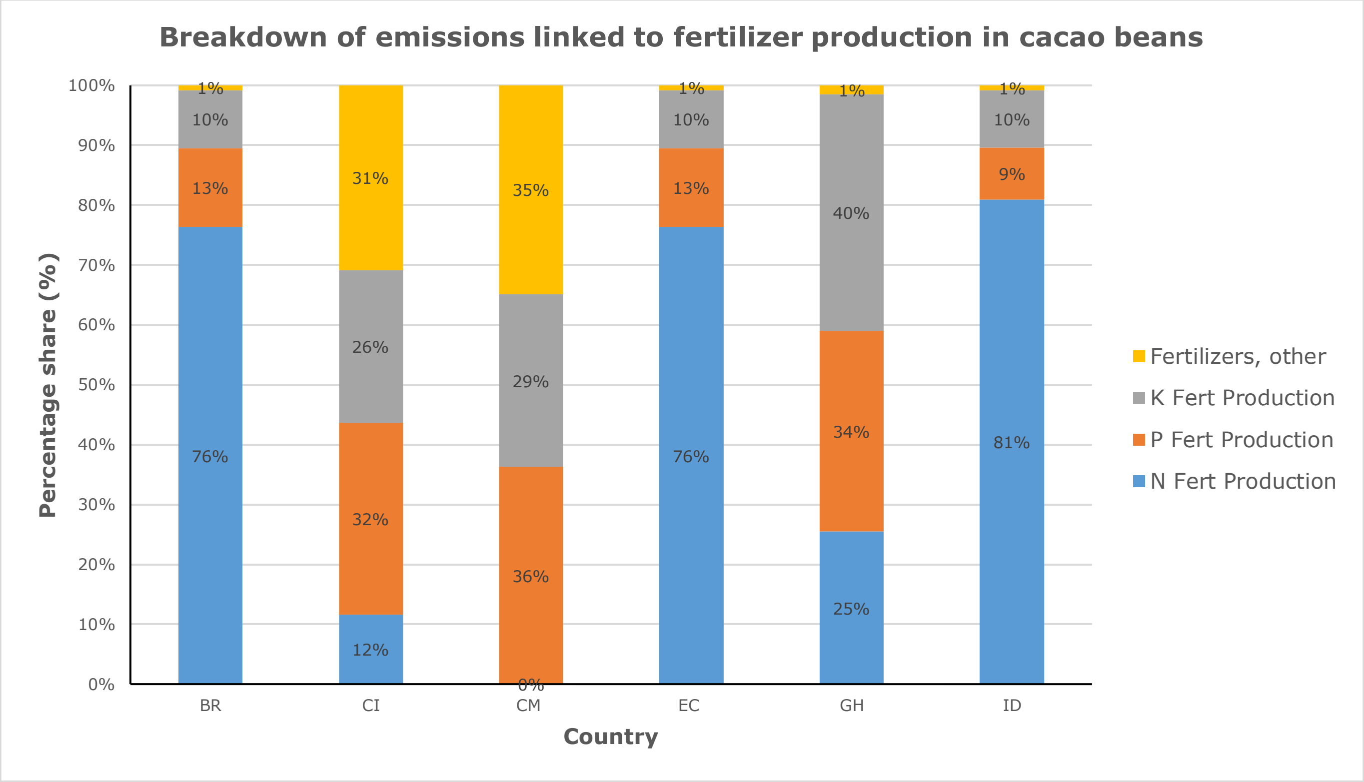

Figure 14. Breakdown of the emissions related to fertilizer production in cacao beans cultivation in Brazil (BR), Ivory Coast (CI), Cameroon (CM), Ecuador (EC), Ghana (GH), Indonesia (ID) expressed in percentage share (%).

In general, emissions due to direct emissions (following fertilizer application) and fertilizer production are comparatively modest in cocoa production (perennial crop) compared to paddy rice (annual crop), as it is a low-intensity commodity that requires minimal inputs (Chapman et al., 2022).

Furthermore, Figure 14 illustrates that the application of fertilizers in cacao farms is more heterogenous compared to rice where nitrogen fertilizer was the most significant contributor across the countries under study (Figure 9). For instance, more than 75% of the fertilizer-related emissions in Brazil, Ecuador and Indonesia is attributed to nitrogen fertilizer production. On the other hand, this contributor was 0% in Cameroon and barely 12% in Ivory Coast. West African countries in the dataset have higher emissions related to the production of phosphorus and potassium fertilizers rather than nitrogen. It could be that their soils are poor in nitrogen, phosphorus and potassium.

Additionally, Ivory Coast and Cameroon have over 30% of their fertilizer carbon footprint coming from a category called fertilizers, others. It was found that these emissions are due to the utilization of sulfites to cacao beans in these countries.

Technically, sulfite compounds are not fertilizers, but rather are likely applied to prevent oxidation and browning of the cacao beans as they are transported to destination markets, e.g., Europe. This finding aligns with reports indicating that these countries are known for exporting unfermented beans (Daymond et al., 2022).

4.2.4. Gas split of cacao beans EF

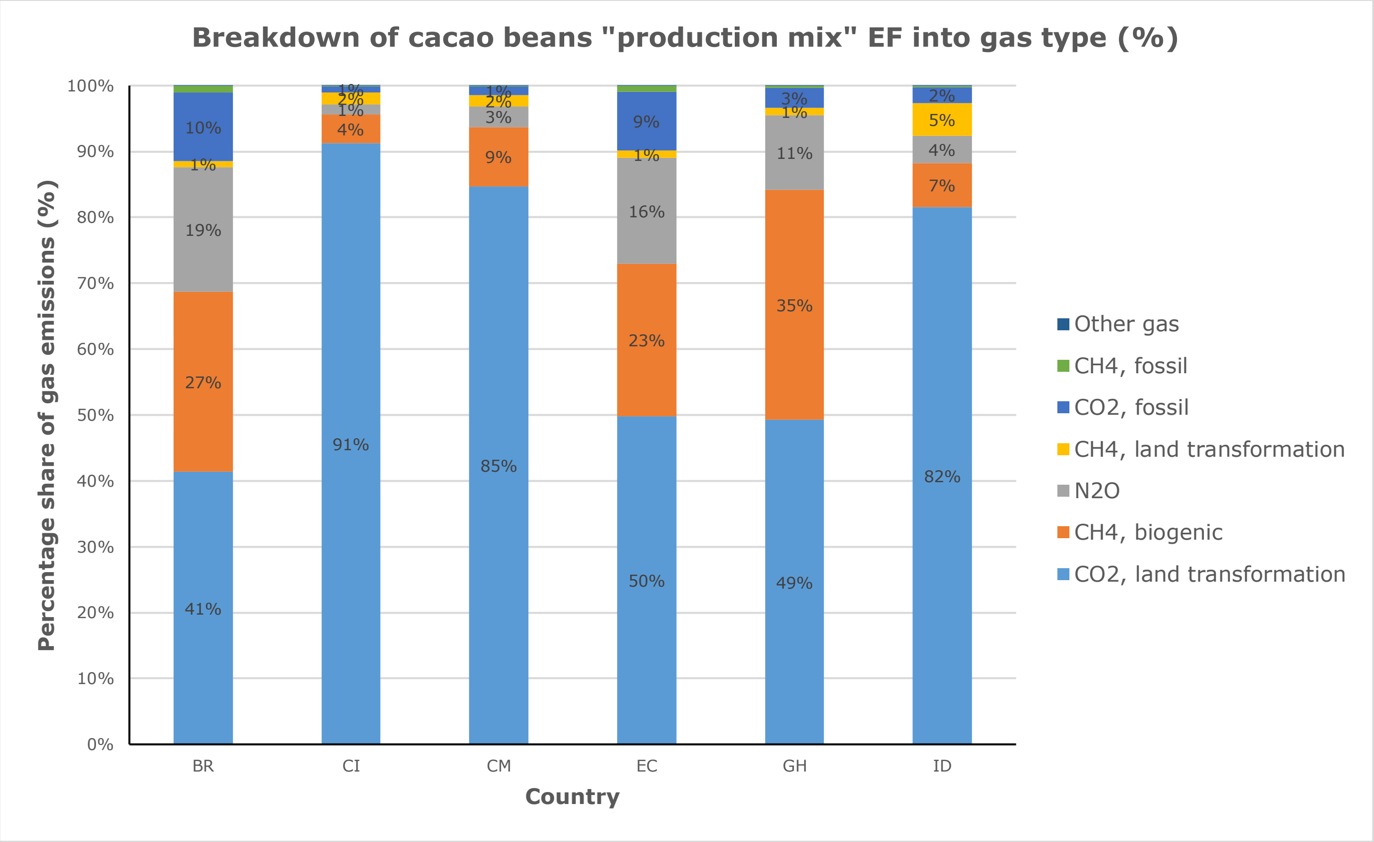

Figure 15. Breakdown of cacao beans (production mix) emission factors into various types of gases in the following countries: Brazil (BR), Ivory Coast (CI), Cameroon (CM), Ecuador (EC), Ghana (GH), Indonesia (ID) expressed in percentage share (%). Other gas category includes HFCs, PFCs, SF6 and NF3.

Since LUC is the highest contributor to the EF of cacao beans based on previous discussions, **CO_2 land transformation** makes up the majority of the type of gas emitted into the atmosphere. This is followed by **CH_4 biogenic** mostly due to the anaerobic degradation of the biowastes such as coconut husk and heap (via non-aerated heap, husks, wet tropical conditions and (2) via spreading on field, pulp, wet tropical conditions). **N_2O** is also emitted in cacao production arising from biowastes and application of N-P-K fertilizers. CO_2 fossil is also a significant contributor arising from all the inputs (fertilizers, pesticides, lime, etc.) and other processes related to cacao cultivation such as seedling production (orchard maintenance) and machinery.

5. DISCUSSION OF RESULTS

5.1. Paddy rice EF – India

Comparing paddy rice EF in India to literature

The EF of rice in India according to WFLDB is 1.5 kg CO_2e/kg paddy rice or 9.3 tCO_2e/ha. This EF was modelled with an average yield of 6250 kg paddy rice/ ha. There are several studies that tried to model the EF of rice in India, although most of them are specific to a rice-producing state in the country. Pathak et al. (2005) modelled the GHG emissions using field experiments data in New Delhi and provided a range of EF values associated with continuously flooded rice fields (3.1 to 6.5 tCO_2e/ha) and intermittently flooded rice fields (2.2 to 5.0 tCO_2e/ha). Sinha et al. (2020) estimated that a paddy rice-wheat (PW) production system in the middle Indo-Gangetic plains releases 3.4 tCO_2e/ha/y while a paddy rice-potato-fallow (PP) system emits 5.1 tCO_2e/ha/y. A more recent study by Ranguwal et al. (2022) calculated the carbon footprint of rice in Punjab state and found it to be 6.34 tCO_2e/ha.

Differences in calculated EF values are likely due to varying methodology, scope and embedded emission factors (e.g., EF for inputs). However, EFs are notably variable, often leading to significant uncertainty in the results. Walling & Vaneeckhaute (2020) investigated the sources of variability in EFs of fertilizer production and usage. They identified the following factors: energy sources used in production, operational conditions, storage, crop and soil types, soil nutrient levels, quantity and method of fertilizer application, soil bacterial communities, and irrigation methods. Furthermore, they noted that knowledge gaps exist regarding EFs for potassium fertilizers and waste valorization processes (anaerobic digestion/composting).

In addition, all the mentioned publications showed less granularity in their input data compared to WFLDB EFs. For India in particular, WFLDB incorporated 63 exchanges (inputs and outputs). This potentially more comprehensive and rigorous approach could explain why WFLDB EF is higher than those in published literature. Finally, neither the WFLDB EFs (methodology document) nor the reviewed publications evaluated the uncertainty of their results; hence, complicating the assessment of whether there are significant differences in the rice EF values based on their uncertainty levels.

For now, it can be deduced that WFLDB EF estimate the EF of paddy rice to be significantly higher than those available in literature, indicating a more comprehensive and/or conservative approach taken by the former.

Comparing the main contributors to the paddy rice EF in India to literature

The key insights regarding the contributors to the environmental footprint of rice cultivation in India reveal some variability across different studies. Based on the contribution analysis of WFLDB EF, direct emissions are identified as the primary contributors, accounting for 66% of the paddy rice EF in India, followed by irrigation (21%), fertilizer production (7%). However, Sinha et al. (2020) reported that fertilizer production was the top contributor to both the PW and PP systems, followed by direct N_2O soil emissions on the farm. Ranguwal et al. (2022) provided a breakdown showing CH_4 emissions as the largest contributor (60.7%), followed by electricity for irrigation (17.9%), N2O emissions (10.8%), plant protection chemicals (7.5%), diesel (6.1%), and fertilizers (3.0%). In their study, CH_4 and N_2O emissions combined made up 70.5% of the EF, closely aligning with the 66% direct emissions identified in the contribution analysis.

Sridhara et al. (2023) examined rice cultivation in Karnataka state in India and found CH_4 emissions (48%) and fertilizers (23%) as the major contributors, with irrigation being the leading energy consumer. Similarly, Odegard et al. (2015) and Jahangir et al. (2023) identified soil emissions, particularly CH_4, as the major contributors to the high GHG emissions of rice crops, with CH_4 emissions accounting for 50 to 80% of the total GHG emissions in rice-based systems in Bangladesh. These studies collectively emphasize the significant impact of direct emissions, irrigation, and fertilizer use on the environmental footprint of rice cultivation.

5.2. Interventions for the paddy rice sector in India

Both the results of this study (i.e., contributions analysis of WFLFB EF – paddy rice in India) and literature review pointed direct soil or field emissions as the leading contributor to the emissions of rice production. Therefore, it is appropriate to focus on the source of these direct soil emissions – flooded paddy rice fields. There have been many studies conducted in the recent years about the application of paddy water management regimes such as alternate wetting and drying (AWD) and direct rice seeding (DRS) in various rice-producing countries.

Alternate wetting and drying (AWD)

AWD is a method employed by lowland paddy rice farmers to conserve water in irrigated fields. This technique involves intermittently flooding the field and then letting it dry for a specific period after the standing water has vanished, thus switching between flooded and dry states (IRRI, 2020).

Most studies about AWD in literature report an overall reduction in GHG emissions, despite an increase in N_2O emissions. This is mainly because the majority of the GWP of rice production is due to CH_4 emissions resulting from continuous flooding (Linquist et al., 2012). A study in Tami Nadu, India by Oo et al. (2018) found that adopting AWD across different rice varieties during dry and wet season in this region in India reduced CH_4 emissions by 52.8% to 61.4% and increased N_2O emissions by 77% compared with continuous flooding. They noted an overall GWP reduction of 16 to 59% when rice was grown under AWD. Another study by Sriphirom & Rossopa (2023) reported a 48.2% reduction in GHG emissions when AWD at 15 cm below soil surface of drainage level was applied in rice fields in Thailand. AWD decreased the GWP of rice cultivation by more than 50% in their study. Meta-analyses of AWD studies in China by Jiang et al. (2019) reported 53% reduction in CH_4 while raising N_2O emissions by 105 %. However, AWD still decreased the GWP of rice by 44%. Finally, a meta-analysis of 437 literature sources encompassing 93% of rice production in the world by Gao et al. (2024) showed a 47% reduction in CH_4, 52% increase in N_2O but 39% reduction in GWP brought by AWD. Despite the added N2O emissions, these studies demonstrated that the global warming potential of rice can still be significantly reduced through AWD practices.

Contrary to previous studies which showed lower CH_4 emissions yet accompanied by higher N_2O emissions (Lagomarsino et al., 2016; Islam et al., 2018; Abid et al., 2019; Balaine et al., 2019; Wu et al., 2022), Loaiza et al. (2024) concluded that AWD decreased N_2O emissions by 12 to 70% with minimum impact on the productivity of the crop. They tested AWD in Colombian rice fields for four consecutive growing seasons (i.e., 2 years) and evaluated the systems' GHG emissions. They found that compared to the control, AWD treatments decreased cumulative CH_4 emissions by 72% to 100%. The reduction was attributed to soil moisture management during events of fertilizer application. Unlike most other studies comparing AWD to continuous flooding, both the control and AWD plots in this study experienced non-continuous flooding, especially during fertilizer application in the first two months of the growing season. In contrast, continuous flooding keeps the soil anaerobic (without oxygen), which leads to complete denitrification and very low N_2O emissions. In these conditions, any drainage tends to increase N_2O losses because it introduces oxygen, thus resulting to enhanced N_2O production in the other studies. In addition, Loaiza et al. (2024) studied AWD on sandy loamy soils, which supported more rapid drainage compared to clay soils. This is supported by the study of Lagomarsino et al. (2016). They showed that concentrated on clay soils discovered that AWD decreased water consumption by 70% and CH_4 emissions by 97% but caused a fivefold increase in N_2O emissions in clay-textured soils. Therefore, AWD in rice cultivation has the potential to not only decrease CH_4 emissions significantly but also reduce those of N_2O depending on the soil type and soil moisture management.

Nevertheless, impact on water resources, yield, and biodiversity and should also be considered before implementing AWD. For instance, Gao et al. (2024) revealed that AWD lowers irrigation water usage by 34% and boosts water use efficiency, irrigation water use efficiency, and water productivity by 20%, 48%, and 30%, respectively. Nonetheless, there is a slight reduction in yield by 1.6%. While more studies should be carried out to determine the impact of AWD on biodiversity, it is essential to evaluate other co-benefits or tradeoffs with nature when implementing pro-climate interventions.

Dry direct seeded rice (DDSR)

Dry direct seeded rice (DDSR) is an agricultural practice where rice is sown directly into tilled or untilled soil without the need for puddling or transplanting (Kumar & Katagami, 2016). On the contrary, rice-transplanting, the common modern practice, involves growing rice plants in a nursery bed before moving them to the paddy field where they grow until they are ready for harvest (Ngo et al., 2019). In addition to reduced water demand, the adoption of DDSR could significantly impact methane emissions since DDSR fields are not continuously submerged in water (Pathak et al., 2013). Thus, DDSR presents a viable option for conserving both water and labor while reducing direct field emissions.

Key insights from various studies highlight the potential of DDSR as an effective intervention for reducing GHG emissions in rice cultivation. Pathak et al. (2013) conducted a two-year field trial in Punjab, India, revealing that DDSR could reduce the global warming potential (GWP) by 33% compared to transplanted rice (TPR), with emissions ranging from 1.3 to 2.9 t CO_2e/ha for DDSR versus 2.0 to 4.6 t CO_2e/ha for TPR. Additionally, DDSR required significantly fewer irrigations (volume), reduced human labor by 45%, and tractor usage by 58%, without compromising yield. Similarly, Susilawati et al. (2019) observed a 47% reduction in CH_4 emissions with DDSR compared to TPR in Central Java, Indonesia, with DDSR emissions averaging 187 kg/ha/season versus 352 kg/ha/season for TPR. The study also noted that DDSR had a 46.4% lower GWP than TPR, with no significant difference in grain yield or N_2O emissions. Chaudhary et al. (2017) further supported these findings, reporting that the GWP of DDSR is 34 to 39% lower than TPR. These studies collectively suggest that DDSR is a viable, low-emission alternative to traditional rice transplanting, offering substantial reductions in GHG emissions without affecting crop yield.

Other potential interventions

On top of alternative water management systems in rice cultivation, many other interventions can help in the climate mitigation of the rice sector. For instance, reducing the fertilizer application, particularly nitrogen can help decrease field level N_2O emissions and upstream fertilizer production emissions while preventing environmental issues such as eutrophication. Another strategy involves improved management of rice straw, i.e., removing straw from the fields to prevent breakdown of the organic waste and associated CH_4 release (Kumar & Katagami, 2016; McKinsey & Company, 2023; Diagne Langston et al., 2023).

Furthermore, these straws can be transformed into biochar, a soil amendment that helps retain water and nutrients in the soil while promoting beneficial soil microorganisms for crops (Wu et al., 2012). According to Mohammadi et al. (2020) who reviewed the challenges and progress of biochar application in rice paddy fields, the primary benefits include the stabilization of carbon in biochar, energy recovery from pyrolysis gases, decreased fertilizer needs, and enhanced crop productivity. They found that biochar-treated soil can significantly reduce the carbon footprint of rice, with emissions ranging from -1.43 to 2.79 kg CO_2e/kg of rice, compared to untreated soil. The negative values indicate carbon sequestration. The most impactful advantage is the reduction of soil methane emissions, accounting for 40 to 70% of climate change mitigation. Economic analysis shows that biochar application can be cost-effective in some scenarios. However, elevated energy and transportation demands of biochar on top of supply chain and transformation considerations are currently impeding its adoption (Mohammadi et al., 2020). Enhancing the economic feasibility for farmers involves subsidizing biochar's initial cost and incorporating a substantial carbon abatement price in future market mechanisms.

5.3. Barriers to implementation of interventions: paddy rice sector in India

Four main barriers to the implementation of AWD and DDSR in the rice sector have been outlined in literature: the farmer’s lack of knowledge of the technique, their reluctance to abandon traditional habits, the lack of (financial and technical) support from the government; and risks associated with the adoption of AWD. Some of the cited risks include decreased yield, growth of weeds and higher fixed costs (Kumar & Katagami, 2016; Waris et al., 2019; Suwanmaneepong et al., 2023). Without the flooded rice paddies suppressing weeds, additional labor and costs must be allocated to effective and sustainable weed management, otherwise rice harvests would be negatively impacted (Kumar & Katagami, 2016) .

The declining yields were reported by the International Rice Research Institute's (IRRI) aerobic rice experiments where they observed gradually declining yields over time in comparison to continuously flooded rice (George et al., 2002; Peng et al., 2006; Kumar & Katagami, 2016). Hence, to sustain DDSR in the long term, Ngo et al. (2019) highlighted how essential it is to have research and development strategies for areas where this method is likely to be adopted.

Although higher fixed costs reduce the likelihood of adoption, variable costs are positively linked to a greater intention to adopt in short-term production decisions. To expand the use of AWD, it is essential to ensure farmers comprehend the safe and correct implementation of AWD and to provide support for crop insurance in case of crop failure (Suwanmaneepong et al., 2023).

5.4. Costs of implementation of interventions: paddy rice sector in India

Based on the study of Lampayan et al. (2015) about the economics and adoption of AWD for irrigated lowland rice, McKinsey & Company (2023) estimated that adopting of AWD can lead to cost savings (\$59/tCO_2e reduced) due to decreased irrigation costs while the suggested and forecasted incremental implementation rate is at least 35% to be aligned with 1.5°C pathway. On the other hand, implementation of DDSR necessitates more preparatory work. According to Ngo et al. (2019), key prerequisites for the success of DDSR include precise land leveling, the use of suitable cultivars, effective crop establishment, accurate water management, and efficient weed and nutrient control. Using their data and findings, McKinsey & Company (2023) approximated that farmers can save an average of \$159/tCO_2e abated. In India, a recent study found that the decreased costs associated with irrigation, fertilization and land preparation results into ₹5192/acre (\$159/ha) additional income for DDSR adopters (Dey et al., 2024). Despite the required initial investment in terms of costs and time, farms that adopt these water-saving- and GHG-abating- strategies are expected to cut down their costs in the long run. However, these values are mere estimates, and they remain high-level with plenty of assumptions. Costs per country and per region are likely to vary.

5.5. Cacao beans EF – Ivory Coast

Comparing cacao beans EF in Ivory Coast to literature

Vervuurt et al. (2022) estimated the EF of cacao beans in Ivory Coast based primary data of 509 farms, using Cool Farm Tool (CFT) and Perennial GHG model. They approximated that the production of 1 kg of cacao beans in Ivory Coast results in the emission of 1.47 kg of CO_2e on average. Deforestation was a key driver of the emissions, similar to the results of the contributions analysis of WFLDB EF. However, their calculated EF is significantly lower than that of WFLDB (34.8 kg of CO_2e/ kg of cacao beans). The 184% difference between the two EF is attributed to several factors: (1) distinct methods of estimating the impact of land use change, (2) inclusion of carbon sequestration in the shade trees associated with cacao trees (which was not considered in the WLFDB EF), (3) and treatment of residue management as a carbon negative activity (i.e., carbon capture) rather than a positive activity (i.e., GHG emissions).

Since 94% of the WFLDB EF for cacao is due to LUC, i.e., 32.7 kg CO_2e/ kg of cacao beans, it is the approach to calculating LUC that made the huge difference. While the impact of deforestation on the GHG emission of cacao farming in Vervuurt et al. (2022)'s study was estimated using CFT, WFLDB is based on a more comprehensive and conservative approach which is detailed in the reports by Nemecek et al. (2023) and Quantis (2024). Although both WFLDB and Vervuurt et al. (2022) followed the distribution of LUC impact and emissions over a 20-year assessment period according to the principles and guidelines of GHG Protocol Land Sector and Removals (Anderson et al., 2022), they differed when it comes to other parameters such as allocation across time, allocation across co-products, source of data to estimate LUC, etc.

The second major factor is that the WFLDB EF did not take into the calculations the carbon sequestration in cacao shade trees. Depending on many factors such as the number, spacing, age and species of the shade trees, the carbon sequestration in the shade trees may vary significantly (Ramachandran Nair et al., 2010). For instance, Vervuurt et al. (2022) estimated that 4 tons of C/ha are stored in shade trees while 19 tons C/ha are stored in cacao biomass (above and below-ground). However, cacao-agroforestry systems whose shade trees are old trees from the primary forest have higher carbon sequestration. For instance, Dawoe et al. (2016) estimated the carbon stocks in cacao-agroforestry systems in West Africa and found that 7.45 ± 0.41 Mg C/ha is the average C stock in cacao biomass, whereas 8.32 ± 1.15 Mg C/ha was in the shade trees. Hence, modelling of carbon sequestration at country level can be difficult due to high sensitivity to the parameters mentioned.

Third, Vervuurt et al. (2022) considered leaving biowaste such as husks and infected fruits on the soil as negative emissions. They assumed that the biowaste materials would be integrated into the soil carbon stock, thereby eventually contributing to carbon sequestration. However this process may take a considerable amount of time. In contrast, the modelling of WFLDB EFs used the assumption that the organic wastes are left on the field to decompose, leading to biogenic methane and nitrous oxide emissions, which have higher global warming potential than carbon dioxide. Due these reasons, the calculated EF of WFLDB was significantly higher than what Vervuurt et al. (2022) estimated.

In the same study, Vervuurt et al. (2022) also calculated another EF for a cacao production system in Ivory Coast with "good agricultural practices (GAP)", which resulted into higher emissions of 2.29 kg of CO_2e/ kg of cacao beans. GAP in cacao farming was characterized as follows: higher inputs usage (fertilizers and pesticides), higher number of shade trees (especially during the first three years), increased yields, burning of residues due to sanitary reasons and zero deforestation. Although GAP led to greater carbon accumulation in shade tree biomass per hectare, the accumulation was lower than anticipated because many shade trees planted initially to protect cacao seedlings are removed in subsequent years. Additionally, GAP recommends plantation renewal after 30 years, whereas current plantations are cultivated for much longer. The main contributors to the emissions of cacao farming with GAP were agricultural inputs and residue management (e.g., burning infected fruits and composting husks). The increased emissions from the use of additional agro-inputs and different residue management practices, such as the recommended burning of residues, were not offset by higher yield.

Following the different EF values generated for cacao beans production in Ivory Coast, it can be deduced that EF can vary greatly depending on the scope, boundaries, assumptions, input data and modelling approach.

Comparing the main contributors to cacao beans EF in Ivory Coast to literature

On the other hand, a report by the World Wildlife Fund (WWF) estimating generic emissions from coffee production showed similar land use change (LUC) estimations as those found in the WFLDB (Jennings et al., 2022). Since both coffee and cacao are classified as perennial crops cultivated in the tropics, they share many characteristics and farm management practices that influence their associated emissions. The WWF report broke down the emission factor (EF) of 1 kg of roasted coffee beans into its components: 0 to more than 35 kg CO_2e can be attributed to LUC alone; 0.5 to over 7 kg CO_2e can be linked to soil emissions; 0.1 to 2 kg CO_2e can be associated with residue management; and 0 to 0.3 kg CO_2e can be attributed to liming. Given the high deforestation rate in Ivory Coast, it is logical that around 32.7 kg CO_2e/ kg of cacao beans is attributed to LUC, aligning with the upper limits of WWF's estimates.

All these points highlight the vital need to address the impact of land use change (LUC) on climate and its significant contribution to emissions in the cacao bean sector in Ivory Coast. Agriculture is the leading cause of cutting down primary forests. Without addressing LUC, particularly deforestation, any efforts to reduce emission in the cacao beans sector would be rendered futile.

5.6. Interventions for the cacao beans sector in Ivory Coast

According to the results of the contributions analyses, the two main hotspots of cacao beans cultivation in Ivory Coast accounting for approximately 99% of the emissions are land use change and biowaste management. Some of the interventions that could abate these emissions are zero-deforestation (i.e., eliminating deforestation in the production), adapting agroforestry and planting more shade trees, biochar, composting and integrated pest management among others.

Zero-deforestation

Achieving zero deforestation in cacao production in Ivory Coast is a complex challenge requiring multifaceted interventions. According to the IPCC, GHG Protocol, and SBTi FLAG Guidance, deforestation must be eradicated by 2030 to achieve net zero emissions by 2050 (Anderson et al., 2022). However, the global cocoa market has seen an average annual production growth rate of 7%, with projections indicating a doubling of production by 2030 compared to 2020 levels (Voora et al., 2019). Despite this growth, cocoa yields have remained stagnant over the past fifty years, leading farmers to expand cultivation areas and significantly contribute to the conversion of tropical forests into cacao fields (Vaast & Somarriba, 2014). In West Africa, cocoa cultivation is recognized as a major driver of forest loss (Ruf et al., 2015; Asubonteng et al., 2018; Acheampong et al., 2019; Hawkins et al., 2024).

In Ivory Coast, between 2000 and 2019, 2.4 million hectares of forest were lost due to cocoa cultivation, averaging 125,000 hectares per year and accounting for 45% of the country's total deforestation during that period. Furthermore, only 43.6% of cacao exports could be traced back to specific departments or cooperatives, highlighting the need for improved traceability (Rénier et al., 2023). Enhancing traceability and transparency in the cacao supply chain can help curb deforestation by holding stakeholders accountable. Despite the existence of laws such as the Ivory Forest Code (2019) and The Cocoa & Forests Initiative (2017), more rigorous implementation is required (Hawkins et al., 2024).

The European Union's "Regulation (EU) 2023/1115 on deforestation-free products" aims to reduce deforestation and GHG emissions related to agricultural expansion, including cacao production. As the EU is a major importer of cacao beans, this regulation is expected to positively impact deforestation efforts in Ivory Coast (OEC, 2022a; European Commission, 2024).

Efforts to increase cacao yields include implementing improved agricultural practices such as proper irrigation, soil health management, pruning, shade management, and pest and disease control (Daymond et al., 2022; Jennings et al., 2022). Additionally, using high-yield, pest- and disease-resistant cacao varieties can help mitigate losses and increase yields. Finally, promoting sustainable farming practices, including agroforestry, and providing farmers with access to training programs and extension services, are crucial for long-term yield stability and environmental preservation as they are one of the major stakeholders who can implement the changes necessary to mitigate GHG emissions (Bockel et al., 2021).

On the whole, addressing deforestation in cacao production in Ivory Coast requires comprehensive solutions that involve policy implementation, improved agricultural practices, and enhanced supply chain traceability.

Integrated Pest Management

According to Daymond et al. (2022), pests and diseases are responsible for decreasing potential yield by 30% to 40%. In Ivory Coast, examples of main pests and diseases include cacao swollen shoot virus (CSSV), parasitic mistletoe, *phytophthora megakarya*, and stem borer. In Ivory Coast, agrochemicals and cultural control are the main methods to address pest and diseases. For instance, fungicides are applied to control blackpod while cutting and replanting cacao trees are the means to address CSSV (Daymond et al., 2022). However, pesticides and fungicides are mostly produced using feedstocks and energy from fossil fuels which further contributes to GHG emissions (Demeneix, 2020). Moreover, many studies have shown its negative impact on biodiversity and creates a train of other problems such as resistance of the targeted pests to agro-chemicals. Hence, cultural (e.g., pruning, removal of diseased pods) and biological control are suggested as more sustainable practices to cut yield loss due to pests and diseases (Narayanasamy, 2013).

Agroforestry

Several meta-analyses studies have been carried out to determine the impact of agroforestry on cacao beans production in terms of economic performance and yield, carbon sequestration and soil health, climate change mitigation, pest and disease management, biodiversity conservation and socio-economic benefits. Regarding economic performance and yield, a meta-analysis of 52 scientific articles by Niether et al. (2020) revealed that cacao yields under agroforestry systems are 25% lower on average compared to monoculture systems (Table 3 in the appendix). However, agroforestry offers ten times higher total system yield (Table 3) as the shade trees also provide fruits, timber and etc. This shows the substantial contribution cacao-agroforestry system to food security and diversification of income despite the lower cacao yield along. Moreover, both production systems (monoculture and agroforestry) demonstrate similar profitability, indicating that the economic performance of agroforestry is competitive with traditional monoculture systems (Niether et al., 2020).

In terms of carbon sequestration and soil health, a meta-analysis study of 53 articles by De Stefano & Jacobson (2018) showed that transforming agricultural land into agroforestry augments soil organic carbon (SOC) by approximately 26% at depths of 0 to 15 cm and 40% at 0 to 30 cm depths. Kim et al. (2016) added that agroforestry systems can sequester substantial quantities of carbon, i.e., 27 ± 14 t CO_2e/ha/y primarily in tree biomass. Moreover, Tschora & Cherubini (2020) concluded that the inclusion of diverse mix of trees boosts soil fertility along with carbon storage, thereby contributing to overall system productivity and climate resilience.

Niether et al. (2020) also reported that cacao agroforestry systems are able to store 2.5 times more carbon than monoculture systems while also mitigating climate change impact by decreasing mean temperatures and providing budder to extreme temperatures and weather events. In West Africa, large-scale deployment of agroforestry could store up to 135 Mt CO_2/year, which highlights this intervention's significant climate mitigation potential (Tschora & Cherubini, 2020).

Furthermore, agroforestry can mitigate pests and diseases in cacao beans production. A meta-analysis by Pumariño et al. (2015) reported that agroforestry generally suppresses the presence of weeds and pests' populations in perennial crops such as cacao, plantain and coffee by increasing the abundance of their natural enemies. Conversely, annual crops like rice and corn are not able to benefit from this according to their analysis. However, the impact of agroforestry on disease in cacao remains dependent on the fungal species concerned (Pumariño et al., 2015; Niether et al., 2020).

Other benefits brought by agroforestry include biodiversity conservation and socio-economic and environmental advantages. Compared to monoculture cacao systems, those of agroforestry support higher biodiversity, hence is instrumental to conservation efforts (Niether et al., 2020). Finally, agroforestry systems provide diversified income sources via co-products of (agroforestry) shade trees, helping them become more resilient to climate change related events such as droughts and disease outbreaks (Tschora & Cherubini, 2020).

In essence, cacao agroforestry presents a multi-dimensional set of benefits including improved total yields, economic viability, enhanced soil health, significant carbon sequestration, better pest and disease management, and higher biodiversity, all contributing to climate change mitigation and adaptation. These benefits underscore the importance of promoting agroforestry practices for sustainable agriculture and environmental conservation.

Biowaste management strategies

Biowaste management strategies in cacao beans production encompass several approaches aimed at handling organic waste effectively and subsequently reduce GHG emissions. This is pertinent as biowaste was identified as a major contributor to cacao beans EF in Ivory Coast – the top producer exporter of the commodity – and other countries. One option for farmers is to leave organic waste unincorporated in the field, which can lead to higher emissions due to decomposition processes. Alternatively, cacao biowaste can be integrated into the soil or converted into compost on-site, which could help moderate emissions. Furthermore, cacao biowaste can be transported off-site to produce biochar via pyrolysis, similar to the discussion made with rice. However, this process requires substantial energy input along with additional costs for farmers to consider (Vásquez et al., 2019). These strategies are crucial for managing emissions on-farm and optimizing agricultural sustainability in cacao cultivation.

5.7. Barriers to implementation of interventions: cacao beans sector in Ivory Coast

Insights from various studies highlights the barriers hindering the implementation of agroforestry in Ivory Coast and elucidates why farmers are hesitant to adopt this climate-mitigating strategy (Middendorp et al., 2018; Kouassi et al., 2021; Niether et al., 2020). These barriers encompass issues surrounding land tenure and tree ownership rights, necessitating greater awareness of policies, e.g., the forest code, to overcome them (Kouassi et al., 2021). Additionally, potential yield reductions brought by agroforestry (shade trees) holds back farmers. As the income of cacao farmers and their families are highly dependent on cacao yields and market price, the decrease in yield can significantly impact them, posing financial and food security concerns (Daymond et al., 2022). The lack of economic incentives discourages farmers from maintaining non-cocoa tree cover, highlighting the importance of payment-for-ecosystem services and certification schemes (Middendorp et al., 2018). Moreover, limited local knowledge on tree selection and inadequate access to markets for agroforestry products further impede adoption (Niether et al., 2020). These multifaceted barriers collectively impede the widespread adoption of agroforestry practices in Ivory Coast, inhibiting the potential benefits for both farmers and the environment.

Similarly, land tenure issues and economic dependence on cacao farming makes zero-deforestation a formidable challenge for the cacao sector in Ivory Coast. This is further aggravated traditional agricultural practices, whereby the conversion of forested land into cacao fields has been a common practice (F. Ruf & Zadi, 1998). Additionally, the lack of traceability, complexity of the cacao supply chain and limited enforcement to combat deforestation, pose constraints to achieving zero-deforestation in the coming years (Rénier et al., 2023). Finally, the increasing demand for cacao and the stagnant or declining yield (due to pests, diseases, water stress amongst others) also contribute to this concern concerns (Daymond et al., 2022; Jennings et al., 2022).

Comparable to the barriers to the adoption of alternative paddy rice water management interventions, those hindering the adoption of integrated pest management (IPM) in the cacao sector in Ivory Coast center on the limited awareness and education of farmers about IPM practices as well as their benefits, initial investments and traditional practices (Edson et al., 2013; Souza Pereira, 2024). This emphasizes the need to provide financial (such as subsidies to access inputs) and technical support to cacao farmers (via IPM education and training).

5.8. Costs of implementation of interventions: cacao beans sector in Ivory Coast

Regarding cacao beans, it was estimated that the costs of running a cacao agroforestry system is \$571.5 ± 322.8/ha/year, which is slightly lower than that of cacao monoculture system (\$652.9 ± 464.4) (Niether et al., 2020). However, this is an average value across many systems with different characteristics. The economic viability of production systems relies on plantation management effectiveness and labor expenses, with cacao agroforestry setups often necessitating increased labor inputs (Armengot et al., 2016). While timber trees enhance the net present value of cocoa agroforestry systems (Ramírez et al., 2001), their potential future benefits may not always be perceived by farmers due to insecure land and tree tenure and the threat of fires (Ruf, 2011).

On the other hand, there is lack of studies regarding the abatement cost of achieving zero-deforestation and integrated pest management, particularly related to the cacao sector of Ivory Coast. Most of the published articles on deforestation focus on carbon pricing (Busch & Engelmann, 2015). Despite this limitation, the potential of these interventions to abate GHG emissions should not be overlooked.

Paddy rice and cacao beans

The economic feasibility of biochar was determined by Robb et al. (2020) through a comprehensive review of 33 relevant published articles. As this economic review is not crop-specific, it can be considered for both Indian paddy rice sector and Ivory Coast's cacao sector. It was found that its average abatement cost applied in developing countries is -\$58/tCO$_2$e, indicating financial feasibility, whereas in developed countries it is +\$93/tCO$_2$e, indicating a lack of financial feasibility. It was advised that climate policies in developing countries with tropical climates incorporate biochar as a component for small-scale climate-smart agriculture to combat land degradation in tropical farming systems. Recent evidence indicates that biochar fertilizers, could offer a commercially viable route for developing the biochar value chain in developed countries.

6. CONCLUSION AND PERSPECTIVES

The imperative to reduce greenhouse gas emissions, particularly within agriculture, has become increasingly urgent amidst escalating climate change challenges. This master's thesis examined the impact and role of two crucial crops essential to the modern diet—rice and cocoa— in climate mitigation by 2050. The analyses and discussion were further contextualized in India, a major producer and exporter of rice, and in Ivory Coast, the world's largest producer and exporter of cocoa beans.

The main drivers of emissions of paddy rice cultivation in India are direct emissions (i.e., methane and nitrous oxide emissions form paddy rice fields) (66%), irrigation (21%), and production of nitrogen-based fertilizers (6%) according to the contribution analysis of the WFLDB emission factor (EF). In terms of gas distribution, rice cultivation emissions are primarily biogenic methane (62%), followed by CO_2 from fossil fuels (30%) and N_2O (5%). Methane is mainly from flooded paddy fields, CO_2 from diesel irrigation and fertilizer production, and N_2O from fertilizer use and early rice growth.

Based on these results, interventions that mitigate direct emissions from paddy rice field should be prioritized. Alternate wetting and drying offers opportunities to decrease methane and nitrous oxide emissions significantly by removing the continuous flooded environment that is conducive to the production of these greenhouse gases. Another strategy is to replace transplanted rice into puddled soil with direct seeded rice into dry or wet soil. These strategies not only abate GHG emissions, but are also effective, water-saving measures, thus simultaneously reducing emission related to irrigation while providing co-benefits with nature. Nevertheless, more optimization studies must be conducted in order to increase yields and prevent N_2O increase in the case of direct seeding of rice. Another technology to further abate emissions related to irrigation, conversion from flood to drip or sprinkler irrigation is also recommended. Furthermore, minimizing the application of nitrogen fertilizers through precise application and better soil nutrient management can also contribute to emission reductions.

On the contrary, almost 99% of cacao beans EF is associated with land use change (94%) and biowaste or residue management (5%) based on the WFLDB methodology. Breaking down the EF into its gas components showed that CO_2 land transformation makes up the majority of the type of gas emitted into the atmosphere since LUC is the highest contributor to the EF of cacao beans based on previous discussions. Other notable gases in terms of share are CH_4 biogenic, N_2O, and CO_2 fossil.

Following these results, several mitigation strategies were identified as particularly effective in addressing these hotspots. It includes eradication of deforestation caused by cacao production by the year 2050 as the massive impact on carbon fluxes take about 20 years. Another critical strategy to improve the resilience of the sector to climate change is agroforestry which presents a multi-dimensional set of benefits including improved total (system) yields, economic viability, significant carbon sequestration, better pest and disease management, enhanced soil health, and higher biodiversity, all contributing to climate change mitigation. Moreover, reducing yield loss to pests and diseases through integrated pest management and agroforestry is expected to help increase production without having to convert forests and other land into cacao fields. Finally, biowaste management such as transformation of organic wastes into biochar is also expected to abate GHG emissions by preventing anaerobic decomposition of the biowastes and boosting yields through healthier soil.

Despite the potential GHG abatement of these interventions, there lies big knowledge gaps in the applicability (i.e., adoption rates), abatement costs, strategies to overcome implementation to barriers. More accurate estimations of GHG abatement are also pivotal in forming strategies and decision-making to reach net zero and be in line with 1.5° pathway of the Paris Agreement. Moreover, transparency in the methodology and assumptions made to simulate models are as crucial. As for the cacao sector, it is recommended to further investigate the carbon reduction and sequestration of available interventions such as zero-deforestation, agroforestry and integrated pest management particularly in West African countries. Conversely for the rice sector, there is a need to investigate how to increase and maximize the adoption of alternative water management strategies such as AWD and DSR in major rice-producing countries like India. Enhanced research and development efforts are essential for decreasing expenses, enhancing scalability, and comprehending broader ramifications. Given sufficient support and motivators (especially for the farmers), agriculture has the potential to attain net zero emissions – although the question lies when.

Finally, current food production systems are major drivers of global biodiversity decline, with profound impacts on biosphere health, human well-being, and food availability. Six of the nine planetary boundaries have already been surpassed, leading to potentially irreversible consequences. This underscores the urgency to consider trade-offs alongside benefits in decarbonization efforts. While GHG emissions are typically the focus of environmental impact assessments, climate change also impacts water resources, biodiversity, and other planetary boundaries. Therefore, decisions regarding investments or transitions should encompass a comprehensive evaluation of their broader impacts on nature, beyond just carbon considerations.

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APPENDICES

Table 3. Comparison of cocoa agroforestry system and cocoa monoculture based on a meta-analysis of 52 scientific articles (Niether et al., 2020).

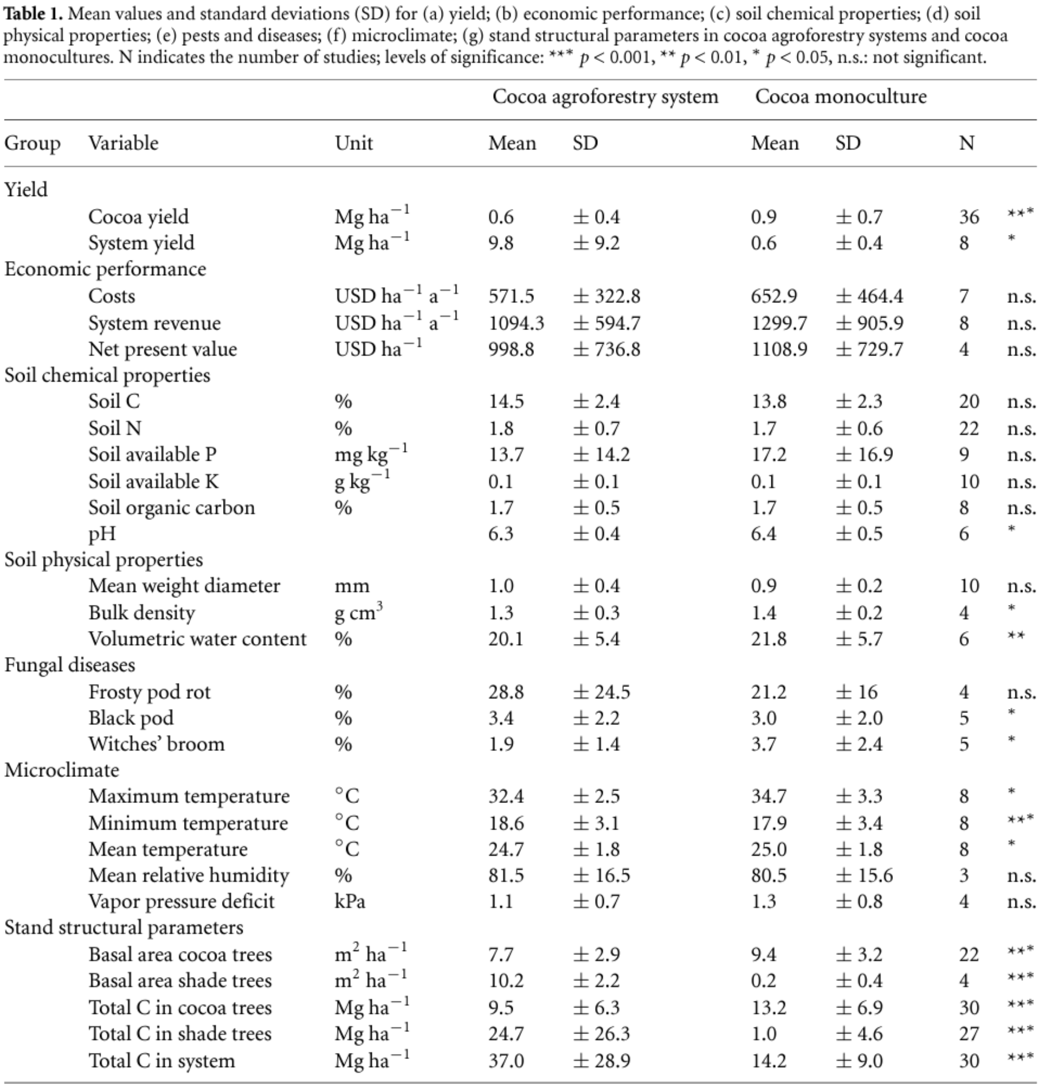

Table 1. Mean values and standard deviations (SD) for (a) yield; (b) economic performance; (c) soil chemical properties; (d) soil physical properties; (e) pests and diseases; (f) microclimate; (g) stand structural parameters in cocoa agroforestry systems and cocoa monocultures. N indicates the number of studies; levels of significance: *** $p < 0.001$, ** $p < 0.01$, * $p < 0.05$, n.s.: not significant.

			Cocoa agroforestry system		Cocoa monoculture			
Group	Variable	Unit	Mean	SD	Mean	SD	N	
Yield								
	Cocoa yield	Mg ha^{-1}	0.6	± 0.4	0.9	± 0.7	36	***
	System yield	Mg ha^{-1}	9.8	± 9.2	0.6	± 0.4	8	*
Economic performance								
	Costs	USD ha^{-1} a^{-1}	571.5	± 322.8	652.9	± 464.4	7	n.s.
	System revenue	USD ha^{-1} a^{-1}	1094.3	± 594.7	1299.7	± 905.9	8	n.s.
	Net present value	USD ha^{-1}	998.8	± 736.8	1108.9	± 729.7	4	n.s.
Soil chemical properties								
	Soil C	%	14.5	± 2.4	13.8	± 2.3	20	n.s.
	Soil N	%	1.8	± 0.7	1.7	± 0.6	22	n.s.
	Soil available P	mg kg^{-1}	13.7	± 14.2	17.2	± 16.9	9	n.s.
	Soil available K	g kg^{-1}	0.1	± 0.1	0.1	± 0.1	10	n.s.
	Soil organic carbon	%	1.7	± 0.5	1.7	± 0.5	8	n.s.
	pH		6.3	± 0.4	6.4	± 0.5	6	*
Soil physical properties								
	Mean weight diameter	mm	1.0	± 0.4	0.9	± 0.2	10	n.s.
	Bulk density	g cm^{3}	1.3	± 0.3	1.4	± 0.2	4	*
	Volumetric water content	%	20.1	± 5.4	21.8	± 5.7	6	**
Fungal diseases								
	Frosty pod rot	%	28.8	± 24.5	21.2	± 16	4	n.s.
	Black pod	%	3.4	± 2.2	3.0	± 2.0	5	*
	Witches' broom	%	1.9	± 1.4	3.7	± 2.4	5	*
Microclimate								
	Maximum temperature	°C	32.4	± 2.5	34.7	± 3.3	8	*
	Minimum temperature	°C	18.6	± 3.1	17.9	± 3.4	8	***
	Mean temperature	°C	24.7	± 1.8	25.0	± 1.8	8	*
	Mean relative humidity	%	81.5	± 16.5	80.5	± 15.6	3	n.s.
	Vapor pressure deficit	kPa	1.1	± 0.7	1.3	± 0.8	4	n.s.
Stand structural parameters								
	Basal area cocoa trees	m^{2} ha^{-1}	7.7	± 2.9	9.4	± 3.2	22	***
	Basal area shade trees	m^{2} ha^{-1}	10.2	± 2.2	0.2	± 0.4	4	***
	Total C in cocoa trees	Mg ha^{-1}	9.5	± 6.3	13.2	± 6.9	30	***
	Total C in shade trees	Mg ha^{-1}	24.7	± 26.3	1.0	± 4.6	27	***
	Total C in system	Mg ha^{-1}	37.0	± 28.9	14.2	± 9.0	30	***

Table 4. Classification of exchanges (input and output processes) as contributors to paddy rice and cacao beans emission factors.

Exchanges	**Contributors**
Pesticide, unspecified, mix for cereal crops, at plant /GLO U	Pesticides
Barley seed, for sowing {GLO}| market for barley seed, for sowing | Cut-off, U	Seeds
Ammonium nitrate (AN), as N, at plant /RER U	N Fert Production
Urea, as N, at plant /RER U	N Fert Production
Urea ammonium nitrate (UAN), as N, at plant /RER U	N Fert Production
Monoammonium phosphate (MAP), as N, at plant /RER U	N Fert Production
Calcium ammonium nitrate (CAN), as N, at plant /RER U	N Fert Production
Inorganic nitrogen fertiliser, as N {RER}| nutrient supply from ammonium sulfate | Cut-off, U	N Fert Production
NPK (15-15-15), as N, at plant /RER U	N Fert Production
Manure, solid, cattle {GLO}| market for manure, solid, cattle | Cut-off, U	Manure
Barley grain, heavy metals uptake /GLO U	Other
Packaging, for fertilisers or pesticides {GLO}| packaging production for solid fertiliser or pesticide, per kilogram of packed product | Cut-off, U	Fertilizers, other
Packaging, for fertilisers or pesticides {GLO}| packaging production for liquid fertiliser or pesticide, per kilogram of packed product | Cut-off, U	Fertilizers, other
Emissions from pesticides, unspecified, mix for cereal crops, at farm /GLO U	Pesticides
Application of plant protection product, by field sprayer {GLO}| market for application of plant protection product, by field sprayer | Cut-off, U	Machinery
Tillage, currying, by weeder {GLO}| market for tillage, currying, by weeder | Cut-off, U	Tillage
Tillage, harrowing, by rotary harrow {GLO}| market for tillage, harrowing, by rotary harrow | Cut-off, U	Tillage
Tillage, ploughing {GLO}| market for tillage, ploughing | Cut-off, U	Tillage
Sowing {GLO}| market for sowing | Cut-off, U	Machinery
Fertilising, by broadcaster {GLO}| market for fertilising, by broadcaster | Cut-off, U	Machinery
Combine harvesting {GLO}| market for combine harvesting | Cut-off, U	Machinery
Solid manure loading and spreading, by hydraulic loader and spreader {GLO}| market for solid manure loading and spreading, by hydraulic loader and spreader | Cut-off, U	Machinery
Statistical land use change mix, Barley (DRYAD)/UA U	LUC
Statistical emissions from peatland degradation from agricultural land occupation (DRYAD) /UA U	LUC
Carbon dioxide, in air	Direct Emissions
Carbon dioxide, fossil	Direct Emissions
Dinitrogen monoxide	Direct Emissions
Irrigating, sprinkler, electricity powered /AU U	Irrigation
Tap water {GLO}| market group for tap water | Cut-off, U	Irrigation

Ammonium nitrate (AN), as N, at plant /RoW U	N Fert Production
Urea, as N, at plant /RoW U	N Fert Production
Monoammonium phosphate (MAP), as N, at plant /RoW U	N Fert Production
Inorganic nitrogen fertiliser, as N {RoW}| nutrient supply from ammonium sulfate | Cut-off, U	N Fert Production
Ammonia (with 100% NH3), steam reforming process, at plant /RoW U	N Fert Production
NPK (15-15-15), as N, at plant /RoW U	N Fert Production
Triple superphosphate, as P2O5, at plant /RoW U	P Fert Production
Monoammonium phosphate (MAP), as P2O5, at plant /RoW U	P Fert Production
Diammonium phosphate (DAP), as P2O5, at plant /RoW U	P Fert Production
Ammonium nitrate phosphate (ANP), as P2O5, at plant /RoW U	P Fert Production
Potassium chloride, as K2O, at plant /RoW U	K Fert Production
Inorganic potassium fertiliser, as K2O {RoW}| nutrient supply from potassium sulfate | Cut-off, U	K Fert Production
Potassium nitrate, as K2O, at plant /RoW U	K Fert Production
Statistical land use change mix, Barley (DRYAD)/AU U	LUC
Statistical emissions from peatland degradation from agricultural land occupation (DRYAD) /AU U	LUC
Irrigating, sprinkler, electricity powered /CA U	Irrigation
Ammonium nitrate (AN), as N, at plant /RNA U	N Fert Production
Urea, as N, at plant /RNA U	N Fert Production
Urea ammonium nitrate (UAN), as N, at plant /RNA U	N Fert Production
Monoammonium phosphate (MAP), as N, at plant /RNA U	N Fert Production
Calcium ammonium nitrate (CAN), as N, at plant /RNA U	N Fert Production
Ammonia (with 100% NH3), steam reforming process, at plant /RNA U	N Fert Production
NPK (15-15-15), as N, at plant /RNA U	N Fert Production
Monoammonium phosphate (MAP), as P2O5, at plant /RNA U	P Fert Production
Diammonium phosphate (DAP), as P2O5, at plant /RNA U	P Fert Production
Ammonium nitrate phosphate (ANP), as P2O5, at plant /RNA U	P Fert Production
Potassium nitrate, as K2O, at plant /RNA U	K Fert Production
Statistical land use change mix, Barley (DRYAD)/CA U	LUC
Statistical emissions from peatland degradation from agricultural land occupation (DRYAD) /CA U	LUC
Irrigating, sprinkler, electricity powered /DE U	Irrigation
Ammonia (with 100% NH3), steam reforming process, at plant /RER U	N Fert Production
Triple superphosphate, as P2O5, at plant /RER U	P Fert Production
Inorganic phosphorus fertiliser, as P2O5 {RER}| nutrient supply from single superphosphate | Cut-off, U	P Fert Production
Monoammonium phosphate (MAP), as P2O5, at plant /RER U	P Fert Production
Diammonium phosphate (DAP), as P2O5, at plant /RER U	P Fert Production
Ammonium nitrate phosphate (ANP), as P2O5, at plant /RER U	P Fert Production
Phosphate rock, as P2O5, at mine /RER U	P Fert Production
Potassium chloride, as K2O, at plant /RER U	K Fert Production

Inorganic potassium fertiliser, as K2O {RER}| nutrient supply from potassium sulfate | Cut-off, U	K Fert Production
Potassium nitrate, as K2O, at plant /RER U	K Fert Production
Lime {RoW}| market for lime | Cut-off, U	Lime/Dolomite Production
Statistical land use change mix, Barley (DRYAD)/DE U	LUC
Statistical emissions from peatland degradation from agricultural land occupation (DRYAD) /DE U	LUC
Irrigating, sprinkler, electricity powered /FR U	Irrigation
Statistical land use change mix, Barley (DRYAD)/FR U	LUC
Statistical emissions from peatland degradation from agricultural land occupation (DRYAD) /FR U	LUC
Irrigating, sprinkler, electricity powered /GB U	Irrigation
Statistical land use change mix, Barley (DRYAD)/GB U	LUC
Statistical emissions from peatland degradation from agricultural land occupation (DRYAD) /GB U	LUC
Statistical emissions from peatland degradation from agricultural land occupation (DRYAD) /IT U	LUC
Irrigating, sprinkler, electricity powered /IT U	Irrigation
Statistical land use change mix, Barley (DRYAD)/IT U	LUC
Irrigating, sprinkler, electricity powered /PL U	Irrigation
Statistical land use change mix, Barley (DRYAD)/PL U	LUC
Statistical emissions from peatland degradation from agricultural land occupation (DRYAD) /PL U	LUC
Statistical emissions from peatland degradation from agricultural land occupation (DRYAD) /RU U	LUC
Irrigating, sprinkler, electricity powered /RU U	Irrigation
Urea ammonium nitrate (UAN), as N, at plant /RoW U	N Fert Production
Calcium ammonium nitrate (CAN), as N, at plant /RoW U	N Fert Production
Inorganic phosphorus fertiliser, as P2O5 {RoW}| nutrient supply from single superphosphate | Cut-off, U	P Fert Production
Phosphate rock, as P2O5, at mine /RoW U	P Fert Production
Statistical land use change mix, Barley (DRYAD)/RU U	LUC
Irrigating, sprinkler, electricity powered /UA U	Irrigation
Statistical land use change mix, Barley (DRYAD)/AR U	LUC
Statistical emissions from peatland degradation from agricultural land occupation (DRYAD) /AR U	LUC
Maize seed, for sowing {GLO}| market for maize seed, for sowing | Cut-off, U	Seeds
Irrigating, sprinkler, electricity powered /AR U	Irrigation
Maize grains, heavy metals uptake /GLO U	Other
Pesticide, unspecified, mix for maize crops, at plant /GLO U	Pesticides
Emissions from pesticides, unspecified, mix for maize crops, at farm /GLO U	Pesticides
Chopping, maize {GLO}| market for chopping, maize | Cut-off, U	Machinery

Statistical land use change mix, Maize (DRYAD)/AR U	LUC
Statistical land use change mix, Maize (DRYAD)/CA U	LUC
Irrigating, sprinkler, electricity powered /CN U	Irrigation
Ammonium nitrate (AN), as N, at plant /CN U	N Fert Production
Urea, as N, at plant /CN U	N Fert Production
Monoammonium phosphate (MAP), as N, at plant /CN U	N Fert Production
NPK (15-15-15), as N, at plant /CN U	N Fert Production
Monoammonium phosphate (MAP), as P2O5, at plant /CN U	P Fert Production
Diammonium phosphate (DAP), as P2O5, at plant /CN U	P Fert Production
Ammonium nitrate phosphate (ANP), as P2O5, at plant /CN U	P Fert Production
Potassium nitrate, as K2O, at plant /CN U	K Fert Production
Statistical land use change mix, Maize (DRYAD)/CN U	LUC
Statistical emissions from peatland degradation from agricultural land occupation (DRYAD) /CN U	LUC
Irrigating, sprinkler, electricity powered /ES U	Irrigation
Statistical land use change mix, Maize (DRYAD)/ES U	LUC
Statistical emissions from peatland degradation from agricultural land occupation (DRYAD) /ES U	LUC
Irrigating, sprinkler, electricity powered /MX U	Irrigation
Statistical land use change mix, Maize (DRYAD)/MX U	LUC
Statistical emissions from peatland degradation from agricultural land occupation (DRYAD) /MX U	LUC
Statistical land use change mix, Maize (DRYAD)/UA U	LUC
Irrigating, sprinkler, electricity powered /US U	Irrigation
Statistical land use change mix, Maize (DRYAD)/US U	LUC
Statistical emissions from peatland degradation from agricultural land occupation (DRYAD) /US U	LUC
Rice grains, heavy metals uptake /GLO U	Other
Tillage, generic /CH U	Tillage
Irrigating, surface, diesel powered /GLO U	Irrigation
Irrigating, sprinkler, diesel powered /GLO U	Irrigation
Transport, tractor and trailer, agricultural {RoW}| market for transport, tractor and trailer, agricultural | Cut-off, U	Machinery
Fungicide, unspecified, mix for cereal crops, at plant /GLO U	Pesticides
Emissions from fungicides, unspecified, mix for cereal crops, at farm /GLO U	Pesticides
Herbicide, unspecified, mix for cereal crops, at plant /GLO U	Pesticides
Emissions from herbicides, unspecified, mix for cereal crops, at farm /GLO U	Pesticides
Insecticide, unspecified, mix for cereal crops, at plant /GLO U	Pesticides
Emissions from insecticides, unspecified, mix for cereal crops, at farm /GLO U	Pesticides
Rice seed, for sowing {GLO}| market for rice seed, for sowing | Cut-off, U	Seeds
Statistical land use change mix, Rice, paddy (DRYAD)/CN U	LUC
Methane, biogenic	Direct Emissions

Ammonium nitrate phosphate (ANP), as N, at plant /RoW U	N Fert Production
Diammonium phosphate (DAP), as N, at plant /RoW U	N Fert Production
Liquid manure spreading, by vacuum tanker {GLO}| market for liquid manure spreading, by vacuum tanker | Cut-off, U	Machinery
Statistical land use change mix, Rice, paddy (DRYAD)/IN U	LUC
Statistical emissions from peatland degradation from agricultural land occupation (DRYAD) /IN U	LUC
Mineral fertilizer, as N, market for /EC U	N Fert Production
Mineral fertilizer, as P2O5, market for /EC U	P Fert Production
Mineral fertilizer, as K2O, market for /EC U	K Fert Production
Statistical land use change mix, Maize (DRYAD)/EC U	LUC
Statistical emissions from peatland degradation from agricultural land occupation (DRYAD) /EC U	LUC
Irrigating infrastructure, sprinkler /GLO U	Irrigation
Irrigating infrastructure, surface /GLO U	Irrigation
Atrazine {GLO}| market for atrazine | Cut-off, U	Pesticides
Pendimethalin {GLO}| market for pendimethalin | Cut-off, U	Pesticides
Triazine-compound, unspecified {GLO}| market for triazine-compound, unspecified | Cut-off, U	Pesticides
Pyridine-compound {GLO}| market for pyridine-compound | Cut-off, U	Pesticides
Organophosphorus-compound, unspecified {GLO}| market for organophosphorus-compound, unspecified | Cut-off, U	Pesticides
Dinitroaniline-compound {GLO}| market for dinitroaniline-compound | Cut-off, U	Pesticides
Cyclic N-compound {GLO}| market for cyclic N-compound | Cut-off, U	Pesticides
[thio]carbamate-compound {GLO}| market for [thio]carbamate-compound | Cut-off, U	Pesticides
Pyrethroid-compound {GLO}| market for pyrethroid-compound | Cut-off, U	Pesticides
[sulfonyl]urea-compound {GLO}| market for [sulfonyl]urea-compound | Cut-off, U	Pesticides
Diesel, burned in agricultural machinery {GLO}| market for diesel, burned in agricultural machinery | Cut-off, U	Machinery
Biowaste {RoW}| treatment of biowaste, industrial composting | Cut-off, U	Direct Emissions
Biowaste {RoW}| treatment of biowaste, open dump | Cut-off, U	Direct Emissions
Carbon dioxide, biogenic	Direct Emissions
Mineral fertilizer, as N, market for /EG U	N Fert Production
Manure, liquid, cattle {GLO}| market for manure, liquid, cattle | Cut-off, U	Fertilizers, other
Statistical land use change mix, Maize (DRYAD)/EG U	LUC
Statistical emissions from peatland degradation from agricultural land occupation (DRYAD) /EG U	LUC
Petrol, unleaded, burned in machinery {GLO}| market for petrol, unleaded, burned in machinery | Cut-off, U	Machinery
Statistical land use change mix, Maize (DRYAD)/PL U	LUC

Diazine-compound {GLO}| market for diazine-compound | Cut-off, U	Pesticides
Mineral fertilizer, as K2O, market for /BR U	K Fert Production
Mineral fertilizer, as P2O5, market for /BR U	P Fert Production
Mineral fertilizer, as N, market for /BR U	N Fert Production
Statistical land use change mix, Maize (DRYAD)/BR U	LUC
Statistical emissions from peatland degradation from agricultural land occupation (DRYAD) /BR U	LUC
Phenoxy-compound {GLO}| market for phenoxy-compound | Cut-off, U	Pesticides
Nitrile-compound {GLO}| market for nitrile-compound | Cut-off, U	Pesticides
Acetamide-anillide-compound, unspecified {GLO}| market for acetamide-anillide-compound, unspecified | Cut-off, U	Pesticides
Naphtha {RoW}| market for naphtha | Cut-off, U	Pesticides
Glyphosate {GLO}| market for glyphosate | Cut-off, U	Pesticides
Mineral fertilizer, as N, market for /TR U	N Fert Production
Mineral fertilizer, as P2O5, market for /TR U	P Fert Production
Mineral fertilizer, as K2O, market for /TR U	K Fert Production
Statistical land use change mix, Maize (DRYAD)/TR U	LUC
Statistical emissions from peatland degradation from agricultural land occupation (DRYAD) /TR U	LUC
Herbicide, unspecified, mix for maize crops, at plant /GLO U	Pesticides
Benzoic-compound {GLO}| market for benzoic-compound | Cut-off, U	Pesticides
Dimethenamide {GLO}| market for dimethenamide | Cut-off, U	Pesticides
Crop, default, heavy metals uptake /GLO U	Other
Mineral fertilizer, as N, market for /FR U	N Fert Production
Mineral fertilizer, as P2O5, market for /FR U	P Fert Production
Mineral fertilizer, as K2O, market for /FR U	K Fert Production
Statistical land use change mix, Maize (DRYAD)/FR U	LUC
Metaldehyde {GLO}| market for metaldehyde | Cut-off, U	Pesticides
Metolachlor {GLO}| market for metolachlor | Cut-off, U	Pesticides
Mineral fertilizer, as K2O, market for /IT U	K Fert Production
Mineral fertilizer, as P2O5, market for /IT U	P Fert Production
Mineral fertilizer, as N, market for /IT U	N Fert Production
Statistical land use change mix, Rice, paddy (DRYAD)/IT U	LUC
Diazole-compound {GLO}| market for diazole-compound | Cut-off, U	Pesticides
Mineral fertilizer, as N, market for /HU U	N Fert Production
Mineral fertilizer, as P2O5, market for /HU U	P Fert Production
Mineral fertilizer, as K2O, market for /HU U	K Fert Production
Statistical land use change mix, Maize (DRYAD)/HU U	LUC
Statistical emissions from peatland degradation from agricultural land occupation (DRYAD) /HU U	LUC
Benzo[thia]diazole-compound {GLO}| market for benzo[thia]diazole-compound | Cut-off, U	Pesticides
Urea {RoW}| market for urea | Cut-off, U	N Fert Production
Mineral fertilizer, as N, market for /CL U	N Fert Production

Mineral fertilizer, as P2O5, market for /CL U	P Fert Production
Mineral fertilizer, as K2O, market for /CL U	K Fert Production
Statistical land use change mix, Rice, paddy (DRYAD)/CL U	LUC
Statistical emissions from peatland degradation from agricultural land occupation (DRYAD) /CL U	LUC
Statistical land use change mix, Maize (DRYAD)/PE U	LUC
Potassium chloride {RoW}| market for potassium chloride | Cut-off, U	P Fert Production
Triple superphosphate {RoW}| market for triple superphosphate | Cut-off, U	P Fert Production
Statistical emissions from peatland degradation from agricultural land occupation (DRYAD) /PE U	LUC
Statistical land use change mix, Rice, paddy (DRYAD)/BR U	LUC
Pyrazole {GLO}| market for pyrazole | Cut-off, U	Pesticides
Statistical land use change mix, Rice, paddy (DRYAD)/PK U	LUC
Electricity, low voltage {PK}| market for electricity, low voltage | Cut-off, U	Machinery
Potassium sulfate {RoW}| market for potassium sulfate | Cut-off, U	K Fert Production
Ammonia, anhydrous, liquid {SAS}| market for ammonia, anhydrous, liquid | Cut-off, U	N Fert Production
Diammonium phosphate {RoW}| market for diammonium phosphate | Cut-off, U	P Fert Production
Statistical emissions from peatland degradation from agricultural land occupation (DRYAD) /PK U	LUC
Diesel, burned in diesel-electric generating set, 18.5kW {GLO}| market for diesel, burned in diesel-electric generating set, 18.5kW | Cut-off, U	Machinery
Mineral fertilizer, as K2O, market for /US U	K Fert Production
Mineral fertilizer, as P2O5, market for /US U	P Fert Production
Mineral fertilizer, as N, market for /US U	N Fert Production
Statistical land use change mix, Rice, paddy (DRYAD)/US U	LUC
Copper, cathode {GLO}| market for copper, cathode | Cut-off, U	Other
Statistical land use change mix, Maize (DRYAD)/CL U	LUC
Mineral fertilizer, as K2O, market for /MX U	K Fert Production
Mineral fertilizer, as P2O5, market for /MX U	P Fert Production
Mineral fertilizer, as N, market for /MX U	N Fert Production
Statistical land use change mix, Rice, paddy (DRYAD)/MX U	LUC
Fosetyl-Al {GLO}| market for fosetyl-Al | Cut-off, U	Pesticides
Mancozeb {GLO}| market for mancozeb | Cut-off, U	Pesticides