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Air pollutant emissions and sources in Lao People's Democratic Republic: a provincial scale analysis for years 2013-2019

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Abstract

Recent rapid economic development in Lao People's Democratic Republic (PDR) has increased national fuel consumption, vehicle fleet, industrial output, waste generation, and agricultural production. This has contributed to national average ambient fine particulate matter ($PM_{2.5}$) air pollutant levels that are four times higher than World Health Organisation guidelines. Emission inventories are a key tool in understanding the major sources to these air pollution levels, and provide a starting point to identify where mitigation action can be targeted. A national air pollutant emission inventory has not been developed in Lao PDR and, combined with a limited air quality monitoring network means there is limited capacity to develop and track the effectiveness of mitigation actions. This study describes the first air pollutant emission inventory at the national and provincial scale for Lao PDR, covering 2013–2019. Emissions of nine air pollutants, and two greenhouse gases, were quantified using national statistics and international default emission factors. In 2019, national total $PM_{2.5}$, Nitrogen Oxides (NO_x), Black Carbon (BC), Sulphur Dioxide (SO_2), Non-Methane Volatile Organic Carbons (NMVOCs), and Ammonia (NH_3) were 125, 83, 9.7, 26, 219, and 99 thousand tonnes respectively. Key source sectors include forest fires, residential cooking, agriculture, electricity generation, and transport. However, the contribution of different sources varies across provinces. Forest fires are the primary source determining the spatial trend of particulate air pollution while residential and agricultural emissions contribute more significantly to rural provinces such as Savannakhet. Key sectors in major urban provinces (Vientiane Capital and Xayaboury) are industry, transport and electricity generation. These sectors are also significant sources of greenhouse gases (CO_2 and CH_4), demonstrating the potential for identification, evaluation and prioritisation of actions that simultaneously improve air quality and achieve Lao PDR's international climate change commitments.

1. Introduction

Exposure to both ambient and household air pollutants such as fine particulate matter ($PM_{2.5}$) and ozone (O_3) is the fourth largest risk factor for premature mortality globally, estimated to cause almost 7 million premature deaths in 2019 (IHME 2020). The health burden from air pollution exposure is not felt equally across the globe with 58% of premature deaths due to air pollution exposure occurring in lower income or lower middle-income countries, predominantly in sub-Saharan Africa and Asia (IHME 2020). Lao People's Democratic Republic (Lao PDR) is a landlocked country in Southeast Asia, whose population of 7 million people are exposed to annual average exposure to $PM_{2.5}$ concentrations of 20 μg m^{-3}, which while among the lowest levels in Southeast Asian countries, is four times higher than World Health Organisation (WHO) ambient air quality guidelines to protect health (WHO 2021, State of Global Air 2022). This exposure results in ~10,000 premature deaths per year, approximately 17% of total annual deaths in Lao PDR (State of Global Air 2022). Simultaneously, Lao PDR has one of the highest rates of households cooking with biomass fuel (wood, charcoal) in Southeast Asia (over 90% of the total population in 2017 (Lao Statistics Bureau 2015, Sánchez-Triana 2021)). Hence household air pollution exposure is also a major health risk, resulting in an estimated 6,332 premature deaths in 2019 (GBD 2019). Household air pollution disproportionately impacts women and children, with under 5's accounting for 16% of total deaths from household and ambient air pollution in 2019 (State of Global Air 2022).

Lao PDR was one of the world's fastest growing economies prior to the COVID-19 pandemic, with GDP increasing on average 8% annually since the beginning of the century (Sánchez-Triana 2021). This economic growth has coincided with urbanisation, expanded electricity production, and increased industrial activity (Lao PDR 2021a, World Bank 2023). These activities can also be major air pollutant emission sources. Globally, fossil-fuel-driven economic development is generally coupled with increasing air pollution (UNEP 2018). Lao PDR's most recent National Socio-Economic Development Plan (NSEDP) targets an annual economic growth rate of 5% to 2025 (Ministry of Planning and Investment 2021), which, could further increase air pollutant emissions.

Several policies which aim to reduce the environmental impacts of economic development have been developed in Lao PDR. In 2019, the Government of Lao PDR adopted a Green Growth Strategy, which establishes a pathway for equitable economic growth that is 'clean and environmentally friendly' including a focus on improving the air pollution control system (Government of Lao PDR 2018). In 2020, the Government submitted its updated Nationally Determined Contribution (NDC) to the United Nations Framework Convention on Climate Change (UNFCCC), which sets an unconditional target to reduce total greenhouse gas emissions by 60% compared to a baseline scenario by 2030 and a target to be net zero by 2050 conditional on international support (Lao PDR 2021a). Mitigation measures to reduce greenhouse gas emissions incorporated into the targets include increasing renewable energy, introduction of energy efficient cookstoves, and increasing non-motorised transport and electric vehicles. The National Pollution Control Strategy and Action Plan 2018–2025 (Ministry of Natural Resources and the Environment 2017), sets out actions and measures which could reduce air, noise, soil, and water pollution. It includes actions to improve waste treatment infrastructure, strengthen vehicle emission standards as well as increasing awareness around waste burning. However, none of these national plans quantify the effect these actions could have on air pollution.

Emission inventories are an essential tool to develop and evaluate strategies to reduce air pollution (European Environment Agency 2023). They enable the contribution of key source sectors to air pollutant emissions to be identified and can be used to assess the extent to which action in a particular sector could be effective at improving air quality (Thailand Pollution Control Department 2023). Progress against policies can be tracked and emission trends over time can be monitored. Historic emission inventories are a prerequisite for the development of mitigation assessments in which various interventions are evaluated to quantify their emissions reduction potential. Emission inventories have been used in air quality planning in elsewhere in Southeast Asia, e.g., in the development of a national Clean Air Plan for Cambodia (Sokharavuth *et al* 2023).

A national emission inventory has been developed in Lao PDR covering greenhouse gases for climate change planning (MONRE 2020). However, this inventory does not include air pollutants and emissions are not disaggregated to the provincial scale. The limited information on the magnitude of air pollutant emissions and their spatial distribution limits the capacity of national institutions to develop informed and targeted policies on air pollutants and greenhouse gases. National strategies recognise the lack of a comprehensive emission inventory and the necessity to fill this gap to take forward actions to reduce air pollution. The National Pollution Control Strategy promotes the integration of pollution prevention and control and refers to the inconsistency in, or lack of, existing emissions data and the development of central database for all pollutants is included as part of the strategy (MONRE 2017). Similarly, the NSEDP identifies the establishment of a database collating information on sources of air pollutant emissions as a priority activity for environmental protection (Ministry of Planning and Investment 2021). Furthermore, the National Pollution Control Strategy seeks to enhance accountability through increasing the involvement of local representatives in decision making processes, but at present, the understanding of local emissions is even more limited than at the national scale.

In 2022, the Ministry of Natural Resources and Environment in Lao PDR (MONRE) and the Natural Resource and Environment Research Institute (NRERI) began to develop an initial air pollutant mitigation assessment for Lao PDR through a project funded by the United Nations Environment Programme (UNEP). This study presents the first national air pollutant emission inventory for Lao PDR developed through this project. It quantifies national total air pollutant emissions in Lao PDR, highlights key source sectors by province, and shows the spatial and temporal variation between 2013 and 2019. The overlap between major sources of air pollutants and greenhouse gases is shown through quantification of carbon dioxide (CO_2) and methane (CH_4)

emissions alongside air pollutants. This inventory therefore provides a foundation to assess the ability of mitigation measures to simultaneously reduce air pollutant and greenhouse gas emissions in Lao PDR.

2. Methodology

2.1. Overarching emissions inventory framework

The inventory quantifies annual air pollutant emissions nationally, and for all 18 provinces individually (Lao Statistics Bureau 2021b). Emissions were quantified from all key emitting source sectors using the Intergovernmental Panel for Climate Change (IPCC) category classifications (grouped in four overarching sectors: energy, Industrial Processes and Product Use (IPPU), agriculture, and waste).

Following international emission inventory guidelines (IPCC 2006, EMEP/EEA 2019), the inventory quantifies emissions of 9 air pollutants including fine particulate matter ($PM_{2.5}$), fine plus coarse particulate matter (PM_{10}), organic carbon (OC), black carbon (BC), nitrogen oxides (NO_x), sulphur dioxide (SO_2), non-methane volatile organic compounds (NMVOCs), ammonia (NH_3) and carbon monoxide (CO). These pollutants were included because they all contribute to $PM_{2.5}$ and ozone concentrations, the air pollutants with largest health burdens (Landrigan *et al* 2018). Carbon dioxide (CO_2) and methane (CH_4) were also included in the analysis to assess the overlap between air pollutants and greenhouse gas emission sources. Emission results are reported for years 2013–2019 as these are the years for which sufficient data was available for all sectors analysed.

Emissions (E) for each subsector were calculated as the product of an activity variable (A) and emission factor (EF):

$$E = A \ x \ EF \tag{1}$$

Activity variables characterise the magnitude of an emission-producing process within a subsector and were taken primarily from the Laos Statistical Information Service (LAOSIS) and national reports such as the 2015 Population and Housing Census (Lao Statistics Bureau 2015) (table 1 and section 2.2). Emission factors from the European Monitoring and Evaluation Programme/European Environment Agency (EMEP/EEA) technical guidance (EMEP/EEA 2019), the IPCC Guidelines for National Greenhouse Inventories (IPCC 2006), and literature were applied due to the lack of country specific data. Emission factors can vary depending on the control technologies that are in place, therefore when choosing emission factors, the technologies most appropriate to Lao PDR were considered.

Activity variables were initially identified at the national level to quantify national emissions. To estimate provincial level emissions, activity variables for each source were either identified at the provincial level, or national activity variables were disaggregated to the provincial level using proxy variables. Table 1 summarises the activity variables used, data sources and how these activity variables were disaggregated for the provincial level analysis. Emissions were quantified at the provincial scale to account for spatial variability and because of the responsibility devolved to provinces for environmental protection. Provinces represent administrative boundaries within which policies can be monitored, for example each province has its own Department of Natural Resources and Environment as well as a Green Growth Focal Point who is responsible for mainstreaming the Green Growth Agenda into strategies, plans, and programmes as well as monitoring progress within their administration (Government of Lao PDR 2018). In addition, data is readily available at the provincial scale for most sectors.

2.2. Sector specific methods

As outlined above, the national air pollutant emission inventory for Lao PDR was developed by quantifying emissions for subsectors within four overarching categories. The following subsections describe how equation (1) was applied to quantify emissions for each of these subsectors.

2.2.1. Energy

Energy sector emissions account for emissions from the combustion of fuels, as well as fugitive emissions from energy infrastructure. The energy subsectors are broadly categorised into energy supply subsectors (which in this inventory include electricity generation and charcoal production), and energy consuming subsectors (transport, households, commercial and public services, industry and agriculture). For both subsector types, emissions were estimated using fuel consumption as the activity variable (disaggregated by fuel type), multiplied by subsector and fuel-specific emission factors from international emission factor databases. The level of disaggregation of fuel consumption activities within each subsector varies, and is described in detail in the following subsections.

Table 1. Summary of the source sectors from which emissions were estimated, the activity data used, and how these emissions were determined at the provincial level.

Source sector	Activity variable	Source of national data	Assumption for provincial level activity variable	Source of provincial data
1A1a Public Electricity and Heat Production	Coal consumed for electricity generation	Ministry of Energy and Mines (2018)	All emissions occur at the location of the Hongsa power plant (Xayabury Province)	Hongsa Power (2023)
1A2 Manufacturing Industries and Construction	Industrial energy consumption	Malik (2020)	National industrial energy consumption disaggregated based on provincial contribution to industrial GDP	Ministry of Planning and Investment (2011)
1A3b Road transportation	Vehicle numbers	LAOSIS (2022)	Provincial data available	LAOSIS (2022)
	Fraction of fuel by vehicle type and fuel consumption by vehicle type	Ministry of Energy and Mines (2018)	Assumed to be the same in all provinces	—
1A4a Commercial/Institutional	Commercial energy consumption by fuel type	Ministry of Energy and Mines (2018)	Data on the number of hotels, guesthouses etc. was used as a proxy for provincial energy consumption	Lao Statistics Bureau (2021b)
1A4b Residential	Number of households	LAOSIS (2022)	Provincial data available	LAOSIS (2022)
	Number of households cooking using different fuels and technologies	Lao Statistics Bureau (2015)	Provincial data available	Lao Statistics Bureau (2015)
	Fuel Consumption for cooking per Household	Ministry of Energy and Mines (2021)	Assumed to be the same in all provinces	—
1A4c Agriculture, Forestry and Fishing	Agricultural energy consumption	Ministry of Energy and Mines (2018)	Used the percentage of farms with machinery as a proxy for agricultural energy consumption	Lao Statistics Bureau 2021a
1B1ci Charcoal Production	Residential and commercial coal consumption	Consumption calculated from sectors 1A4a and 1A4b	Assumed that coal is produced in rural provinces	Provincial data on rural populations (Lao Statistics Bureau 2015)
	Conversion efficiency	Calculated from Ministry of Energy and Mines (2018)	Assumed to be consistent	—
2A Mineral Industry	Production of cement	LAOSIS (2022)	Assumed that the provincial contribution of industrial GDP is a proxy for industrial production	Ministry of Planning and Investment (2011)
2C1 Metal Industry	Production of iron and steel	LAOSIS (2022)	Assumed that the provincial contribution of industrial GDP is a proxy for industrial production.	Ministry of Planning and Investment (2011)
3A Livestock	Number of animals by animal type	LAOSIS (2022)	Provincial data available	LAOSIS (2022)

Table 1. (Continued.)

Source sector	Activity variable	Source of national data	Assumption for provincial level activity variable	Source of provincial data
3C Aggregate sources and non-CO_2 emission sources on land	Biomass Burning		Area burnt apportioned based on percentage of farms cleared by burning in each province, and provincial area of forest area burnt	Lao Statistics Bureau (2021a) and Tyukavina *et al* (2022)
	– Biomass consumption and combustion factor	IPCC (2019)	Assumed to be consistent	—
	– Combustion factor			
	– Area burnt	FAO (2023)		
	Rice Production			
	– Annual harvested area by irrigation regime	LAOSIS (2022)	Provincial data available	LAOSIS (2022)
	– Cultivation period	IPCC (2019)	Assumed to be the same for all provinces	—
	Agricultural Residue Burning			
	– Annual crop production	LAOSIS (2022)	Provincial data available	LAOSIS (2022)
	– Crop residue ratios	IPCC (2019)	Assumed to be the same for all provinces	—
	– Fraction of residue burnt	Lao Statistics Bureau (2021a)	Provincial data available	—
4A Solid Waste Disposal on Land	Per capita waste generation rates	MONRE (2020)	Assumed to be the same for all provinces	—
	Waste collection rates	MONRE (2021)	Assumed to be the same for all provinces	—
	Fraction of uncollected waste burnt	IPCC (2006) default value	Assumed to be the same for all provinces	—
	Urban/rural population	Lao Statistics Bureau (2015)	Provincial data available	Lao Statistics Bureau (2015)
4D Liquid Waste	Wastewater treatment systems	Lao Statistics Bureau (2015)	Provincial data available	Lao Statistics Bureau (2015)
	Urban/rural population	Lao Statistics Bureau (2015)	Provincial data available	Lao Statistics Bureau (2015)

Table 2. Key statistics used to estimate coal consumption for electricity generation between 2015 and 2019. Note, prior to 2015, there was no coal consumption for electricity generation in Lao PDR.

Activity variable	Units	2015	2016	2017	2018	2019	Data source
Electricity generated from coal	GWh	2,259	—	—	—	—	Ministry of Energy and Mines 2018
Electricity generated from coal	GWh	2,259	7,962	10,927	12,019	11,406	IEA 2023
Electricity and heat generated from coal	GWh	2,461	6,564	12,441	13,703	12,194	UN Statistics Division 2023
Coal consumed in electricity generation	GWh	16,394	—	—	—	—	Ministry of Energy and Mines 2018
Coal consumed in electricity generation	GWh	11,557	32,306	41,391	42,840	38,140	UN Statistics Division 2023
Power plant efficiency	%	15.7					Ministry of Energy and Mines 2018
Power plant efficiency	%	21.3	20.3	30.1	32.0	32.0	UN Statistics Division 2023
Final coal consumption estimated	GWh	16,394	39,184	36,354	37,575	35,676	electricity generated / power plant efficiency

2.2.1.1. Electricity generation

In 2015, Lao PDR produced 16,302 GWh of electricity from hydro (86%), coal (14%), and biomass (0.02%) (Ministry of Energy and Mines 2018). Of this, 11,549 GWh (71%) was exported to neighbouring countries while 2,050 GWh was imported (Ministry of Energy and Mines 2018). Due to the small contribution of biomass and the lack of provincial data, emissions were only estimated for coal-based electricity production. Consumption of coal used in electricity generation was derived from Lao PDR Energy Statistics prepared by the Ministry of Energy and Mines (2018) and multiplied by Tier 1 default emission factors from the IPCC (2006) and EMEP/EEA (2019), with the exception of NH_3 and SO_2. The NH_3 emission factor was from Battye *et al* (1994), while SO_2 emissions were calculated as a product of the coal consumption and the coal sulphur content (0.65%). Emission reduction technologies were also accounted for. SO_2 emissions were multiplied by 0.08 to account for an emissions reduction of 92% resulting from Flue Gas Desulfurization technology that is present in the Hongsa power plant (Hadek 2023). Data on fuel consumption was only available up until 2015, and therefore to estimate emissions from coal-based electricity generation post-2015, electricity generation taken from IEA (2023) was multiplied by the power plant efficiency calculated from UN Statistics Division (2023) to estimate 2016–2019 coal consumption for electricity generation (table 2). The only coal power plant in Lao PDR (Hongsa power plant) is located in Xayabury province.

2.2.1.2. Charcoal production

The activity variable used to estimate charcoal production emissions is wood consumption. It was estimated based on charcoal consumption statistics and the efficiency of converting wood to charcoal. The mass of charcoal produced was assumed to equal the mass of charcoal consumed in the residential and services sectors, where national statistics were available. Charcoal consumption in the residential sector was calculated by multiplying the total number of households consuming charcoal by the charcoal consumption per household (723 and 425 kg charcoal per household per year in urban and rural households, respectively (Ministry of Energy and Mines 2021)). Data on household numbers are available to 2019 (LAOSIS 2022), whereas the most recent national statistics on the fraction of households cooking with charcoal was from 2015 (Lao Statistics Bureau 2015). It was therefore assumed that the proportion of households cooking with charcoal remains constant over the study period. Service sector charcoal consumption was taken from Ministry of Energy and Mines (2018) and projected from 2015 to 2019 using GDP.

To estimate the fuelwood required to produce this charcoal, consumption was divided by the process efficiency (0.25) estimated from the charcoal production and wood consumption in charcoal production from national statistics (table 3, Ministry of Energy and Mines 2018). As charcoal production largely occurs informally in rural areas (Barney *et al* 2015), the fraction of the national rural population in each province was used to disaggregate charcoal production provincially. Emissions were estimated by multiplying wood consumption by emission factors from Bertschi *et al* (2003) and Bond *et al* (2004).

2.2.1.3. Residential

The residential sector encompasses emissions from fuel use for cooking. Residential cooking emissions were estimated for urban households, rural households with a road, and rural households without a road (table 4). Nationally, 46% of urban households cook with wood, compared to 79% and 90% of rural households with and without roads, respectively. In urban households, a substantially larger fraction of households cook with charcoal (table 4) (Lao Statistics Bureau 2015). The fraction of households in each category (urban, rural with

Table 3. National fuel wood consumption assumed in charcoal production (thousand tonnes).

Sector	2013	2014	2015	2016	2017	2018	2019
Residential	633	664	667	682	705	723	725
Services	413	433	452	485	519	555	589
Total	1,046	1,096	1,119	1,167	1,224	1,278	1,314

Table 4. Total number of households in Lao PDR in 2019, percentage fuel shares in each household type, and average annual fuel consumption.

Variable	Urban	Rural with road	Rural without road
Number of households (2019)	441,546	742,908	94,320
Fuel use (% households)			
Electricity	10.5	1.07	0.27
Paraffin	0.1	0.2	0.15
Wood	46.3	78.7	90.28
Charcoal	36.8	19.0	8.74
LPG	5.1	0.4	0.1
Other/not stated	0.2	0.6	0.5
Annual average fuel use (TJ per households)			
Electricity	0.016	0.008	
Paraffin	0.002	0.002	
Wood	0.010	0.030	
Charcoal	0.021	0.012	
LPG	0.002	0.002	

road, urban without road) was calculated using results of the 2015 population and housing census (Lao Statistics Bureau 2015). The activity variable to estimate emissions from residential cooking was total consumption of each fuel (*f*, electricity, paraffin, wood, coal, charcoal, LPG) in Lao PDR and each province in each category, estimated using equation (2).

$$TC_{f,c,g} = HH_{c,g} \quad * \quad FT_{f,c,g} \quad * \quad Av_{f,c} \tag{2}$$

Where *TC* is total fuel consumption for each fuel type (*f*), category (*c*) (urban etc.) and geography (*g*) (Lao PDR, or Province). *HH* is the number of households (LAOSIS 2022), *FT* is the percent share of households cooking with each fuel type (Lao Statistics Bureau 2015) and *Av* is the average fuel consumption per household (table 4). Average total fuel consumption in households was taken from the Ministry of Energy and Mines (2021). It is assumed that fuel consumed is for cooking, and that the fuel used for space heating is negligible in Lao PDR. Total consumption for each region was then multiplied by fuel and pollutant specific emission factors. Emission factors were taken from the IPCC (2006) and literature (Smith *et al* 2000, Zhang *et al* 2000, Bertschi *et al* 2003, Bond *et al* 2004, Akagi *et al* 2011).

2.2.1.4. Transport

During the study period (2014–2019), there were no major railway lines operating in Lao PDR therefore this inventory includes emissions from road transport only. Some off-road mobile sources are accounted for in this analysis including fuel consumed by agricultural machinery. However, these are accounted for under agricultural energy consumption.

Exhaust emissions from road transport were estimated separately for 8 vehicle categories (motorcycles, three-wheel cars/tuck tucks, sedans/passenger cars, pick-ups, jeeps, vans, trucks, and buses). Fuel consumption per vehicle (*v*) and fuel (*f*) type was then calculated using equation (3).

$$TC_{v,f} = L_{v,f} \quad * \quad K_{v,f} \quad * \quad D_f \quad * \quad N_{v,f} \tag{3}$$

Where *TC* is the total fuel consumed, *L* is the fuel economy (in km/litre), *K* is the average distance travelled (km/year), *D* is the fuel density and *N* is the number of vehicles, taken from LAOSIS (2022) for 2013–2022 at national and provincial levels. Total number of vehicles increased from 1.4 million to 2.2 million within this period, with motorcycles being the largest vehicle type. Data on the proportion of petrol and diesel vehicles was taken from the Ministry of Energy and Mines (2018) (table 5) and was used to disaggregate vehicles by fuel type (only gasoline and diesel were considered). Data on fuel economy, average distance travelled (table 5), and fuel density

Table 5. Number of vehicles, the percentage gasoline and diesel, the average fuel economy, and the average distance travelled by vehicle type in Lao PDR. Number of vehicles shown is for year 2019, all other variables are assumed to stay constant over time. Data sources: LAOSIS (2022), and Ministry of Energy and Mines (2018).

Vehicle type	Number of vehicles (2019)	Percentage of vehicles using fuel		Average fuel consumption (km/litre)		Average distance travelled (km/year)	
		Gasoline	Diesel	Gasoline	Diesel	Gasoline	Diesel
Motorcycles	1,688,380	100	0	20.5	—	5,104	—
Three-wheelers	9,001	100	0	10	—	15,974	—
Sedans	84,943	80	20	9.6	9.5	15,236	16,276
Pick-ups	284,384	0	100	—	9.1	—	16,712
Jeeps	60,376	45	55	9.9	9.3	16,006	16,995
Vans	37,622	0	100	—	9.2	—	18,206
Trucks	63,330	47	53	9.8	9.8	31,633	14,080
Buses	5,649	0	100	—	6.3	—	11,598

Table 6. National fuel consumption assumed for 2019 in the agriculture, service, and industry sectors (Terajoules). Data sources: Ministry of Energy and Mines (2018) and Malik (2020), projected from 2015 using GDP growth.

Fuel consumption	Agriculture	Services	Industry
Diesel	9,710	0	1,995
LPG	—	120	—
Gasoline	—	—	—
Wood	—	10,384	3042
Charcoal	—	4,242	—
Coal (Anthracite)	—	—	4,437
Coal (Lignite)	—	—	16,942
Fuel Oil	—	—	526

were from the Ministry of Energy and Mines (2018). Fuel density is 0.737 kg/litre for gasoline and 0.839 for diesel.

Total consumption for vehicle type and fuel were then multiplied by fuel-, vehicle- and pollutant-specific emission factors. The IPCC 2006 tier 1 default emission factor for CH_4 was used, all other emission factors were taken from EMEP/EEA (2019). Sulphur content of diesel and gasoline fuel in Lao PDR was assumed to be 3000 and 165 ppm based on UNEP (2023) and EMEP/EEA (2019) respectively.

Emissions of NMVOCs from gasoline evaporation, and $PM_{2.5}$ and PM_{10} from road vehicle tyre and brake wear were also estimated following EMEP/EEA (2019) Tier 1 methodologies. For gasoline evaporation, NMVOC emissions were calculated as a product of the number gasoline vehicles (by type) and an annual emission factor (EMEP/EEA 2019). Tyre and brake wear were calculated as the product of the number vehicles (by type and fuel), the average per vehicle milage, and a vehicle type specific emission factor (EMEP/EEA 2019). Road dust resuspension was not included in this analysis as, although ~78% of roads are unpaved in Lao PDR (LAOSIS 2022), there is no data available on the distanced travelled by vehicles on unpaved roads.

2.2.1.5. Agricultural, services, and industrial energy consumption

Fuels used in these subsectors include LPG, gasoline, diesel, biomass, fuel oil, coal, and electricity (Ministry of Energy and Mines 2018, Malik 2020, table 6), and national fuel consumption for each subsector (Ministry of Energy and Mines 2018, Malik 2020) was multiplied by fuel- and pollutant-specific emission factors (IPCC 2006, EMEP/EEA 2016, Klimont et al 2017, Battye *et al* 1994). Data on fuel consumption was only available up until 2015. Consumption to 2019 was therefore projected using GDP growth (World Bank 2023), assuming that fuel share remained constant.

Due to the lack of provincial level data in these sectors, proxy data was used to disaggregate fuel consumption. For agriculture, national fuel consumption was disaggregated based on the percentage of total farm households using machinery nationally located in each province (Lao Statistics Bureau 2021a). The percentage of the national total number of hotels, guest houses, resorts, restaurants, and entertainment venues reported in Lao Statistics Bureau (2021b) in each province was used to allocate service sector fuel usage to each province. For industrial fuel consumption, the percentage of national industrial GDP contributed by each

Table 7. Production of industrial products (thousand tonnes).

Industrial production	2013	2014	2015	2016	2017	2018	2019
Cement	2156	2201	3099	3407	3938	4800	5208
Iron and Steel	41	42	93	110	118	138	161

Table 8. Crop production for which crop burning emissions were estimated (tonnes).

Crop production	2013	2014	2015	2016	2017	2018	2019
Maize	1,214,085	1,412,440	1,516,250	1,552,360	1,192,525	768,025	793,625
Soybean	54,805	59,250	18,675	19,130	7,960	4,705	5,100
Cotton	3,160	1,225	1,910	2,530	2,235	1,615	2,435
Total Rice	3,414,560	4,002,425	4,102,000	4,148,800	4,055,409	3,279,110	3,534,500
Upland Rice	240,440	235,755	224,360	216,800	217,694	184,695	169,000
Lowland Rice	2,734,970	3,211,584	3,357,640	3,428,000	3,347,830	2,732,450	2,910,700
Dry Season Rice	439,150	555,086	520,000	504,000	489,885	361,965	454,800

province was used, as reported by Ministry of Planning and Investment (2011). As the data on provincial GDP predates Xaysomboon (established in 2013), industry emissions in this province were assumed to be zero.

2.2.2. Non-energy

2.2.2.1. Industrial processes and product use

Emissions from cement and iron and steel production were included in the IPPU sector. The activity variable was the production of cement, iron and steel, respectively (table 7, LAOSIS 2022) and was multiplied by tier 1 default emission factors from the IPCC (2006) and EMEP/EEA (2016). Provincial production was estimated by disaggregating total national production to each province based on the fraction of national total industrial GDP contributed by each province (see section 2.2.1.5).

2.2.2.2. Agriculture, forestry and other land use (AFOLU)

Three emission sources were included within the AFOLU sector: crop burning, livestock (enteric fermentation and manure management), rice production, and vegetation fires.

Agricultural crop burning

Emissions from the open burning of agricultural residues were estimated by multiplying the mass of crop residue openly burned in fields by crop and pollutant-specific emission factors (IPCC 2006, EMEP/EEA 2019). The mass of residue burned was calculated using the following equation:

$$AR_{c,g} = P_{c,g} \ * \ S_c \ * \ DM_c \ * \ PB_g \ * \ CF_c \tag{4}$$

Where *AR* is the mass of residue burned for each crop (*c*) and geographic region (national or province). *P* is crop production in kg per year, *S* is the crop to residue ratio, *DM* is the fraction of dry matter, *PB* is the proportion of residue that is burned and *CF* is the combustion factor. Crop production was taken from LAOSIS (2022) for maize, soybean, cotton and rice (table 8). IPCC (2019) default values were used for crop to residue ratios, dry matter fractions, and combustion factors for each crop. A recent agricultural census reported the fraction of farms which openly burn crop residue in fields in each province (Lao Statistics Bureau 2021a). This was used as the estimate of the fraction of residue burned in fields, assuming that there is not a systematic difference in the magnitude of production and characteristics of residue generation between farms which do and do not burn their residue. Across provinces, the fraction of residue burnt ranges between 0.08–0.6 (table S1).

Livestock

Livestock emissions encompass CH_4 from enteric fermentation, and CH_4 and NH_3 emissions from manure management. Livestock emissions were calculated for cattle, goats and sheep, pigs, poultry, and buffalo and the number of livestock was the activity variable, with data for 2011–2020 from LAOSIS (2022) used (table 9). Default Tier 1 emission factors were used for all pollutant and activities (IPCC 2006, EMEP/EEA 2019).

Rice production

Rice is cultivated in 3 different systems in Lao PDR, with lowland rice contributing the largest fraction of production (table 8). CH_4 emissions from rice production were calculated following the Tier 1 IPCC (2019) methodology:

Table 9. Livestock numbers in Lao PDR (thousand heads).

Livestock number	2013	2014	2015	2016	2017	2018	2019
Cattle	1,714	1,766	1,828	1,923	1,984	2,041	2,110
Buffalo	1,190	1,153	1,165	1,177	1,189	1,200	1,222
Goats and Sheep	470	481	533	560	588	616	647
Swine	2,948	3,122	3,258	3,700	3,869	3,825	4,114
Poultry	30,727	32,408	34,422	35,150	36,960	39,217	43,600

Table 10. Area of vegetation burnt (thousand ha).

Vegetation Type	2013	2014	2015	2016	2017	2018	2019
Forest	361	326	294	469	163	128	294
Grassland, savanna, and shrubland	486	293	410	554	228	165	370

$$E_r = PA_r \ast CL \ast EF \ast SF_r \quad (5)$$

Where E is the CH_4 emissions for rice under each water regime (r). PA is the area of paddy, CL is the cultivation period, EF is emission factor (kg CH_4 ha^{-1} day^{-1}) and SF is the scaling factor. National and provincial data on rice paddy area was taken from LAOSIS (2022). Cultivation period for lowland rainfed and dry season rice was assumed to be 105 days based on a growing season of between 3 and 4 months, while the cultivation period of upland rice was assumed to be 135 days based on a growing season of between 4 and 5 months (Schiller *et al* 2006). Emission factor and scaling factors were all taken from the IPCC (2019) guidelines. The guidelines distinguish between upland, irrigated, rainfed and deep-water water regimes and provide scaling factors for each. The data extracted from LAOSIS refers to lowland rainfed paddy, upland rainfed paddy and dry season paddy. Upland and lowland (wet season) rice is rainfed, while dry season rice is dependent on irrigation (Lao Statistics Bureau 2021a), so scaling factors were applied accordingly. It was assumed that irrigated rice (dry season paddy) is continuously flooded. The same emission factors were applied to each water regime type. The CH_4 emissions from rice under each water regime were summed to provide total emissions from rice production within each province, and at the national scale.

2.2.2.3. Vegetation fires

Emissions from vegetation fires were quantified using equation (6), taken from IPCC (2019).

$$E_t = A_t \ast Mb_t \ast Cf_t \ast EF \quad (6)$$

Where E is the pollutant emissions from vegetation burning for each vegetation type (t). A is the area burnt (ha), Mb is the dry matter available for combustion, Cf is a combustion factor representing the fraction of available dry matter which is burnt, and EF is a pollutant specific emissions factor (kg per kg dry matter burnt). Area burnt was taken from FAO (2023) (table 10), default values of Mb and Cf were taken from IPCC (2019), while emission factors were taken from Andreae and Merlet (2001).

FAO (2023) data on area burnt is not provided at the provincial scale, therefore provincial level data on the area of forest lost due to forest fires (ha) from Tyukavina *et al* (2022) was used to disaggregate the national forest area burnt as estimated in FAO (2023). The area burnt in each province, as a fraction of total burnt area, was calculated from Tyukavina *et al* (2022). These fractions were then multiplied by the total forest area burnt in FAO (2023), to give the area of forest burnt in each province. Tyukavina *et al* (2022) does not account for low understorey fires. Therefore, the area burnt of grassland, savanna, and shrubland was estimated at the provincial level using the fraction of farms which clear land through burning as calculated from the Lao Census of Agriculture (Lao Statistics Bureau 2021a). The agricultural census provides the number of farms clearing new area, the percentage of farms clearing using slash and burn, and the total number of farms in each province. This was used to calculate the number of farms clearing land using slash and burn in each province as a fraction of all farms practicing slash and burn to clear land. The fraction of the national total number of farms burning located in each province was multiplied by the total area burnt of shrubland, grassland, and savanna (FAO 2023) to give the provincial area burnt of each vegetation type. The provincial fraction of vegetation burning taking place in each province is shown in tables S2 and S3.

2.2.2.4. Waste

Solid waste

Solid waste is still commonly burnt in Lao PDR. Solid waste generation and collection is typically higher in urban areas so emissions from open burning of solid waste were quantified for urban and rural populations

Table 11. Waste generation rates and percentage of self-disposed waste applied.

	Waste generation rate (kg/person/year)	Waste self-disposed (%)
Urban	288	40
Rural	113	75
Vientiane Capital	—	54

Waste generation rates adopted for Vientiane Capital were the same for other provinces, i.e., 288 kg/person/year for urban population and 113 for the rural population.

Table 12. Sanitary systems by household type at the national level (percentage of households).

Sanitation system	Urban	Rural with road	Rural without road
Septic Tank	20	14	9
Latrine	75	53	36
Other	5	33	55

separately. Emissions were calculated by multiplying the total mass of municipal solid waste burned by subsector- and pollutant-specific emission factors (US Environmental Protection Agency 1995, Akagi *et al* 2011, Yokelson *et al* 2011, Woodall *et al* 2012). The amount of waste that is burnt was estimated using equation (7):

$$WB_g = WG_g \ * \ Pop_g \ * \ F_g \ * \ FB \tag{7}$$

Where *WB* is the waste burnt for each geographic region (*g*, urban, rural, provincial, national), *WG* is the waste generation rate (kg/person/year), *Pop* is the population (number of urban and rural people at provincial and national scale), *F* is the fraction of waste that is not collected (urban and rural), and *FB* is the fraction of uncollected waste that is burnt (assumed to be the same for urban and rural areas and across provinces).

Urban and rural waste generation rates were taken from MONRE (2020). Due to the lack of provincial level data, urban and rural waste generation rates were assumed to be the same for each province (table 11). Though the fraction of population in each province that live in urban and rural areas varied based on population data from Lao Statistics Bureau (2015). Population data was sourced from LAOSIS (2022).

The fraction of waste that is self-disposed (rather than being collected or recycled) was taken from MONRE (2021). Waste flow diagrams are provided for Vientiane capital and for 4 district and 2 rural areas across 4 provinces. For Vientiane capital, the waste flow was not disaggregated between urban and rural areas and so the same fraction of self-disposed waste was applied to both urban and rural populations in the province. Due to the lack of data for other provinces, the percentage of self-disposed waste for urban populations was calculated as the average across the 5 districts for which there is waste flow data. Similarly, the percentage for rural populations was calculated by averaging the collection rate reported for 2 rural areas in Xiengkhouang province (table 11). It was assumed that 60% of this self-disposed waste is burnt following IPCC (2006). This default fraction was applied to urban and rural areas and was assumed to be the same for all provinces.

Waste burnt was then multiplied by pollutant specific emission factors sourced primarily from Akagi *et al* (2011), but also Woodall *et al* (2012), Yokelson *et al* 2011), and the US Environmental Protection Agency (1995). While MONRE (2021) provides data on waste collection rates in 5 provinces, there is no data available on the solid waste management systems adopted across Lao PDR. Consequently, emissions from collected waste or landfills were not included.

Liquid waste

The 2015 Population and Housing Census provides information on the different types of sanitary systems in Lao PDR (table 12, Lao Statistics Bureau 2015). CH_4 emissions generated from domestic wastewater were quantified using equation (8).

$$E_{t,g} = Pop_g \ * \ BOD \ * \ F_{t,g} \ * \ MPC \ * \ MCF_t \tag{8}$$

Where *E* is the CH_4 emissions for each treatment type (*t*) in each geographic region (*g*) (urban, rural, national and provincial), pop is the population BOD is the Biochemical Oxygen Demand in liquid waste, *F* is the fraction of liquid waste in each treatment type, *MPC* is the CH_4 producing capacity and *MCF* is the CH_4 conversion factor for each treatment type.

Census data on sanitary services in urban and rural households was used to estimate the fractions of liquid waste in each treatment type for each province (Lao Statistics Bureau 2015). It was estimated that 22% of flush/pour toilets go to a septic tank with the remainder going to pit latrines (Baetings and O'Leary 2010). Population was taken from LAOSIS (2022) while IPCC (2006) default values were used for *BOD, MPC and MCF*. CH_4 emissions from each treatment type were then summed to provide total emissions from liquid waste treatment.

3. Results

3.1. National emissions

In 2019, national total emissions of air pollutants were 125 thousand tonnes of $PM_{2.5}$, 83 thousand tonnes of NO_x, 9.7 thousand tonnes of BC, 219 thousand tonnes NMVOCs, and 99 thousand tonnes of NH_3 (table 13). The largest source of particulate air pollution ($PM_{2.5}$, PM_{10}, BC, and OC) emissions nationally was vegetation burning, specifically forest fires (figure 1). Forest fires account for 69% of $PM_{2.5}$ emissions, with residential cooking as the second largest source contributing 8% (See figure S1b for sector contributions if vegetation fires are excluded). Electricity generation is the largest source of NO_x contributing 38%, followed by forest fires at 20%. Forest fires are also the primary source of NMVOCs, however charcoal production, transport and residential sectors also make up significant portion of the emissions (~20% each). Livestock is responsible for the largest share of NH_3, accounting for 82%. Due to the emission reduction technology built into the Hongsa power plant, SO_2 emissions are driven by industrial energy consumption (figure S1).

Between 2013 and 2019, total air pollutant emissions in Lao PDR varied substantially (figure 1) due to variability in area of forest burnt each year. Emissions peaked in 2016 when almost 470 thousand hectares of forest area was burnt and were lowest in 2018 when 128 thousand hectares were burnt (table 10) (FAO 2023). Excluding vegetation fires, air pollutant emissions have increased substantially (figure 1). The largest increases were in emissions from the transport and IPPU sectors which increased on average 42% and 10% annually across all air pollutants. NO_x emissions doubled between 2014 and 2016, primarily driven by emissions from electricity generation due to the completion of the first and second units of the Hongsa coal power plant in Xayabury province in 2015, and the third unit in 2016 (Hongsa Power 2023).

There are commonalities in the sources of air pollutants and greenhouse gases. Electricity generation is the largest source of NO_x and CO_2 emissions, accounting for 60% of CO_2 emissions in 2019 (figure S1a). CO_2 emissions increased by almost 4-fold between 2014 and 2016 (figure 1), again due to the establishment of the Hongsa power plant. Transport is also a key source of NMVOCs and CO_2, while agriculture is a key source of NH_3, and CH_4. Manure management contributes to emissions of both NH_3, and CH_4, but with enteric fermentation as the primary source of CH_4. Therefore, taking action in these sectors to reduce air pollutants in Lao PDR could also reap benefits in terms of national climate commitments. Other sectors, however, could see trade-offs between air pollution and greenhouse gases. For example, reducing open burning of solid waste could reduce air pollutants, but may see an increase in CH_4 from landfill (not accounted for here), or increased used of LPG for cooking would increase direct fossil-CO_2 emissions in households.

3.2. Provincial emissions

The magnitude of air pollutant emissions varies substantially by province (table S4). Figure 2 illustrates the spatial variability in emissions of $PM_{2.5}$, NH_3 and NO_x across Lao PDR. These pollutants are used to demonstrate the 3 broad spatial trends present in the emission inventory. Figure 2(a) represents the common spatial distribution of $PM_{2.5}$, PM_{10}, CO, BC, and OC emissions. Emissions from forest fires dominate the emissions of these pollutants so the spatial trend is also shown when forest fires are excluded (figure 2(b)). In 2019, the largest area of forest burn was in Xaboury, followed by Sekong, accounting for 14 and 13% of forest area burnt that year. However, the spatial distribution of forest fires has varied annually and subsequently the spatial distribution of $PM_{2.5}$, PM_{10}, CO, BC, and OC emissions vary. Figure S2 shows the spatial distribution of $PM_{2.5}$ emissions between 2013 and 2019, and the same spatial trend is seen in PM_{10}, CO, BC, and OC (figure S3). On average, across 2013–2019, Houaphan, Champasak, and Sekong account for largest area of forest burnt per year (13%, 11%, and 11% respectively).

The spatial distribution of other sources vary according to population and economic activities. For example, residential emissions are high in populous rural provinces (figure 2(d)). Savannakhet is the most populous province (1.05 million people in 2019) with 77% of households in rural areas. As a result, emissions from residential cooking and agriculture are high due to the large proportion of households cooking with biomass, and the substantial land area used for crop and livestock production. In 2019, 1254 tonnes of $PM_{2.5}$ were emitted

Table 13. Total emissions from Lao PDR for all sectors, year 2019. Units: thousand tonnes. Rounded to 2 significant figures.

Source Sector		BC	CH_4	CO	CO_2	NH_3	NMVOCs	NO_x	OC	PM_{10}	$PM_{2.5}$	SO_2
1A1a	Public Electricity and Heat Production	0.0041	0.13	1.1	13000	0.0023	0.18	32	0.041	1	0.41	0.0000086
1A2	Manufacturing Industries and Construction	0.29	0.31	22	2200	0.0017	2.9	5.3	0.34	3	2.8	15
1A3b	Road transportation	0.48	0.86	180	3600	0.23	50	13	0.88	1.7	1.6	4.0
1A4a	Commercial/Institutional	0.57	4.4	8.3	7.6	0.00054	4.4	1.3	1.1	2.1	2	0.16
1A4b	Residential	1.4	8	150	0.0000042	1.4	40	3.5	4.3	12	10	0.00015
1A4c	Agriculture, Forestry and Fishing	0.00045	0.00011	0.0014	0.83	0.0000018	0.00056	0.01	0.00031	0.0011	0.0011	0.0051
1B1ci	Charcoal Production	0.25	18	130	0	0.49	43	0.24	1.7	3.4	3.4	0
2A & 2C1	IPPU	0.00064	0	0.0043	2800	0	0	0.0013	0.00016	1.3	0.73	0.0061
3A	Livestock	0	170	0	0	81	0	0	0	0	0	0
3C	Aggregate sources and non-CO2 emission sources on land[a]	6.4	120	1000	0	16	69	26	64	130	100	0.41
4A	Solid Waste Disposal on Land	0.26	1.5	15	0	0.45	9.1	2.0	2.1	4.8	3.9	0.2
4D	Liquid Waste	0	33	0	0	0	0	0	0	0	0	0
Total		9.7	330	1500	22,000	99	220	83	75	160	130	26

[a] Includes crop residue burning, vegetation forest, and rice cultivation.

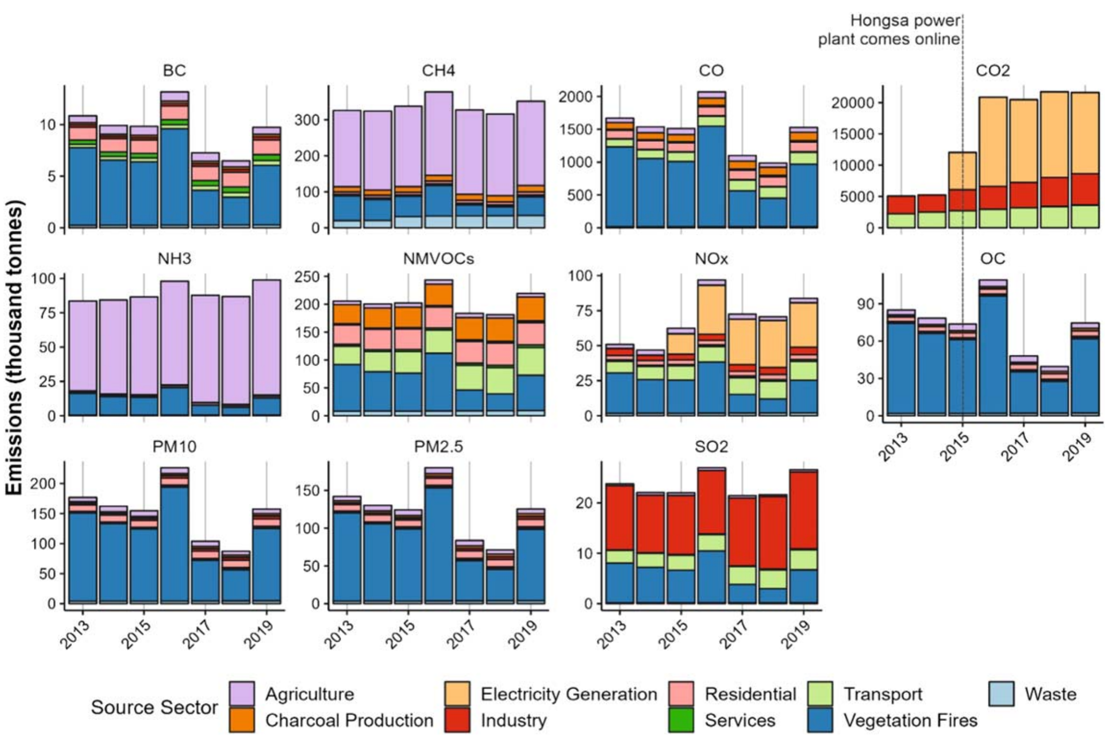

Figure 1. Total air pollutant and greenhouse gas emissions in Lao PDR for years 2013–2019. Colours denote the source sector of emissions. Agriculture includes emissions from crop burning, enteric fermentation, manure management, rice cultivation, and agricultural energy consumption. The waste sector includes emissions from solid and liquid waste. Industry includes industrial processing and product use and industrial energy consumption.

from residential cooking, and 52,889 tonnes of CH_4 from agriculture in Savannakhet. $PM_{2.5}$ emissions from Champasak exhibit a similar composition to Svannakhet with rural households making up 75% of households in the province. Luangprabang, Oudomxay, and Vientiane Province also contributed higher emissions from the residential sector due to the prevalence of wood fuel use; even in urban areas over 80% of households cook with wood in these provinces. Emissions from charcoal production is also high in rural provinces, with Savannakhet and Champasack accounted for highest emissions from this source. Crop burning is also a significant source of PM, OC, CO, and BC. In 2019, crop burning emissions were highest in Luangnamtha. This province contributed 12% of crop burning $PM_{2.5}$, despite only accounting for 4% of crop production. This is a consequence of a high crop burning ratio in the region (55% of farms burning residue). Champasak is the largest crop producer of crops accounting for 18% of production, but due to a relatively low burning ratio (13%), emissions are lower. Vientiane Capital also has high $PM_{2.5}$, PM_{10}, CO, BC, and CO emissions from biomass fuel consumption in industry.

For NH_3 and CH_4, there is also a concentration of emissions in 3 provinces: Savannakhet, Saravan and Champasak (figure 2(c)). These emissions are driven by the agricultural sector (figure S2) with the 3 provinces combined accounting for around 40% of livestock and crop production. Manure management dominates the NH_3 emissions with crop residue burning and residential cooking also contributing.

Figure 2(d) shows the common spatial distribution of NO_x, and CO_2 emissions. These pollutants are concentrated in Xayaboury with the largest source being electricity generation. The second highest emitter is Vientiane Capital where emissions are primarily from road transport. Emissions of SO_2 follow a similar trend, but are highest in Vientiane Capital (table S4) with industrial energy consumption as the primary source. Due to the lack of available data on the geographic spread of industry, industrial energy consumption was disaggregated based on provincial GDP, which is highest in Vientiane Capital and explains the concentration of SO_2 emissions here. Emissions from road transport are also concentrated in Vientiane Capital, accounting for 50% of road transport emissions. NO_x emissions in 2019 were double that of other provinces (excluding Xayaboury) with transport contributing 95% of these emissions. This results from the high number of vehicles in the capital (43% of total vehicles in the country). NMVOCs are also high in Vientiane Capital (table S4) due to high vehicle numbers, but also in rural provinces such as Savannakhet due to charcoal production and crop residue burning.

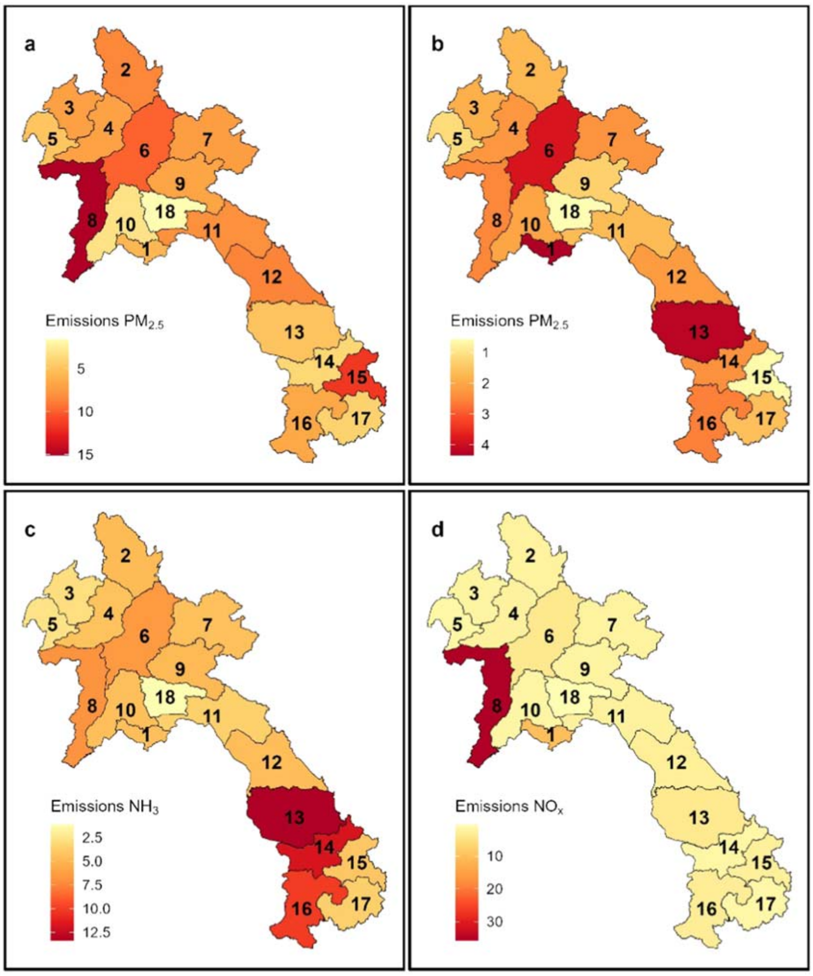

Figure 2. Air pollutant emissions across Lao PDR in 2019. Total emissions of three key pollutants are shown to illustrate the general trends: $PM_{2.5}$ including forest fires (a) and with emissions from forest fires excluded (b), NH_3 (c), and NO_x (d). Colour denotes the magnitude of emissions with red indicating higher, and yellow indicating lower emissions. Units: thousand metric tonnes. 1 = Vientiane Capital, 2 = Phongsaly, 3 = Luangnamtha, 4 = Oudomxay, 5 = Bokeo, 6 = Luangprabang 7 = Huaphanh, 8 = Xayaboury, 9 = Xiengkhuang, 10 = Vientiane Province, 11 = Borikhamxay, 12 = Khammoune, 13 = Savannakhet, 14 = Saravan, 15 = Sekong, 16 = Champasack, 17 = Attapeu, 18 = Xaysomboon.

4. Discussion

4.1. Relevance for air quality management in Lao PDR

This study provides the first national air pollutant emission inventory for Lao PDR, and all 18 provinces individually. The inventory highlights priority sectors for mitigating action including vegetation fires (particularly forest fires), residential cooking, agriculture, waste, transport, and electricity generation.

The need for a national inventory in Lao PDR has been highlighted in numerous national strategies including the National Pollution Control Strategy and the NSEDP (MONRE 2017, Ministry of Planning and Investment 2021), while elsewhere in Southeast Asia, emission inventories have been used as a starting point to identify possible mitigation measures and evaluate how effective they could be in improving air quality (Sokharavuth *et al* 2023). The emission inventory presented here provides a starting point for a mitigation assessment which could quantify the potential emission reductions under different mitigation scenarios. Lao PDR has existing actions which could be a starting point for evaluation, for example, the measures outlined in Lao PDR's most recent NDC could be evaluated in terms of their ability to reduce air pollutants so that the opportunity of climate and air pollution co-benefits can be identified (Vandyck *et al* 2018). For example, the introduction of energy efficient cookstoves included in the NDC will also help to reduce residential air pollutant emissions.

This emission inventory identifies forest fires as the largest source of $PM_{2.5}$ and other toxic air pollutants in Lao PDR. Mitigating forest fires should therefore be a priority for air quality management. Actions to mitigate forest fires include, for examples, improved forest and agricultural management, establishing effective monitoring systems, implementing clear legislation and strengthening capacity and stakeholder coordination

(World Bank 2020). Improved forest management can include practices such as fuel load management and fire breaks (Cui *et al* 2019, World Bank 2020), while managing fires in Lao PDR also concerns crop residue burning and shifting agriculture. It has long been recognised in Lao PDR that shifting agriculture cannot be irradicated without provision of alternative livelihoods for rural communities (Ministry of Agriculture and Forestry 2005) and the National REDD+ (Reducing Emissions from Deforestation and forest Degradation) identifies stabilising uncontrolled shifting cultivation and the control of forest fires as a priority (Lao PDR 2021b). The programme includes ambitions to enhance implementation of existing policies to control shifting cultivation, promote and develop local livelihoods, improve near real-time monitoring systems of cultivation and raising awareness on the impacts of slash and burn agriculture, and forest fire prevention. It also highlights the inclusion of local communities and the need to develop alternative forms of income in rural areas. There are agricultural systems which have shown to be effective alternatives to shifting agriculture, such as alley-cropping (Hands 2021) but this kind of research is scarce in Lao PDR. Forest fire management is also a key component of The Association of Southeast Asian Nations (ASEAN) Transboundary Haze Agreement (ASEAN Secretariat 2021) and is therefore a regional priority.

At present, forest monitoring system capacity is limited in Lao PDR. The National Forest Monitoring system provides data on forest area change but does not currently include any data on forest fires (Ministry of Agriculture and Forestry 2023). Reporting of forest fires could be integrated into the National Forest Monitoring System as a way to more effectively use resources. Traditional and local knowledge should also be integrated into fire management and community-based fire management could be implemented, whereby communities are actively engaged in fire management (FAO 2011). However, such approaches need to be motivated by the communities themselves and require institutional support (London 2001, FAO 2011). Effective management requires investment in both the prevention and suppression of fires and such actions need to be supported by clear institutional coordination whereby tasks and responsibilities in fire management are clearly defined (World Bank 2020).

Mitigating forest fires will not only substantially improve air quality in Lao PDR but will also contribute to national commitments on climate change. Forest fires have been identified as a major source of greenhouse gases in Lao PDR with Agriculture, Forestry, and Other Land Uses accounting for almost 80% of national total greenhouse gas emissions (MONRE 2020). Consequently, in the 2020 NDC, Lao PDR included an unconditional measure to reduce forest degradation and a conditional mitigation target to increase forest cover to 70% of national land area by 2030 (Lao PDR 2021a). The REDD+ Strategy highlights key challenges to achieving this ambition and includes factors such as the lack of strict monitoring and management systems and limited resources coupled with rising land values which make it difficult for the government and stakeholders to resolve and prevent unplanned land conversion (Lao PDR 2021b). This emission inventory helps to emphasise the importance of forest fire mitigation and the results can be used to raise awareness of the issue and emphasise that there are multiple benefits to improved forest management.

The emission inventory also highlights the residential sector as a key source of particulate air pollution. The primary interventions to mitigate emissions from the residential sector are the introduction of more efficient cookstoves and cleaner fuels. Improved cookstoves have shown to reduce fuel consumption by 40% in Lao PDR (Hill *et al* 2015) and the introduction on 50,000 energy efficient cookstoves was incorporated into the 2021 NDC as an unconditional mitigation target. Not only could this reduce emissions from cooking, but it could also diminish demand for charcoal and the emissions associated with the production process. Reducing reliance on fuelwood could help contribute to national commitments on forest preservation. Cleaner cooking alternatives have been advocated in Lao PDR and the promotion and market deployment of cleaner cook stoves was incorporated in the 2011–2025 Renewable Energy Development Strategy (Ministry of Energy and Mines 2011). However, given the lack of national gas reserves or oil refineries, LPG must be imported, rendering it unaffordable for many households. Biogas may therefore provide a more suitable alternative in Lao PDR, as advocated elsewhere in the region (Cambodia Ministry of Environment 2021). Hill *et al* (2015) also found a disadoption of improved technologies and highlight the necessity for servicing and repair facilities. There are numerous health issues associated with exposure to household air pollution due to cooking with traditional biomass fuels with the health burden often felt more strongly by women and infants. Household air pollution was the number one risk factor for premature mortality in Lao PDR in 2019 and consequently, reducing the number of households cooking with traditional biomass stoves will have multiple benefits for reducing both ambient and household air pollution (Sánchez-Triana 2021, State of Global Air 2022).

Agricultural mitigation options relate to restricting crop burning, reducing enteric fermentation and improving manure management. Crop burning could be mitigated through encouraging the alternate uses of residue and through an increased awareness of the associated health risks. Livestock emissions can be alleviated through increased productivity of animals, and through improved feed composition which is lower in nitrogen. The Green Growth Strategy (Government of Lao PDR (2018) outlines raising efficiency and reusing wastes as priorities in the development of the agricultural sector. While the Agriculture Development Strategy to 2025 and

Vision to 2030 (Ministry of Agriculture and Forestry 2015) includes the establishment of farmer groups and cooperatives. These networks could be used to share best practices on livestock management to reduce emissions.

Increasing electricity production capacity has been a key driver of socio-economic development in Lao PDR over the last decade but has also contributed to increasing air pollutant emissions where the capacity has been increased through thermal (coal) power generation. Currently, Lao PDR exports a large proportion (68% in 2015) of its generated electricity to neighbouring countries such as Thailand and Cambodia (Ministry of Energy and Mines 2018). As economic growth continues, requirements for electricity will also increase, with electricity generation targeted to increase by an average 15.8% per year to 2025 (Ministry of Planning and Investment 2021). To meet this demand, there are plans to increase the capacity of renewable sources including the construction of 26 hydropower dams (Ministry of Planning and Investment 2021), and 6 new thermal power plants up to 2030 with some already under construction, accompanied by mining concessions (Ministry of Energy and Mines *et al* 2020, Power Technology 2023). Emissions from domestic use of electricity can be mitigated through increasing the energy efficiency of appliances, which can be realised through the implementation of energy performance standards, or the introduction of more energy efficient electrical motors and boilers. Technologies, such as the Flue Gas Desulfurization incorporated in the Hongsa power plant can help to minimise some air pollutant emissions from thermal electricity generation.

This emission inventory also highlights the need for province specific plans to effectively reduce emissions. For example, in Vientiane Capital industry and solid waste burning are the largest sources of $PM_{2.5}$ after forest fires emissions. Emissions from road transport are also concentrated in Vientiane Capital. However, in provinces such as Savannakhet, with high concentrations of rural households, residential cooking is the largest source of $PM_{2.5}$ after vegetation fires. Crop residue burning is also a significant source of $PM_{2.5}$ in agricultural regions. Increased understanding of provincial variability enables decision makers to develop targeted informed policies. For example, action to mitigate emissions from road transport should be focused in Vientiane Capital, whereas improved agricultural practices should be promoted in Savannakhet, Saravan and Champasak, with a particular focus on restricting crop burning in Oudoxmay.

This inventory also highlights the opportunity for integrated air pollution and climate change strategies. When vegetation fires are excluded, all air pollutants and greenhouse gases in Lao PDR were estimated to increase over the historical period (2013–2019) considered in this analysis, with total $PM_{2.5}$ emissions increasing from 25 to 31 thousand tonnes and total CO_2 emissions increasing from 5 to 22 million tonnes over this period. Both greenhouse gases and air pollutants share common sources, including energy production (electricity and charcoal), agriculture, and transport (figure S1). Through the development of an integrated approach, mitigating action can simultaneously benefit air quality and climate, whilst contributing to national climate change commitments.

This emission inventory could be used to conduct a health impact assessment, as well as quantifying other secondary benefits, to clearly demonstrate the effects of air pollution and provide an economic case for mitigating pollutants. For example, the World Bank estimated that ambient and household air pollution combined were responsible for approximately 7000 deaths in Lao PDR in 2017, equating to a financial cost equivalent to almost 10% of national GDP (Sánchez-Triana 2021). Evaluating multiple impacts of emission reductions, including impacts to human health, the economy, and to crop yields, can help to identify the options that would reap the greatest benefits and therefore be more persuasive to decision makers and the wider public. However, conducting health impact assessments also requires external emissions to be accounted for.

The emission inventory presented here can be updated over time, and therefore used as a monitoring tool in Lao PDR. The inventory was developed using national reports and statistics which are freely available and regularly updated, making it possible to easily maintain the tool in the future. As policies and plans to reduce air pollution are implemented, emission inventories can be updated to reflect these advancements and quantify the benefits which have been achieved.

Emission inventories are not the only tool needed for air quality management. For example, this emission inventory does not account for the transboundary impacts of air pollution, where pollution emitted in Lao PDR may impact neighbouring countries, and vice versa. Furthermore, atmospheric modelling is required to translate air pollutant emissions into pollutant concentrations. Pollutant concentrations can then be used in exposure and health impact assessments to understand the levels of pollution which people are exposed to, and the impacts this has on their health. Effective air quality management requires the use of emission inventories and monitoring networks in combination. This study shows that emissions from residential cooking make a substantial contribution to air pollutant emissions in Lao PDR. This suggests that the indoor air quality of households cooking with solid biomass is substantially affected (Malley *et al* 2020). For other households, without large indoor emission sources, the infiltration of outdoor air pollution indoors will determine indoor air quality. The deployment of a monitoring network to understand air pollutant concentrations in different microenvironments (e.g. households, places of work, transport, outdoors etc.) could allow for a better understanding of how the emissions accounted for in this inventory impact population exposure to air pollution in Lao PDR (Malley *et al* 2020, O'Dell *et al* 2023).

4.2. Comparison to previous studies

Previous studies quantifying air pollutant emissions for Lao PDR mainly come from international global emission inventory databases. For example, the Emissions Database for Global Atmospheric Research (EDGAR) directly quantifies total air pollutant and greenhouse gas emissions in Lao PDR based on international data sources (European Commission Joint Research Centre and Netherlands Environmental Assessment Agency 2022). Greenhouse gas emissions were compared with national inventories in Lao PDR's Biennial Update Report (BUR) submitted to the UNFCCC (MONRE 2020).

The results presented in this emission inventory broadly show good agreement with EDGAR (table S5) and the BUR (table S6). However, there are some discrepancies. For example, the SO_2 emissions from energy industries in EDGAR (81 thousand tonnes) are substantially higher than estimated here ($<$0.001 thousand tonnes). This suggests EDGAR does not account for the Flue Gas Desrulfurization technology installed in the Hongsa power plant. Previous studies have also identified discrepancies between global EDGAR emissions and local emissions, including inconsistencies in power plant accounting within global datasets (Ahn *et al* 2023). Though it should be noted that the effectiveness of this technology at Hongsa has been questioned (ICEM 2022). Estimates of other air pollutants from energy industries also vary, with EDGAR estimates exceeding those in this study (e.g., 15 thousand tonnes versus 0.43 thousand tonnes of $PM_{2.5}$). As there is currently only one power plant in Lao PDR, it suggests that EDGAR assume a higher volume of coal consumption, however fuel consumption data used in this study were taken directly from the national Ministry of Energy and Mines. In the transport sector, there is only a 10% difference in CO_2 emissions estimated in this study and in EDGAR, however, emissions of air pollutants, e.g. SO_2 and CO vary by 2 or 3 orders of magnitude. This suggests that different assumptions were made regarding the fuel quality and emissions controls present in Lao PDR. Furthermore, national data shows total vehicle numbers to have increased by 46% between 2013 and 2018. However, transport emission in EDGAR only show an 8% increase in NO_x and a decrease in NMVOCs over the same time period, suggesting that it may not account for the rapidly increasing vehicle fleet in Lao PDR.

EDGAR estimates $PM_{2.5}$ emissions from biomass burning to be 25 thousand tonnes, compared to 46 thousand tonnes in this study. This variation is likely to be associated with uncertainties in forest area burnt. This study used data from FAO (2023) which is estimated using the National Aeronautics and Space Administration (NASA) Moderate Resolution Imaging Spectroradiometer (MODIS) data on burnt area. The MODIS data provides 500 m grids containing per-pixel burned area, this is then combined with the MODIS Land Cover product to determine types of vegetation (FAO 2023). EDGAR also uses MODIS data but a different landcover product was used (Crippa *et al* 2023). EDGAR emissions from biomass burning remain relatively constant over time (ranging from 24–29 thousand tonnes over 2013–2018), suggesting it does not account for the annual variation in vegetation fires. Other methods to estimate area burnt include using fire count data (ICEM 2022) and mapping land use change (Tyukavina *et al* 2022). Forest area loss to fires in Tyukavina *et al* (2022) is lower than that estimated by FAO (2023). They estimate only 480 ha of forest loss due to fire across Lao PDR in 2019, compared to 294 thousand ha in FAO (2023). Tyukavina *et al* (2022) use 30-meter resolution global forest loss maps generated from Landstat. To determine forest loss due to fire, forest loss maps are combined with change detection metrics which include spectral reflectance and topography metrics. Increasing national monitoring and management of forest fires would help to improve emission estimates from this source.

CH_4 emissions from rice cultivation were 127 thousand tonnes in EDGAR, and only 60 thousand tonnes in this study. The data sources adopted by EDGAR were different from those used here. EDGAR uses data from the International Rice Research Institute to determine irrigation systems (Janssens-Maenhout *et al* 2019) whereas here, nationally reported data from LAOSIS (2022) was used. Furthermore, EDGAR adopts emission factors from the GAINS database as opposed to those provided in the IPCC guidelines (Janssens-Maenhout *et al* 2019). Finally, the estimates of CH_4 from rice in this study are more comparable with that reported in the BUR (55 thousand tonnes in the BUR, 68 thousand tonnes in this study in 2014).

In the waste sector, EDGAR emissions are lower than that estimated in this study (0.86 versus 3.8 thousand tonnes). This is likely a product of uncertainties in the amount of waste burnt. EDGAR uses waste generation and burning rates from the IPCC guidelines (Crippa *et al* 2023), but there are various estimates of waste generation, collection, and burning rates. Estimates of the percentage of waste collected generally range between 30%–50%, however this is typically for Vientiane capital with limited information on other provinces and rural waste collection. The collection rate applied in this study for rural areas was an average of two rural sites both located in the same province (Xiengkhuang) and this may not accurately reflect waste collection in other rural provinces. Variability in the rate of waste which is burnt also introduces uncertainty in the analysis. This study adopted an average collection rate of 39% meaning it provides a central estimate of waste emissions.

Greenhouse gas emissions reported in the most recent BUR show good agreement with this study for some sectors, e.g. transport, IPPU, and livestock (Table S6) (MONRE 2020). The BUR reports on emissions from 2014, prior to the completion of the Hongsa power plant meaning there are no CO_2 emissions from this source. The CH_4 emissions from energy industries reported in the BUR are generated from the use of biomass in electricity generation, which was not accounted for in this study. The emissions reported in the BUR for energy use in manufacturing and industry are 27 thousand tonnes of CO_2. This is unexpectedly low, given that the emissions of CO_2 in the sector were reported to be 446 thousand tonnes in 2000 in the previous National Communication (Lao PDR 2013) and the sector has expanded over the last decade.

ICEM (2022) also estimate air pollutant emissions from crop residue and vegetation burning in Lao PDR. They estimate higher emissions from crop burning (~14,000 tonnes of $PM_{2.5}$ compared to 6,300 in 2019) but this is due to the higher crop burning ratios adopted and lower volume of biomass burnt assumed. ICEM (2022) take the crop burning ratios from academic literature, which is not specific to Lao PDR, whereas in this study, data from the Lao PDR agricultural census was used. Trends in emissions follow the same pattern due to the FAO data on crop production showing the same trends as the Lao statistics. Conversely, ICEM (2022) estimate lower emissions from vegetation burning. They highlight the difficulties in estimating the area burnt and so assume fire-counts are proportional to area burnt and count fire pixels in satellite data to estimate area burnt. The area burnt is not reported, but their dry matter density factors are lower than the values from IPCC used here. The resulting assumed quantity of forest biomass burnt is substantially lower than that assumed here (in 2019 approximately 200 thousand versus over 15 million tonnes). However, they note that this method should only be used as an approximation. ICEM (2022) use fire counts to identify the northern provinces, for example Luangprabang, Xayaboury, Huaphanh, Oudomxay, Phongsaly, and Xiengkhuang as the where the land clearing emissions are highest. Their results corresponds with results of this study for 2019, but figure 2 shows some southern provinces also have high emissions (e.g Sekong) and this trend varies over time (figure S2).

4.3. Uncertainties and limitation

One limitation of this study was the scope of sources and subsectors that could not be included in the emission inventory. For example, this study does not include fertiliser application on crops which is a key source of NH_3 and NO_x globally, or other sources of NMVOCs such as other consumer products, architectural coatings, or biogenic sources. Improving the official production statistics in Lao PDR would allow for the future inclusion of additional industrial emission sources. Incorporating these emissions would also have implications for the relative contributions of sources. The emission inventory could also be further developed through a higher level of disaggregation in key sectors. For example, due to lack of available data, this study assumed that all vehicles did not have any emission controls which are important for transport policies, while improved data on waste generation and collection could increase the accuracy of the provincial analysis. Furthermore, recent research in Lao PDR also showed that though some sectors may contribute a small amount to national emissions, they are responsible for extremely high levels of exposure. Grilled street food vendors are responsible for a very small contribution of national emissions, but render workers exposed to $PM_{2.5}$ concentrations ranging from 22–225 $\mu g/m^3$, significantly exceeding WHO and national guidelines on air pollution (Sychareun *et al* 2023). The emission inventory presented here could therefore be most effective in air pollution management if it is paired with on the ground monitoring programs.

Due to the lack of, or variability in national data, there are some uncertainties in the emissions calculated. Where possible data directly from the Lao Statistical Website (LAOSIS) was used, however for some source sectors, key activity data either wasn't available or was highly variable. The data used to determine household fuel use is from 2015 as this was the most recent census for which results were available. Programs to increase the adoption of cleaner fuels may have caused a decline in the use of wood and charcoal for cooking. However, in a more recent social indicator survey (UNICEF 2020), 43% of urban and 77% of rural household members primarily used wood for cooking. This corroborates with the 2015 census (43% of urban and 78% of rural households) and suggests the proportion of households using wood fuel has remained consistent over the study period.

There are also uncertainties surrounding the spatial allocation of emissions at the provincial scale. There was a lack of spatial data regarding the industrial and the IPPU sectors. Consequently, the data used to allocate these emissions is for years 2006–2010 and may therefore not reflect more recent developments in this sector. The production of charcoal in Lao PDR is largely informal (Barney *et al* 2015) and as a result there is limited data on the location of production. Given that the process relies on the availability of fuel wood and is more commonly used by rural households, the spread of rural people was used as proxy data. Due to the informality of charcoal production, the sector may also be underestimated. Furthermore, even data reported at the provincial level may not directly relate to where emissions are produced. For example, the number of vehicles in each province likely represents where a vehicle is registered but not necessarily where it is driven.

5. Conclusions

The air pollution and greenhouse gas emission inventory presented here provides, for the first time, evidence on the magnitude of emissions and key source sectors in Lao PDR at the national and subnational scale. This inventory is an important first step in enhancing understanding and the evidence base of air pollution in Lao PDR. It can be used as a key tool in future air quality management to inform future policy development and an integrated air pollution and climate change planning process in Lao PDR, with benefits for both human health and the environment. Given the economic trajectory of Lao PDR, a key next step in the process would be to build on this initial emissions inventory and to project emissions into the future for a baseline or business as usual scenario. The most recent NSEDP targets an annual economic growth rate of 5% to 2025 and therefore, without policy intervention, we can expect that emissions will increase in conjunction. Understanding how emissions are projected to increase into the future, and what the key contributing sectors will be, enables the mitigation potential of various policies and measures to be quantified. Future work should seek to estimate the response in emissions under these socio-economic trends and evaluate the efficacy of potential new policies and interventions. Mitigating options should be analysed in terms of their emission reduction potential, but also how they can contribute to the socio-economic development ambitions of Lao PDR.

A mitigation assessment could then form the basis of a national clean air action plan for Lao PDR, similar to that which has been developed elsewhere within the region e.g., in Cambodia (Cambodia Ministry of Environment 2021). Through an awareness of key sources sectors and the means to mitigate these, Lao PDR would be better equipped to achieve its green growth strategy without hampering the progress of national development plans. In conclusion, as socio-economic development prevails, air pollution in Lao PDR poses an increasing risk to human health, climate, and sustainable development. This national emission inventory provides an evidence base for the development of informed policies on air pollution and climate change and can be used as a baseline from which to measure the success of emission reduction action.

Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

Disclosure statement

The authors report there are no competing interests to declare.

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