CEDA-FLAG - A Hybrid Model for Forestry, Land Use and Agriculture Emissions in Global Supply Chains

Mo Li[1], Steve Davis[1,2], Julianne DeAngelo[1], Sangwon Suh[1,3]

[1] *Watershed, San Francisco, California, United States*
[2] *Department of Earth System Science, Stanford Doerr School of Sustainability, Stanford University, Stanford, California, United States*
[3] *Bren School of Environmental Management, University of California, Santa Barbara, California, United States*

Abstract

Forest, Land, and Agriculture (FLAG) sectors contribute about one-quarter of global anthropogenic greenhouse gas (GHG) emissions, yet current measurement approaches lack either the necessary resolution or supply chain coverage for effective climate action. While process-based models like CALUE offer detailed, product-level emissions estimates but miss upstream impacts, input-output models like CEDA capture broad supply chain emissions but with limited commodity detail. To address these gaps, we introduce CEDA-FLAG—a hybrid model that integrates the granularity of CALUE with the global, supply chain scope of CEDA—providing both monetary and physical emissions factors for 400 sectors and 150 agricultural commodities across 65 countries. Through a case study of a global retailer's food supply chain, we demonstrate how CEDA-FLAG enables regionally specific emissions assessment, hotspot identification, and mitigation planning, supporting robust FLAG emissions accounting in line with emerging climate standards.

1. Introduction

1.1 Background and Motivation

Forest, Land, and Agriculture (FLAG) sectors are fundamental to both global food security and the fight against climate change. Representing roughly one-quarter of anthropogenic greenhouse gas (GHG) emissions, these sectors are uniquely positioned at the intersection of environmental stewardship, economic development, and societal wellbeing. The surge in global population, coupled with evolving dietary preferences and increased demand for food, fiber, and bioenergy, has intensified land-use pressures, driving deforestation, soil degradation, and other environmentally consequential changes.

In response, both regulatory and voluntary frameworks—such as the Science-Based Targets initiative (SBTi), the Greenhouse Gas Protocol (GHG Protocol), and national climate commitments under the Paris Agreement—are raising expectations for accuracy, transparency, and comprehensiveness in FLAG emissions accounting. Businesses and governments alike are seeking robust, actionable data to inform emissions reduction targets, design mitigation strategies, and demonstrate climate leadership.

However, the complexity of FLAG emissions—arising from diverse sources such as deforestation, agricultural practices, and globalized supply chains—poses significant measurement challenges. Emissions are distributed across direct (on-site) and indirect (supply chain) activities, requiring data systems and models that can capture both physical and economic flows at adequate spatial and sectoral resolution.

1.2 Existing Models and Databases

A variety of models and databases have been developed to quantify GHG emissions from the FLAG sectors, each with distinct strengths and limitations.

Current accounting approaches, while important, are marked by significant limitations. The Comprehensive Accounting of Land-Use Emissions (CALUE) database (Hong et al., 2021), for instance, offers impressive granularity regarding process- and product-specific emissions but is limited to direct emissions, omitting crucial cradle-to-gate and supply chain impacts. Conversely, input-output models like the Comprehensive Environmental Data Archive (CEDA) account for supply chain emissions at a global scale but fall short in sectoral and product-level detail, particularly within agriculture (Suh, 2009).

1.3 Research Gap and Objectives

While both process-based accounting (e.g., CALUE) and MRIO-based EEIO models (e.g., CEDA) play essential roles in FLAG GHG measurement, each exhibits critical limitations. Process-based models provide high-resolution, mass-based estimates for direct emissions but often exclude upstream supply chain impacts. Conversely, MRIO-based models offer comprehensive coverage of supply chain emissions but lack the commodity-level granularity required for targeted FLAG interventions.

This research addresses the urgent need for a hybrid approach that integrates the granularity of process-based models with the supply chain completeness of MRIO-based EEIO frameworks. The primary objective is to present the CEDA-FLAG model—a novel integration of CALUE and CEDA that delivers both monetary and physical emissions factors for 400 economic sectors and 150 agricultural commodities per country across 65 countries.

By bridging these methodological and data gaps, CEDA-FLAG empowers decision-makers with regionally specific, actionable insights, supporting emissions hotspot identification, mitigation strategy prioritization, and alignment with emerging climate disclosure standards. The subsequent sections detail the methodology, demonstrate its application in a real-world supply chain context, and discuss implications for advancing science-based FLAG sector climate action.

2. Method and Data

2.1 Overview of the CEDA Model

CEDA is a Multi-Regional Input-Output (MRIO) model that provides comprehensive coverage of the global economy and global trade flows across 400 sectors and 148 countries plus one Rest of World (ROW) region. It combines national input-output tables, UN COMTRADE trade statistics, and GHG inventories to estimate GHG emissions embedded in the production and consumption of goods across countries. The detailed treatment of emissions and economic transactions in CEDA makes it a practical choice for modeling scenarios that require alignment with U.S. economic data and regulatory frameworks.

In this study, we selected 65 out of the 148 countries represented in the original CEDA model for hybridization with the CALUE model. This selection was based on data availability, economic significance, and the completeness of country-level agricultural and forestry statistics in FAOSTAT and the FLAG emission inventories. By focusing on these 65 countries, which collectively account for the majority of global agricultural production and land-use change emissions, we ensured that the hybrid CEDA-FLAG framework covers regions and supply chains most relevant for comprehensive, high-resolution emissions accounting. This targeted integration enables robust, regionally specific assessment of FLAG emissions while maintaining methodological consistency and data quality across countries.

2.2 Overview of the CALUE Model

The CALUE model ingests land management (LM) emissions estimates from the UN Food and Agriculture Organization (FAOstat) and land use change (LUC) emissions estimates from the BLUE model (Hansis, Davis, and Pongratz, Global Biogeochemical Cycles, 2015) and allocates them to 185 agricultural and forestry commodities and 226 countries (1961-2021) according to the base case methods explained in Hong et al. The model provides country-, process-, and product-specific emissions estimates. While this yields high-resolution, mass-based results for direct emissions, it typically omits upstream (cradle-to-gate) emissions, such as those from fertilizer production, machinery, or energy use in supply chains.

In this study, we updated the CALUE model to incorporate more recent data from the FAO through 2021 and to use a 20-year lookback period from 2021 for the LM and the LUC emissions. This results in emission factors (EFs) for the twelve categories by country (Table 1).

Table 1. FLAG emissions category in the CALUE model.

	Emission category
Land Management	• Rice • Organic soils • Manure soil • Manure pasture • Manure management

	• Fertilizer • Enteric fermentation • Crop residues • Burning residues
Land Use Change	• Wood harvest • Pasture • Cropland

2.3 Model Hybridization Procedures

We implemented an integrated hybrid approach following the framework of Suh (2004), combining detailed physical data on agricultural and forestry commodities with the economic structure of the CEDA input-output model. The procedure involved three main steps described in the following sections.

2.3.1 Commodity Classification and Allocation

We classified 150 agricultural and forestry commodities using UN CPC codes at the class and subclass levels, aligning each product with the most representative category. Production quantities for each commodity and country were sourced from FAOSTAT and mapped to US Bureau of Economic Analysis (BEA) sectors via a concordance table.

Table 2. CEDA’s FLAG sectors hybridized with the CALUE model

BEA Code	**BEA Commodities**
1111A0	Oilseed farming
1111B0	Grain farming
111200	Vegetable and melon farming
111300	Fruit and tree nut farming
111900	Other crop farming
112120	Dairy cattle and milk production
1121A0	Beef cattle ranching and farming
112300	Poultry and egg production
112A00	Animal production, except cattle and poultry and eggs
113000	Forestry and logging

2.3.2 Hybrid Matrix Construction

The classified commodities were integrated into the CEDA model through a hybrid input-output framework.The A matrix (Figure 1) captures inter-sectoral relationships, linking mass-based agricultural outputs to monetary economic sectors. Adjustments were made to ensure that agricultural inputs and outputs reflect actual production quantities and to avoid double-counting. The B matrix (Figure 2) allocates direct FLAG GHG emissions (from land management and land-use change) by dividing total FLAG emissions by production quantities and direct Non-FLAG GHG emissions based on the original CEDA sector data, adjusted to exclude FLAG-related emissions and preserve national totals.

A Matrix	FLAG commodities	BEA commodities
FLAG commodities	0	Distribution of FLAG commodities to BEA commodities in kg per $
BEA commodities	Inputs of BEA commodities to FLAG commodities in $ per kg	Original A matrix adjusted to the hybrid framework in $ per $

Figure 1. Structure of the A matrix in CEDA+FLAG Model.

B Matrix	FLAG commodities	BEA commodities
FLAG emissions (land management)	Direct FLAG emissions from land management per commodity in kg CO2e per kg	0
FLAG emissions (land-use change)	Direct FLAG emissions from land-use change per commodity in kg CO2e per kg	0
Non-FLAG emissions	Direct non-FLAG emissions per commodity in kg CO2e per kg	Direct non-FLAG emissions of BEA commodity in kg CO2e per $

Figure 2. Structure of the B matrix in CEDA+FLAG Model.

2.3.3 Emissions Factor Calculation

The total (direct and supply chain) GHG emissions factors are calculated using the Leontief inverse:

$$L = (I - A)^{-1} \quad (1)$$

where A is a square matrix that represents the units of direct input (row) required to produce one unit of output (column)with the final M matrix (equation 2) expressing the direct and upstream emissions required to produce one unit of each output:

$$M = BL \quad (2)$$

3. Results

By integrating the CEDA and CALUE models, the CEDA+FLAG hybrid framework incorporates additional FLAG emissions data—most notably land use change (LUC)—into the emissions profiles of the original CEDA sectors. Figure 3 presents a detailed breakdown of total GHG emissions in Brazil by FLAG commodity group and emission source, contrasting the baseline CEDA model with the enhanced CEDA+FLAG results. The findings demonstrate that, in the hybrid model, LUC emissions (green) overwhelmingly dominate the total emissions for several major commodity groups, particularly oilseed, grain, and forestry, with oilseed alone reaching nearly 600 Mt CO_2e. In contrast, beef cattle emissions are primarily attributed to land management practices (orange). This highlights the significant impact of explicitly accounting for FLAG emissions—especially LUC—on the overall emissions landscape of Brazil's key agricultural and forestry sectors.

The elevated LUC emissions of nearly 600 Mt CO_2e associated with oilseed products are largely attributable to the extensive conversion of forests to soybean farms in Brazil in recent years, as illustrated in Figure 4. The annual trends in LUC emissions from oil crops across Latin America and the Caribbean clearly indicate that Brazil has consistently been the dominant contributor, with emissions rising sharply in the early 2000s and exhibiting considerable year-to-year variability in the past decade. Taking into account the 20-year lookback period used for LUC emissions accounting, the linearly discounted LUC emissions from Brazilian oil crops are estimated to be around 600 Mt CO_2e—closely aligning with the oilseed-related LUC emissions depicted in Figure 4.

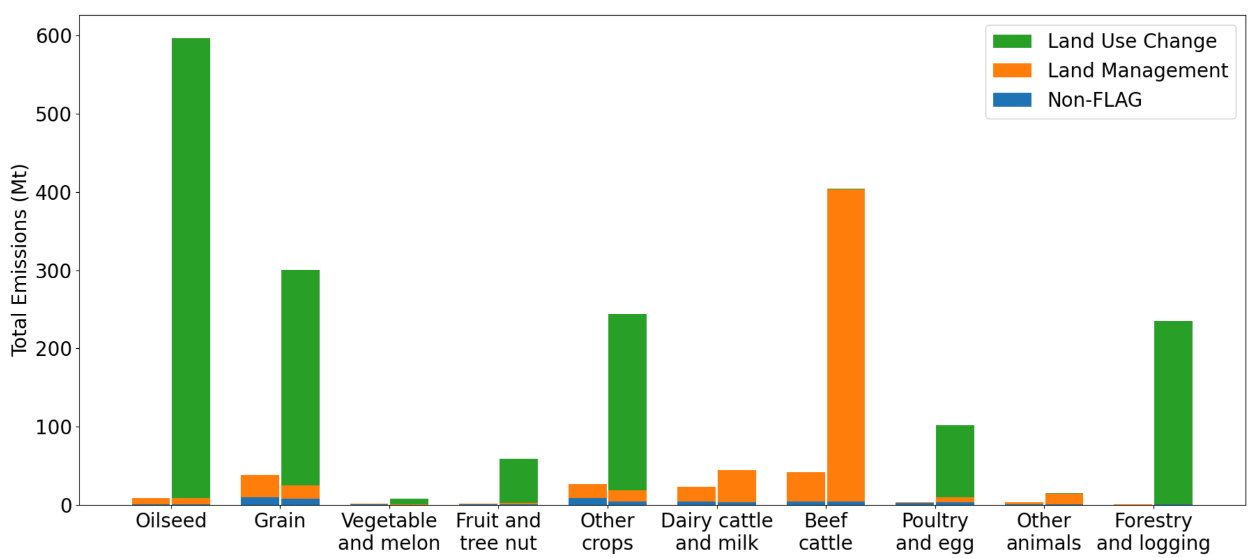

Figure 3. Total GHG emissions in Brazil by FLAG commodity group and emission source, comparing baseline CEDA model results (left bar of each pair) to the integrated CEDA+FLAG hybrid model (right bar of each pair). Each bar is segmented according to emissions from land use change (green), land management (orange), and non-FLAG sources

(blue). The figure illustrates how the inclusion of detailed FLAG emissions in the hybrid model (CEDA+FLAG) changes the estimated contributions of various sources—particularly for oilseed, grain, and beef cattle—highlighting the importance of accounting for land use and land management in comprehensive FLAG sector emissions assessments.

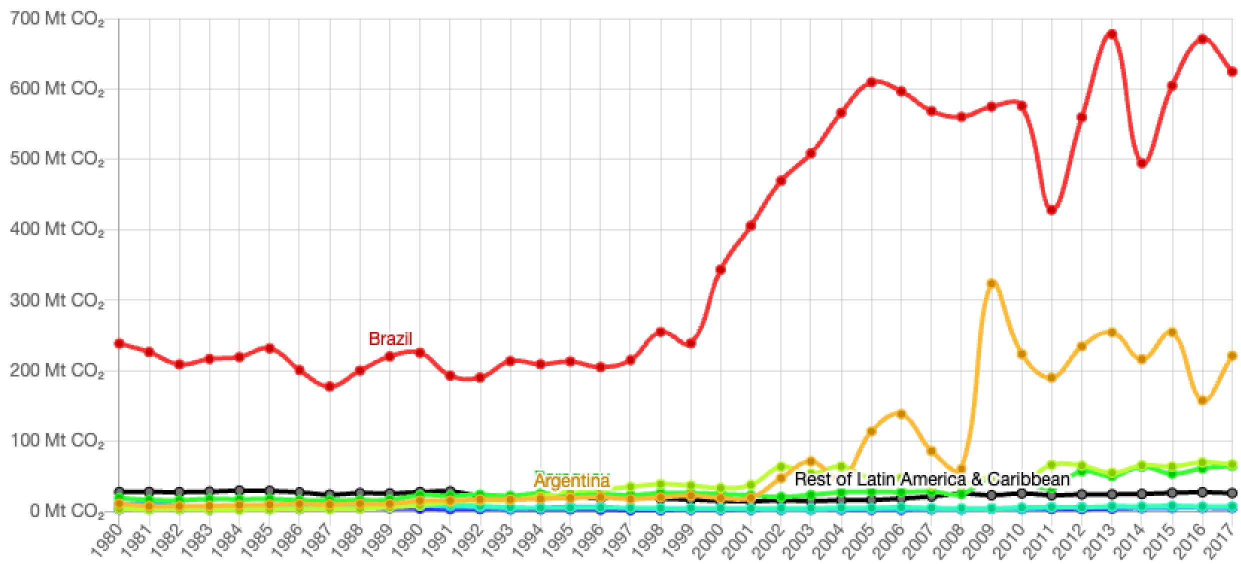

Figure 4. Trends in annual LUC GHG emissions associated with oil crops in Latin American & Caribbean countries from 1980 to 2017. Brazil (red line) dominates regional emissions over the entire period, with notable increases in the early 2000s and significant interannual variation in recent years. The figure highlights the outsized role of Brazil in land use change emissions within Latin America and underscores the importance of region-specific mitigation strategies. (obtained from: https://sustsys.ess.uci.edu/CALUE.html)

The CEDA+FLAG hybrid model reveals notable FLAG, particularly LUC, emissions embodied in the global, upstream supply chains of food products. In Figure 5, we compare the supply chain —direct and indirect— emission factors (kg CO_2e per USD) for two food products—cheese as well as coffee and tea—that are produced in the US where supply chains are highly globalized and Brazil where land use changes are evident in recent years (Figure 4). For each product and country, the left bar represents the baseline EF from CEDA, while the right bar incorporates FLAG-specific emissions in the EF. The figure reveals that accounting for LUC (green) dramatically increases the total EFs for coffee and tea, by 220% in the US and 316% in Brazil, and becomes the dominant component. For cheese in Brazil, hybridizing CEDA with CALUE raises the total EF, with notable increases in both LM (orange) and LUC (green) contributions, likely because CALUE estimates LM emissions with more granular data of from milk cattle ranching activities in Brazil, such as manure management and enteric fermentation, than CEDA. Overall, the results emphasize that incorporating high-resolution FLAG data can significantly shift the estimated GHG intensity of agricultural products, especially those with supply chains linked to land conversion, thereby providing a more accurate basis for identifying emission hotspots and prioritizing mitigation strategies.

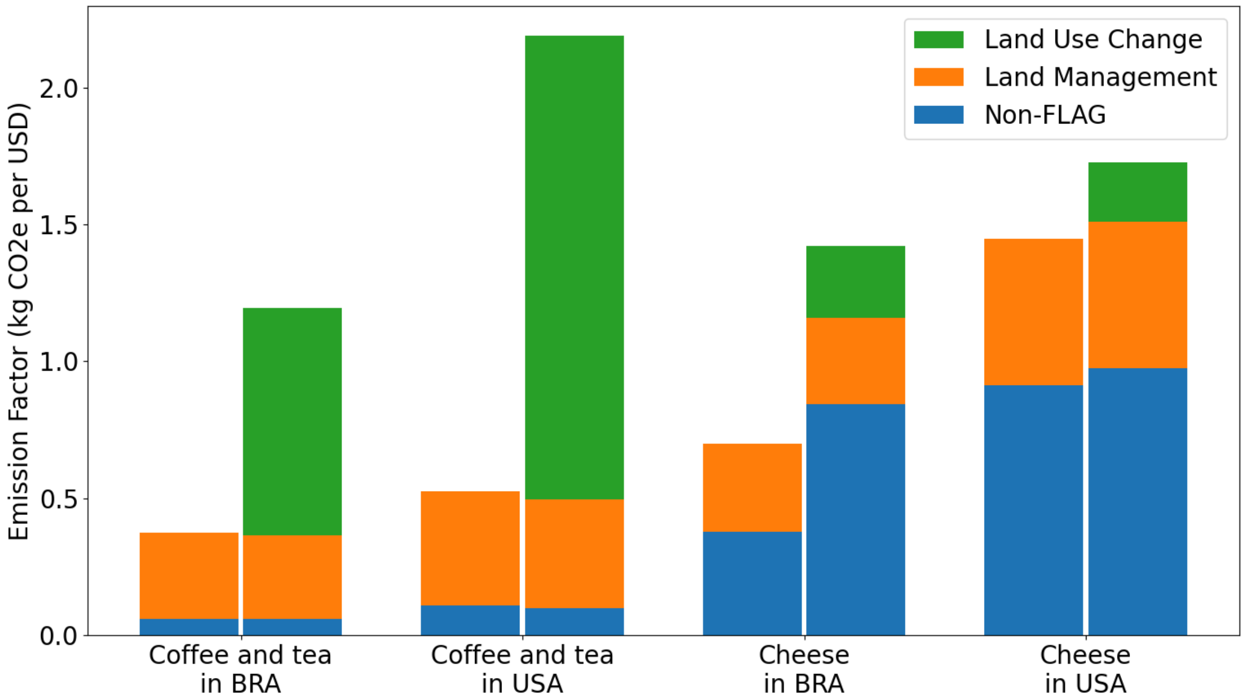

Figure 5. Direct and indirect emission factors (kg CO_2e per USD) for selected food products and countries, comparing CEDA (left bar in each pair) and CEDA+FLAG hybrid model results (right bar in each pair). Each bar is segmented by contributions from land use change (green), land management (orange), and non-FLAG sources (blue). The results show how incorporating detailed FLAG emissions from CALUE into CEDA can significantly change EFs of food products, particularly for land use change-intensive products such as cheese, coffee and tea in Brazil and the US.

4. Discussion

This study introduces the CEDA+FLAG framework, which integrates the process-based CALUE model with the multi-regional input-output CEDA model to produce sector- and region-specific estimates of GHG emissions, encompassing both land management and land use change sources. This integration addresses the respective limitations of the standalone models, namely the limited supply chain coverage in CALUE and the restricted commodity resolution in CEDA.

The application of CEDA+FLAG generally results in higher EFs compared to those produced by either CEDA or CALUE alone. This increase is attributable to the hybridization approach, which leverages the supply chain coverage of CEDA together with the commodity and FLAG resolution of CALUE, thereby expanding the scope and improving the attribution of emissions across activities. The results enable identification of sectors and regions with high direct and indirect emissions, which can inform targeted mitigation analyses. Furthermore, the outputs are aligned with the requirements for explicit reporting of FLAG emissions in both regulatory and voluntary disclosure frameworks.

The CEDA+FLAG framework provides a tool for practitioners in corporate sustainability and reporting to evaluate FLAG-related emissions and support compliance with emerging standards. Depending on the sector and country of procurement, total emissions may be 200% to 316% higher when CEDA+FLAG emission factors are applied, as compared to CEDA alone. This finding underscores the importance for practitioners to consider the characteristics of underlying data sources and methodologies in their GHG accounting processes.

Some uncertainties remain regarding the attribution of land use change emissions to specific commodities and the temporal consistency of the datasets utilized. The approach is amenable to updates as new data become available and may be refined through the integration of spatially explicit land use information.

Reference

C. Hong, J. A. Burney, J. Pongratz, J. E.M.S. Nabel, N. D. Mueller, R. B. Jackson, and S. J. Davis. (2021). Global and regional drivers of land-use emissions 1961-2017, Nature, v. 589, p. 554-561, doi:10.1038/s41586-020-03138-y

Suh, S. (2009). Developing the sectoral environmental database for input-output analysis: Comprehensive environmental data archive of the US. In Handbook of Input-Output Economics in Industrial Ecology (pp. 689-712). Dordrecht: Springer Netherlands.