



Climate Justice and Sectoral Responsibility for Energy-Related Carbon Emissions in Thailand: An Inter-Sectoral EEIO Framework

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ABSTRACT

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Aligning carbon emission reductions with equity requires assessing the fair distribution of responsibility for embodied carbon across production networks, particularly in relation to climate-vulnerable agricultural sectors. Using the 2015 input-output table for Thailand, we develop an environmentally extended input-output (EEIO) model covering 30 sectors, with 12 agricultural and 18 non-agricultural, to quantify sectoral emissions, energy-specific emission intensities, and inter-industry linkages. Embodied emissions were found to be highly concentrated in upstream energy and heavy industry, whereas agricultural sectors exhibit comparatively modest emission levels. Especially, most crop-related activities remain below heavy industries in total emissions. These results reveal a distributive imbalance: upstream fossil-energy industries generate the bulk of embodied carbon, while agriculture contributes relatively little yet remains highly climate-sensitive. Grounded in climate justice principles, our scenario analysis suggests that redistributive funds, aligned with the concept of the Polluter Pays Principle, can increase agricultural adaptation and mitigate the impact from climate change.

1. INTRODUCTION

Agricultural production remains highly climate-sensitive, relying on rainfall patterns, temperature stability and ecosystem services that are increasingly disrupted by intensified droughts, floods and heat stress [1-3]. This escalating environmental volatility necessitates a systemic shift toward climate-resilient agriculture, a transition that is fundamentally predicated on the mobilization of significant capital investment. Substantial investment is required to bridge the widening adaptation gap, specifically for the development and deployment of climate infrastructure, such as advanced irrigation systems and flood-resistant storage facilities.

Grounded in climate justice, such financing mechanisms should extend beyond conventional public budgeting by incorporating redistributive instruments that channel resources from carbon high-emitting sectors to vulnerable agricultural systems [4, 5]. Under a carbon accountability approach, funds can be systematically collected from sectors ranked by their carbon intensity, such as energy, transportation, and heavy industry, and redirected toward smallholder farmers and climate-exposed rural communities [6, 7]. This approach internalizes environmental externalities while enhancing equity, ensuring that those contributing most to emissions bear a proportionate share of adaptation costs. In doing so, climate finance becomes both a corrective and enabling mechanism, strengthening agricultural resilience while advancing

distributive justice across sectors.

Because production systems are deeply interconnected, sector specific carbon policies may generate economy wide adjustments [3, 8, 9]. To address this challenge, we therefore employ an environmentally extended input-output (EEIO) analysis framework to examine the economy wide and distributive implications of carbon taxation and sectoral emission responsibility in Thailand. We integrate sectoral greenhouse gas accounts into national input-output tables and attempt to trace both direct and embodied emissions across production and consumption networks.

In Thailand, recurrent El Niño–Southern Oscillation variability amplifies hydrological extremes, directly constraining crop yields, livestock productivity and water availability [10, 11]. Especially, related impacts on Thailand's agricultural sector are projected to result in economic losses of THB 17,912–83,826 million per year between 2011 and 2045 owing to variability in temperature and rainfall, extreme events, and associated yield declines [12].

This context positions Thailand as a compelling case for examining climate justice-oriented financing in the agricultural sector. The country combines high climate exposure with structural dependence on smallholder farming, alongside uneven carbon emission contributions across sectors such as energy, transport, and industry. These conditions create a clear empirical basis for analyzing the inter-sectoral linkages of carbon emissions throughout the Thai economy. By tracing how emissions flow between high-emitting sectors

and climate-vulnerable agriculture, this study establishes a structural framework to identify key leverage points for policy intervention. Ultimately, this enables policymakers to design targeted redistribution mechanisms and supportive policies that allocate resources from heavy emitters toward bolstering the climate-threatened agricultural sector.

2. CONCEPTUALIZATION

Production processes are primary determinants of carbon emissions. As shown in Figure 1, sectors across the economic

system, including industry, manufacturing and agriculture, consume energy that generates carbon dioxide (CO₂) as a byproduct. Emissions are driven largely by the combustion of fossil fuels such as coal, oil and natural gas to power machinery, transportation and industrial operations. Indirect emissions arise when electricity inputs are sourced from fossil fuel-based power generation. These emissions intensify climatic change, which in turn feeds back into production systems. Climate sensitive sectors are therefore likely to bear disproportionate impacts, particularly agriculture, where productivity remains closely tied to temperature and precipitation patterns.

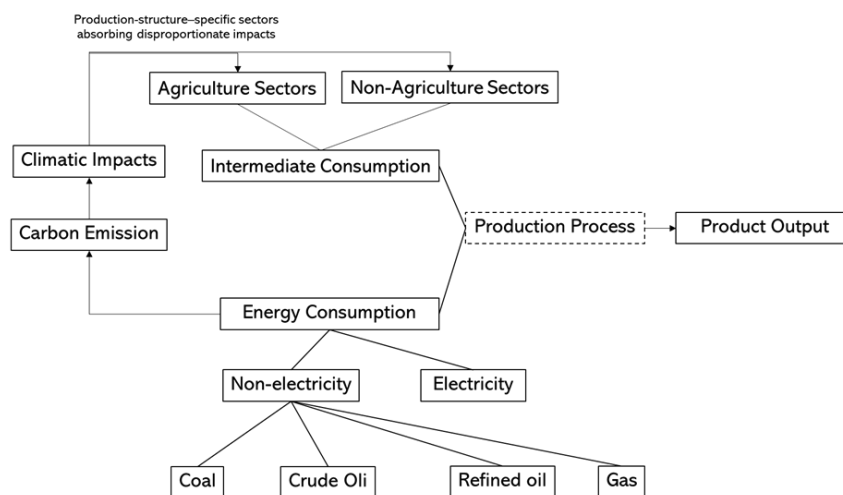


Figure 1. Production structure

Source: Developed by authors.

Within this framework, questions of environmental justice emerge prominently in the allocation of responsibility for carbon emissions and the distribution of climate burdens across sectors. In Thailand, structural differences in production systems shape both emission intensity and vulnerability. Energy intensive industries contribute substantially to national greenhouse gas emissions through fossil fuel combustion and industrial processes, whereas the agricultural sector generates emissions primarily from rice cultivation, livestock production and land use practices. Although agriculture contributes a smaller share of total emissions relative to heavy industry and power generation, it remains highly exposed to climate variability and extreme events.

This asymmetry raises normative concerns regarding responsibility and capacity. Smallholder farmers, who constitute a significant proportion of Thailand's agricultural workforce, often operate with limited capital, technological access, and adaptive infrastructure. Yet they bear disproportionate risks from drought, flooding, and temperature variability. Assigning mitigation obligations without accounting for differentiated capacities may therefore exacerbate existing rural inequalities. Within this logic, redistributive fiscal instruments warrant consideration. A carbon levy imposed on energy related sectors with high emission intensity could generate public revenue that is earmarked for strengthening agricultural resilience. By internalizing the external costs of carbon intensive production while channeling resources toward climate vulnerable sectors, this approach aligns the Polluter Pays Principle with adaptive equity.

The argument advanced here is grounded primarily in three complementary principles: The Polluter Pays Principle, the capability principle, and vulnerability-based justice. The Polluter Pays Principle assigns fiscal responsibility to sectors that generate high levels of energy-related CO₂ and exert strong structural influence within the production network. The capability principle recognizes that sectors with greater capital intensity and technological flexibility, such as electricity and heavy industry, are better positioned to absorb transition costs. Vulnerability-based justice, in contrast, emphasizes exposure: agricultural sectors contribute relatively little to energy-related emissions yet face heightened climate risk.

We adopted environmentally extended input-output (EEIO) framework to operationalize these principles empirically. By tracing embodied emissions through inter-industry linkages, it identifies not only sectors with high direct emissions but also those with strong forward linkages that diffuse carbon across the economy, thereby capturing their structural influence. This enables justice to be assessed along three dimensions: (i) emissions magnitude (who emits), (ii) structural centrality (who drives embodied carbon through supply chains), and (iii) exposure to climate impacts (who bears risk). Within this framework, redistributive fiscal instruments, such as carbon levies on energy-intensive sectors, can be justified not solely on the basis of direct emissions, but also on their systemic carbon propagation capacity, while revenues are directed to climate-vulnerable agricultural sectors. Justice, therefore, is not framed as uniform mitigation burden-sharing, but as differentiated responsibility that reflects emissions, structural power within production networks, and adaptive capacity.

3. METHOD

3.1 Environmentally extended input–output

EEIO analysis links economic flows between sectors with environmental flows (emissions, resource use) to show how final demand drives environmental pressures along supply chains [13]. In this study, we applied this framework to quantify sectoral carbon emissions and examine the distribution of environmental responsibility across production systems, as demonstrated in prior studies on carbon management [14–16]. By coupling national input–output tables with environmental accounts, the model captures both direct emissions and those embodied in supply chains and establishes a rigorous empirical basis for assessing redistributive policy instruments, including carbon taxation and revenue recycling, within a governance framework that seeks to balance allocative efficiency with distributive equity.

Relative to the Agriculture, Forestry and Other Land Use (AFOLU) literature, which typically emphasizes land-use change, methane abatement, and on-farm efficiency [17], this approach reorients attention toward upstream energy inputs embedded in agricultural production. Rather than treating agriculture solely as a direct biological emitter, we employ an EEIO framework to reveal how a substantial share of agricultural embodied emissions originates in electricity generation, fertilizer production, petroleum refining, and transport services. This extends AFOLU mitigation pathways by identifying systemic leverage points beyond farm-level practices. Furthermore, compared with existing EEIO studies that focus primarily on consumption-based accounting or trade-embedded emissions [18], our integration of climate justice principles extends the analytical scope by examining structural transmission mechanisms. We link forward linkage centrality with emission intensity, arguing that responsibility is tied not only to the volume of emissions but also to network influence within the production system. By combining linkage analysis with scenario-based emission coefficient adjustments, this study moves EEIO applications from a static attribution approach toward a policy-relevant structural transformation analysis in emerging economies such as Thailand.

It is important, however, to clarify the accounting boundary. Our present EEIO specification primarily captures energy-related CO₂ emissions associated with fossil fuel combustion across sectors. Biological non-CO₂ emissions, most notably methane (CH₄) from rice cultivation and enteric fermentation in livestock, are not fully represented in the energy-based satellite accounts. Inclusion of these biological emissions would likely increase the absolute emission levels attributed to certain agricultural sectors, particularly paddy and livestock. Nonetheless, because the structural centrality of upstream electricity, fossil energy supply, and carbon-intensive materials arises from their strong forward linkages and economy-wide input provision, incorporating CH₄ would alter the magnitude of sectoral totals but not necessarily overturn the observed structural concentration of embodied carbon in energy-anchored industries. Accordingly, the results should be interpreted as reflecting energy-related carbon responsibility within the production network, while acknowledging that a comprehensive greenhouse gas assessment would require the integration of biological emissions inventories into the satellite framework.

Let A denote the matrix of technical coefficients derived from the national input–output table, where each element

represents the intermediate input required from sector i to produce one unit of output in sector j . Total sectoral output X is determined by final demand Y according to the standard Leontief formulation, as illustrated in Eq. (1):

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

where, $(I - A)^{-1}$ is the Leontief inverse matrix capturing both direct and indirect production requirements. Let $L = (I - A)^{-1}$, then backward linkage or output multiplier of sector j (BW_j) is expressed in Eq. (2):

$$BW_j = \sum_i L_{ij} \quad (2)$$

and forward linkage can be noted in Eq. (3):

$$FW_i = \sum_j L_{ij} \quad (3)$$

Backward linkage captures the induced demand for upstream inputs generated by sectoral expansion, with the growing sector operating as a purchaser that stimulates activity across its supply chain. In contrast, forward linkage describes the transmission of output expansion from a given sector to downstream industries that use its products as intermediate inputs, whereby the originating sector functions as a supplier within the production network

To incorporate environmental dimensions, a vector of direct emission coefficients or intensities (f) is constructed, representing carbon dioxide emissions per unit of sectoral output. Total embodied emissions associated with final demand (E) are then estimated in Eq. (4) as:

$$E = f(I - A)^{-1}Y \quad (4)$$

where,

$$f_i = \frac{F_{i,k}}{x_i} = F_k \hat{x}^{-1}$$

$F_{i,k}$ = Total direct CO₂ emissions from sector i using energy type k

F_k = Column vector of sectoral emissions using energy type k

x_i = Total gross output of sector i

$\hat{x}^{-1}$ = Diagonal matrix of inverse sectoral outputs

This formulation decomposes emissions into production- and consumption-based accounts, revealing how carbon-intensive sectors diffuse environmental burdens across supply chains. The relationship can be expressed as: emission intensities (f) provide the basis for estimating direct emissions ($F_{i,k}$), while the input–output structure extends these direct emissions across inter-sectoral supply chains to estimate embodied emissions (E). Thus, direct emissions represent the emissions occurring within a sector, whereas embodied emissions capture the broader carbon footprint attributable to final demand, including emissions generated indirectly through the sector's purchases of intermediate inputs.

Therefore, sectors with strong forward linkages, such as electricity and petroleum refining, propagate emissions systemically because their outputs serve as essential inputs for

multiple downstream activities [19, 20]. Structural position therefore matters alongside emission magnitude: a sector's network centrality determines how widely its carbon is embodied throughout the economy [19, 21]. Responsibility, in this framework, is thus tied not only to the volume of emissions generated, but also to the sector's capacity to transmit carbon through the production system.

3.2 Scenario analysis

Within an EEIO framework, a justice-oriented shock is introduced as an exogenous change. Therefore, in this study, we propose a simulation to explore the possibility of reallocating funds collected from sectors with high carbon emissions to support agriculture, which produces lower emissions, based on the Polluter Pays Principle.

Beginning with general assumption, climate damage reduces agricultural productivity. In input–output (I–O) terms, lower productivity means higher input requirements per unit output. This is modeled as an increase in agricultural column coefficients in matrix A , indicating in Eq. (5):

$$A_{i,j}^{Shock} = A_{ij}(1 + \theta) \quad (5)$$

where, θ represents climate-induced inefficiency (unit: %). Then the new output is shown as Eq. (6):

$$X^{Shock} = (I - A^{Shock})^{-1}Y \quad (6)$$

Eq. (6) captures how climate stress amplifies backward linkages and increases embodied input dependence. In EEIO terms, resilience reduces technical coefficients (efficiency improvement) and/or shifts input structure away from vulnerable inputs. Therefore, when we propose climate funds (collected from high-emission sectors) finance to increase the resilience of agricultural sectors, the coefficient matrix of the agriculture can be defined as Eq. (7):

$$A_{i,j}^{Res} = A_{ij}(1 - \tau) \quad (7)$$

where, τ represents efficiency gain from resilience investment (unit: %). Then the new output is shown as Eq. (8):

$$X^{Res} = (I - A^{Res})^{-1}Y \quad (8)$$

Then we decompose the effect as:

$$\text{Output preservation ratio (OPR)} = 1 - \frac{X^{Res,agri}}{X^{Shock,agri}} \quad (9)$$

and change in carbon embodied emissions:

$$\Delta E = f[(I - A^{Res})^{-1} - (I - A^{Shock})^{-1}]Y \quad (10)$$

Eq. (9) captures the structural efficiency improvements in agriculture, illustrating how resilience financing reduces the volume of embodied emissions relative to the shock condition, while also decreasing systemic input amplification within the production network. Eq. (10), in turn, reflects the change in embodied emissions resulting from the reallocation of funds under different resilience financing schemes.

We propose that the reallocated funds must be invested in climate-resilience activities in agricultural sectors where the marginal efficiency gains are projected to exceed the marginal

losses in agricultural productivity. Therefore, the value of τ should be higher than θ . Table 1 demonstrates the baseline assessment.

Table 1. Baseline assessment of reallocating funds from key polluters to enhance agricultural climate resilience

Scenario	Changes in Technical Coefficients of Agricultural Sectors	
	θ	τ
1	5%	10%
2	10%	15%
3	15%	20%

Source: Developed by authors.

3.3 Data

This study simplified Thailand's official input–output table from the Office of the National Economic and Social Development Council (NESDC) into 30 sectors. We grouped these sectors based on the production traits and economic activities of the original 180-sector table. This process keeps detailed information on key agricultural and high-emitting industrial sectors while keeping the model easy to calculate. The final 30 sectors include 12 agricultural and 18 non-agricultural activities. Details of the mapping process can be downloaded at the supplementary material.

We employed the 2015 I–O table rather than the 2021 edition to avoid structural distortions associated with the COVID-19 pandemic. The pandemic generated abrupt disruptions in production, consumption, and trade, producing atypical intersectoral linkages and temporary demand contractions that do not reflect the economy's underlying structural relationships. Incorporating crisis-period data would risk conflating transitory shocks with long-run production structures, thereby biasing multiplier and linkage estimates.

In terms of carbon emission, we obtained data from Global Trade Analysis Project (GTAP) 12-Satellite Data and Utilities Year (2017 reference year) [22]. Emission coefficients from GTAP were used to calculate the sectoral carbon emission by multiplying with the output level reported in Thailand's 2015 NESDC input–output table. To reconcile the two datasets, total emissions from all production sectors were scaled to match Thailand's official 2015 greenhouse gas (GHG) emission level reported in World Resources Institute [23]. In this balancing adjustment, we also assume that production technologies, energy structures, and carbon intensities remain relatively stable over short timeframes, ensuring structural consistency between the emission satellite data and the national economic framework. All financial values will be reported in US dollars (USD), with local currency amounts converted at an exchange rate of THB 34.25 per USD, based on the 2015 annual average exchange rate [24].

4. RESULTS

4.1 Technical coefficients

The backward (BW) and forward (FW) linkage indices reveal a clear structural asymmetry between agricultural and energy–industrial sectors as shown in Figure 2. Most agricultural activities exhibit stronger backward than forward linkages, indicating greater dependence on upstream inputs than their influence over downstream production. Paddy (BW

= 1.76; FW = 1.42), Maize (1.90; 1.14), Cassava (1.83; 1.21), and Sugarcane (1.91; 1.19) show moderate backward dependence but relatively weak forward transmission. Livestock (2.36; 1.38) and Fishery (2.26; 1.19) display comparatively high backward multipliers, reflecting their

intensive use of feed, fuel, and services, yet their forward effects remain limited. Agricultural Services (2.09; 1.43) similarly function as input-dependent support activities rather than dominant downstream drivers. Overall, agriculture appears structurally dependent on upstream inputs.

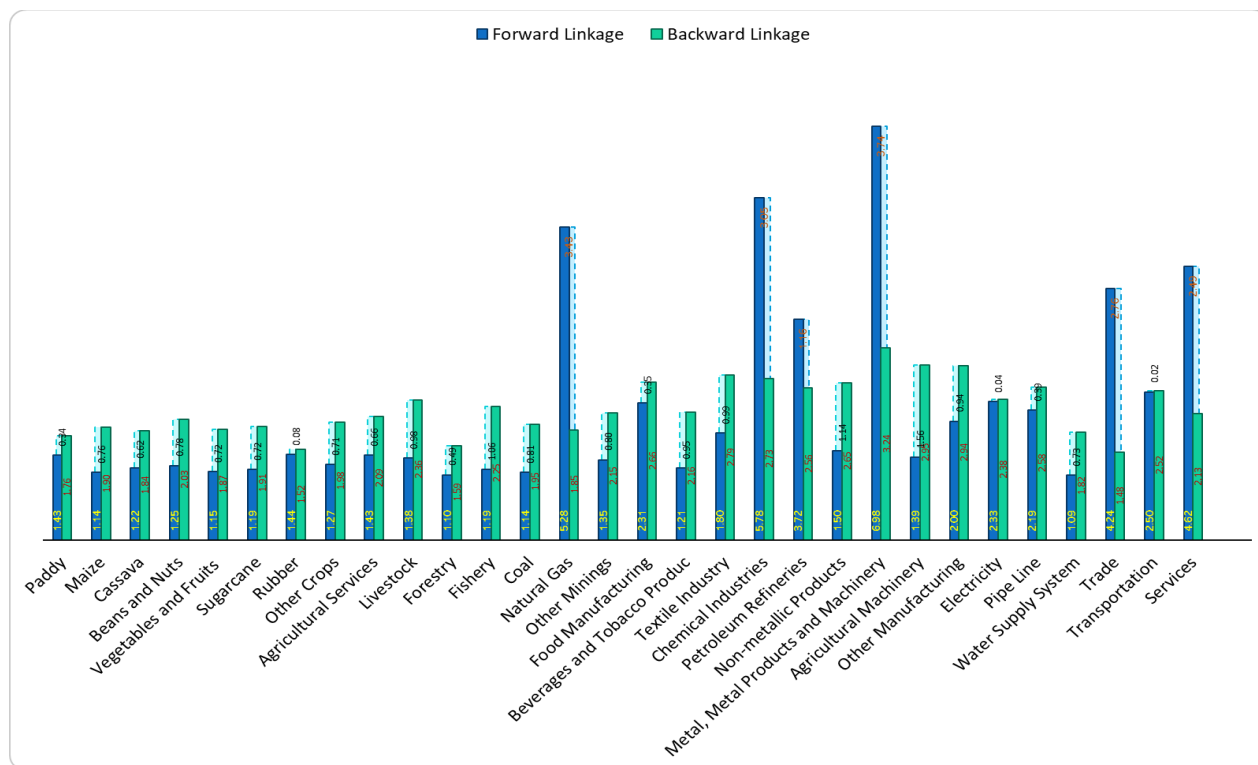


Figure 2. Forward (FW) and backward (BW) linkage in Thai economic structure
Source: Calculated by authors.

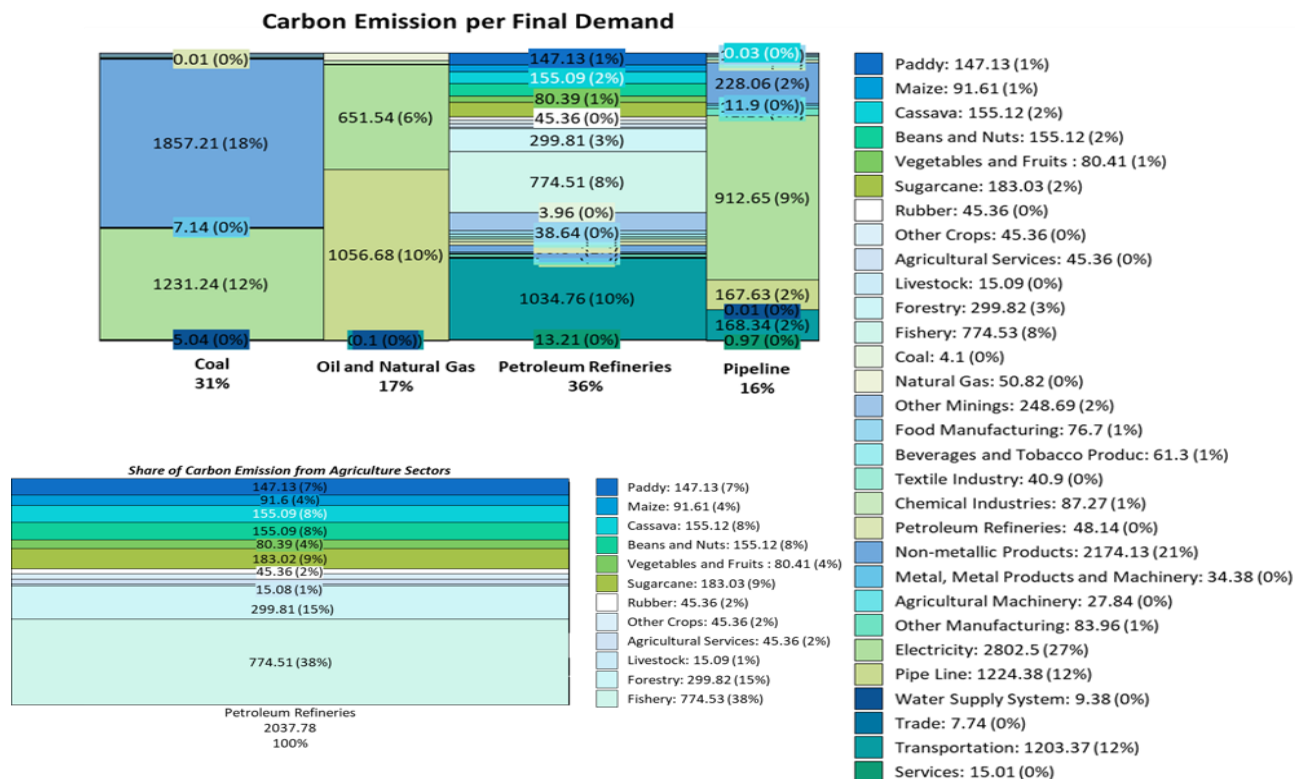


Figure 3. Vector of direct emission intensities (f)
Source: Calculated by authors.
Unit: tCO₂e/million USD.

By contrast, fossil-energy and heavy industrial sectors demonstrate pronounced forward linkages. Natural Gas (1.85; 5.29), Chemical Industries (2.73; 5.78), Metal and Machinery (3.24; 6.98), Petroleum Refineries (2.56; 3.72), Trade (1.48; 4.24), and Services (2.13; 4.63) exhibit strong forward multipliers, indicating their central role in supplying intermediate inputs across the economy. Their production structures therefore exert systemic influence, with emissions and cost changes propagating widely through value chains.

4.2 Energy-specific emission intensities

The energy-specific emission intensities (f) show that agricultural sectors are overwhelmingly linked to petroleum refinery-based emissions, with negligible contributions from coal and only minor effects from oil and natural gas. As shown in Figure 3 (tCO₂e/million USD), Paddy (147.13), Maize (91.61), Sugarcane (183.033), Beans and Nuts (155.12), and Forestry (299.82) show moderate petroleum-related carbon intensities relative to output. Vegetables and Fruits (80.41) and Other Crops (45.36) display similar dependence, while Livestock remains comparatively low (15.09). Fishery is a clear outlier within agriculture, with a petroleum intensity of 774.53, substantially higher than other primary activities, indicating strong reliance on fuel-intensive marine operations. Direct coal-based emissions are virtually absent across agriculture, underscoring the limited role of coal in farm-level production.

On the other hand, heavy industry and energy sectors

exhibit structurally different intensity patterns. Non-metallic Products (47.173 from coal), Electricity (79.923 from oil and gas; 35.199 from coal), and Transportation (25.832 from petroleum) demonstrate extremely high carbon intensities relative to output. Chemical Industries and Petroleum Refineries also display strong oil and gas linkages. This comparison highlights a pronounced structural imbalance: agriculture's carbon intensity is concentrated in petroleum-based inputs and remains modest relative to energy and heavy industrial sectors.

4.3 Total embodied emissions in final demands

Table 2 (unit: t-CO₂e/million USD) reveals a pronounced asymmetry in sectoral emission structures across Thailand's final demands. High emission intensity per unit consumption of final demands are overwhelmingly concentrated in upstream energy and heavy industrial sectors. Electricity records the highest total emission intensity (98.09), driven primarily by coal inputs (38.20), underscoring its role as a systemic carbon hub. Non-metallic products follow (89.55), with emissions dominated by coal (67.11), reflecting the carbon intensity of cement and construction materials. Transportation (49.90) and pipeline activities (48.41) are likewise structurally tied to petroleum systems, with transportation emissions heavily concentrated in petroleum refineries (36.02) and pipelines dependent on oil and gas flows (38.54).

Table 2. Emission intensity by energy types per unit consumption of final demands

Sector	Coal	Oil and Natural Gas	Petroleum Refineries	Pipeline	Total Emission
Agricultural Sectors					
Paddy	0.89111	0.89376	5.88150	0.78836	8.45472
Maize	0.99992	0.93421	4.84440	0.93868	7.71722
Cassava	0.92817	0.88982	6.68659	0.84099	9.34557
Beans and Nuts	0.98969	0.87799	6.83633	0.81094	9.51495
Vegetables and Fruits	1.36435	1.16666	4.18319	1.16254	7.87675
Sugarcane	1.13302	0.99926	7.62469	0.99489	10.75185
Rubber	0.74879	0.67245	2.41043	0.64318	4.47486
Other Crops	1.63882	1.30296	3.37909	1.28880	7.60967
Agricultural Services	1.38287	1.48936	2.98195	1.18225	7.03643
Livestock	2.06678	1.38498	3.55313	1.53472	8.53961
Forestry	1.25760	0.54566	10.04656	0.68532	12.53514
Fishery	1.45387	1.22228	25.95911	1.07087	29.70613
Non-Agricultural Sectors					
Coal	1.09657	1.40400	7.38951	1.92263	11.81272
Natural Gas	1.44038	2.47524	1.27079	0.93902	6.12543
Other Minings	2.57088	2.00635	9.78468	2.17502	16.53693
Food Manufacturing	3.36126	1.95297	5.92185	2.33236	13.56843
Beverages and Tobacco Product	3.84722	1.39381	3.39586	1.83865	10.47555
Textile Industry	5.25282	4.07568	3.50804	4.82346	17.66000
Chemical Industries	3.82985	4.43901	4.27061	3.47442	16.01390
Petroleum Refineries	1.44957	2.68007	2.69179	1.09818	7.91961
Non-metallic Products	67.11160	3.89568	7.30438	11.23920	89.55086
Metal, Metal Products and Machinery	4.49758	2.52134	3.32664	3.37704	13.72260
Agricultural Machinery	4.12770	2.39306	3.03034	3.16983	12.72093
Other Manufacturing	4.07864	2.28735	4.35571	4.23550	14.95720
Electricity	38.19933	28.56606	1.78067	29.54344	98.08949
Pipeline	1.66789	38.54110	1.27575	6.92953	48.41427
Water Supply System	7.04433	4.73991	1.12961	4.95311	17.86697
Trade	1.80458	1.26779	1.84428	1.45143	6.36808
Transportation	2.25373	4.04982	36.02327	7.57327	49.90009
Services	4.79883	2.09642	3.18426	2.52210	12.60160

Source: Calculated by authors.
Unit: tCO₂e/million USD.

Table 3. Baseline assessment for investment in climate-resilience activities in agricultural sectors

Sector	Scenario 1 ($\theta = 0.05, \tau = 0.10$)			Scenario 2 ($\theta = 0.10, \tau = 0.15$)			Scenario 3 ($\theta = 0.15, \tau = 0.20$)		
	χ^{Shock}	χ^{Res}	OPR	χ^{Shock}	χ^{Res}	OPR	χ^{Shock}	χ^{Res}	OPR
Agricultural Sectors									
Paddy	1.24	1.07	13.96%	1.30	1.01	22.24%	1.36	0.95	29.81%
Maize	1.19	1.02	14.27%	1.24	0.96	22.70%	1.30	0.90	30.40%
Cassava	1.22	1.04	14.21%	1.27	0.99	22.61%	1.33	0.93	30.28%
Beans and Nuts	1.28	1.09	14.24%	1.34	1.03	22.66%	1.40	0.97	30.35%
Vegetables and Fruits	1.09	0.94	14.19%	1.14	0.89	22.58%	1.20	0.83	30.25%
Sugarcane	1.18	1.01	14.19%	1.23	0.95	22.58%	1.29	0.90	30.25%
Rubber	1.25	1.08	14.17%	1.31	1.02	22.55%	1.37	0.96	30.21%
Other Crops	1.20	1.03	14.19%	1.26	0.98	22.58%	1.32	0.92	30.25%
Agricultural Services	1.47	1.26	13.99%	1.54	1.19	22.27%	1.61	1.13	29.85%
Livestock	1.22	1.05	14.00%	1.27	0.99	22.30%	1.33	0.93	29.88%
Forestry	1.05	1.05	0.10%	1.05	1.04	0.17%	1.05	1.04	0.24%
Fishery	1.10	1.10	0.50%	1.10	1.10	0.83%	1.11	1.09	1.16%
Non-Agricultural Sectors									
Coal	0.02	0.01	12.15%	0.02	0.01	19.47%	0.02	0.01	26.23%
Natural Gas	0.84	0.75	10.83%	0.87	0.72	17.42%	0.90	0.69	23.57%
Other Minings	0.04	0.04	11.87%	0.04	0.04	19.03%	0.05	0.03	25.67%
Food Manufacturing	0.70	0.63	10.37%	0.72	0.60	16.71%	0.75	0.58	22.63%
Beverages and Tobacco Product	0.02	0.02	12.09%	0.02	0.02	19.37%	0.02	0.02	26.11%
Textile Industry	0.08	0.07	11.19%	0.09	0.07	17.99%	0.09	0.07	24.31%
Chemical Industries	2.26	1.96	13.37%	2.36	1.86	21.33%	2.46	1.76	28.64%
Petroleum Refineries	0.96	0.86	10.52%	1.00	0.83	16.94%	1.03	0.79	22.94%
Non-metallic Products	0.07	0.07	10.45%	0.08	0.06	16.83%	0.08	0.06	22.80%
Metal, Metal Products and Machinery	1.16	1.04	10.60%	1.20	0.99	17.07%	1.24	0.95	23.11%
Agricultural Machinery	0.14	0.12	12.96%	0.15	0.12	20.71%	0.16	0.11	27.84%
Other Manufacturing	0.16	0.14	11.59%	0.17	0.14	18.59%	0.17	0.13	25.10%
Electricity	0.27	0.23	12.29%	0.28	0.22	19.68%	0.29	0.21	26.51%
Pipeline	0.17	0.15	12.45%	0.18	0.14	19.92%	0.19	0.14	26.82%
Water Supply System	0.02	0.02	13.20%	0.02	0.02	21.08%	0.02	0.02	28.31%
Trade	1.27	1.11	12.47%	1.33	1.06	19.95%	1.38	1.01	26.86%
Transportation	0.39	0.34	12.57%	0.41	0.33	20.10%	0.42	0.31	27.06%
Services	1.00	0.88	12.05%	1.04	0.84	19.31%	1.08	0.80	26.02%
Total Effects	24.07	21.18	12.00%	25.03	20.21	19.24%	25.99	19.25	25.93%

Note: θ is climate-induced inefficiency (unit: %); τ is efficiency gain from resilience investment (unit: %); OPR is Output preservation ratio.

Source: Calculated by authors.

The agricultural emission intensity of final consumption exhibits marked variation by both subsector and energy type. Overall, emissions are modest relative to heavy industry, although their structure reveals differentiated fossil-fuel dependence across final products. Crop-based sectors, such as Paddy (8.45), Maize (7.71), Vegetables and Fruits (9.51), and Sugarcane (10.75), are primarily linked to petroleum refinery outputs, reflecting fuel use in mechanization, irrigation, and Agro-processing.

Coal plays only a minor role across most crop activities. Sugarcane records the highest total among crops, driven largely by petroleum-based inputs (1.13). Cassava (0.93) and Rubber (0.75) display comparatively low emission levels, with limited reliance on petroleum-derived energy. In contrast, Beans and Nuts (6.84) and Forestry (10.05) show relatively high petroleum refinery linkages, indicating energy-intensive processing or transport requirements.

The final consumption of livestock (8.54) requires a more balanced energy mix, with notable contributions from oil and natural gas (3.55) and coal (2.07), suggesting both direct fuel use and indirect energy inputs. Agricultural Services (7.04) similarly rely on oil and natural gas, underscoring the role of mechanized support systems. Fishery (29.71) is the clear outlier within agriculture. Its emissions are overwhelmingly petroleum-based (25.96), indicating strong dependence on liquid fuels for marine operations. This sharply contrasts with land-based cropping systems, where emissions are more

diversified and substantially lower.

4.4 Scenario analysis

Resilience financing directed to agricultural sectors generates economy-wide reductions in embodied emissions relative to the shock condition, operating through intersectoral linkages. Table 3 demonstrates baseline assessment for investment in climate-resilience activities in agricultural sectors.

The results indicate that under the lowest investment scenario ($\tau = 0.10$), investment improves production efficiency in core agricultural sectors by approximately 14%, with consistent gains across Paddy (13.96%), Maize (14.27%), Cassava (14.21%), Sugarcane (14.20%), and related crops. Crucially, these efficiency gains propagate upstream. Energy and extractive sectors show 10–12% improvements (Coal 12.15%, Natural Gas 10.83%, Petroleum Refineries 10.52%), while manufacturing and infrastructure sectors record 10–13% gains (Chemicals 13.37%, Electricity 12.29%, Transportation 12.57%). This pattern confirms that restored efficiency in agriculture reduces intermediate demand pressures across the network. Detailed baseline assessments are presented in Table 3.

Regarding Scenario 1 in Table 4, the change in final demands induced carbon embodied emissions intensity indicates a net economy-wide reduction of 33.95 tCO₂e/million

USD, confirming that resilience financing that increases agricultural technologies generates systemic mitigation effects. Agricultural sectors show consistent declines, led by Sugarcane (−1.79), Livestock (−1.46), Paddy (−1.47), and Maize (−1.31). These reductions reflect improved input efficiency and lower embodied energy use within climate-resilient production systems. Rubber (−0.79) and Fishery (−0.16) display smaller responses, while Forestry and Coal show no measurable change, indicating possible structural rigidity or low linkage sensitivity. Furthermore, the largest absolute declines occur in upstream energy and industrial sectors. Electricity records −3.21 and Chemical Industries −4.84, the two largest reductions in the economy. Transportation (−2.46) and Trade (−1.01) also decline notably. This pattern confirms strong forward-linkage effects: efficiency gains in agriculture reduce intermediate demand for electricity, fertilizers, fuels, and logistics, thereby lowering embodied emissions in structurally central sectors.

Taken together, the results show that resilience financing in

agriculture works as a linkage-based mitigation mechanism. Improving efficiency in agricultural production not only reduces the impacts of climate change at the farm level but also generates wider benefits across the economy. When agricultural systems become more efficient, they require fewer inputs such as energy, fertilizers, and transport services. This reduces pressure on upstream sectors that supply these inputs. These changes extend beyond agriculture through strong economic linkages. As demand for energy, chemicals, and logistics declines, production processes in these sectors become less intensive, leading to lower emissions. The most noticeable effects occur in sectors that are closely connected to agriculture, particularly energy generation, chemical production, and transportation. This pattern highlights the improvements in agricultural systems can influence upstream activities by reducing intermediate demand. As a result, investments in agricultural resilience do not only support adaptation but also contribute to broader emission reductions across the economic system.

Table 4. Change in final demands induced carbon embodied emission intensity from baseline assessment

Sector	Change in Carbon Embodied Emissions		
	Scenario 1 ($\theta = 0.05, \tau = 0.10$)	Scenario 2 ($\theta = 0.10, \tau = 0.15$)	Scenario 3 ($\theta = 0.15, \tau = 0.20$)
Agricultural Sectors			
Paddy	-1.46794	-2.44656	-3.42519
Maize	-1.30573	-2.17621	-3.04670
Cassava	-1.61386	-2.68977	-3.76568
Beans and Nuts	-1.72947	-2.88245	-4.03543
Vegetables and Fruits	-1.22110	-2.03517	-2.84924
Sugarcane	-1.79348	-2.98914	-4.18479
Rubber	-0.79465	-1.32441	-1.85418
Other Crops	-1.29857	-2.16428	-3.03000
Agricultural Services	-1.44548	-2.40913	-3.37278
Livestock	-1.45554	-2.42590	-3.39627
Forestry	-0.01353	-0.02254	-0.03156
Fishery	-0.16273	-0.27122	-0.37971
Non-Agricultural Sectors			
Coal	-0.02309	-0.03849	-0.05388
Natural Gas	-0.56001	-0.93335	-1.30669
Other Minings	-0.08447	-0.14079	-0.19710
Food Manufacturing	-0.98386	-1.63976	-2.29566
Beverages and Tobacco Product	-0.02579	-0.04299	-0.06019
Textile Industry	-0.16633	-0.27722	-0.38811
Chemical Industries	-4.84147	-8.06911	-11.29676
Petroleum Refineries	-0.80295	-1.33825	-1.87355
Non-metallic Products	-0.69726	-1.16210	-1.62693
Metal, Metal Products and Machinery	-1.68583	-2.80971	-3.93359
Agricultural Machinery	-0.23536	-0.39227	-0.54917
Other Manufacturing	-0.27911	-0.46518	-0.65125
Electricity	-3.20531	-5.34218	-7.47906
Pipeline	-1.03206	-1.72011	-2.40815
Water Supply System	-0.05070	-0.08450	-0.11830
Trade	-1.01028	-1.68381	-2.35733
Transportation	-2.45723	-4.09538	-5.73353
Services	-1.51108	-2.51846	-3.52585
Total Change	-33.95427	-56.59045	-79.22663

Note: θ is climate-induced inefficiency (unit: %); τ is efficiency gain from resilience investment (unit: %).

Source: Calculated by authors. Unit: tCO₂e/million USD.

5. DISCUSSION

5.1 Empirical discussion

The empirical results reveal a highly asymmetric carbon structure in which embodied emissions are concentrated in a

small group of upstream energy and industrial sectors. In absolute terms, Electricity records the highest total emissions. Electricity records the highest total emissions because power generation is an intermediate input to nearly all sectors [25, 26]. Consistent with Muangthai et al. [25], electricity generation shows one of the highest forward linkage indices,

explicitly indicating that it is “a vital input to other industries” and a key basis of industrial activity. In addition, transportation is strongly petroleum-based, confirming that embodied emissions in Thailand driven by final demand are structurally anchored in fossil-fuel systems. This figure reflects the direct combustion of liquid fuels in freight and passenger mobility, while pipeline activities rely on sustained oil and natural gas throughput. Because logistics and distribution networks underpin both production and final consumption, emissions from these sectors increase in close alignment with expanding trade, services, and household demand [27–29]. This reinforces their role as key transmission channels of embodied carbon across the economy.

By contrast, agricultural sectors display comparatively modest emission levels, consistent with existing studies showing that most crop-based agricultural activities are less energy-intensive per unit of output than heavy industry [30–32]. Energy and industry are dominated by CO₂ emissions from fossil fuel combustion, a long-lived stock pollutant that accumulates in the atmosphere [33, 34], but agriculture is dominated by methane (CH₄) and nitrous oxide (N₂O) emissions from enteric fermentation, manure, agricultural soils, and rice cultivation, with a relatively smaller share of fossil-fuel-based CO₂ [35, 36]. When all gases are converted into CO₂-equivalents, the high fossil-CO₂ volumes from upstream energy and industry overshadow non-CO₂ gases from agriculture, making the agricultural sector’s share look smaller even where it is a leading CH₄/N₂O source [33, 36, 37].

A redistributive design for climate investment is essential. Our scenario analysis supports this approach, emphasizing a concept of climate justice grounded in differentiated responsibility, structural capability, and vulnerability. Resilience investment generates the largest efficiency gains in climate-vulnerable agricultural sectors, particularly rain-fed crops. Existing studies show that smallholder, rain-fed crops in Africa, Asia, and Latin America are highly sensitive to drought, floods, and heat, leading to substantial yield and income losses. Because baseline productivity and resilience are low, investments with a redistributive design that target sectors involved in their technical production, such as water management and infrastructure, can generate disproportionately large improvements in performance and resilience. In addition, embodied emission reductions are amplified in structurally central and carbon-intensive sectors, with most notably electricity and chemical production.

Although investment is directed toward agriculture, input–output linkages transmit efficiency gains upstream, reflecting their strong backward linkages. This confirms that responsibility should not be assigned solely on the basis of direct emissions, but also according to their structural influence within the production network [20, 21].

In summary, the results demonstrate a quantitative mismatch between carbon responsibility and structural influence. High-forward-linkage sectors combine high emission intensity with strong transmission capacity, making them central drivers of embodied emissions. Agriculture, by comparison, contributes relatively low direct emissions and exhibits weaker forward influence, yet remains highly climate-sensitive. The transfer of responsibility from high-emission sectors to the agricultural sector is therefore required.

5.2 Policy discussion

By quantifying total embodied emissions driven by final demand, this study constructs illustrative structural scenarios to map how downstream consumption patterns generate upstream carbon loads across the supply chain (Figure 4). Rather than serving as empirical forecasts of fiscal mechanisms or specific tax instruments, these scenarios provide a baseline target map for policymakers. By identifying which non-agricultural sectors account for the highest carbon intensity linked to agricultural demand, this approach establishes a structural rationale for policy design—offering an empirical foundation to evaluate how mitigation efforts and supportive resource allocation could be strategically targeted across interconnected sectors.

Figure 4 synthesizes these structural findings into a conceptual policy framework for climate justice in agriculture, drawing on the rationale of the Polluter Pays Principle. By linking sectoral emission intensities identified in the EEIO model to overarching policy design, this framework illustrates how carbon-pricing mechanisms could conceptually assign greater responsibility to emission-intensive sectors, such as fossil energy, heavy manufacturing, and petrochemicals. Rather than simulating specific tax rates or fiscal revenue streams, this conceptual model highlights how revenues from high-emitting supply chains could strategically feed into a dedicated climate fund to support climate-vulnerable, low-emitting sectors like agriculture.

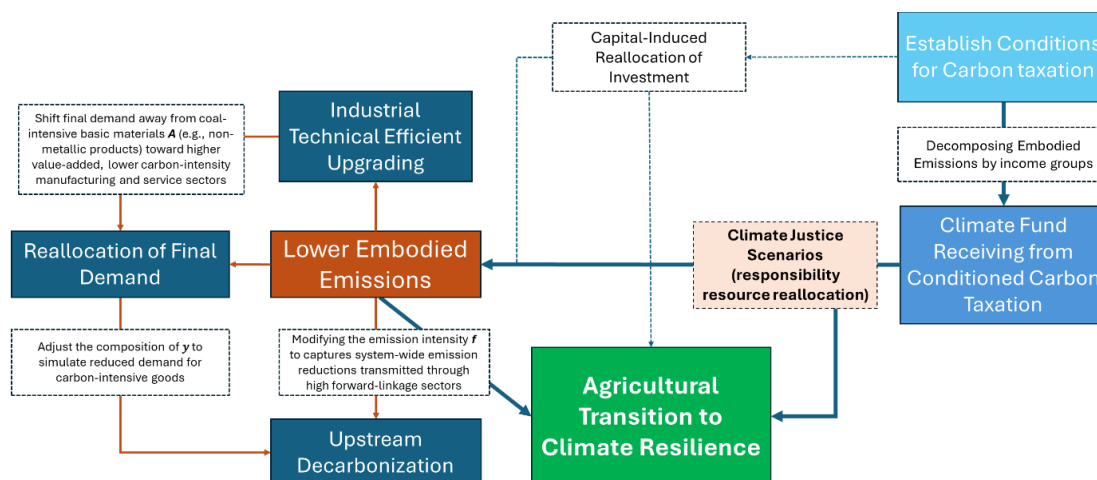


Figure 4. Policy pathway for climate justice scenario
Source: Developed by authors.

Targeted allocation to on-farm adaptation such as, clean technology deployment, resilient infrastructure and risk transfer instruments strengthens the adaptive capacity of farming systems that experience disproportionate climate exposure despite modest per unit emissions [17]. When revenue recycling is structured progressively, carbon pricing can mitigate regressive effects and enhance policy legitimacy [38, 39]. Embedded within a consumption-based accounting framework [40], this redistributive mechanism aligns mitigation obligations with emission drivers while directing financial flows toward sectors characterized by high livelihood sensitivity, thereby advancing climate justice through accountable public finance.

A climate justice scenario reallocates responsibility by tracing embodied emissions across the production network. Consumption-based accounting shows that high-revenue, carbon-intensive sectors drive disproportionate upstream emissions [41]. Linking these sectors to climate-vulnerable agriculture, such as rain-fed Paddy, Maize, and Sugarcane, aligns responsibility with structural drivers, while directing fiscal support toward sectors with limited adaptive capacity. Mitigation and resilience thus become mutually reinforcing. Structural transformation complements this approach. Shifting final demand from coal-intensive materials toward higher value-added manufacturing and services lowers embodied emissions through compositional change [42, 43]. Embedded in just transition policies, such shifts redistribute opportunity and prevent carbon lock-in [44].

Furthermore, consumption reallocation away from electricity-intensive materials, petrochemicals, construction, and transport targets sectors with strong forward linkages, where small demand changes generate amplified upstream emission reductions [45, 46]. Evidence from China indicates that dominant emission pathways are concentrated along a limited number of structurally embedded supply chain routes [46, 47]. Structural path and decomposition analyses show that trajectories such as non-metallic minerals to construction to capital formation, and electricity to intermediate production sectors to final consumption, account for a substantial share of embodied carbon dioxide and methane emissions. These findings highlight the centrality of investment driven construction demand and electricity intensive intermediate inputs in amplifying upstream emission flows. Accordingly, moderating capital formation and construction related expenditure can suppress emissions in core supplying sectors, particularly energy generation and basic materials, generating system-wide mitigation effects that exceed the immediate reduction in final demand.

The energy transition scenario should place explicit emphasis on upstream decarbonization by reducing emission intensities in electricity generation, petroleum refining and natural gas supply through renewable substitution and efficiency gains. These interventions are especially impactful in sectors with strong forward linkages including with energy supply chains that influence downstream sectors [48]. In oil and gas systems, the transitional options include process efficiency improvements, carbon capture and storage (CCS), fuel switching and the integration of renewable energy into refinery and upstream operations. These measures can deliver near-to medium-term emission reductions in contexts where fossil fuels remain embedded in the energy mix [49-51]. By lowering emission coefficients in core supplying sectors, the energy transition scenario generates cascading reductions in

embodied emissions throughout supply chains, thereby reinforcing both mitigation effectiveness and distributive equity. These strategies align with evidence from emerging economies where electricity and petroleum sectors function as structural emission hubs. Studies of China and India show that decarbonizing power generation yields economy-wide mitigation effects disproportionate to the sector's direct emission share because of its pervasive forward linkages [52, 53]. Similar dynamics are observed in Southeast Asia (see Discussion).

6. CONCLUSION AND FUTURE RESEARCH

This study, using a case study of Thailand, demonstrates that embodied carbon is structurally concentrated in upstream fossil-energy and heavy industrial sectors, while agricultural activities contribute comparatively modest carbon emissions. As discussed, this asymmetry justifies applying the Polluter Pays Principle as a corrective fiscal mechanism. By collecting funds from high emission sectors and reallocating the proceeds to climate-resilient investment in agriculture, responsible justice is then aligned with both carbon emission magnitude and systemic influence.

Such transfer mechanisms are not merely redistributive. Because agriculture is deeply embedded in upstream energy, fertilizer, transport, and service supply chains, improving its efficiency and adaptive capacity reduces intermediate demand pressures across the production network. As the scenario results demonstrate, resilience financing lowers embodied emissions not only within agriculture but also in electricity generation, chemical production, and transport services. Supporting agricultural adaptation therefore generates economy-wide mitigation co-benefits.

This study intentionally focuses strictly on energy-related CO₂ emissions associated with inter-sectoral production chains. Consequently, non-CO₂ greenhouse gas emissions—such as methane CH₄ and nitrous oxide N₂O from rice cultivation, livestock, and agricultural soils—are excluded from the empirical scope. Furthermore, while this paper introduces a climate justice framing by illustrating how funds collected from high-emitting sectors could support climate-resilient agricultural investments based on supply-chain emission intensity, it does not assess micro-level farmer vulnerabilities, income distribution, or carbon tax incidence. The conclusions regarding sectoral emission contributions are therefore bounded by energy-CO₂ accounting, and future research incorporating full non-CO₂ inventories alongside empirical socio-economic vulnerability indicators is recommended.

In addition to the analytical framework, future research should complement the EEIO analysis with a Computable General Equilibrium (CGE) model to evaluate the dynamic and distributional effects of climate finance targeted at agricultural mitigation. Unlike the static input-output framework which limits dynamic interpretation, a CGE approach can capture price adjustments, substitution effects, and income redistribution under carbon pricing and fiscal transfers. Simulating climate funds financed by high-emitting upstream sectors would clarify whether reallocating resources toward low-carbon technologies, renewable-based irrigation, and resilient infrastructure in agriculture can deliver both emission reductions and rural income stabilization.

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DATA AVAILABILITY

The data supporting the findings of this study are available within the article and its supplementary materials. The primary input–output data utilized to construct the EEIO framework were obtained from the publicly available official statistics of the National Economic and Social Development Council (NESDC) of Thailand. Any additional inquiries regarding the specific sectoral emission calculations can be directed to the corresponding author upon reasonable request.

SUPPLEMENTARY MATERIAL

The detail of sector mapping between Thailand input-output table and GTAP database can be downloaded at <https://doi.org/10.6084/m9.figshare.33261180>.

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