The economics of emissions in rice production: a survey-data-driven approach in Vietnam

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Abstract

Purpose – This paper aims to focus on scrutinizing the economics of greenhouse gas (GHG) emissions in Vietnam's rice production sector.

Design/methodology/approach – Using surveyed data from household rice producers, the smallest available production scale, the author delves into the economics of GHG emissions, constructs a data-driven bottom-up marginal abatement cost curve for Vietnam's rice production, and evaluates the impacts of carbon pricing on production outputs and GHG emissions.

Findings – The author's estimates reveal that the average profit earned per tonne of GHG emissions is $240/tCO2. Notably, the profit earning per tonne of GHG emissions varies substantially across producers, indicating significant opportunities for improvement among low-efficiency producers. The analysis suggests that a reasonable carbon price would yield a modest impact on the national rice output. The quantitative analysis also reaffirms that the primary driver of GHG emissions in Vietnam's rice production stems from non-energy inputs and industrial processes rather than the utilisation of energy inputs, emphasizing the importance of improving cultivation techniques.

Originality/value – This research is original.

Keywords Climate change, Cost structure, Emission intensity, Energy inputs, Household producers

Paper type Research paper

> Climate policymaking suffers not only from uncertainty about climate sensitivity but also from uncertainty about the ability to provide approximate measures of consumers' and producers' responses to policy changes.
>
> Ngo-Van Long (Long, 2015, p. 280)

1. Introduction

Rice production is fundamental for sustaining human populations through the provision of food and nutrition, yet it also plays a significant role in anthropogenic climate change (FAO, 2020). Greenhouse gas (GHG) emissions are linked to rice cultivation both directly and indirectly. Direct emissions stem from the utilization of fossil fuels and industrial processes during the cultivation phase, with methane and nitrous oxide being the primary GHGs associated with this type of emission (Chakraborty *et al.*, 2017; Wang, Akiyama, Yagi, & Yan, 2018; Nikolaisen *et al.*, 2023). Furthermore, rice cultivation relies on substantial

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quantities of non-energy inputs, such as synthetic fertilizers, the production of which emits GHGs—constituting indirect emissions (Menegat, Ledo, & Tirado, 2022). While the promotion of agriculture is vital for ensuring food security, it is equally crucial to address emissions from rice production as tangible threats to the global climate system, thereby striking a balance between beneficial and adverse impacts (Long & Stähler, 2012).

Economic incentives play a pivotal role in shaping individual behaviours towards collective actions aimed at controlling externalities (Long, 1992), including climate change mitigation. These incentives, whether in the form of taxes, subsidies, grants or tradable permits, can alter the cost-benefit analysis for economic agents, rendering environmentally friendly choices more financially appealing. A lack of understanding regarding these economic incentives can lead to the so-called 'green paradox', wherein resource utilization choices that seem environmentally friendly in the short term may yield opposite effects in the long term (Long & Stähler, 2014; Long, 2015). Therefore, comprehending the economic incentives of GHG emitters (on the supply side) is of paramount importance in ensuring the sustainability of climate actions (Sinn, 2012).

This paper examines the economics of GHG emissions in Vietnam's rice production. Vietnam holds a significant position in the global rice market, consistently ranking among the world's largest rice producers and exporters (OECD and FAO, 2021). Rice production stands as a cornerstone of Vietnam's agricultural sector, ensuring food security, fostering economic prosperity and generating employment opportunities for millions of households across all regions of the country. While Vietnam acknowledges the pivotal role of rice production, it is also cognizant of its substantial contribution to GHG emissions. Consequently, emissions reduction within rice production assumes a pivotal role in Vietnam's Nationally Determined Contribution (NDC) to climate change mitigation (Government of Vietnam, 2020).

We aim to make a threefold contribution to the literature by investigating the economics of GHG emissions within Vietnam's rice production sector. First, we utilized survey data collected from rice producers at the smallest production scale—namely, the household level—to gain insights into the emissions intensity of each surveyed producer, quantifying the volume of emissions per tonne of rice produced. We calculated the cost structure of each surveyed producer, including the distribution of fossil energy and non-energy inputs. We also computed the profitability per tonne of GHG emissions in rice production, shedding light on potential profit losses that producers might face when compelled to reduce their emissions.

Second, we constructed a survey-data-driven marginal abatement cost curve (MACC) for rice production in Vietnam. MACCs serve as an intuitive tool in environmental economics and policy analysis, providing insights into the most cost-effective strategies for reducing environmental pollutants (Yue, Deane, O'Gallachoir, & Rogan, 2020). A notable advantage of MACCs lies in their capacity to visually represent the marginal costs linked to abating an additional unit of pollutant, arranged in ascending order. This arrangement enables policymakers and stakeholders to systematically prioritize abatement measures based on cost-efficiency, thus facilitating the optimal allocation of resources to interventions that yield maximal environmental benefits for minimal costs. The MACC framework has gained widespread application in the realm of climate change mitigation within agriculture and forestry (e.g. Lu, Liu, Okuda, & Zhang, 2018; Bamière *et al.*, 2023; USDA, 2023).

Third, utilizing the data-driven MACC and the results obtained on emission intensity, we conducted an estimation of the potential impact of carbon pricing on both the production output and emissions within Vietnam's rice production. Carbon pricing stands as a pivotal policy instrument for climate mitigation and is scheduled to commence in Vietnam by 2028 (Prime Minister of Vietnam, 2022). However, there also exist concerns regarding its potential to pose economic development challenges. While we term our estimates utilizing the MACC as a 'first-order approximation,' acknowledging that – like many other methodologies – they cannot account for all potential changes resulting from carbon pricing, they are nonetheless grounded in surveyed data and offer valuable insights into the anticipated effects of implementing carbon pricing.

The remainder of the paper is organized as follows: In section 2, we provide an overview of Vietnam's rice sectors. Section 3 outlines our methods and datasets. In section 4, we present our results, including the distribution of the cost structure in Vietnam's rice production (i.e. expenditure on energy inputs, non-energy inputs and profit earning), the emission intensity, the data-driven MACC and the estimated impact of carbon pricing. Section 5 discusses the results and provides policy implications. Finally, Section 6 concludes the paper.

2. Overview of Vietnam's rice sector and policies towards rice sector

Vietnam's rice production is important to the national economy in terms of income, employment and trade balance. It accounts for around 30% of the national production value in agriculture (Maitah, Smutka, Sahatqija, Maitah, & Nguyen, 2020) and over 10% of agro-forestry–fishery export turnover (General Statistics Office, 2023). Vietnam produces, on average, 43 million tonnes of rice per year (General Statistics Office, 2023), globally ranked 5th in production output and 3rd in export (FAO, 2023). Vietnam's rice is exported to 75 countries (UNCOMTRADE, 2023). The sector provides income sources for nearly 40% of households in Vietnam; the Vietnam Household Living Standards Survey (VHLSS) in 2018, i.e. 3,558 among 9,399 surveyed households were involved in rice production (see section 3).

Vietnam's expansive rice cultivation is distributed across all regions of the country. The Mekong Delta, often referred to as the "Rice Bowl" of Vietnam, stands out as a major rice-producing region with its intricate network of rivers and fertile alluvial soil. This region is renowned for producing more than 50% of Vietnam's total rice output (General Statistics Office, 2023), benefitting from its favourable climate and water resources. Moving northwards, the Red River Delta showcases another significant rice-growing area, where centuries of agricultural expertise have been honed to optimize yields. The coastal areas of Central Vietnam also play roles in rice cultivation, blending their unique geographical characteristics with traditional farming methods. Overall, the diverse regions of Vietnam collectively contribute to the nation's status as a prominent global rice exporter.

Vietnam's policy towards rice production reflects its commitment to ensuring food security and rural development. The government has implemented multiple policies to promote rice production. These policies range from command-and-control disallowing farmers to grow non-rice crops (Chu, Nguyen, Kompas, Dang, & Bui, 2021) to providing economic incentives, e.g. waiving irrigation fees (Phu, 2023) and providing subsidies to ensure profitability of rice producers (OECD, 2022). Overall, Vietnam's rice production policy reflects its priority in food security and livelihood of rice farmers.

Vietnam has recognized the importance of the rice sector in mitigating climate change and has implemented significant strategies to support its development, while also prioritizing the enhancement of climate resilience and sustainability. Notable examples of these strategies include (1) The project of sustainable development of one million hectares of high-quality rice associated with green growth in the Mekong Delta (MARD, 2023) (2) The project of Transforming Rice Value Chains for Climate Resilient and Sustainable Development in the Mekong Delta (SNV, 2022) and (3) Decision 555/QD-BNN-TT on approving scheme for restructuring of Vietnam's rice industry by 2025–2030 (MARD, 2021). However, despite Vietnam's strong commitment to achieving net-zero emissions by 2050 (Giles *et al.*, 2021; Prime Minister of Vietnam, 2022), there is a lack of information and understanding regarding how Vietnam's rice sector and associated agricultural industries can effectively respond to climate risks and contribute to climate change mitigation.

3. Methods and materials

3.1 Energy, non-energy and industrial-process emissions

Consider F rice producers, indexed by f ($f \in [1..F]$). Each producer utilizes a subset (or all) of E energy inputs (e.g. petrol, diesel oil and coal) and N non-energy inputs (e.g. labour, material and fertilisers). The quantity of inputs required to generate one unit of output can differ among producers. In this study, due to the small scale of each production unit, i.e. households compared to the scale of the industry, we assume that rice production for each producer exhibits Leontief properties, whereby the output can be scaled up or down by proportionally adjusting all inputs. In other words, increasing output would proportionally increase all inputs and emissions. The price of rice may vary across producers due to variations in product variety, and all producers incur similar input prices.

Denote $Q^{rice}_{<f>}$ and $P^{rice}_{<f>}$ as the quantity and rice price of producer f, the quantity of energy and non-energy inputs are determined in equations (1) and (2). In these equations, $Q^{e}_{<f>}$ and $Q^{n}_{<f>}$ are the quantity of energy input e and non-energy input n utilised by producer f; $K^{e}_{<f>}$ and $K^{n}_{<f>}$ are the quantity of energy and non-energy inputs required to produce one unit of rice by producer f.

$$Q^{e}_{<f>} = Q^{rice}_{<f>} K^{e}_{<f>} \; \forall e \in [1..E], \forall f \in [1..F] \tag{1}$$

$$Q^{n}_{<f>} = Q^{rice}_{<f>} K^{n}_{<f>} \; \forall n \in [1..N], \forall f \in [1..F] \tag{2}$$

The total quantity of emissions is the emission from using energy inputs, non-energy inputs and also from industrial process, which chemically transforms materials (IPCC, 1996, chapter 2). A typical example of GHG emissions from the industrial process in rice cultivation is methane. The anaerobic decomposition of organic material in flooded rice fields produces this GHG, which escapes into the atmosphere primarily through diffusive transport through the rice plants during the growing season (IPCC, 1996, chapter 4).

We denote C^{e} as the quantity of emissions from using one unit of energy input e; C^{n} as the quantity of emissions from using one unit of non-energy input n (e.g. fertilisers) which are generated in the previous stage of the value chain rather than during rice production (i.e. indirect emissions). We also denote $C^{ip}_{<f>}$ as the quantity of emissions from industrial process (i.e. the chemical interaction among inputs) per unit of output. The total emission is formalised in equation (3) where $G_{<f>}$ is the quantify of emissions of producer f.

$$G_{<f>} = \sum_{e=1}^{E} Q^{e}_{<f>} C^{e} + \sum_{n=1}^{N} Q^{n}_{<f>} C^{n} + Q^{rice}_{<f>} C^{ip}_{<f>} \tag{3}$$

3.2 Production profit and the cost of reducing emissions

Production profit is the difference between revenue and cost. The cost includes the cost of energy inputs and the cost of non-energy inputs. This is formalised in equation (4) where $\Pi_{<f>}$ is the profit of producer f. In this equation, P^{e} and P^{n} are the prices of energy input e and non-energy input n. We included the cost of all surveyed inputs, e.g. land rent, repairs, labour, irrigation, borrowing expenditure and depreciation, in the calculation of the profit.

$$\Pi_{<f>} = P^{rice}_{<f>} Q^{rice}_{<f>} - \left(\sum_{e=1}^{E} P^{e} Q^{e}_{<f>} + \sum_{n=1}^{N} P^{n} Q^{n}_{<f>} \right) \tag{4}$$

We estimate the cost of reducing emissions of a producer by the profit that must be foregone to reduce emissions from using energy and non-energy inputs. Substituting the input quantities in equations (1) and (2) and the total emissions in equation (3) into equation (4) and differentiating lead to (5), where the right hand size is the foregone production profit of producer f when the total emission is reduced by one unit.

$$\frac{d\Pi_{<f>}}{dG_{<f>}} = \frac{P^{rice}_{<f>} - \left(\sum_{e=1}^{E} P^e K^e_{<f>} + \sum_{n=1}^{N} P^n K^n_{<f>}\right)}{\sum_{e=1}^{E} K^e_{<f>} C^e + \sum_{n=1}^{N} K^n_{<f>} C^n + C^{ip}_{<f>}} \tag{5}$$

Equation (5) indicates that the cost of reducing emissions varies across rice producers. It depends on the combination of energy and non-energy inputs used by a producer, i.e. parameters $K^e_{<f>}$ and $K^n_{<f>}$ and the industrial process $C^{ip}_{<f>}$. We calibrate these parameters for each rice-producing household using the calibration process as described by Dawkins, Srinivasan, and Whalley (2001), and the household data from VHLSS. In particular, the calibration production functions assumes that household rice producers were attempting to maximize their farming profit given their current knowledge of production conditions, i.e. that farmers had been using the optimal input combination and technology within their own conditions to maximize profits. This assumption allows us to calibrate the input demands for individual farmers without imposing a single production function for all or a group of producers. On the other hand, but that also means farmers would not have incentives to change without any changes in production conditions.

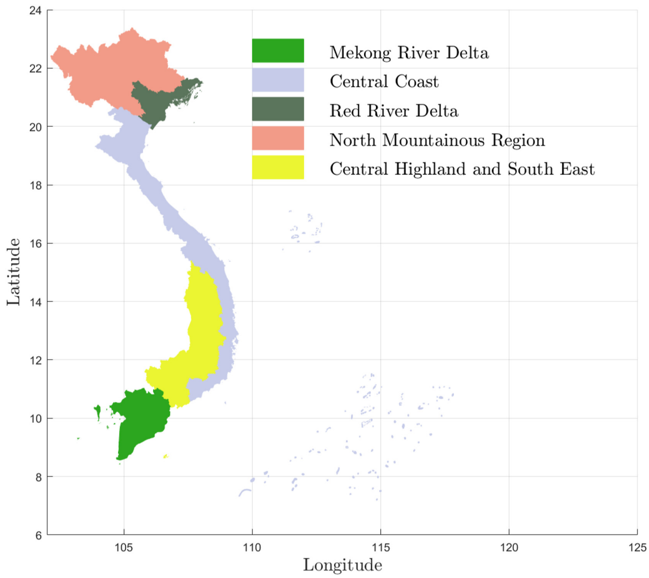
3.3 Data and data sources

We use data from the VHLSS conducted by the General Statistics Office of Vietnam in 2018. This survey represents a nationwide sample of 9,399 households distributed across 3,133 communes spanning all 63 provinces within the country. The sampling employed is recognized as representative at the national, regional, urban, rural and provincial levels, as confirmed by Vietnam's General Statistics Office (General Statistics Office, 2019). The VHLSS data have gained extensive utilization in prior studies involving Vietnam's households within the realm of climate change and environmental economics (Arouri, Nguyen, & Youssef, 2015; Trinh, 2018; Chu *et al.*, 2021; Feeny, Trinh, & Zhu, 2021).

Not all surveyed households in the VHLSS are engaged in rice production, and non-engaged households are excluded from our analysis. We consider zero land-use as data-entry errors and exclude these observations from our analysis because rice production must incur some land use. This data cleaning process results in a refined dataset comprising 3,558 rice-producing households. Figure 1 shows the map of key rice producing regions in Vietnam, and Table 1 provides a description of the regional distribution of surveyed households.

Production inputs vary across household producers. Energy inputs encompass a range of sources, such as electricity, coal, petrol, kerosene, mazut, diesel, LPG and natural gas. Non-energy inputs encompass labour, tools, machinery (including costs related to repairs, depreciation, rent and fertilizers) and consumables. Unobservable inputs, such as farming expertise, were not included because there were no available data on the costs associated with these inputs, such as education or training expenses to acquire farming expertise.

To compute emissions associated with energy inputs, we translated survey expenditures for each input into quantities using market price reports and information sourced from the Ministry of Industry and Trade (MOIT; Nguyen, 2022) and the emission factors of each input from the US Environmental Protection Agency (EPA, 2022). To estimate emissions from non-energy inputs (i.e. emissions in the previous stage of value chain) and industrial process (i.e. emissions from chemical interactions); we use emission factors in the guideline of the International Panel of Climate Change (IPCC, 2019a, b). These emission factors are provided



Source(s): Figure by the author

Figure 1. Vietnam geographical regions

Table 1. The regional distribution of household rice production in VHLSS 2018

Regions	Number of producers	Share in rice plantation area	Share in rice outputs
Mekong River Delta	464	55.1%	58.6%
Central Coast	942	15.8%	15.9%
Red River Delta	865	10.7%	10.9%
Northern Mountainous Area	1,055	13.1%	9.8%
Central Highlands and Southeast	232	5.3%	4.7%
Country	3,558	100.0%	100.0%

Source(s): Table by the author

in the Appendix. Monetary values are converted to USD dollars (2018 value) using the USD/VND exchange rate and the CPI index of the USD.

4. Results

4.1 Cost structure in rice production

In this section, we present the cost structure of rice production. Table 2 provides a breakdown of the cost structure for surveyed rice producers categorized by regions, showing the proportions of energy inputs, non-energy inputs and profit within the total production revenue. The numerical value accompanying each region's name signifies its respective contribution to the overall rice output of the country.

According to Table 2, the average proportion of energy inputs in the total production revenue for all regions remains relatively small, approximately 1% or 2%. In the meantime, the average share of non-energy inputs exhibits slight variation among regions, spanning from 29% in the Northern and Mountainous Area to 43% in the leading rice-producing region

Region	Energy inputs	Non-energy inputs	Profit (compensation to business owners)
Mekong River Delta (58.6%)	1.2% [0.1%–5.6%]	43.4% [13.5%–90%]	55.4% [8.5%–85.5%]
Central Coast (15.9%)	0.8% [0.1%–4.7%]	38.2% [6%–83.7%]	60.9% [15.1%–93.1%]
Red River Delta (10.9%)	1.1% [0.1%–3%]	33.3% [12.8%–74.4%]	65.6% [23.7%–86.7%]
Northern Mountainous Area (9.8%)	2% [0.2%–10.3%]	29.4% [8.3%–80.3%]	68.6% [14.3%–91.2%]
Central Highlands and Southeast (4.7%)	1.4% [0%–19.1%]	36.4% [8.6%–101.5%]	62.1% [−3.3%–89.7%]
Country (100%)	1.2% [0.1%–8.2%]	39.4% [8.6%–85.2%]	59.4% [12.9%–90.2%]

Note(s): • Numbers next to each region are the regional contribution to the national output as reported in Table 1
• The shares of energy inputs, non-energy inputs and profits are the percentage of each category in the total revenue
• Outsides brackets are the mean, inside the brackets are ranges excluding 1% outliners from both sides (i.e. from the 1st percentile to the 99th percentile)
Source(s): Table by the author

Table 2. The cost structure of household rice producers

of the Mekong River Delta, with a national average of almost 40%. Profits constitute nearly 60% of the production revenue on average, encompassing a range from 55% to 69% across different regions.

Table 2 provides insights into inter-regional heterogeneity in production techniques. For example, the profit share in the Mekong River Delta (55%) is lower than that in the Northern Mountainous region (69%). This difference arises from the fact that roughly 43% of the revenue from rice sales in the Mekong River Delta is allocated to cover the cost of non-energy inputs, whereas in the Northern Mountainous Area, this figure is only 29%. One possible explanation for this variance is that rice production in the Mekong River Delta involves intensive cultivation methods aimed at maximizing rice yield per hectare of land. Consequently, farmers in this region rely more heavily on industrial inputs such as chemical fertilizers, pesticides, water and machinery. In contrast, rice production in the Northern Mountainous Area operates on a smaller scale and utilizes more manual and cost-effective inputs, resulting in a lower rice quantity per hectare of cultivation land. The fact that cultivation techniques in the Mekong River Delta are more focused on productivity per hectare of land than in the Northern Mountainous Area is also reflected in the dataset. The Mekong River Delta accounts for 59% of the national rice output with only 55% of the plantation area, while the Northern Mountainous Area accounts for less than 10% of the national output with 13% of the plantation area, as indicated in Table 1.

Table 2 also highlights substantial variation in the cost structure among household producers within each region. For instance, in the Mekong River Delta, the average proportion of energy inputs in production revenue stands at 1.2%. However, the specific figures display a range from 0.1% to 5.6%, even when excluding 1% outliers from both ends. Likewise, across all producers in the Red River Delta, the average proportion of energy inputs is 1.1%, yet among individual producers, this share varies from less than 0.1%–3%. Similar ranges in the share of energy inputs within the total production revenue are evident in other regions as well.

Substantial variations are also observed in the proportions of non-energy inputs across all regions. In the Mekong River Delta, for instance, the share of non-energy inputs in production revenue spans from 14% to 90%. Furthermore, there exist extreme cases in which the share of non-energy inputs surpasses 100%. This indicates instances where costs for certain producers exceeded their revenue. Such occurrences stem from factors like natural disasters affecting production, resulting in losses rather than profits.

The broad variations observed in the proportions of energy inputs and non-energy inputs can be attributed to several factors. These factors might encompass variations in productivity driven by natural conditions, fluctuations in output prices (such as market variations) and heterogeneity in production techniques. The interplay of these factors influences the cost-effectiveness of input utilization in rice production and, consequently, impacts the efficiency of GHG emissions during the production process.

4.2 The economics of emissions in rice production

In this section, we present an analysis of the economics pertaining to GHG emissions within rice production. Table 3 provides a comprehensive overview of the estimated emission intensity for rice production, i.e. emissions per tonne of rice produced. This inclusive metric encompasses emissions stemming from energy inputs, non-energy inputs, and industrial processes. Table 3 also includes estimations for profit per tonne of rice produced and profit per tonne of emissions. It is important to note that lower profit would not necessarily mean lower profit per unit of GHG if the quantity of GHG emissions is also low, e.g. eco rice cultivation.

The estimated national average emission intensity stands at approximately 0.7 tCO2e per tonne of rice produced, with variations observed across regions and among individual producers. In the Mekong River Delta region, which is the largest rice-producing area, the emission intensity is estimated at 0.6 tCO2 per tonne of rice. This regional average is the lowest in the country, attributed to the region's highest average productivity (accounting for 59% of the national output with only 55% of the plantation area – as indicated in Table 1). Emission intensity displays variability among households; for instance, households cultivating 'eco-rice' with minimal energy and chemical inputs exhibit very low emission intensity, while producers who incurred output losses due to natural disasters after utilizing all inputs would exhibit high emission intensity.

Other regions exhibit slightly higher emission intensities than the Mekong River Delta, albeit not significantly so. The Central Coast region displays an average emission intensity of 0.7 tCO2 per tonne of rice produced, while the Red River Delta's average emission intensity is 0.8 and the Northern Mountainous Region records a figure of 0.9. Among these regions, the Red River Delta demonstrates smaller variations among producers. This can be attributed to the extensive experience in rice production of these traditional rice producers. The Northern Mountainous Area, due to its lower productivity in rice production in comparison to other regions, exhibits the highest emission intensity. This area contributes 9.8% of the national output while accounting for over 13% of the plantation area (as shown in Table 1).

In terms of profit per unit of output, the national average stands at approximately $164 per tonne of rice produced, with regional variations ranging from $146/tonne in the Mekong River Delta to $221/tonne in the Northern Mountainous Area. Variations are also evident within each region. Across all regions, there are household producers experiencing negative profit—indicating losses in rice production, but most of them belong to the 1% outliner group.

In terms of profit earning per unit of GHG emissions, the national average stands at $240/tCO2e. This average number slightly surpasses the estimated average cost of reducing 1 tCO2e in agriculture as per Vietnam's NDCs (Government of Vietnam, 2020). Variations are also significant across regions and specific producers, indicating opportunities for targeting emission reduction in areas where earnings are the lowest. In the Mekong River Delta, the average earnings are $242/tCO2e, ranging from $15 to $1000/tCO2e. The Central Coast region demonstrates average earnings of $225 per tonne of tCO2 emission. The Red River Delta and the Northern Mountainous area exhibit average earnings of $276/tCO2e and $235/tCO2e,

Table 3. The economics of emissions in rice production

Region	GHG emission per tonne of rice produced (tCO2/tonne)				Profit per tonne of rice produced ($/tonne)	Profit per tonne of emissions ($/tCO2)
	Energy	Non-energy	Industrial process	Total		
Mekong River Delta (58.6%)	<0.1 [<0.1–0.1]	0.1 [<0.1–0.7]	0.5 [0.2–1.8]	0.6 [0.3–2.2]	146 [17–344]	242 [15–1,000]
Central Coast (15.9%)	<0.1 [<0.1–0.1]	0.2 [<0.1–1.6]	0.5 [<0.1–2.8]	0.7 [<0.1–2.8]	160 [34–384]	225 [26–4,272]
Red River Delta (10.9%)	<0.1 [<0.1–<0.1]	0.3 [<0.1–1.1]	0.5 [0.3–1.1]	0.8 [0.3–1.9]	212 [62–439]	276 [51–839]
Northern Mountainous Area (9.8%)	<0.1 [<0.1–0.1]	0.4 [<0.1–1.8]	0.6 [0.2–2.3]	0.9 [0.2–3.1]	221 [34–388]	235 [30–1,516]
Central Highlands and Southeast (4.7%)	<0.1 [<0.1–0.1]	0.3 [<0.1–1.9]	0.6 [<0.1–1.9]	0.8 [<0.1–2.4]	170 [−9–403]	201 [−5–3,584]
Country (100%)	<0.1 [<0.1–0.1]	0.2 [<0.1–1.5]	0.5 [0.1–1.8]	0.7 [0.2–2.6]	164 [31–381]	240 [25–1,223]

Note(s): • Numbers next to each region are the regional contribution to the national output as reported in Table 1
• Outsides brackets are the mean, inside the brackets are ranges excluding 1% outliners from both sides (i.e. from the 1st percentile to the 99th percentile)
Source(s): Table by the author

respectively. Conversely, the Central Highlands and Southeast region display the lowest average earnings of $201/tCO2e.

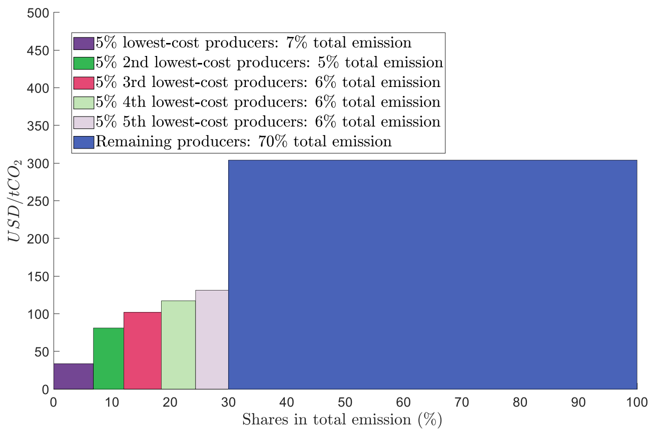
It is noted that both emissions per tonne of rice and profit earned per tonne of emissions reflect the emission content in rice production, but they are not identical. Emissions per tonne of rice are a technical indicator reflecting the production process, while profit earned per tonne of emission is an economic indicator (the income in dollar terms generated by activities that emit GHG). Thus, profit earned per tonne of emission is a more relevant indicator that reflects the economic incentives of rice producers in relation to GHG emissions.

4.3 Marginal abatement cost curves

We use estimated profit earnings per unit of emissions from the datasets to formulate the MACC for rice production. The construction of our MACC assumes that if a household discontinues production—either in part or in entirety—both the emissions associated with production and the potential profits derived from said production would be reduced. Consequently, the most cost-effective strategy for emission reduction is to target producers or producer groups exhibiting the least favourable profit-to-emission ratios. Accordingly, the MACC is structured to initiate with producers having the lowest profit per unit of emission and subsequently progresses towards higher levels.

Figure 2 illustrates the estimated MACC, presenting a stepwise visualization that begins with the 5% of producers characterized by the lowest profit per unit of emission. Each subsequent block of 5% is depicted in sequence. As depicted in the MACC, the initial 5% of producers collectively contributed to about 7% of the total emissions. On average, these producers incur a cost of approximately $35/tCO2e for emission reduction.

The subsequent block, consisting of the subsequent 5% of producers, contributed to approximately 5% of the total emissions within rice production. If these producers were to reduce their production scale to mitigate emissions, their resulting profit loss would reach $80/tCO2, assuming other factors remains constant. The following three blocks, each composed of 5% of producers and contributing to 6% of the total emissions in rice production, respectively. Should these producers choose to curtail their production for emission reduction, the consequent profit losses would amount to $100/tCO2, $120/tCO2 and $130/tCO2, respectively. The remaining 75% of producers, constituting the final block,



Source(s): Figure by the author

Figure 2.
MACC in household rice production

accounted for 70% of the total production. Should these producers decide to downsize their production to lower emissions, the ensuing profit loss would total \$300/tCO2.

4.4 Impact of carbon pricing

We evaluated the impact of carbon pricing on production output and emissions through the surveyed household rice producers. Our estimates assume that production would cease if carbon pricing rendered ongoing production economically inviable, essentially eliminating all profit. Considering that the minimum average cost for emission reduction is approximately 11 USD/tCO2 on a broader scale as documented in Vietnam NDC (Government of Vietnam, 2020: Table 3), we examined the repercussions of carbon pricing across a range of price levels, spanning from 10 USD/tCO2 to 25 USD/tCO2.

Table 4 delineates the estimated impacts of carbon pricing on rice production. The estimation assumes if farmers reduce rice production in response to carbon pricing, alternative land use would have minimal (net) GHG emissions – if any, such as in organic agriculture, fruit trees or agroforestry. At a carbon price of 10 USD/tCO2, the overall output is projected to decline by 0.6%, which is equivalent to a reduction of roughly 264,000 tonnes of rice. Concurrently, emissions would reduce by 1.3%, approximately amounting to a reduction of 384,000 tCO2. With a carbon pricing of 15 USD/tCO2, rice output would likely decrease by 0.62% (equivalent to about 273,000 tonnes of rice) with an associated emissions reduction estimated at 1.34% or 402,000 tCO2. Setting the carbon price at 20 USD/tCO2 would result in a 6.66% reduction in total output and a 1.45% reduction in emissions. Incremental elevations in the carbon price would further impact production output and correspondingly diminish emissions from rice production.

5. Discussions and policy implications

Our analysis estimates a significant cost for reducing GHG emissions in rice production in Vietnam. While we acknowledge this is a first order approximation, subject to data quality and accuracy as well as the scope of surveys, we contend that the estimation is constructed from micro data, taking into account the heterogeneity across producers at smallest production scale. Our results highlight some important implications for policymaking in Vietnam and possibly in other countries.

First, the estimated emission intensity in Vietnam's rice production is, on average, nearly 0.7 tCO2e/tonne of rice. These estimates fall within the typical range suggested by previous studies conducted in various agricultural regions (Chakraborty *et al.*, 2017; Wang *et al.*, 2018; Nikolaisen *et al.*, 2023). When these figures are scaled up to represent national outputs, it is estimated that the rice sector contributed approximately 30 million tCO2e per year. This quantity of emissions from the rice sector accounts for approximately 10% of Vietnam's total emissions, whereas the rice sector contribution to the national GDP is only around 3%

Estimated impacts (rounded to the nearest integers)		Carbon price (USD/tCO2) 10	15	20	25
Percentage terms	Output	−0.6%	−0.62%	−0.66%	−0.81%
	Emissions	−1.28%	−1.34%	−1.45%	−1.74%
Absolute values	Output (1,000 tonne per year)	−264	−273	−291	−357
	Emission (1,000 tCO2 per year)	−384	−402	−435	−523

Note(s): Negative numbers indicate reductions
Source(s): Table by the author

Table 4. Estimated impact of carbon pricing on rice production

(Connor, Cuong, Demont, Sander, & Nelson, 2022). In other words, the emission quantity per dollar contributed to the national GDP in the rice sector is higher than the higher than the economy-wide average.

Second, it is important to note that there is room for improvement. The variation in emission intensity across producers suggests the existence of technical potential for those with low profits per unit of emissions to enhance their efficiency. By doing so, these producers can effectively reduce the overall emission intensity of the rice sector. Our results underscore the possibility of implementing measures and strategies aimed at encouraging and assisting such producers in adopting more environmentally sustainable practices. These practices include improving water management in combination with low-CH4 hybrids and the use of soil-enhancing amendments (Höglund-Isaksson, Gómez-Sanabria, Klimont, Rafaj, & Schöpp, 2020); alternate wetting and drying (Islam *et al.*, 2022; Wang *et al.*, 2023); adopting new rice varieties (Wang *et al.*, 2023), using low GHG fertilizers (Islam *et al.*, 2022; Wang *et al.*, 2023) or implementing crop establishment and tillage methods (Chakraborty *et al.*, 2017). Promoting these changes can lead to significant progress in mitigating the sector's environmental impact and advancing towards a more sustainable future.

Third, our estimates reaffirm that it is not fossil fuels, but non-energy inputs such as fertilizers and cultivation technology, that are the key drivers of GHG emissions in rice production. Rice cultivation is a major source of methane emissions, constituting about 6%–11% of the global methane emissions from anthropogenic sources (Höglund-Isaksson *et al.*, 2020; Smith, Reay, & Smith, 2021; Nikolaisen *et al.*, 2023; Wang *et al.*, 2023). Additionally, the supply chain of synthetic fertilizer, a pivotal input in rice cultivation, is a significant source of GHG emissions (Xu *et al.*, 2020). Synthetic nitrogen fertilizer production accounted for 38.8% of the total emissions associated with synthetic nitrogen fertilizers, while field emissions accounted for 58.6% and transportation accounted for the remaining 2.6% (Menegat *et al.*, 2022). Consequently, it is more crucial to promote greener cultivation technology rather than decarbonizing rice production through the pathway of fossil fuel inputs.

Fourth, the average cost of reducing GHG emissions in Vietnam's rice production is relatively higher than the estimated costs in other sectors. Our analysis indicates that, on average, the estimated cost in terms of profit loss is \$240/tCO2e. These estimates surpass the costs associated with certain mitigation options outlined in Vietnam's NDCs (Government of Vietnam, 2020: Table 3). For instance, the estimated cost of reducing one tCO2 is \$11/tCO2 in industrial processes, \$120/tCO2e in land use, land-use change and forestry (LULUCF), and \$105/tCO2e in waste processing. The relatively higher costs of emissions reduction in rice production underscore the challenges and economic trade-offs involved in implementing sustainable practices within these sectors.

Fifth, our findings provide evidence that carbon pricing is an effective tool for climate mitigation, demonstrating that reasonable carbon pricing measures have modest impacts on production output. While it is possible that carbon pricing may have some negative impacts on production sectors (Fragkos *et al.*, 2021; Peñasco, Anadón, & Verdolini, 2021), especially agriculture (Stepanyan, Heidecke, Osterburg, & Gocht, 2023), our analysis indicates that these negative impacts are modest with a reasonable carbon price. Our estimates reveal that implementing a carbon price of \$10–\$15 per tonne of CO2 would result in a reduction of less than 1% in production output. This demonstrates the economic feasibility and compatibility of carbon pricing policies with sustainable growth in the industry, highlighting the potential for policy interventions to align economic incentives with environmental goals.

Sixth, while we are not able to evaluate the impacts of carbon pricing on farmers' income without reliable information on the choice of alternative land use, low-income farmers may be among the most impacted producers. As a result, it is important to consider supplementary policies that may be needed to support low-income rice farmers (Lencucha, Pal, Appau, Thow, & Drope, 2020; Prager, 2022). These policies could include targeted financial assistance, training programs to help farmers transition to more sustainable practices and the development of market incentives that encourage environmentally friendly farming methods. By implementing such supportive measures alongside carbon pricing, policymakers can ensure that the transition to a low-carbon agricultural sector is sustainable, benefiting both the environment and vulnerable farming communities.

Finally, while rice production sectors contribute to anthropogenic emissions and global warming, they themselves are vulnerable to the impacts of climate change. Vietnam possesses one of the most vulnerable rice production sectors in the face of climate change and extreme events (Tran *et al.*, 2022). Rising sea water levels, salinity intrusion, increased frequency of floods and droughts all pose threats to the rice sector in Vietnam. It is estimated that by 2050, Vietnam may lose 30%–60% of the land suitable for rice production due to climate change. This highlights a significant aspect for climate policy, as farmers have direct incentives to participate in climate change mitigation and adaptation programs (Khong, Young, Loch, & Thennakoon, 2018; Ho & Shimada, 2021).

6. Conclusions

Promoting sustainable farming practices stands as a paramount priority in numerous countries across the globe. Within the context of climate change, low-carbon production emerges as a vital facet of ensuring both sustainability and economic viability in rice production. In the realm of rice production, emissions predominantly emanate from non-energy inputs and industrial processes. Consequently, it is important to foster policies targeting these specific areas.

We employed surveyed data from rice producers in Vietnam to delve into the economics of GHG emissions within the country's rice production. Our methodology enables us to scrutinize the cost structure of individual producers, encompassing their expenditures on both energy and non-energy inputs. By utilizing data at the smallest production scale, our approach also facilitates the estimation of emission intensity for each producer and their profit earned per unit of emission quantity. Furthermore, we constructed a bottom-up MACC based on survey data to assess the potential for emissions reduction within Vietnam's rice sector.

Our findings underscore substantial variation in the profit earned per tonne of GHG emissions among producers, signifying noteworthy room for improvement among those with lower efficiency. The implementation of complementary policies, such as knowledge transfer and sharing, has the potential to augment farm-level skills and further optimize input efficiency within Vietnam's rice sector. Our analysis also suggests that the introduction of a reasonable carbon price would only yield modest impacts on production output. It is noteworthy that the quality of our estimates, rooted in surveyed data, could be enhanced with the availability of additional data in future research endeavours.

References

Arouri, M., Nguyen, C., & Youssef, A. B. (2015). Natural disasters, household welfare, and resilience: Evidence from rural Vietnam. *World Development*, *70*, 59–77. doi: 10.1016/j.worlddev.2014.12.017.

Bamière, L., Bellassen, V., Angers, D., Cardinael, R., Ceschia, E., Chenu, C., . . . Pellerin, S. (2023). A marginal abatement cost curve for climate change mitigation by additional carbon storage in French agricultural land. *Journal of Cleaner Production*, *383*, 135423. doi: 10.1016/j.jclepro.2022.135423.

Chakraborty, D., Ladha, J. K., Rana, D. S., Jat, M. L., Gathala, M. K., Yadav, S., . . . Raman, A. (2017). A global analysis of alternative tillage and crop establishment practices for economically and environmentally efficient rice production. *Scientific Reports*, *7*, 9342. doi: 10.1038/s41598-017-09742-9.

Chu, L., Nguyen, H.-T.-M., Kompas, T., Dang, K., & Bui, T. (2021). Rice land protection in a transitional economy: The case of Vietnam. *Heliyon*, *7*, e06754. doi: 10.1016/j.heliyon.2021.e06754.

Connor, M., Cuong, O. Q., Demont, M., Sander, B. O., & Nelson, K. (2022). The influence of climate change knowledge on consumer valuation of sustainably produced rice in Vietnam. *Sustainable Production and Consumption*, *31*, 1–12. doi: 10.1016/j.spc.2022.01.034.

Dawkins, C., Srinivasan, T., & Whalley, J. (2001). Calibration. In J. H. James, & L. Edward (Eds.), *Handbook of Econometrics*. Elsevierpp.

EPA (2022). GhG emissions factor hub. United States Environmental Protection Agency. Available from: https://www.epa.gov/climateleadership/ghg-emission-factors-hub

FAO (2020). Emissions due to agriculture: Global, regional and country trends 2000–2018. FAO. Available from: https://www.fao.org/3/cb3808en/cb3808en.pdf

FAO (2023). *FAOSTAT Statistical Database*. FAO, Rome.

Feeny, S., Trinh, T.-A., & Zhu, A. (2021). Temperature shocks and energy poverty: Findings from Vietnam. *Energy Economics*, *99*, 105310. doi: 10.1016/j.eneco.2021.105310.

Fragkos, P., Fragkiadakis, K., Sovacool, B., Paroussos, L., Vrontisi, Z., & Charalampidis, I. (2021). Equity implications of climate policy: Assessing the social and distributional impacts of emission reduction targets in the European Union. *Energy*, *237*, 121591. doi: 10.1016/j.energy.2021.121591.

General Statistics Office. (2019). *Result of the Vietnam household living Standards survey 2018*. Hanoi: General Statistics Office of Vietnam.

General Statistics Office (2023). *Statistical yearbook of Vietnam 2022*. Hanoi: Statistical Publishing House.

Giles, J., Grosjean, G., Le Coq, J.-F., Huber, B., Bui, V. L., & Läderach, P. (2021). Barriers to implementing climate policies in agriculture: A case study from Viet Nam. *Frontiers in Sustainable Food Systems*, *5*. doi: 10.3389/fsufs.2021.439881.

Government of Vietnam. (2020). *Updated nationally determined contribution*. Hanoi: Government of Vietnam.

Ho, T. T., & Shimada, K. (2021). The effects of multiple climate change responses on economic performance of rice farms: Evidence from the Mekong Delta of Vietnam. *Journal of Cleaner Production*, *315*, 128129. doi: 10.1016/j.jclepro.2021.128129.

Höglund-Isaksson, L., Gómez-Sanabria, A., Klimont, Z., Rafaj, P., & Schöpp, W. (2020). Technical potentials and costs for reducing global anthropogenic methane emissions in the 2050 timeframe –results from the GAINS model. *Environmental Research Communications*, *2*. doi: 10.1088/2515-7620/ab7457.

IPCC (1996). Revised 1996 IPCC guidelines for national greenhouse gas inventories: Reference manual, intergovernmental panel on climate change.

IPCC (2019a). Cropland. In Calvo Buendia, E., Tanabe, K., Kranjc, A., Baasansuren, J., Fukuda, M., Ngarize, S., . . . Federici, S. (Eds.), *2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories*. IPCC.

IPCC (2019b). N2O emissions from managed soils, and CO2 emissions from lime and urea application. In Calvo Buendia, E., Tanabe, K., Kranjc, A., Baasansuren, J., Fukuda, M., Ngarize, S., . . . Federici, S. (Eds.), *2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories*. Switzerland: IPCC.

Islam, S. M. M., Gaihre, Y. K., Islam, M. R., Ahmed, M. N., Akter, M., Singh, U., & Sander, B. O. (2022). Mitigating greenhouse gas emissions from irrigated rice cultivation through improved fertilizer and water management. *Journal of Environmental Management*, *307*, 114520. doi: 10.1016/j.jenvman.2022.114520.

Khong, T. D., Young, M. D., Loch, A., & Thennakoon, J. (2018). Mekong River Delta farm-household willingness to pay for salinity intrusion risk reduction. *Agricultural Water Management*, *200*, 80–89. doi: 10.1016/j.agwat.2017.12.010.

Lencucha, R., Pal, N. E., Appau, A., Thow, A. M., & Drope, J. (2020). Government policy and agricultural production: A scoping review to inform research and policy on healthy agricultural commodities. *Global Health*, *16*, 11. doi: 10.1186/s12992-020-0542-2.

Long, N. V. (1992). Pollution control: A differential game approach. *Annals of Operations Research*, *37*, 283–296. doi: 10.1007/BF02071061.

Long, N. V. (2015). The green paradox in open economies: Lessons from static and dynamic models. *Review of Environmental Economics and Policy*, *9*, 266–284. doi: 10.1093/reep/rev004.

Long, N. V., & Stähler, F. (2012). Should the good and the selfish be taxed differently?. *The Scandinavian Journal of Economics*, *114*, 932–948. doi: 10.1111/j.1467-9442.2012.01705.x.

Long, N., & Stähler, F. (2014). Resource extraction and backstop technologies in general equilibrium. In K. Pittel, R. van der Ploeg, & C. Withage (Eds), *Climate Policy and Nonrenewable Resources: The Green Paradox and Beyond* (pp. 151–170). The MIT Press. Available from: http://www.jstor.org/stable/j.ctt9qf9d6.10

Lu, H., Liu, G., Okuda, T., & Zhang, C. (2018). Marginal abatement cost curves for REDD+ in Kalimantan, Indonesia and the potential role of cost-saving plantations. *Environmental Research Letters*, *13*, 075006. doi: 10.1088/1748-9326/aac83f.

Maitah, K., Smutka, L., Sahatqija, J., Maitah, M., & Nguyen, A. (2020). Rice as a determinant of Vietnamese economic sustainability. *Sustainability*, *12*, 5123. doi: 10.3390/su12125123.

MARD (2021), *Decision 555/QD-BNN-TT on Approving Scheme for Restructuring of Vietnam's Rice Industry by 2025 and 2030*, Ministry of Agriculture and Rural Development, Hanoi.

MARD (2023). *Sustainable development of 1 million hectares of high-quality rice in the Mekong Delta*. Ministry of Agriculture and Rural Development. Available from: https://www.mard.gov.vn/en/Pages/sustainable-development-of-1-million-hectares-of-high-quality-rice-in-the-mekong-delta.aspx?item=23

Menegat, S., Ledo, A., & Tirado, R. (2022). Greenhouse gas emissions from global production and use of nitrogen synthetic fertilisers in agriculture. *Scientific Reports*, *12*, 14490. doi: 10.1038/s41598-022-18773-w.

MOIT Ministry of Industry and Trade. Available from: http://minhbach.moit.gov.vn

Nikolaisen, M., Cornulier, T., Hillier, J., Smith, P., Albanito, F., & Nayak, D. (2023). Methane emissions from rice paddies globally: A quantitative statistical review of controlling variables and modelling of emission factors. *Journal of Cleaner Production*, *409*, 137245. doi: 10.1016/j.jclepro.2023.137245.

Nguyen, C. N. (2022). Giá than đối với ngành than, nhiệt điện than Việt Nam [Kỳ 1]: Dự báo thị trường quốc tế (in Vietnamese). Available from: https://nangluongvietnam.vn/gia-than-doi-voi-nganh-than-nhiet-dien-than-viet-nam-ky-1-du-bao-thi-truong-quoc-te-29201.html. Nang luong Viet Nam

OECD (2022), *Agricultural Policy Monitoring and Evaluation 2022*. Available from: https://www.oecd-ilibrary.org/content/publication/7f4542bf-en

OECD and FAO. (2021). Rice projections: production and trade. doi: 10.1787/9a60eee4-en.

Peñasco, C., Anadón, L. D., & Verdolini, E. (2021). Author correction: Systematic review of the outcomes and trade-offs of ten types of decarbonization policy instruments. *Nature Climate Change*, *11*, 274. doi: 10.1038/s41558-021-00992-0.

Phu, L. V. (2023). Water value, irrigation policy, and implementation hazards in Vietnam's rural economy. *Water Resources and Economics*, *43*, 100229. doi: 10.1016/j.wre.2023.100229.

Prager, K. (2022). Implementing policy interventions to support farmer cooperation for environmental benefits. *Land Use Policy*, *119*, 106182. doi: 10.1016/j.landusepol.2022.106182.

Prime Minister of Vietnam. (2022). Decision No. 896/QĐ-TTg, dated 26/07/2022 of the Prime minister approving the national strategy on climate change to 2050, government of Vietnam.

Sinn, H.-W. (2012). *The green paradox: A supply-side approach to global warming*. The MIT Press. doi: 10.7551/mitpress/8734.001.0001.

Smith, P., Reay, D., & Smith, J. (2021). Agricultural methane emissions and the potential for mitigation. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, *379*, 20200451. doi: 10.1098/rsta.2020.0451.

SNV (2022). Transforming rice value chain for climate resilient and sustainable development in the Mekong Delta. Available from: https://www.snv.org/project/transforming-rice-value-chain-climate-resilient-and-sustainable-development-mekong-delta

Stepanyan, D., Heidecke, C., Osterburg, B., & Gocht, A. (2023). Impacts of national vs European carbon pricing on agriculture. *Environmental Research Letters*, *18*. doi: 10.1088/1748-9326/acdcac.

Tran, D. D., Park, E., Tuoi, H. T. N., Thien, N. D., Tu, V. H., Anh Ngoc, P. T., . . . Quang, C. N. X. (2022). Climate change impacts on rice-based livelihood vulnerability in the lower Vietnamese Mekong Delta: Empirical evidence from can Tho City and Tra Vinh province. *Environmental Technology and Innovation*, *28*, 102834. doi: 10.1016/j.eti.2022.102834.

Trinh, T. A. (2018). The impact of climate change on agriculture: Findings from households in Vietnam. *Environmental and Resource Economics*, *71*, 897–921. doi: 10.1007/s10640-017-0189-5.

UNCOMTRADE (2023). UN Comtrade database. Available from: https://comtrade.un.org/

USDA (2023). *Marginal abatement cost curves for greenhouse gas mitigation on U.S. Farms and ranches, Office of the chief economist*. Washington, DC: U.S. Department of Agriculture.

Wang, J., Akiyama, H., Yagi, K., & Yan, X. (2018). Controlling variables and emission factors of methane from global rice fields. *Atmospheric Chemistry and Physics*, *18*, 10419–10431. doi: 10.5194/acp-18-10419-2018.

Wang, J., Ciais, P., Smith, P., Yan, X., Kuzyakov, Y., Liu, S., . . . & Zou, J. (2023). The role of rice cultivation in changes in atmospheric methane concentration and the Global Methane Pledge. *Global Change Biology*, *29*, 2776–2789. doi: 10.1111/gcb.16631.

Xu, P., Zhou, W., Jiang, M., Khan, I., Shaaban, M., Jiang, Y., & Hu, R. (2020). Nitrogen fertilizer application in the rice-growing season can stimulate methane emissions during the subsequent flooded fallow period. *Science of the Total Environment*, *744*, 140632. doi: 10.1016/j.scitotenv.2020.140632.

Yue, X., Deane, J. P., O'Gallachoir, B., & Rogan, F. (2020). Identifying decarbonisation opportunities using marginal abatement cost curves and energy system scenario ensembles. *Applied Energy*, *276*, 115456. doi: 10.1016/j.apenergy.2020.115456.

Appendix

Inputs	Values	Units	Source
Petrol	2.241	kg CO2e/litter	EPA (2022)
Diesel	2.676	kg CO2e/litter	
Coal	2.625	kg CO2e/kg	
Crude oil	3.1	kg CO2e/kg	
Electricity	0.722	kg CO2e/kWh	
Kerosene	2.7	kg CO2e/litter	
LPG	2.985	kg CO2e/kg	
Industrial emissions	42	kgCO2/ha/day	IPCC (2019a)
N – fertiliser	0.45	kg CO2e/kg	IPCC (2019b)
P – fertiliser	7.8	Kg CO2/kg	
K – fertiliser	0.14	Kg CO2e/kg	

Note(s): Emissions from using other inputs are assumed to be negligible
Source(s): Table by the author

Table A1. Emission factors

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