



Anthropogenic CO and NO_x Emission Inventory in Thailand

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Article History; Received: 11 March 2026, Accepted: 29 June 2026, Published: 21 August 2026

Abstract

Air pollution remains a critical environmental issue in Thailand, particularly in relation to Carbon Monoxide (CO) and Nitrogen Oxides (NO_x), which are closely linked to transportation, industrial activities, biomass burning, and energy consumption. Although CO and NO_x concentrations in Thailand may not always exceed national air quality standards, they are critical primary precursors for secondary pollutants, particularly tropospheric ozone [5], making the monitoring of their emission inventories essential for effective air quality management. This study aimed to investigate the spatial distribution, emission sources, and seasonal variability of anthropogenic CO and NO_x emissions in Thailand during 2014–2024 using the CAMS-GLOB-ANT v6.2 emission inventory obtained from the ECCAD database. It should be noted that this dataset covers strictly anthropogenic sources and agricultural open burning, and does not include natural forest fire emissions. The results indicate that CO and NO_x exhibit similar spatial distributions, with relatively high emissions concentrated in the Central and Eastern regions, particularly in major urban, industrial, and transportation corridors. In contrast, emissions in the Northeastern region are more spatially dispersed, whereas the Northern and Southern regions display localized or corridor-like patterns influenced by topography and settlement structure. Road transportation was identified as the dominant source of emissions in most regions, while agricultural waste burning, industrial processes, refineries, and power generation contributed differently depending on regional economic characteristics. Monthly analysis showed that both CO and NO_x emissions increased from March to May, with peak levels in May, reflecting the combined effects of late dry-season biomass burning and meteorological conditions favorable to pollutant accumulation. Overall, the findings demonstrate that anthropogenic CO and NO_x emissions in Thailand are strongly shaped by regional economic activities, land-use characteristics, and seasonal factors, underscoring the need for region-specific air pollution management strategies.

Keywords : anthropogenic; carbon monoxide; nitrogen oxides; Thailand; emission inventory

Introduction

Air pollution is a major global environmental problem [1]. The impacts are not limited to local emission sources; rather, pollutants can be transported across borders and react in atmosphere, thereby affecting air quality at regional and global levels. In addition, primary pollutants can interact in chemical reactions to form secondary pollutants, such as ground-level ozone and secondary particulate matter [2]. These pollutants pose risks to public health and can accumulate and be transported over long distances in the atmosphere.

Thailand's economic development across the agricultural, industrial, transportation, and tourism sectors, in conjunction with technological advancement and population growth, has resulted in a sustained increase in the demand for natural resources and energy [3]. Energy consumption particularly the use of fossil fuels in industrial production processes, transportation, and other anthropogenic activities has led to the emission of air pollutants from point sources, area sources, and mobile sources. These emissions exert significant impacts on environmental quality and public health and constitute a critical challenge for long-term sustainable development. Major air pollutants include Particulate Matter (PM₁₀ and PM_{2.5}), Sulfur Dioxide (SO₂), Nitrogen Oxides (NO_x), Carbon Monoxide (CO), Ozone (O₃), and Volatile Organic Compounds (VOCs) [4].

Carbon Monoxide (CO) is one of the air pollutants that can influence to greenhouse gas emission such as Carbon Dioxide (CO₂) and Methane (CH₄). CO emissions are predominantly generated by anthropogenic activities, including biomass burning, fossil fuel combustion, industrial processes, and transportation. The accumulation of CO in the atmosphere therefore not only deteriorates air quality and adversely affects human health but also alters atmospheric chemical composition. In particular, CO plays a significant role in tropospheric ozone formation through its involvement in photochemical reactions [5]. Consequently, elevated atmospheric CO concentrations have implications for both the climate and the environment at regional and global levels [4].

Nitrogen Oxides (NO_x), comprising nitric oxide (NO) and nitrogen dioxide (NO₂), which have negative impacts on the environment and human health [6]. The primary sources of NO_x are high-temperature combustion processes, particularly from the transportation sector, electricity generation from fossil fuels, industrial processes, and open burning, such as agricultural residue burning and forest fires [7, 8]. In urban areas characterized by high vehicle density, NO_x emissions from road transportation are recognized as the most significant source and are closely associated with urban air quality problems. In the atmosphere, NO_x undergoes chemical reactions that lead to the formation of secondary pollutants, including ozone and acid rain [5, 9]. These processes contribute to the degradation of ecosystems, water resources, soils, and infrastructure.

Emission Inventory is a comprehensive database that quantifies the amounts of air pollutants released into the atmosphere over a specific year or other defined time period [7]. Emissions are categorized by source type in order to identify major contributors to air pollution and to support the development of targeted control strategies. Emission inventories have a wide range of applications, including their use as input data for atmospheric and geographic modeling, forecasting future pollution scenarios, and informing the design of air quality management policies and mitigation measures [8].

Previous studies on air pollutant emission inventories in Thailand have employed both bottom-up and top-down approaches. Vongmahadlek et al. (2009) developed a national emission inventory for Thailand using activity-based bottom-up methods, providing valuable sectoral and regional estimates [10]. Pham et al. (2007) estimated ozone precursor emissions from power plants and industrial facilities in the Central and Eastern regions, highlighting the significant contributions of energy and industrial sectors to NO_x emissions [11]. Despite these efforts, there remains a need for long-term, nationally consistent analyses that cover all regions and emission sectors over a recent multi-year period. This study addresses that gap by utilizing the CAMS-GLOB-ANT v6.2 global anthropogenic emission inventory, which

provides spatially and temporally consistent data from 2014 to 2024.

This study aims to examine the emissions of Carbon Monoxide (CO) and Nitrogen Oxides (NO_x) in Thailand using data derived from an emission inventory. It also seeks to identify and analyze the various emission sources contributing to these air pollutants. The findings are intended to provide supporting information for sustainable environmental management and public health protection.

It is also important to note that while ambient concentrations of CO and NO_x in Thailand may not always be extremely high compared to national air quality standards, their critical importance lies in their role as primary precursors for secondary pollutants, particularly tropospheric ozone [5], which remains a persistent air quality challenge in the country. Therefore, a comprehensive understanding of their emission inventories is essential for effective secondary pollutant management.

Materials and Methods

Study Area

This study investigates air pollutant emissions across Thailand, which is located in Southeast Asia between latitudes 5°37'–20°27'N and longitudes 97°22'–105°37'E. The analysis covers the entire territory of the country and is divided into six regions: Northern, Northeastern, Central, Eastern, Western, and Southern Thailand. This regional classification allows for the

examination of spatial emission patterns and the identification of differences in emission sources associated with regional economic activities and geographical characteristics.

Data Sources

This study utilizes secondary data obtained from the Emissions of Atmospheric Compounds and Compilation of Ancillary Data (ECCAD) database, which compiles emission inventory data from multiple global datasets. Specifically, the study employs data from the Copernicus Atmosphere Monitoring Service (CAMS-GLOB-ANT) version 6.2.

The CAMS-GLOB-ANT v6.2 dataset provides global anthropogenic air pollutant emission data with a spatial resolution of 0.1° × 0.1°. The dataset includes both monthly and yearly emission data and is categorized by pollutant type and emission sector. The CAMS-GLOB-ANT dataset is developed by integrating multiple existing global and regional expert emission inventories, utilizing a combination of atmospheric modeling, meteorological data, and satellite observations. It scales historical baseline emissions to the current year using projected activity data and trend analyses. This methodology ensures a consistent global representation of anthropogenic emissions, although it relies on broader assumptions compared to localized bottom-up inventories [12]. In this study, emission data for the period 2014–2024 were selected. The detailed dataset description is presented in **Table 1**.

Table 1 Detail of information

Parameter	Unit	Introduction	Sector	Data sources
CO	Tg	CAMS Global anthropogenic emissions	Road transportation (TRO)	CAMS-GLOB-ANT-v6.2
NO _x			Agriculture waste burning (AWB)	
			Refineries (REF)	
			Industrial process (IND)	
			Residential (RES)	
			Commercial (COM)	
			Solids waste and wastewater (SWD)	
			Fugitives (FEF)	
			Off Road Transportation (TNR)	
			Power generation (ENE)	
			Ships (SHP)	
			Agriculture livestock (AGL)	
			Agriculture soils (AGS)	

The selection of CAMS-GLOB-ANT v6.2 as the primary dataset provides a consistent and comprehensive top-down anthropogenic emission inventory, which is crucial for long-term national-scale monitoring. While Thailand has several bottom-up emission inventories that offer localized details [10], bottom-up approaches in developing countries often face limitations regarding data availability, frequent updates, and spatial consistency across all sectors. Compared to other well-known global and regional emission inventories such as EDGAR (Emission Database for Global Atmospheric Research) and REAS (Regional Emission inventory in Asia), the CAMS-GLOB-ANT v6.2 offers a distinct advantage in terms of temporal recency. While REAS version 3 provides detailed Asian emissions but extends only up to the year 2015, and EDGAR updates may exhibit temporal lags, CAMS-GLOB-ANT integrates historical baselines with projected activity data to provide highly consistent, updated monthly emissions up to the year 2024. This continuous temporal coverage makes it particularly suitable for analyzing recent long-term trends, including capturing the emission anomalies during the COVID-19 pandemic. It must be explicitly clarified that this dataset focuses strictly on anthropogenic sources and agricultural open burning, and does not capture natural forest fire emissions. In Thailand, forest fires are a dominant source of CO and a significant contributor to NO_x; therefore, fire-specific datasets such as FINN (Fire Inventory from NCAR), GFED (Global Fire Emissions Database), or GFAS (Global Fire Assimilation System) would be more appropriate for fire-inclusive studies. By excluding forest fires, the present study avoids the extreme seasonal anomalies introduced by natural fire events, thereby allowing for a focused evaluation of human-induced emission trends [13-15].

Data Processing and Analysis

The emission data from the CAMS-GLOB-ANT v6.2 database are provided in NetCDF (Network Common Data Form) format. In this study, data processing and analysis were conducted using the Python programming language, following a systematic three-step workflow: (1) Data extraction: NetCDF files were downloaded from the ECCAD database and read using the netCDF4 and xarray libraries

in Python, extracting CO and NO_x emission variables for each sector and year from 2014 to 2024. (2) Spatial processing: A shapefile boundary of Thailand and its six administrative regions was used to spatially clip the global dataset, and gridded emission values were aggregated by region using GeoPandas and regionmask libraries. (3) Data analysis and visualization: Aggregated emission data were analyzed to examine spatial distribution patterns, inter-annual emission trends by sector, and monthly seasonal variability. Results were visualized using Matplotlib and Cartopy libraries to produce spatial maps, time-series plots, and stacked bar charts.

Results and Discussion

CO and NO_x Emissions in Thailand

The spatial distribution maps of the average emissions of Carbon Monoxide (CO) (**Figure 1a**) and Nitrogen Oxides (NO_x) (**Figure 1b**) In Thailand, during the period 2014–2024 indicate that both pollutants exhibit similar spatial patterns. Areas with relatively high emission levels are mainly concentrated in the Central region, particularly the Bangkok Metropolitan Region and its surrounding areas, as well as along major urban corridors and key economic zones of the country. This pattern may be explained by the geographical characteristics of the Central region, which consists largely of river plains with several major rivers flowing through the area [16]. Consequently, riverbank areas have historically developed as important economic centers, supporting various activities that act as major sources of NO_x and CO emissions [17].

In the Northeastern region, the spatial distribution of CO and NO_x emissions covers a broader area compared with other regions and is not limited to major urban centers but extends across communities in several provinces. This pattern corresponds with the region's topography, which is predominantly characterized by plateau landscapes [16], together with an extensive transportation network connecting different provinces. In addition, the Northeastern region contains the largest agricultural areas in Thailand [18], where fuel combustion activities, including agricultural practices and transportation, may contribute to CO and NO_x emissions.

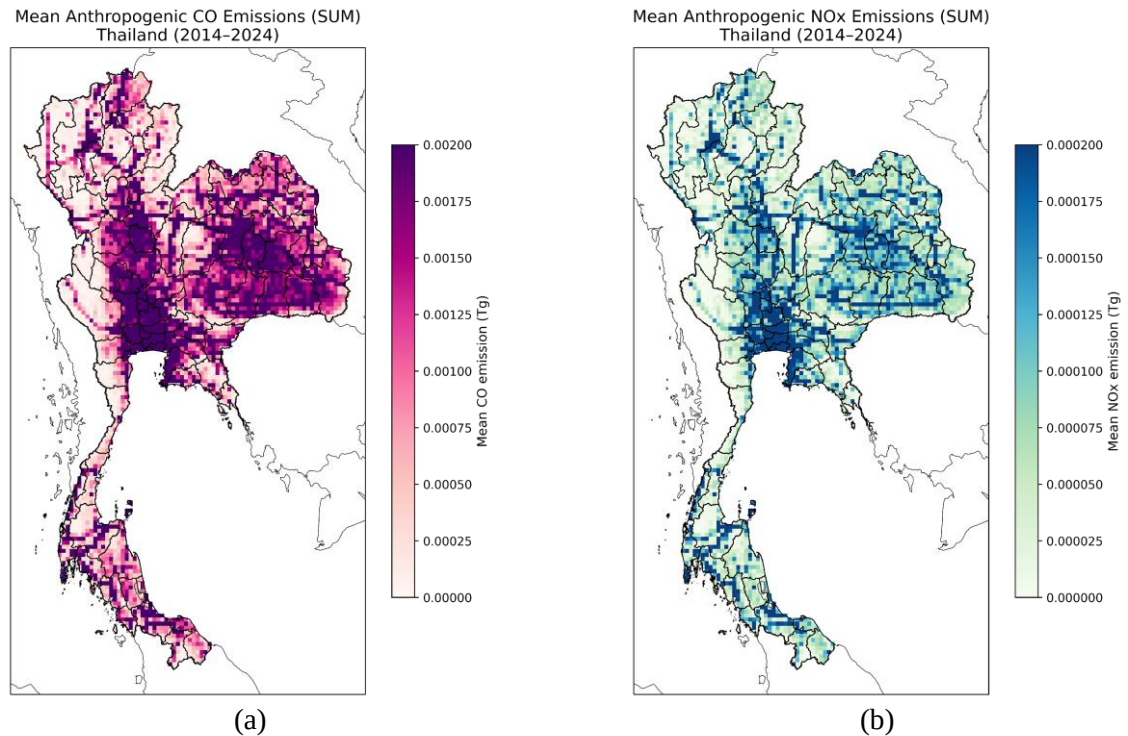


Figure 1 Spatial distribution of the average anthropogenic Carbon Monoxide (a) and Nitrogen Oxides (b) emissions during the period 2014–2024

In the Northern region, emissions of CO and NO_x appear as scattered clusters within urban basins and valley areas rather than forming a continuous distribution, as observed in the Central region. This spatial pattern is consistent with the region's mountainous terrain, which consists of high mountain ranges and intermontane valleys or river plains [16]. As a result, emission hotspots tend to occur along transportation corridors that pass-through valleys, where economic activities and population are more concentrated, leading to higher energy consumption and combustion-related emissions of both CO and NO_x.

In the Eastern region, relatively high emissions of CO and NO_x are observed in several areas. This pattern is consistent with the location of the Eastern Economic Corridor (EEC), which covers three provinces Chachoengsao, Chonburi, and Rayong [19]. These areas host numerous industrial estates, refineries, power plants, and transportation infrastructure, all of which contribute to elevated emissions of NO_x and CO.

In the Southern region, the distribution of CO and NO_x emissions generally follows a linear pattern along the peninsula and coastal

urban centers rather than being uniformly distributed across the entire region. This pattern corresponds with the geographical characteristics of southern Thailand, which consists of a narrow peninsula extending along the coastline [16]. Economic activities and settlements are concentrated along major transportation routes, port cities, tourism centers, and coastal areas [19]. Consequently, pollutant emissions tend to cluster along key infrastructure corridors rather than being widely dispersed. Moreover, compared with the Central and Eastern regions, the Southern region has a relatively smaller heavy industrial base and lower urban density, resulting in lower overall average emissions of both pollutants.

Overall, the spatial analysis indicates that the distribution of CO and NO_x emissions in Thailand during 2014–2024 is closely associated with both geographical characteristics and regional economic structures. Major economic regions, such as the Central and Eastern regions, exhibit higher emission levels due to the concentration of urban areas, industrial activities, and transportation networks. In contrast, emissions in the Northeastern region are more widely dispersed due to extensive transportation

networks and agricultural land use, while emissions in the Northern and Southern regions tend to appear as localized clusters or linear patterns along transportation corridors. These findings suggest that the spatial distribution of air pollutants not only reflects the locations of emission sources but also mirrors the broader spatial development patterns of Thailand, highlighting the importance of region-specific air pollution control strategies rather than a uniform national approach. However, it should be emphasized that the relationships between emission distributions and socio-economic factors such as population density, regional GDP, and land use are presented here as hypotheses based on descriptive spatial patterns. Further quantitative analyses incorporating statistical correlation with population density, regional GDP, and land-use data are required to scientifically confirm these underlying drivers.

CO and NO_x emissions in each region of Thailand

The total anthropogenic CO and NO_x emissions, along with their top sectoral contribution percentages across all six regions, are quantitatively summarized in **Table 4**. This sectoral breakdown highlights the significant variations in emission sources driven by specific regional economic activities.

CO emission

(**Figure 3**) The trends in annual average Carbon Monoxide (CO) emissions in Thailand during the period 2014–2024, classified by region and emission source. The results indicate that road transportation is the dominant source of CO emissions in several regions of the country, including the Central, Eastern, Northern, and Western regions. This is followed by agricultural waste burning and refinery activities, respectively. This trend highlights the important role of the transportation sector as a major source of Carbon Monoxide emissions, which mainly result from fuel combustion in internal combustion engines, particularly in densely populated urban areas and major economic centers where vehicle use is intensive [20].

In the Northeastern region, the pattern of CO emissions varies over time. During 2014–2019, road transportation remained the primary emission source, followed by agricultural waste burning. However, during 2020–2024, emissions from agricultural waste burning exceeded those

from transportation. This pattern corresponds with the economic structure of the region, which is characterized by extensive agricultural areas and the cultivation of major crops such as rice, sugarcane, and cassava. Post-harvest burning of agricultural residues therefore contributes significantly to CO emissions [21].

In the Southern region, although transportation remains the primary source of CO emissions, refinery activities represent the second-largest source, exceeding emissions from agricultural waste burning. This reflects the role of energy-related activities and petroleum industries in certain parts of the region, as well as transportation associated with trade and tourism, which are important components of the regional economy.

Another important finding is the noticeable reduction in CO emissions from the transportation sector in 2020 across all regions of Thailand, with a decrease of approximately 27.47% compared with 2019. This reduction is consistent with the global situation during the COVID-19 pandemic, when many countries implemented restrictions on travel and economic activities, resulting in significant decreases in vehicle usage and fuel combustion. This observation is also consistent with the Thailand Pollution Situation Report 2020 by the Pollution Control Department, which reported that the COVID-19 outbreak led to reduced travel and transportation activities in the country [22]. Several studies have similarly reported significant reductions in emissions from transportation and industrial activities during this period [23, 24].

To quantitatively validate the visual similarity in spatial patterns, a spatial correlation analysis was conducted between the mean anthropogenic CO and NO_x emissions across all grid cells. The results demonstrated a statistically significant positive correlation between the spatial distributions of CO and NO_x (Pearson $r = 0.695$, $R^2 = 0.482$, $p < 0.001$), as illustrated in **Figure 2**. This significant correlation confirms that the primary anthropogenic sources of both pollutants are highly co-located, predominantly driven by the same combustion activities in urban, industrial, and transportation hubs.

As shown in **Table 2**, AWB exhibited a significant increasing trend in CO emissions during 2014–2024 ($p < 0.01$), whereas RES, COM, REF, and SWD showed significant decreasing trends ($p < 0.05$). The remaining

sectors did not exhibit statistically significant temporal trends.

Overall, the analysis of CO emission trends by region and emission source indicates that emission patterns are closely related to the dominant economic activities of each region. Regions with highly developed urban areas and transportation infrastructure tend to have transportation as the main emission source, whereas regions with extensive agricultural land are more influenced by emissions from biomass or agricultural residue burning. Therefore, examining emissions by both region and source sector is essential for developing air pollution control measures that are appropriate to regional contexts.

NO_x emission

(**Figure 4**) The trends in annual average Nitrogen Oxides (NO_x) emissions in Thailand during the period 2014–2024, classified by region and emission source, indicate that NO_x emissions are strongly associated with regional economic structures, energy consumption patterns, and human activities. Road transportation represents the primary emission source in several regions, including the Central, Northern, Northeastern, Western, and Southern regions. This is mainly due to high-

temperature combustion processes in internal combustion engines, which promote reactions between nitrogen and oxygen in the air, leading to the formation of NO_x. Diesel engines, widely used in the transportation sector, are particularly significant contributors because of their higher combustion temperatures [25].

The Central region, which serves as the country's main economic hub and has a high population density, shows that NO_x emissions are predominantly generated from the transportation sector, followed by industrial processes and energy production. This pattern reflects the concentration of urban activities, transportation networks, and industrial estates in the Bangkok Metropolitan Region and its surrounding areas, where energy and fuel consumption are substantial. Previous research has also indicated that power plants and industrial facilities in the Central and Eastern regions play an important role in generating air pollutants such as NO_x [11]. Furthermore, a detailed statistical trend analysis of NO_x emissions by key sectors in the Central region is summarized in **Table 3**. The results highlight the significant trends and statistical reliability ($p\text{-value} < 0.05$) of major emission sources over the study period.

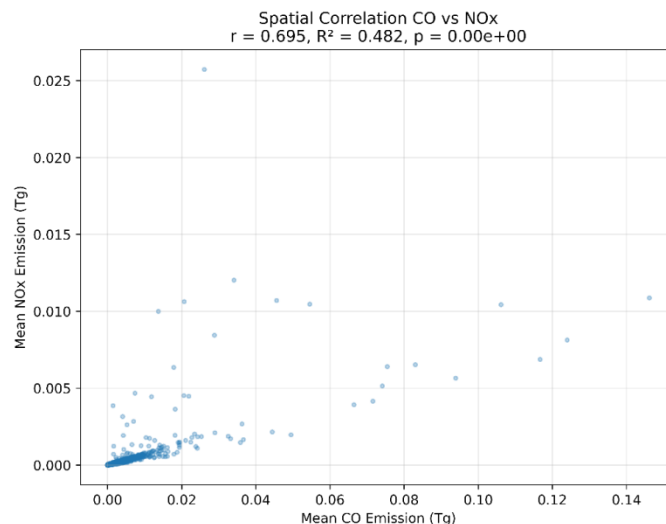


Figure 2 Spatial correlation between the mean anthropogenic Carbon Monoxide (CO) and Nitrogen Oxides (NO_x) emissions in Thailand during the period 2014–2024

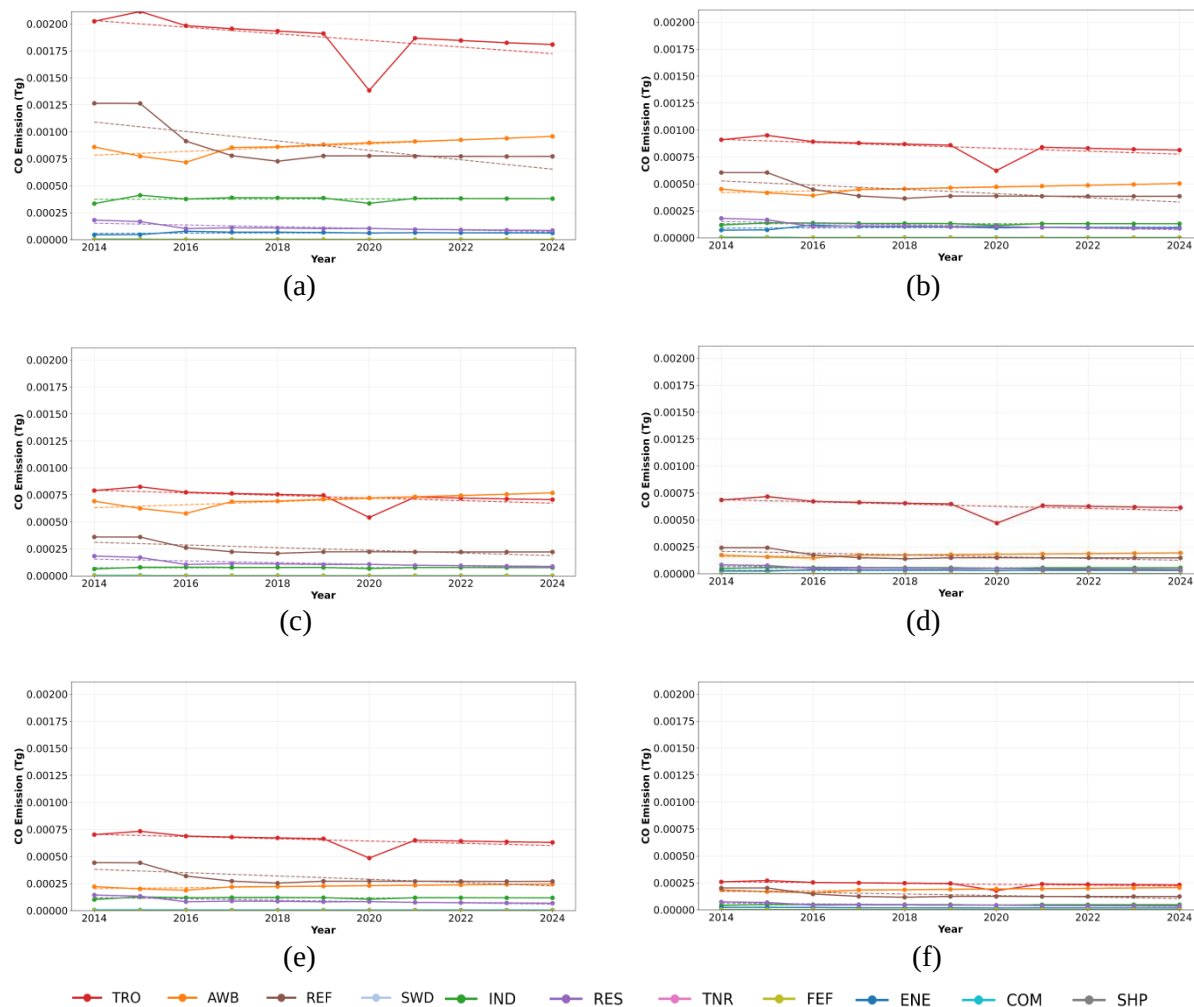


Figure 3 Trends of Carbon Monoxide (CO) emission by sector across the (a) Central, (b) Eastern, (c) Northeastern, (d) Northern, (e) Southern, and (f) Western regions of Thailand during the period 2014–2024. Abbreviations: TRO (Road transportation), AWB (Agriculture waste burning), REF (Refineries), IND (Industrial process), RES (Residential), COM (Commercial), SWD (Solids waste and wastewater), FEF (Fugitives), TNR (Off-Road Transportation), ENE (Power generation), SHP (Ships), AGL (Agriculture livestock), AGS (Agriculture soils)

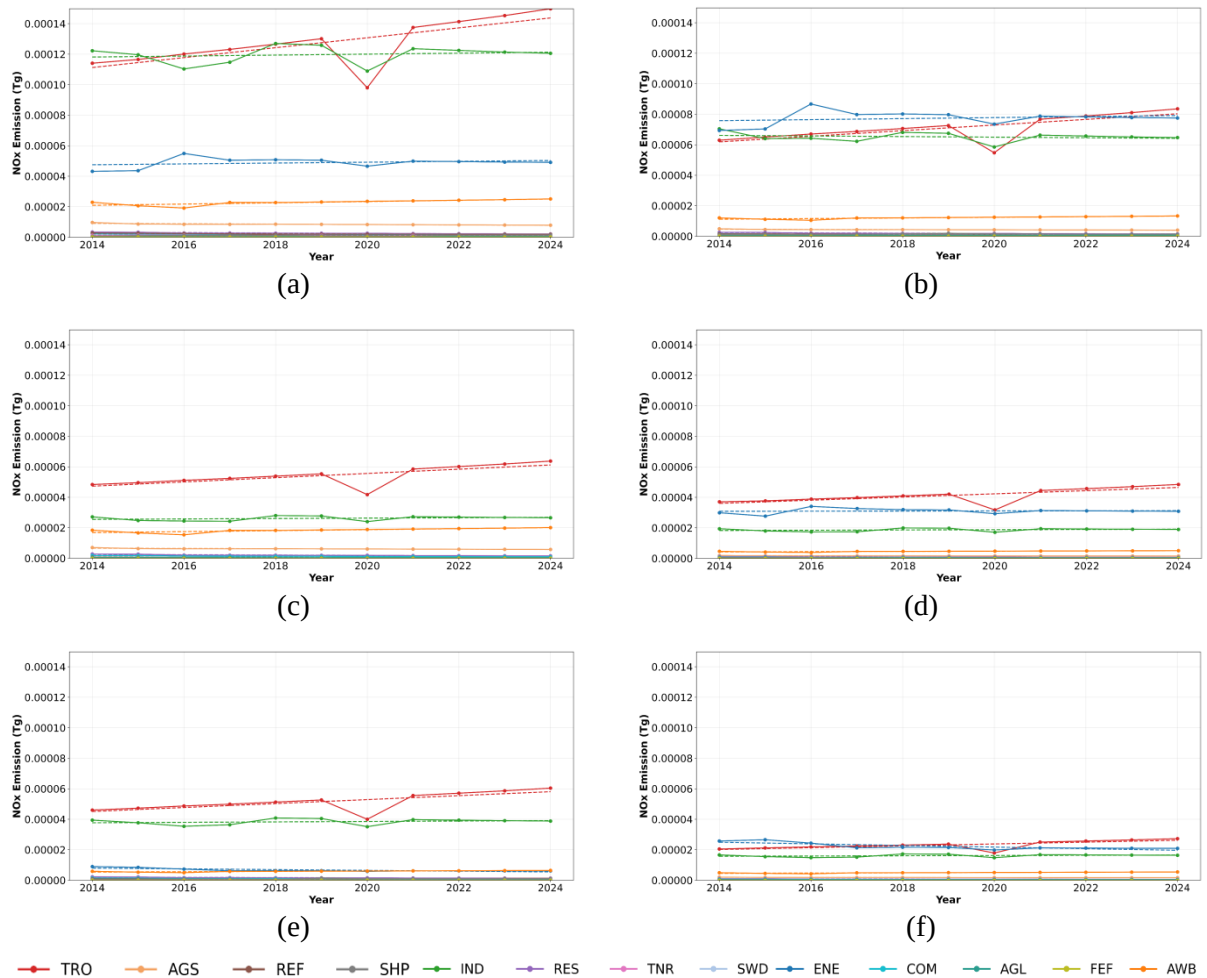


Figure 4 Trends of Nitrogen Oxide (NO_x) emission by sector across the (a) Central, (b) Eastern, (c) Northeastern, (d) Northern, (e) Southern, and (f) Western regions of Thailand during the period 2014–2024. Abbreviations: TRO (Road transportation), AWB (Agriculture waste burning), REF (Refineries), IND (Industrial process), RES (Residential), COM (Commercial), SWD (Solids waste and wastewater), FEF (Fugitives), TNR (Off-Road Transportation), ENE (Power generation), SHP (Ships), AGL (Agriculture livestock), AGS (Agriculture soils)

In the Eastern region, emissions from the energy production sector constitute the largest share of NO_x emissions, followed by transportation and industrial processes. This finding corresponds with the role of the region as a major industrial and energy base of Thailand, particularly within the Eastern Economic Corridor (EEC), where numerous power plants, oil refineries, and large industrial facilities are located [19]. Combustion processes associated with electricity generation and energy production therefore, represent significant sources of NO_x emissions.

For the Northern and Western regions, the results indicate that transportation remains the dominant emission source, followed by energy production and industrial activities. This pattern reflects the importance of transportation networks that connect medium-sized cities and facilitate regional goods movement.

In the Northeastern region, although transportation is the primary emission source, industrial processes and agricultural waste burning represent secondary sources of NO_x emissions. This pattern corresponds with the economic structure of the region, which is

characterized by extensive agricultural areas. Biomass burning can also generate NO_x emissions, although the emission intensity per activity is generally lower than that associated with fossil fuel combustion [26].

In the Southern region, NO_x emissions are primarily generated from road transportation, followed by industrial processes. This pattern is consistent with the regional economic structure, which relies heavily on goods transportation, tourism, and urban development along coastal areas.

Another notable observation is the reduction in NO_x emissions from road transportation, industrial processes, and energy production in 2020 across all regions. Compared with 2019, emissions decreased by 15.26%, 24.53%, and 13.22%, respectively. This decline is likely associated with travel restrictions and the slowdown of economic activities during the COVID-19 pandemic, consistent with the CO emission reduction discussed above. Satellite-based studies have reported significant decreases in NO_2 , a key component of NO_x , in many countries during lockdown periods [24]. Le Quéré et al. reported that global carbon emissions declined substantially in early 2020, with nearly half of the reduction attributed to changes in ground transportation activity, highlighting the transportation sector as one of the most responsive sources to disruptions in social and economic activities [23]. Therefore, the decline in NO_x emissions observed across all regions in 2020 is likely linked to the simultaneous reductions in mobility, industrial production, and energy demand.

Overall, the results indicate that NO_x emissions in Thailand are closely related to the dominant economic activities of each region. Areas with highly developed urban systems and dense transportation networks tend to be dominated by emissions from the transportation sector, whereas regions with large industrial and energy bases, such as the Eastern region, show a greater contribution from energy production and industrial activities.

Average monthly CO and NO_x emissions

(Figure 5) The monthly average emissions of Carbon Monoxide (CO) and Nitrogen Oxides (NO_x) in Thailand during the period 2014–2024 indicate that emissions of both pollutants tend to

increase from March to May, corresponding to the summer season, with the highest values observed in May. Emissions then gradually decline from the middle to the end of the year. This pattern reflects the seasonal variation of emission activities, which is influenced by both anthropogenic activities and meteorological conditions. To better understand the underlying activities driving these monthly patterns, emissions were further disaggregated by sector (Figure 5). The sectoral monthly variations reveal that while baseline emissions from road transportation (TRO) and industrial processes (IND) remain relatively constant throughout the year, the sharp peak observed between March and May is predominantly driven by a surge in Agricultural Waste Burning (AWB). This quantitative sectoral breakdown confirms that the late dry-season emission peak is strongly tied to specific agricultural calendar events rather than uniform increases across all anthropogenic sectors.

The elevated emissions of CO and NO_x in May can be explained by the seasonal characteristics of Thailand. This period corresponds to the late dry season and the transition period before the onset of the monsoon. In many parts of the country, particularly in the Northern and Northeastern regions, agricultural residue burning, stubble burning commonly occur as farmers prepare land for the next cultivation cycle. These biomass burning activities are important sources of CO and NO_x emissions [27].

From a meteorological perspective, weather conditions and ventilation capacities vary significantly across Thailand's regions and cannot be generalized. During the hot season, when emissions peak, the atmosphere is not necessarily stable; in fact, the boundary layer height is often higher due to strong solar radiation. However, pollutant accumulation during this period is largely driven by specific meteorological events, such as temperature inversions or periods of cooler and more stable atmospheric conditions that occasionally trap emissions near the surface. Coupled with the absence of wet scavenging from rainfall during the late dry season, these localized conditions exacerbate the build-up of biomass burning emissions near ground level.

From a meteorological perspective, the period before the monsoon season is often characterized by relatively stable atmospheric conditions, low wind speeds, and limited air circulation. These conditions reduce the dispersion of pollutants and promote the accumulation of pollutants near the surface. In addition, the absence of rainfall during the late dry season limits the wet removal of pollutants from the atmosphere, resulting in higher pollutant accumulation compared with the rainy season [28].

As the rainy season begins, typically from June onwards, emissions or the atmospheric accumulation of CO and NO_x tend to decrease. Increased rainfall enhances the removal of pollutants from the atmosphere and reduces their

accumulation. Damsri, S. and Promkaew, A. reported that concentrations of Carbon Monoxide and Nitrogen Oxides are generally higher during the summer season than during the winter season [29].

Overall, emissions of CO and NO_x are influenced by multiple factors, including biomass burning during the late dry season, energy consumption, and transportation activities in urban areas, as well as meteorological conditions before the monsoon that favor the accumulation of pollutants in the atmosphere. These findings highlight the combined influence of anthropogenic activities and natural factors in shaping the seasonal variability of air pollutant emissions in Thailand.

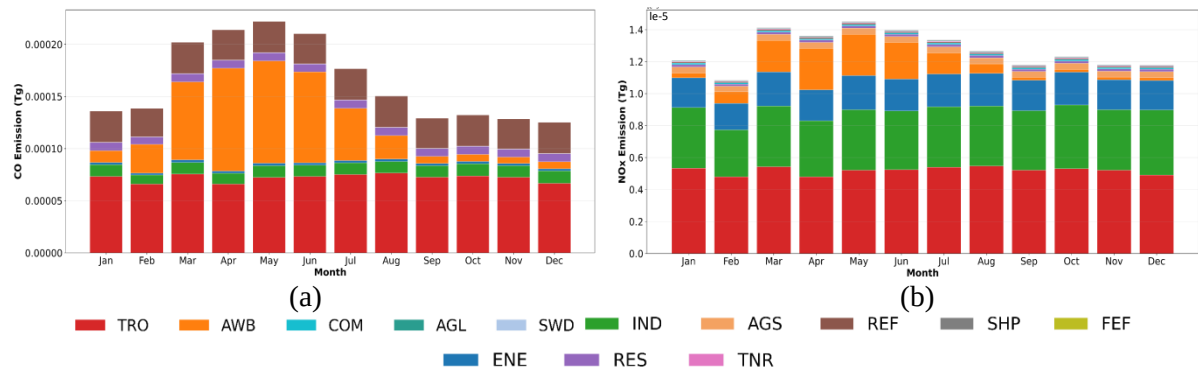


Figure 5 Monthly average emissions of (a) Carbon Monoxide (CO) and (b) Nitrogen Oxides (NO_x) classified by emission sectors in Thailand during the period 2014–2024.

Table 2 Annual trend analysis of CO emissions by key sectors in the Central region (2014–2024).

Sector	Slope (Tg/year)	Correlation (R)	R-squared (R ²)	P-value	Significance
Road transportation (TRO)	-3.06E-05	-0.542	0.294	0.085	Not Sig.
Industrial process (IND)	5.16E-07	0.076	0.006	0.825	Not Sig.
Power generation (ENE)	7.89E-07	0.274	0.075	0.416	Not Sig.
Agriculture waste burning (AWB)	1.76E-05	0.813	0.660	0.002**	Significant
Residential (RES)	-7.86E-06	-0.819	0.671	0.002**	Significant
Commercial (COM)	-2.27E-07	-0.813	0.660	0.002**	Significant
Refineries (REF)	-4.37E-05	-0.728	0.531	0.011*	Significant
Off-Road Transportation (TNR)	-3.51E-09	-0.291	0.085	0.386	Not Sig.
Ships (SHP)	1.10E-08	0.539	0.291	0.087	Not Sig.
Solid waste and wastewater (SWD)	-8.72E-10	-0.779	0.606	0.005**	Significant
Fugitives (FEF)	-1.01E-08	-0.550	0.303	0.080	Not Sig.

(Note: * Indicates statistical significance at $p < 0.05$, and ** indicates statistical significance at $p < 0.01$)

Table 3 Annual trend analysis of NO_x emissions by key sectors in the Central region (2014–2024).

Sector	Slope (Tg/year)	Correlation (R)	R-squared (R ²)	P-value	Significance
Road transportation (TRO)	3.25E-06	0.702	0.493	0.016*	Significant
Industrial process (IND)	3.16E-07	0.176	0.031	0.604	Not Sig.
Power generation (ENE)	2.79E-07	0.276	0.076	0.411	Not Sig.
Agriculture waste burning (AWB)	4.11E-07	0.782	0.611	0.004**	Significant
Agriculture soils (AGS)	-1.23E-07	-0.856	0.734	0.001**	Significant
Residential (RES)	-1.17E-07	-0.945	0.893	< 0.001**	Significant
Commercial (COM)	-7.80E-08	-0.921	0.848	< 0.001**	Significant
Refineries (REF)	-8.36E-08	-0.833	0.694	0.001**	Significant
Off-Road Transportation (TNR)	-2.11E-08	-0.513	0.263	0.107	Not Sig.
Agriculture livestock (AGL)	1.99E-10	0.426	0.181	0.191	Not Sig.
Ships (SHP)	3.80E-08	0.429	0.184	0.188	Not Sig.
Solid waste and wastewater (SWD)	8.91E-10	0.536	0.288	0.089	Not Sig.
Fugitives (FEF)	-3.31E-09	-0.818	0.669	0.002**	Significant

(Note: * Indicates statistical significance at $p < 0.05$, and ** indicates statistical significance at $p < 0.01$)

Table 4 Total anthropogenic CO and NO_x emissions and their sectoral contribution percentages by region in Thailand (Average 2014–2024).

Region	Average CO (Tg/year)	Top 3 CO Sectors (%)	Average NO _x (Tg/year)	Top 3 NO _x Sectors (%)
Central	4.18E-03	TRO (44.9%), REF (20.9%), AWB (20.8%)	3.37E-04	TRO (38.0%), IND (35.3%), ENE (14.5%)
Eastern	2.08E-03	TRO (40.6%), AWB (22.2%), REF (20.7%)	2.38E-04	ENE (32.6%), TRO (29.9%), IND (27.4%)
Northeastern	1.88E-03	TRO (39.0%), AWB (37.3%), REF (13.3%)	1.11E-04	TRO (48.8%), IND (23.5%), AWB (16.6%)
Northern	1.12E-03	TRO (56.9%), AWB (15.7%), REF (14.9%)	9.94E-05	TRO (41.5%), ENE (31.2%), IND (18.8%)
Southern	1.40E-03	TRO (46.7%), REF (21.8%), AWB (16.0%)	1.09E-04	TRO (47.3%), IND (35.2%), ENE (6.2%)
Western	6.80E-04	TRO (35.3%), AWB (27.6%), REF (20.5%)	7.03E-05	TRO (32.9%), ENE (31.6%), IND (22.9%)

Limitations

This study has several limitations that should be considered when interpreting the results. First, the CAMS-GLOB-ANT v6.2 dataset covers only anthropogenic emission sources and agricultural open burning, and excludes natural forest fire emissions. In Thailand, forest fires are a dominant and highly seasonal source of CO and NO_x, particularly in the Northern and Northeastern regions during the dry season. Consequently, the results presented here underestimate total national emissions during peak fire periods and are not directly comparable with studies that incorporate fire emissions. Future studies should integrate fire-

specific datasets such as FINN, GFED, or GFAS to provide a more comprehensive picture of total CO and NO_x emissions in Thailand.

Second, as a top-down global inventory, CAMS-GLOB-ANT may not fully capture fine-scale spatial heterogeneity or local emission variations that would be better represented by bottom-up national inventories [10].

Conclusions

This study investigated the spatial distribution, emission sources, and seasonal variability of anthropogenic Carbon Monoxide (CO) and Nitrogen Oxides (NO_x) emissions in Thailand from 2014 to 2024. It is important to

note that the results reflect strictly anthropogenic and agricultural open burning sources, and do not include natural forest fire emissions, which are also a major contributor to CO and NO_x in Thailand. Both pollutants exhibit similar spatial patterns, heavily concentrated in the Central and Eastern regions due to urbanization, dense transportation networks, and industrial activities. In contrast, the Northern and Northeastern regions are strongly influenced by agricultural waste burning, resulting in significant late dry-season emission peaks from March to May.

To effectively manage these precursors of secondary pollution, policy strategies must be region-specific. In the Central and Eastern economic hubs, actionable interventions should target the transportation and industrial sectors, such as accelerating the adoption of zero-emission vehicles, implementing stricter vehicle emission standards (e.g., Euro 6) [30], and enforcing continuous emission monitoring systems (CEMS) for industrial facilities. Conversely, in the Northern and Northeastern regions, mitigating agricultural waste burning through incentivizing biomass utilization or providing alternative crop residue management technologies is crucial. Finally, while this study isolated anthropogenic drivers, comprehensive air quality management in Thailand must ultimately integrate natural forest fire mitigation to address the full scope of seasonal pollutant accumulation and to better protect public health from secondary pollutants such as tropospheric ozone [5].

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