Food and Agriculture Organization of the United Nations

# Spatio-temporal dynamics of air pollution and the delineation of hotspots in the Lao People's Democratic Republic

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# Contents

# Figures

## Tables

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# Abbreviations and acronyms

| | |
|---|---|
| ABC | Atmospheric Brown Cloud |
| AERONET | AErosol RObotic NETwork |
| AFOLU | Agricultural, forestry and other land use |
| AGL | above ground level |
| AHI | Advanced Himawari Imager |
| AOD | Aerosol optical depth |
| AOI | Area of interest |
| ARL | Air Resources Laboratory |
| ASEAN | Association of Southeast Asian Nations |
| BB | Biomass burning |
| BC | Black carbon |
| CALIOP | Cloud – Aerosol Lidar with Orthogonal Polarization |
| $CH_4$ | Methane |
| CI | Confidence interval |
| CO | Carbon monoxide |
| $CO_2$ | Carbon dioxide |
| COPD | Chronic obstructive pulmonary disease |
| DAFO | District Agriculture and Forest Office |
| DALAM | Department of Agriculture Land and Management |
| DMH | Department of Meteorology and Hydrology |
| DoF | Department of Forestry |
| EDGAR | Emissions Database for Global Atmospheric Research |
| EF | Emission factor |
| ENSO | El Nino˜–Southern Oscillation |
| EO | Earth observation |
| EPA | Environmental Protection Agency |
| FAO | Food and Agriculture Organization of the United Nations |
| FEER | Fire Energetics and Emissions Research |
| FIRMS | Fire Information for Resource Management System |
| FRP | Fire radiative power |
| FTIR | Fourier-transform infrared spectroscopy |
| GDAS | Global Data Assimilation System |
| GEMS | Geostationary Environment Monitoring Spectrometer |
| GEMS | Geostationary Environment Monitoring Spectrometer |
| GFED | Global Fire Emissions Database |
| GFWED | Global Fire WEather Database |
| GHGs | Greenhouse gases |
| GIS | Geographic information system |
| GOCI | Geostationary Ocean Color Imager |
| GOME-2 | Global Ozone Monitoring Experiment-2 |
| GOSAT | Greenhouse gases Observing SATellite |
| GWIS | Global Wildfire Information System |
| HTAP | Hemispheric Transport of Air Pollution |

| | |
|---|---|
| HYSPLIT | Hybrid Single-Particle Lagrangian Integrated Trajectory |
| IASI | Infrared Atmospheric Sounding Interferometer |
| IPCC | Intergovernmental Panel on Climate Change |
| IPPU | Industrial processes and product use |
| MAF | Ministry of Agriculture and Forestry |
| MAIAC | Multi-Angle Implementation Atmospheric Correction |
| MISR | Multi-Angle Imaging SpectroRadiometer |
| MODIS | Moderate-Resolution Imaging Spectroradiometer |
| MONRE | Ministry of Natural Resources and Environment |
| MRV | Measurement, reporting and verification |
| $N_2O$ | Nitrous oxide |
| NASA | National Aeronautics and Space Administration |
| NCEP | National Centre for Environmental Protection |
| NDC | Nationally Determined Contributions |
| NGD | National Geographic Department |
| $NH_3$ | Ammonia |
| NIER | National Institute of Environmental Research |
| NMVOCs | Non-methane volatile organic compounds |
| $NO_2$ | Nitrogen dioxide |
| NOAA | National Oceanic and Atmospheric Administration |
| $NO_X$ | Nitrogen oxides |
| NRESRI | Environmental Statistics and Research Institute |
| NSL | Land and Water Division |
| $O_3$ | Ozone |
| OC | Organic carbon |
| OCO-2 | Orbiting Carbon Observatory-2 |
| OMI | Ocean Monitoring Instrument |
| OMPS-Nadir | Ozone Mapping Profiler Suite-Nadir |
| PM | Particulate matter |
| PSC | Pioneering shifting cultivation |
| REDD+ | Reducing Emissions from Deforestation and Forest Degradation |
| RSC | Rotational shifting cultivation |
| SCIAMACHY | Scanning Imaging Absorption Spectrometer for Atmospheric Chartography |
| $SO_2$ | Sulphur dioxide |
| TCP | Technical corporation project |
| TEMPO | Tropospheric Emissions: Monitoring of Pollution |
| TEOM | Tapered element oscillating microbalance |
| TROPOMI | TROPOspheric Monitoring Instrument |
| TSP | Total suspended particles |
| UNEP | United Nations Environment Programme |
| UNFCCC | United Nations Framework Convention on Climate Change |
| UV | Ultraviolet |
| UVAI | Ultraviolet aerosol index |
| VIIRS | Visible/Infrared Imager Radiometer Suite |
| VOCs | Volatile organic carbons |
| WHO | World Health Organization |

# Summary

In this report, the air pollution dynamics of the Lao People's Democratic Republic are investigated given its increasing industrial and economic development, and the employment of frequent biomass burning as an agricultural practice. The Lao People's Democratic Republic is also surrounded by countries that undergo recurrent agricultural burning, with strong winds at certain times in the year potentially resulting in transboundary pollution. The national information systems could better support actions that encourage the reduction of atmospheric pollution. The lack of an effective national system for air pollution monitoring magnifies the impacts of atmospheric pollution, particularly on health, climate, and agricultural inputs.

Thus, several atmospheric pollution indicators (nitrogen dioxide ($NO_2$), sulphur dioxide ($SO_2$), ozone ($O_3$), aerosol optical depth (AOD) and the ultraviolet aerosol index (UVAI)) are selected to analyse the spatio-temporal dynamics of atmospheric pollution in the Lao People's Democratic Republic for the period 2015–2021 and to determine the corresponding pollution hotspots. The sources of pollution are investigated based on potential drivers including climate variables, population, transport, industrial activity, biomass burning and agricultural production. Spatial and temporal trends are analysed at different spatial (national, zonal and provincial) and temporal (seasonal, monthly and yearly) scales. A satellite-derived active fire product is used to determine the fire dynamics and identify hotspots to help understand the pollution dynamics in the country and the contribution of biomass burning to local air quality. The relationship between pollution indicators and potential drivers is derived within the different spatial and temporal levels.

The majority of the pollution indicators peak during the dry (and burning) season and in the north and central zones of the country. Four provinces in the north, namely Bokeo, Phongsaly, Oudomxay, and Luangprabang; and Savannakhet in the south, were determined as pollution hotspots. Luangprabang, Savannakhet and Oudomxay were also determined as cropland fire hotspots, along with Xayabury and Vientiane. Climate, agricultural production and fire activity were observed to have the strongest impact on the pollution indicators compared to the other potential drivers. The modelling of back-trajectory air parcels implies the potential transport of air pollution from neighbouring countries to the Lao People's Democratic Republic. The main fire season occurs between February and May, with peaks in March–April. This coincides with the peaks of the air pollution indicators AOD, UVAI and $NO_2$. The observations from the fieldwork reveal that the country observes a huge number of forest fires, especially in the north, with forest fires ranked as making a "severe" contribution to air pollution, while agricultural fires and slash-and-burning are reported to make "medium" and "low" contributions, respectively.

It is important to provide evidence-based information in support of national action plans based on satellite observation products to monitor air pollution, improve the population's health and ensure sustainable development. However, this work highlights the potential to strengthen the national information systems to support actions for pollution reduction. Indeed, limited technical capacities (e.g. unavailable advanced atmospheric pollution monitoring and modelling), as well as the lack of integrated multi-sectoral and spatio-temporal datasets, for example no data on waste/household biomass burning, incomplete and outdated data on industry/mining activity etc, can be enhanced. In order to fully optimize the potential of satellite products for this application, they can be integrated with datasets collected on the ground, for example qualitative data from local communities and quantitative data from air quality monitoring stations. Furthermore, there is an absence of information and data sharing between sectors and governmental departments. Lastly, currently there are limited policies supported with evidence from geospatial data on pollution. This report demonstrates the use of geospatial techniques to aid the Government in monitoring air pollution. In particular, the results provide insight to the Government on pollution hotspots and potential sources, in particular in the agricultural sector, which can be accounted for in future policies.

Based on the limitations and research from this work, several recommendations were made. These include the improvement of technical capacities (training on Earth observation, Big Data, machine learning techniques etc.) and monitoring techniques on air pollution, as well as updated and spatially complete data/information on pollution, climate and national data (for locations across the entire country at a high temporal resolution). A national platform supported with cross-sectoral data sharing protocols (e.g. integration of national datasets, activity data, field data, etc.) is also suggested. Further recommendations include the implementation of national pro-poor policies (ensuring that the most vulnerable population are not negatively affected by emission reduction policies), the application of strategies to reduce the impacts of transboundary air pollution (e.g. air quality forecasts, the development of a comprehensive forest fire detection system, use of Earth observation data to monitor air pollution), and capacity development for local communities and national staff to raise the awareness of the impact of air pollution and open burning for local communities. Lastly, government subsidies would be helpful for farmers to adopt sustainable land management technologies and approaches, for example through equipment for low emission alternative approaches.

# 1. Introduction

The Lao People's Democratic Republic is a landlocked country in Southeast Asia surrounded by Cambodia, China, Myanmar, Thailand and Viet Nam. According to the Food and Agriculture Organization of the United Nations (FAO), agriculture in the Lao People's Democratic Republic is a major sector representing 16.1 percent of GDP in 2021 (along with forestry and fishing) (World Bank, 2022) and 10 percent of total land area (FAO, 2020a). Rice is the dominant annual crop (approx. 850 000 ha in 2018), followed by maize (150 000 ha in 2019) and cassava (100 000 ha in 2019), whereas coffee, rubber, and banana are the main perennial crops (FAO, 2020a).

The country has recently experienced a growing industrial sector, attributed to the development of the economy. However, production technologies have not advanced at the same rate, and are often out-dated, lack maintenance and may not consistently follow pollution guidelines (GMS Environment Operations Center, 2016). Furthermore, increases in the number of vehicles, as well as the heavy usage of charcoal and wood for household cooking, have raised concerns in terms of air pollution. There has also been a recent surge in investment (both domestic and foreign) in the mining, hydropower and agricultural industries (Ministry of Natural Resources and the Environment, 2017). Agricultural burning and slash-and-burn cultivation are also common across the country.

The Lao People's Democratic Republic is one of the most vulnerable countries to be potentially affected by climate change, with expected increases in extreme heat events and a rise in population exposed to flooding as example projections of climate change impacts. These impacts are expected to be enhanced by the poverty and malnourishment faced by communities across the country (World Bank Group and Asian Development Bank, 2021).

With a focus on the mitigation and adaptation to climate change, the Lao People's Democratic Republic has joined numerous conventions, policies and frameworks, including the United Nations Framework Convention on Climate Change (UNFCCC), the United Nations Sustainable Development Goals, the Paris Agreement, the National Green Growth Strategy, and the Reducing Emissions from Deforestation and Forest Degradation (REDD+) framework (Ministry of Natural Resources and the Environment, 2020).

However, the country lacks the financial support, technical capacity, and structure to effectively apply the required strategies. In particular, there is no comprehensive and routine monitoring of air pollution and its sources, and the implementation of pollution reduction policies based on geospatial technologies is lacking. Moreover, the required data availability and information sharing is relatively restricted. Based on this, in collaboration with the Natural Resources and Environment Statistic and Research Institute (NRESRI), part of the Ministry of Natural Resources and Environment (MONRE) of the Lao People's Democratic Republic, the principle objective of this technical cooperation programme (TCP) is to analyse the spatio-temporal dynamics of air pollution and the contribution of air pollution from the agricultural sector, and in particular biomass and crop residue burning, using geospatial technologies. This report provides technical support for policy implementations.

# 2. Overview of the global status of air pollution

## 2.1. Key pollutants

Air pollution is defined as "a phenomenon harmful to the ecological system and the normal conditions of human existence and development when some substances in the atmosphere exceed a certain concentration" (Bai *et al.*, 2018). Such substances include gaseous species (e.g. carbon monoxide (CO), nitrogen dioxide ($NO_2$), sulphur dioxide ($SO_2$) and particulate matter (PM)) in the atmosphere, both from natural and anthropogenic sources. Exposure to air pollution is detrimental to human health, placing great pressure on the global burden of disease over the past few decades (Cohen *et al.*, 2017) and is an environmental health risk (World Health Organization, 2016). Emissions from anthropogenic activities are considered to dominate those from natural sources, particularly with increasing global populations, industrialization and changing lifestyles (Amann *et al.*, 2020). The WHO (World Health Organization, 2018) attributed 7 000 000 deaths to the effects of household and ambient pollution in 2016, with 94 percent of these deaths from low- to middle-income countries. The associated diseases include lung cancer, lower respiratory diseases, chronic obstructive pulmonary diseases, and heart diseases.

Key atmospheric pollutants include $CO_2$, CO, $NO_2$, $N_2O$, $SO_2$, $O_3$, $CH_4$, $NH_3$, and aerosols. Many of which are greenhouse gases (GHGs). Among them, $CO_2$, which is mainly emitted from the burning of fossil fuels, is the principal contributor to radiative forcing (changing the atmospheric energy flux), followed by $CH_4$ and $N_2O$ (Bytnerowicz, Omasa and Paoletti, 2007). $NO_2$ and $SO_2$ can cause acid rain, haze, smog etc. and are typically released from biomass burning, vehicle exhaust, and fossil fuel combustion (Zheng *et al.*, 2018). Atmospheric $NH_3$ plays an important role in the formation of particulate matter and has been linked to the acidification of terrestrial ecosystems (Battye *et al.*, 2016; Van Damme *et al.*, 2015). Although CO is not a GHG, high concentrations of this gas can affect the chemical and physical properties of the atmosphere, for example its influence on the atmospheric oxidizing ability, which is linked to the 'self-cleaning' properties of the atmosphere (Edwards *et al.*, 2004). Aerosols are significant particles that have both warming and cooling effects on the climate by absorbing and scattering incoming solar energy, respectively (Wang *et al.*, 2021). Different studies have been performed to link the impact of aerosol emissions on human health. For example, Cohen *et al.* (2017) studied the exposure of $PM_{2.5}$ (aerosol particles with a diameter less than 2.5 $\mu$m), concluding that 4 200 000 deaths annually (2015, 7.6 percent of global total) are attributed to higher $PM_{2.5}$ concentrations.

Sources of atmospheric pollution can be grouped into natural and anthropogenic sources. Natural sources consist of volcanic activity, wildfires, animal digestion and dust storms, while anthropogenic sources include the burning of fossil fuels in factories, power plants, waste facilities, transport activity etc. In particular, the biomass burning is both a natural (wildfire) and anthropogenic (e.g. slash-and-burn fires) source, with corresponding emissions exerting a detrimental effect on the atmosphere. This is particularly true when transboundary haze is developed, considering that the long lifetime of some of the haze components (e.g. CO) can last approximately one month in tropical atmospheres (Mahmud, 2008).

**$O_3$ Emissions**

Lower tropospheric and surface ozone ($O_3$) is also important when studying air pollution dynamics. $O_3$ is generally produced via reactions between pollutants including CO, $CH_4$, $NO_X$ and non-methane volatile organic compounds (NMVOCs) (typically emitted from biomass burning) and has a direct impact on climate change. Ozone is a GHG and also has an impact on the lifetime of other GHGs such as $CH_4$ (Bytnerowicz, Omasa and Paoletti, 2007; Wang *et al.*, 2018b).

Air pollution emission sources at the national level are generally grouped into the following sectors based on the 2006 IPCC (Intergovernmental Panel on Climate Change) national GHG inventory guidelines under the UNFCCC (United Nations Framework Convention on Climate Change) framework (IPCC *et al.*, 2006): energy (e.g. transport, household energy consumption); industrial processes and product use (IPPU) (e.g. cement, chemicals); agricultural, forestry and other land use (AFOLU) (e.g. crop burning, deforestation); and waste (e.g. landfilling, wastewater).

**Emissions by Sector**

**GHG emissions from the industrial sector** have been on the rise over the past century, with $CO_2$ and $CH_4$ as the dominant species and the Asia region making the greatest contribution (over 52 percent in 2010) (Fischedick *et al.*, 2014). The energy supply sector has previously been reported as the greatest contributor to global GHG emissions (Bruckner *et al.*, 2014), with enhanced energy supply emissions attributed to accelerated economic growth and a rise in the percent of coal in the global fuel mix. Among the energy sector, emissions from transport sources include $NO_2$, $PM_{2.5}$, $SO_2$, CO and $NH_3$. Transport emissions of $PM_{2.5}$ were observed to contribute 11.7 percent to global $PM_{2.5}$-related mortality in 2010 and 2015, with on-road vehicles making the greatest contribution (Anenberg *et al.*, 2019). The waste sector is reported to contribute the least to emissions (less than 5 percent), with $CH_4$ as the dominant emission species (mainly from solid waste management), followed by smaller amounts of other gases such as $N_2O$, $CO_2$ and NMVHCs (non-methane volatile hydrocarbons) (Bogner *et al.*, 2007). Emissions from the AFOLU sector are particularly important due to the relevance of this sector to multiple areas, including food security, climate change mitigation, land use practices, sustainable development etc. and considering agriculture is the livelihood of a large part of the global population (Smith *et al.*, 2014). Thus, AFOLU emissions are described in more detail in the following section.

## 2.2. Agricultural forestry and land-use sector emissions

Agricultural lands cover approximately 50 percent of the planet, and emissions from this sector have been estimated at around 25 percent of global anthropogenic greenhouse gas emissions (Pradhan, Chaichaloempreecha and Limmeechokchai, 2019). Emissions from the agriculture sector include species such as $NO_X$, $SO_X$, $NH_3$, carbon compounds etc. $N_2O$ agricultural emissions are associated with the application of manure and synthetic fertilizers, while $CH_4$ is linked to the enteric fermentation of livestock, the decomposition of manure, rice cultivation, and crop residue burning. $CO_2$ emissions are dominated by the conversion of ecosystems (e.g. forests and peatlands) to farmlands, as well as microbial decay (FAO, 2020b; Smith *et al.*, 2007). $NH_3$ emission sources from agriculture include the application of fertilizers and animal waste management (Battye *et al.*, 2016).

Fires are an important source of GHG emissions, and have experienced an increase in frequency due to severe dry seasons, forest deprivation, and agricultural expansion (Carmenta *et al.*, 2013). Biomass burning (BB), namely the burning of dead and living organic matter (Yadav and Devi, 2019), is widely practiced across the globe. GHG emissions from biomass burning have long-term effects on carbon sequestration (Konovalov *et al.*, 2014; Lorenz and Lal, 2010) and contribute to climate change in different ways. BB is mainly responsible for non-carbon emissions, $CH_4$ (methane), $N_2O$, and a range of hydrocarbons (Smith *et al.*, 2007). Furthermore, it is the second largest source of trace gases emissions such as $NO_X$ and volatile organic compounds, which act as a precursor to tropospheric $O_3$ and secondary aerosols (Bo, Cai and Xie, 2008; Lin *et al.*, 2013). Such emissions not only source extensive local pollution, but are also responsible for transboundary pollution to neighbouring countries, resulting in serious health problems for those living downstream (Afroz, Hassan and Ibrahim, 2003; Koe, Jr and McGregor, 2001). Biomass burning is a great source of particulate matter (Popovicheva *et al.*, 2017; Yadav and Devi, 2019). The PM from biomass burning is generally released as organic carbon (OC), black carbon (BC) and inorganic forms (Popovicheva *et al.*, 2017). Due to its solar radiation-absorbing property, BC can have a strong influence on the radiative forcing of the atmosphere (Wang *et al.*, 2021), for example the possible warming of the atmosphere (Bond *et al.*, 2013). Furthermore, PM emitted from BB reduces visibility and increases the occurrence of respiratory and cardiovascular diseases (Arbex, Canc and Hila, 2007; Bond-Lamberty *et al.*, 2007; Lin *et al.*, 2018; Marlier *et al.*, 2013; Pun *et al.*, 2017; Reddington *et al.*, 2015).

## 2.3. Air pollution and Southeast Asia

The Asia region makes a significant contribution to global GHG industrial emissions, with the fastest growing emissions between 2005 and 2010 (Fischedick *et al.*, 2014). The developing countries in Southeast Asia (Brunei Darussalam, Cambodia, Indonesia, the Lao People's Democratic Republic, Malaysia, Myanmar, Philippines, Singapore, Thailand, Timor-Leste and Viet Nam) have heavy industries and are pollution hotspots, resulting in this region experiencing a heavy burden of air-pollution related diseases (Babatola, 2018). Moreover, crop residue burning is a common activity, especially for rice straw, and contributes greatly to the air pollution in the region (Chang, Liu and Tseng, 2013; Garivait, Bonnet and Kamnoed, 2008).

Previous research has linked air pollution to respiratory diseases in Southeast Asia. For example, Babatola (2018) determined Southeast Asia to experience the highest serious chronic obstructive pulmonary disease (COPD)-related death rate attributed to air pollution (along with the Western Pacific region) from 1990 to 2015 compared to other global regions. Southeast Asia also exhibited a continuous increase in the burden of bronchus, trachea and lung cancer diseases related to air pollution during 2010–2015 (Babatola, 2018). According to the WHO, household and ambient pollution statistics, Southeast Asia experienced 2 000 000 deaths related to ambient pollution in 2016 (World Health Organization, 2018). In addition, the majority of Southeast Asian countries face an annual mean $PM_{2.5}$ exposure that is above the WHO air quality guidelines, resulting in 109 000 annual premature deaths. The dominant sources of $PM_{2.5}$ in the region are residential, industrial and open biomass burning sectors (Reddington *et al.*, 2019).

The frequency of BB is high in the majority of the Southeast Asia region and is affected by droughts induced by the El Nino˜–Southern Oscillation (ENSO) (Yin, 2020). Massive amounts of GHGs are released by ENSO driven forest fires, for example the 1997/1998 Borneo fire emitted 0.95 Gt of carbon (Turetsky *et al.*, 2015; van der Werf *et al.*, 2008). According to a study by Marlier *et al.* (2013) conducted during the strong El-Nino years, fires contribute up to 200 $\mu g/m^3$ and 50 ppb in annual average fine particulate matter ($PM_{2.5}$) and ozone surface concentrations near fire sources, respectively. This corresponds to a fire contribution of 200 additional days per year, exceeding the World Health Organization interim target of 50 $\mu g/m^3$ 24-hr $PM_{2.5}$, with an estimated 10 800 (6 800–14 300)-person (~2 percent) annual increase in regional adult cardiovascular mortality. Large scale uncontrolled BB in order to clear land is common in Southeast Asia, often causing transboundary haze, deteriorating air quality and reducing visibility for neighbouring countries. This is particularly true during the burning season (Mahmud, 2008).

As a dominant food source in the region, Southeast Asia rice emissions dominate global $CH_4$ emissions (82 percent of total) (Smith *et al.*, 2007). Furthermore, it has been reported that prior to 2010, 35 percent of peatlands in the region were converted to agricultural land, principally by smallholder farmers and industrial oil palm plantations, and consequently increasing carbon emissions from peatlands (Wijedasa *et al.*, 2018).

## 2.4. Air pollution in the Lao People's Democratic Republic

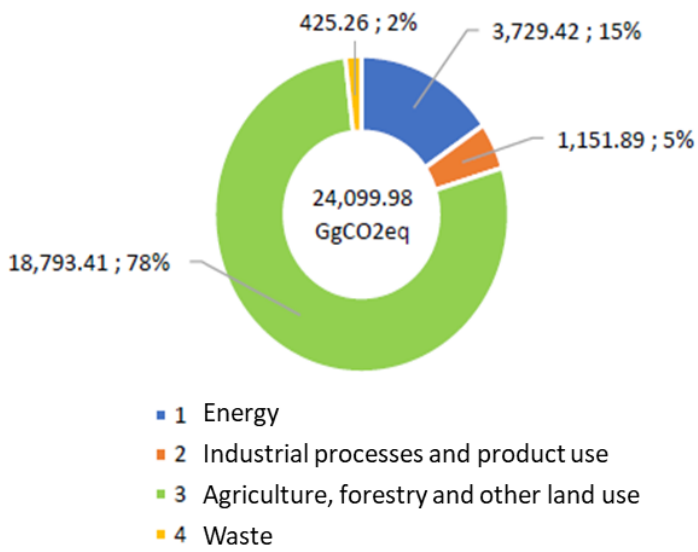
The Lao People's Democratic Republic in Southeast Asia is vulnerable to the air pollution from the surrounding countries of Cambodia, China, Myanmar, Thailand, and Viet Nam, as well as those further away. The rise in migration from rural to urban areas has affected the environment, particularly the atmosphere, water, land, chemical pollution, haze, waste etc. (Ministry of Natural Resources and the Environment, 2020). The latest available data determined average $PM_{2.5}$ concentrations of 20.46 µg/m3 for the country in 2016, exceeding the recommended maximum of 10 µg/m3 (WHO, 2016).

As well as slash-and-burn practises, the dumping and burning of waste also plays a significant role in emitting atmospheric pollution. In addition, charcoal and wood are employed by the majority of the country for domestic usage (cooking, heating), particularly among poorer communities (Ministry of Natural Resources and the Environment, 2017). The combustion of fuels in factories can be grouped into the burning of firewood and fossil fuel. PM and CO dominate the emissions of the former, however the burning of fuel oil (diesel) is becoming more popular with technological advancements, which generally emits black fumes, $SO_2$ and $NO_X$ (Ministry of Natural Resources and the Environment, 2017).

Vehicle emissions have been reported to be the dominant source of $PM_{2.5}$, TSP (total suspended particles), $SO_2$ and $NO_2$ due to the typical vehicle types in the Lao People's Democratic Republic, particularly two-stroke-engine motorcycles, which make up 78 percent of on-road vehicles (58 percent of which were located in the country's capital, Vientiane) (Japan International Cooperation Agency, 2013). Although the greatest proportion of fuel used in the capital is unleaded (low in S), CO, $PM_{10}$ and TSP are still released in large amounts (Ministry of Natural Resources and the Environment, 2017).

The landlocked country also suffers from transboundary emissions from its neighbouring high-polluting countries (WHO, 2015), especially during the dry season and the popularity of agricultural burning, for example the clearing of land for crops (e.g. corn, rice) and tree (rubber, oil palm) plantations. Such fires can cause huge damage to property, humans and crops if they become uncontrollable. The haze episodes observed over the region also originate from peat fires, especially following the draining of peatlands (Sunchindah, 2015). In a study on the biomass burning emissions from the Mekong Region (Cambodia, the Lao People's Democratic Republic, Myanmar, Thailand, Viet Nam, and Yunnan province and Guangxi Zhuang Autonomous Region, China) Junpen *et al.* (2020) determined the neighbours of the Lao People's Democratic Republic to emit greater amounts of biomass burning pollutants compared to the Lao People's Democratic Republic. The most pertinent cause of vegetation fires in the Lao People's Democratic Republic is arguably the use of fire for the clearing of land for agricultural purposes, particularly for the shifting of cultivation. Shifting cultivation is still widespread in the Lao People's Democratic Republic and typically follows slash-and-burn practices, where the vegetation of a plot of land is cut in January or February and is left to dry for several weeks. The dried vegetation is burned toward the end of the dry season, primarily during March and April (Van Gansberghe, 2005).

**Figure 1:** Total emissions ($CO_2$, CO and $N_2O$) across Lao People's Democratic Republic in 2014




*Source:* Ministry of Natural Resources and the Environment. 2020. *The first biennial update report of the LAO PDR*. Vientiane, Ministry of Natural Resources and the Environment. https://unfccc.int/sites/default/files/resource/The%20First%20Biennial%20Update%20Report-BUR_Lao%20PDR.pdf

The Lao People's Democratic Republic Ministry of Natural Resources and Environment *et al.* (2020) determined the AFOLU sector to be the biggest GHG emitter ($CO_2$, $CH_4$ and $N_2O$) in 2014, followed by the energy sector, industrial processes and product use and lastly, waste, with emissions generally exhibiting an increasing trend (Figure 1). However, the emissions were determined based on default IPCC 2006 EFs as country specific EFs were unavailable at the time of analysis.

Research emphasises that fires in the country are mostly of anthropogenic nature, however it is difficult to quantify this information due to the lack of local data. Slash-and-burn activities are generally well organised as farmers have been following these practices for a long time, yet when they become uncontrollable, they can damage vegetation nearby. Numerous studies have been conducted at the regional, national and sub-national scale for fire mapping, mainly using MODIS fire alerts and burning products, including hotspot monitoring. Hurni *et al.* (2013) combined time series analysis with different MODIS products for fire hotspot monitoring using moving window techniques, focusing on shifting cultivation plots. Müller *et al.* (2013) used MODIS active fire data for the measurement, reporting and verification (MRV)[1] of the REDD+ project at the national scale, revealing the north-eastern region of the Lao People's Democratic Republic as a fire hotspot due to the dominance of shifting cultivation systems. Furthermore, Lasko *et al.* (2019) used the OMI-derived ultraviolet aerosol index (UVAI) to evaluate atmospheric aerosols in Lao People's Democratic Republic and surrounding countries.

Such approaches based on Earth observation (EO) data to monitor air pollution and fire activity dynamics in Lao People's Democratic Republic can help the Government in minimizing the levels and impacts of pollution. In the next section, common EO approaches used to investigate air pollution are described.

[1] Measurement, Reporting and Verification (MRV) helps countries to monitor emissions and emission reductions for better climatic actions and reporting. It also help countries to identify the drivers and trend of GHG emissions (Singh *et al.*, 2016).

# 3. Monitoring atmospheric pollution-a review of methods

This section presents a review of the geospatial methods employed in previous work on the detection and investigation of atmospheric pollution across the globe.

## 3.1. Spatio-temporal trends in atmospheric pollutant emissions

Air pollution is a crucial issue both at the regional and global scale and requires accurate and timely monitoring. Satellite observations are an effective tool for the top-down quantification and monitoring of emissions at different spatial and temporal scales and have thus been employed in an extensive amount of research over the past few decades. Table 1 summarizes the satellite instruments currently employed to monitor air pollution at the global scale.

**Table 1:** Examples of satellite instruments employed to investigate pollutant emissions

| Instrument | Species | Temporal resolution | Spatial resolution | Data availability |
|---|---|---|---|---|
| Ocean Monitoring Instrument (OMI) | $O_3$, $NO_X$, $SO_2$, AOD | Daily | 13 × 25 km | Oct 2004 until present |
| Cloud–Aerosol Lidar with Orthogonal Polarization (CALIOP) | Aerosols | Every 16 days | 5 km | May 2006 |
| Moderate-Resolution Imaging Spectroradiometer (MODIS) | AOD | Daily | 10 km | 1999 until present |
| Global Ozone Monitoring Experiment-2 (GOME-2) | $SO_2$, $NO_2$, AOD, $O_3$ | Every 2–3 days | 40 × 40 (80) km | 2007 until present |
| Scanning Imaging Absorption Spectrometer for Atmospheric Chartography (SCIAMACHY) | $SO_2$, $NO_2$, AOD, $O_3$ | Every 1.5 days | 30 × 60 (120) km | 2002–2012 |
| TROPOspheric Monitoring Instrument (TROPOMI) | $SO_2$, $NO_2$, AOD, $O_3$ | Daily | 7 × 7 km | 2017 until present |
| Infrared Atmospheric Sounding Interferometer (IASI) | $NO_X$, $SO_2$, $O_3$, CO | Approx. twice a day | 48 × 48 km | 2006 until present |
| Orbiting Carbon Observatory-2 (OCO-2) | $CO_2$ | Every 16 days | 1.3 × 2.25 km | 2014 until present |
| Multi-angle Imaging SpectroRadiometer (MISR) | AOD | Every 7–9 days | 18 km | 1999 until present |
| Geostationary Environment Monitoring Spectrometer (GEMS) | $NO_2$, $SO_2$, $O_3$, aerosols | Hourly | 3.5 × 8 km | 2020 until present |
| Ozone Mapping Profiler Suite-Nadir (OMPS-Nadir) | $O_3$ | Daily | 50 × 50 km | 2012 until present |

The majority of the satellite products in Table 1 have been evaluated and validated for the monitoring of air pollutants (Borsdorff *et al.*, 2020; Castellanos, Boersma and Werf, 2014; Eltahan and Magooda, 2019; Fu *et al.*, 2019; Jiang *et al.*, 2017; Kajino *et al.*, 2019; Lasko *et al.*, 2019; Liao *et al.*, 2021; Ma *et al.*, 2016; Martínez-alonso *et al.*, 2020; Qu *et al.*, 2019; Reddy, Zhang and Bi, 2018; Shim *et al.*, 2019; Wang *et al.*, 2021, 2018b). Previous studies have also comprehensively compared the available products. For example, OMI has been demonstrated to exhibit a stronger ability to detect smaller $SO_2$ sources compared to SCIAMACHY and GOME-2 (Fioletov *et al.*, 2013). As part of the KORUS-AQ campaign, Choi *et al.* (2019) compared the AOD determined from MODIS, the Visible/Infrared Imager

Radiometer Suite (VIIRS), MISR, the Advanced Himawari Imager (AHI) and the Geostationary Ocean Color Imager (GOCI) over East Asia, the last two of which are geostationary. The geostationary satellites proved to be more accurate in detecting fast-changing AOD trends (e.g. smoke plume movements) due to their high temporal resolution, while the Earth orbiting satellites provided a coarser temporal resolution (daily/twice a day coverage, which can be further reduced due to cloud cover). However, the geostationary satellites have a slightly lower spatial resolution.

As the most important GHG, estimating and monitoring $CO_2$ emissions is crucial, yet it can be somewhat problematic. Shim *et al.* (2019) estimated column integrated $CO_2$ retrievals from GOSAT to monitor urban and local-scale anthropogenic $CO_2$ emissions in East Asia. The authors determined the $CO_2$ GOSAT product to be highly sensitive to the summer monsoon (greater cloud cover) and strong downwind effects with high aerosol loadings. This downwind effect is particularly strong due to the strong outflow of $CO_2$ across China. Compared to other polar-orbiting satellites, the swaths of GOSAT and OCO-2 (another satellite mission dedicated to monitoring $CO_2$) are substantially narrower, thus multiple observations of numerous locations prove to be difficult (Goldberg *et al.*, 2019). $CO_2$ emissions can also be estimated indirectly via co-emitting species (e.g. $NO_X$ or CO) with more widely available satellite products (Goldberg *et al.*, 2019; Zheng *et al.*, 2020).

The advancement in Earth observation technology has resulted in the launch of several new satellite missions over the past few years, with corresponding products that can be used to monitor atmospheric pollution. Amongst these, TROPOMI generally has a superior spatial and temporal resolution compared to its predecessors (Table 1). However, the instrument was launched in 2017, thus limiting its role in long-term studies. Also, due to its relatively recent launch, the products from this instrument are less validated than those of other instruments. The Geostationary Environment Monitoring Spectrometer (GEMS) was launched even more recently by the National Institute of Environmental Research (NIER) of the Ministry of Environment, Korea, offering the hourly monitoring of pollutants in Asia for the first time from a satellite (7 × 8 km spatial resolution). Furthermore, numerous satellite missions targeted at air pollution monitoring are projected to be launched in the future, further advancing air quality investigations from space, with the potential for hourly real-time data. These include the Tropospheric Emissions: Monitoring of Pollution (TEMPO) satellite instrument (a joint NASA and NOAA project), and ESA's Sentinel 5.

In terms of fire monitoring, quantitative estimates of burned area are required to address different ecological and environmental problems, such as changes in the disturbance caused by fires. Satellite data can facilitate the detection of vegetation fires (GOFC-GOLD, 2009; Justice *et al.*, 2006; Kaufman *et al.*, 1998).

Satellites can capture the time and location of actively burning fires at the time of the satellite overpass and can therefore provide an indication of the density of fire activity (Csiszar, Morisette and Giglio, 2006). Detecting changes in fire dynamics will help assess the rapid transformation of land use in upland Southeast Asia to tree plantations, mainly rubber, tea and pulpwood. Careful fire monitoring also supports the estimation of the forest degradation caused by a shortening of fallow cycles or by an increase in fire density due to other causes. For example, increasing fire return intervals can indicate shorter fallow periods in shifting cultivation systems. Decreasing fire activities in one location but increasing fire activity in neighbouring locations may imply a local shift in fire use. More fires over time per unit area may inhibit tree growth and the regeneration of successional vegetation into young, closed forests, with potentially detrimental effects on soil fertility and above- and belowground carbon sequestration. Therefore, an assessment of both the spatial distribution and the temporal dynamics of vegetation fires is important (GOFC-GOLD, 2009).

Despite their great advantages and substantial advancement in Earth observation analysis, satellite products also have limitations. Perhaps the greatest of which is the presence of cloud cover in satellite imagery, which prohibits obtaining useful information from the affected areas. This is particularly a problem during rainy and monsoon seasons. Furthermore, the spatial resolution of current freely available verified satellite products is not suitable for small-scale investigations.

Ground-based remote sensing techniques can overcome these limitations and are commonly applied to monitor emissions ($PM_{2.5}$, $PM_{10}$, $NO_2$, $SO_2$, CO, $O_3$, etc.) at the surface as well as to validate satellite-based products. Measurements are typically collected at monitoring stations distributed across the study region/country equipped with the relevant sensors (e.g. $SO_2$/$NO_X$/CO analysers, $PM_{2.5}$ tapered element oscillating microbalance [TEOM], infra-red sensors, etc.) (Hanan *et al.*, 2020; Ma *et al.*, 2016; Maji and Sarkar, 2020; Reddy, Zhang and Bi, 2018; Singh, Kumar and Singh, 2018; Xue *et al.*, 2017; Zeri, Oliveira-Junior and Lyra, 2011; Zheng *et al.*, 2018). The AERONET (AErosol RObotic NETwork) project is also used to validate satellite-determined AOD data (Choi *et al.*, 2019; Ma *et al.*, 2016; Nguyen *et al.*, 2019; Wang *et al.*, 2021). AERONET observations consist of ground-based sun photometer measurements of atmospheric aerosol properties, including AOD, with monitoring stations located across the globe.

Investigating the spatial and temporal transportation of emissions from their sources is crucial in understanding the underlying impacts of pollution, particularly the long-range impacts, and their corresponding influence on measured concentrations. The Hybrid Single-Particle Lagrangian Integrated Trajectory (HYSPLIT) model from NOAA is typically used to determine simple air parcel trajectories (Wang *et al.*, 2018a).

Choommanivong, Wiriya and Chantara (2019) modelled air mass movements using HYSPLIT in order to track transboundary air pollution from open burning in Southeast Asia. Sirimongkonlertkun (2018) also adopted HYSPLIT to investigate trajectories from a haze episode across Thailand, the Lao People's Democratic Republic and Myanmar. The HYPSLIT model has also been used to explain season variations in aerosols (Reddy, Zhang and Bi, 2018). Wang *et al.* (2018a) employed HYSPLIT to investigate the 5-day backward trajectory of pollutants.

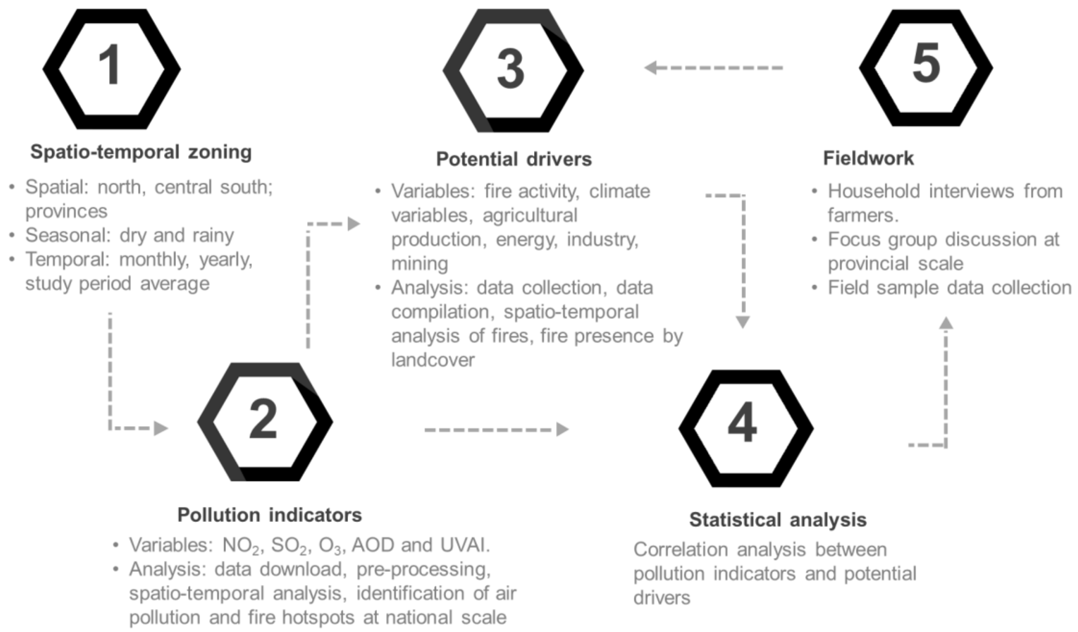
In summary, to perform the accurate top-down monitoring of atmospheric pollution, adequate satellite products must be selected based on the temporal and spatial resolution requirements of the project, as well as the length of the study period. Ideally, satellite observations should be validated with measurements on the ground. The analysis of pollution trajectories can be performed via the modelling of air mass movements.

Numerous platforms have been developed in order to provide users with easy access to global Earth observation datasets (gas species column amounts, meteorology, fire hotspots, vegetation indices etc.). These include NASA Worldview, the Global Fire WEather Database (GFWED), NASA Giovanni, GFED, the Urban Action Air Platform, the ESA Air Quality Platform, the Fire Information for Resource Management System (FIRMS), the Global Fire Atlas and the Global Wildfire Information System (GWIS).

# 4. Methodology

The methodological approach employed for this project can be summarized into five key components: 1) the spatial and temporal division of the study area and study period, respectively; 2) the investigation of the spatio-temporal trends of the atmospheric pollution indicators; 3) the exploration of the potential drivers of the pollution indicators; 4) the statistical analysis between the pollution indicators and potential drivers; and 5) the collection of field data and its integration with the remote sensing data. Figure 2 summarizes these five steps, and they are described in more detail in the following sections.

**Figure 2:** Workflow of the methodology used in this assessment



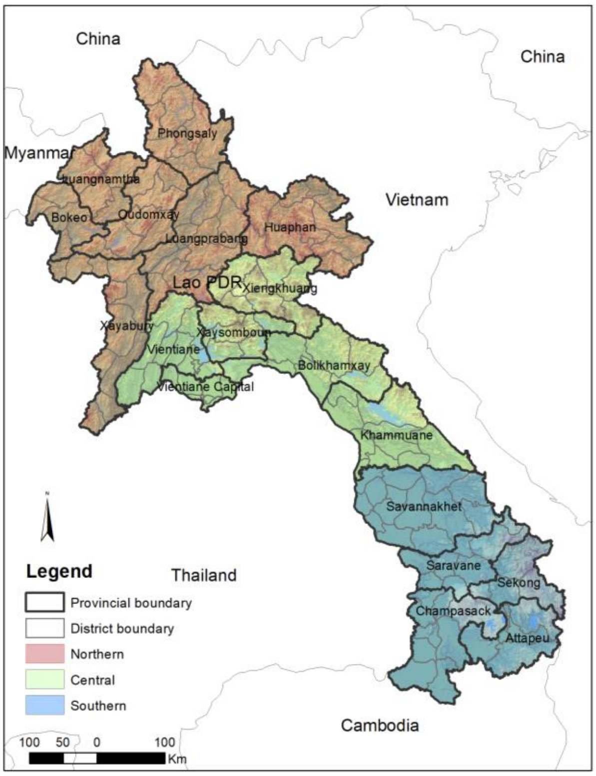

*Source:* Authors' elaboration.

## 4.1. Division of study area and study period

In order to investigate the spatial trends of the pollution indicators and their potential drivers, the country was divided into zones (northern, central and southern) and 18 provinces based on elevation and the provincial limits used by the National Geographic Department (NGD) of the Lao People's Democratic Republic, respectively (Figure 3). The NGD administrative boundaries used are those employed by the Lao People's Democratic Republic in their national research.

As well as exploring the annual and monthly trends in the data analysis, the seasonal patterns were considered based on the dry (November–April) and wet (May–October) seasons. This division considered local knowledge, rainfall data during the study period and seasonal time period used by MONRE of the Lao People's Democratic Republic.

**Figure 3:** Division of Lao People's Democratic Republic into northern, central, and southern zones. Also shown are the provincial limits for the 18 provinces




*Source:* Authors' elaboration. Administrative boundaries obtained from National Geographic Department (NGD) of Lao People's Democratic Republic.

## 4.2. Investigating the spatio-temporal trends of atmospheric pollution indicators in the Lao People's Democratic Republic

### 4.2.1. Retrieval of pollution indicators

In order to investigate the air pollution trends in the Lao People's Democratic Republic across space and time, and to determine links to potential pollution sources, nitrogen dioxide ($NO_2$), sulphur dioxide ($SO_2$), ozone ($O_3$), aerosol optical depth (AOD) and the ultraviolet aerosol index (UVAI) were selected as indicators of atmospheric pollution. The levels of these pollution indicators were quantified in the atmosphere using the satellite products reported in Table 2.

**Table 2:** Details of products used to investigate pollution indicators in Lao People's Democratic Republic between 2015 and 2021. L3 – level 3; OMI – Ozone Monitoring Instrument; and MODIS – Moderate Resolution Imaging Spectrometer

| Pollution indicator | Product | Instrument | Temporal resolution | Spatial resolution | Unit |
|---|---|---|---|---|---|
| $NO_2$ | L3-OMNO2d v003 | OMI | Daily | 13 × 24 km | Tropospheric column amounts (molec/cm$^2$) |
| $SO_2$ | L3 OMSO2e v003 | OMI | Daily | 13 × 24 km | Tropospheric column amounts (DU) |
| $O_3$ | L3 OMDOAO3e v003 | OMI | Daily | 13 × 24 km | Tropospheric column amounts (DU) |
| UVAI | L3 OMAEROe v003 | OMI | Daily | 13 × 24 km | -- |
| AOD | L2 MCD19A2 | MODIS | Daily | 1 km | -- |

The Ozone Monitoring Instrument (OMI) onboard NASA's Aura satellite is employed to retrieve $NO_2$, $SO_2$ and $O_3$ column amounts, as well as the UVAI. Numerous studies have used this nadir-viewing instrument for the retrievals of atmospheric gas amounts and aerosol properties due to its higher spatial and temporal resolution (nadir pixel size of 13 × 24 km$^2$ and daily coverage) and improved performance compared to other satellites (Goldberg *et al.*, 2019; Krotkov *et al.*, 2016; Lasko *et al.*, 2019; Qu *et al.*, 2019). OMI has a spectral range of 270 nm to 500 nm, a spectral resolution of approximately 0.5 nm and a swath width of 2600 km. Although OMI was launched in 2004, since 2009 the collected cross-track positions are affected by row anomalies (the blocking of the field of view [FOV] and scattering of light) that must be accounted for in the analysis (Krotkov *et al.*, 2016; Qu *et al.*, 2019).

The OMI level three daily products OMNO2d, OMSO2e, and OMDOAO3e were used to retrieve the column amounts of $NO_2$ (molec/cm$^2$), $SO_2$ (DU), and $O_3$ (DU) respectively, gridded at 0.25° × 0.25°. OMNO2d is derived from spectral measurements in the visible region across 405 to 465 nm, OMSO2e is determined from UV (ultraviolet) readings within the spectral region of 310–370 nm, and OMDOAO3e is retrieved from the region 331–336 nm. In addition, OMAEROe was used to obtain the daily gridded (0.25° × 0.25°) UVAI values for the Lao People's Democratic Republic during 2015–2022. The UVAI is an indicator of the UV absorbing effect of aerosols and can be used to estimate the amount of absorbing aerosols in the atmosphere (Li, 2022). The aforementioned products are available at https://disc.gsfc.nasa.gov/.

In addition to the OMI products, the level 2 MCD19A2 Version 6 data product from MODIS on-board NASA's Aqua and Tierra was used to determine the daily AOD (calculated at 0.47 µm) for the Lao People's Democratic Republic during the study period 2015–2021, with a 1 km spatial resolution. MCD19A2 is derived from the Multi-Angle Implementation Atmospheric Correction (MAIAC) algorithm using MODIS L1B radiance and has been used to investigate atmospheric aerosols in numerous studies (e.g. Wei *et al.*, 2019). AOD is an indicator of the amount of aerosols distributed in a column of the atmosphere (Li, 2022). The product was obtained from Google Earth Engine and the LAADS DAAC search engine https://ladsweb.modaps.eosdis.nasa.gov/s9earch/.

### 4.2.2. Spatio-temporal trends of the pollution indicators

All data were pre-processed, which mainly include clipping and reprojections of spatial data. The datasets were clipped using national geographic admin boundaries and projected to the same reference system WGS84.

## 4.3. Exploration of the potential drivers of the pollution indicators

In order to explore the explanatory factors of the determined air pollution trends, the following potential drivers were considered: fire activity, climate, population, transport, industrial activity and agricultural production.

### 4.3.1. Fire activity

#### 4.3.1.1. Spatial and temporal analysis of fires

Numerous studies have been conducted at the regional, national, and sub-national scale for fire mapping, mainly using MODIS fire alerts and burning products. This includes hotspot monitoring. MODIS daily fire near real time alert data has been available since late 2000 with a 1 km spatial resolution, which makes it a perfect choice to study hotspots and is widely used across the globe. In 2013, VIIRS was launched to complement the MODIS fire data with an improved spatial resolution of 375 m. Therefore, for the current study, only VIIRS is used, as both products are identical for hotspot identification, while VIIRS is best suited to capture smaller fire events such as shifting cultivation due to its higher spatial resolution.

The VIIRS fire data from the FIRMS website was downloaded over the area of interest for the period 2015–2021. The data was clipped using the national boundaries and filtered. The dataset comes with multiple attributes such as spatial coordinates, date, time, sensor information, fire radiative power (FRP) and the confidence interval (CI). For the current study, only the data with high CI values was used. Trends were then analysed at different spatial (national, zonal and provincial levels) and temporal (study period average, yearly, monthly, dry and rainy season) scales. The fire data was mainly used to understand the spatial behaviour of fires in the Lao People's Democratic Republic, generating three key outputs:

1) Length of the fire season: the fire data was organised and analysed by month over the study period.
2) Fire presence by land cover classes: the land cover class information was collected against each fire incident and grouped by land cover class. This helped to understand the presence of fires in different classes.
3) Fire hotspots: the fire season and fire presence by land cover data were combined to identify the fire hotspots.

### 4.3.2. Meteorological variables and national datasets

Data was collected through collaboration with the Natural Resources and Environment Statistic and Research Institute (NRESRI) and MONRE in the Lao People's Democratic Republic. The datasets were obtained from various government entities at the central and provincial levels, as well as from online publications and are based on government statistics, relevant government plans and other related information on administrative data, production statistics, land concession data etc. on the following fields: agriculture, energy, transport, mining, population, industrial activity and meteorology (Table 3).

**Table 3:** Details of national datasets used in the analysis

| Field | Variables | Temporal coverage | Spatial level | Source |
|---|---|---|---|---|
| Agricultural production | Lowland rainfed paddy production; dry season paddy production; maize production; upland rainfed paddy production; starchy roots production, sugarcane production | 2015–2019 | All provinces (upland paddy rice production missing Vientiane Capital and Champasack Provinces; Sugarcane missing Bokeo Province) | Department of Planning and Cooperation, Ministry of Agriculture and Forestry https://laosis.lsb.gov.la/ |
| Energy | Number of energy projects per province and district; total energy generated per province, energy sector type (thermal, solar, hydro), major operating companies and equity owners, installation capacity, year completed | 2000–2018 | All provinces | Department of Energy Policy and Planning, Ministry of Energy and Mines |

| Field | Variables | Temporal coverage | Spatial level | Source |
|---|---|---|---|---|
| Transport | Number of vehicles per province (includes motorcycle, motorcycle taxi, three-wheeled car, Seda, taxi, pick-up, Jeep, van, truck, public bus and bus) | 2016–2020/yearly | All provinces | Department of Planning and Cooperation, Ministry of Public Works and Transport https://laosis.lsb.gov.la/ |
| Population | Number of people per province, number of females per province | 2015–2020/yearly | All provinces | Lao Statistics Bureau, Statistical yearbook 2020, https://laosis.lsb.gov.la/ (Lao Statistics Bureau, 2021) |
| Mining | Type of mineral, number of mines per province and district, major operating companies and equity owners, location of mines, year*; area*; capacity (majority of mines), status*; fuel/energy used*; | 2006+ | Bokeo, Bolikhamxau, Houaphanh, Khammouane and Savannakhet, Luang Prabang, Luangnamtha, Oudomxay, Saravan, Savannakhet, Xayabury, Sekong, Vientiane Capital, Xiengkhuang | USGS, Mineral of Lao, 2017–2018 Minerals Yearbook<br><br>Land concession 2010,<br><br>Natural Resources and Environment Research and Statistic Institute (NRERSI), MONRE |
| Industry | Number of main industrial facilities per province and district, location of facility, type of production (e.g. bio-fertilizer, plastic, furniture etc.), major operating companies, year*; capacity* | 2006–2021 | Vientiane, Xayabury, Borikhamxay, Vientiane Capital, Khammouane, | Department of Planning and Cooperation, Ministry of Industry and Commerce, https://laosis.lsb.gov.la/<br><br>Land concession 2010,<br><br>Natural Resources and Environment Research and Statistic Institute (NRERSI), MONRE |
| Meteorology | Minimum temperature, maximum temperature, wind speed, minimum relative humidity, maximum relative humidity, precipitation | 2015–2021/daily | All provinces apart from Huaphan | Department of Meteorology and Hydrology, Ministry of Natural Resources and Environment |

*missing for most facilities

Note that numerous datasets exhibited gaps both spatially and temporally for the entire country and study period. This is particularly true for the mining and industry datasets, where detailed up-to-date information for the whole country is lacking. This must be taken into consideration when analysing the results.

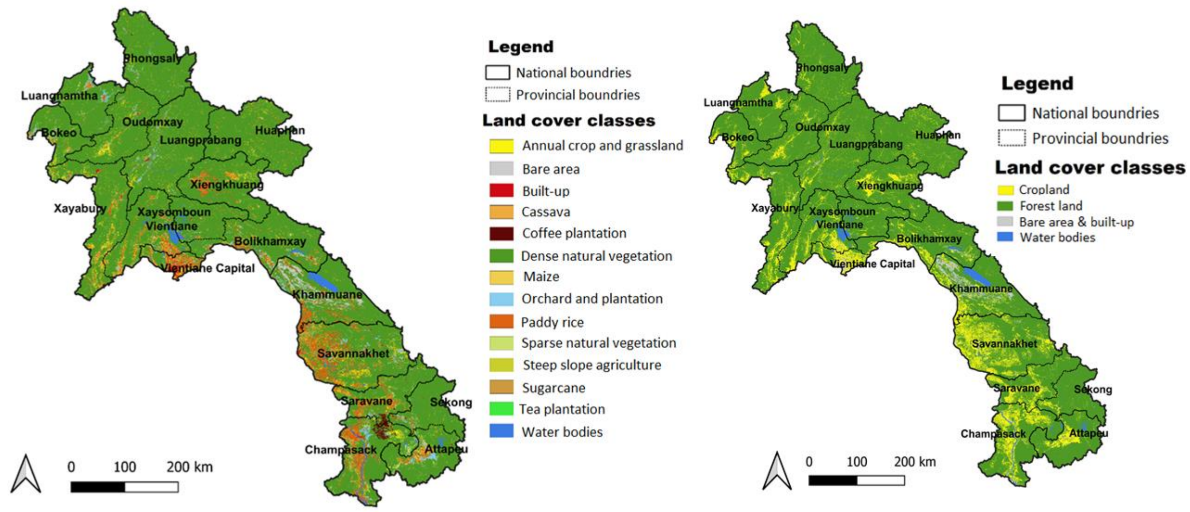
### 4.3.3. Land cover map

The 2018 land cover map was obtained from the Lao People’s Democratic Republic Department of Agricultural Land Management (DALaM) of the Ministry of Agriculture and Forestry (FAO, 2021), the Lao People’s Democratic Republic (Figure 4). The map contains 14 land cover classes, including seven cropland categories, two forest and three plantation categories. These classes were then aggregated into just four classes, namely, forest (dense and sparse vegetation classes), cropland (all cropland and plantation classes, including coffee, tea, and orchard plantation), bare plus built-up, and water bodies.

### 4.3.4. Back-trajectory modelling

The online version of the Hybrid Single-Particle Lagrangian Integrated Trajectory (HYSPLIT) model from the National Oceanic and Atmospheric Administration (NOAA) Air Resources Laboratory (ARL) (www.ready.noaa.gov/HYSPLIT.php) was adopted to evaluate the pollution transport back-trajectory of pollution hotspots identified by the satellite observations (Rolph, Stein and Stunder, 2017). Due to time restrictions, just two provinces were selected for the trajectory modelling, namely, Bokeo in the north and Saravane in the south, during 2021. HYSPLIT requires gridded meteorological data as the input. Here, the Global Data Assimilation System (GDAS) at 1 degree from the National Centre for Environmental Protection (NCEP) was used. Each back trajectory lasted 48 hours and was calculated every 24 hours for 5 days at 500, 1500 and 2000 m ABL (above ground level) (Karaca, Anil and Alagha, 2009).

**Figure 4:** (a) – 2018 land cover map with 14 classes; (b) – land cover map with classes aggregated to four categories




*Source:* FAO. 2021. *State of the art agricultural land cover maps for the Lao People's Democratic Republic: part of the Land Resources Information Management System (LRIMS).* Vientiane, Laos, FAO. https://www.fao.org/publications/card/en/c/CB3699EN/

## 4.4. Relationship between pollution indicators and potential drivers

The relationship between the pollution indicators and potential drivers described in the previous sections were explored using the (Pearson) correlation between the two data groups within the different spatial and temporal levels. In particular, correlations were determined at the provincial and zonal (north, central, south) levels for the study period averages of all variables; using the yearly averages of each variable at the national level; and using the monthly averages across the study period at the national and provincial levels. In addition, spatial and temporal trends were examined using the Kruskal-Wallis test.

## 4.5. Fieldwork

Fire is a difficult dynamic to capture by remote sensing and sometimes requires very high resolution data both in terms of space and time to effectively capture fire events. In most cases fire traceability is very low, because of the low temporal resolution of freely available satellite information. For example, the Landsat revisit time is 15/16 days whereas MODIS has a high temporal resolution, but spatial resolution is too coarse to capture the fires in the agriculture strata, which are typically small fire events. Thus, a good understanding of local dynamics is key to identify such events, particularly in tropical countries when land is converted to agriculture and farmers burn everything prior to planting the seeds to clear the land and prepare for crops. This part of the process often cannot be captured by satellite imagery due to the limitations in remote sensing data. In addition, fires may occur prior to or after the satellite pass-over time. Therefore, field data collection is a crucial step to verify satellite-based methods.

### 4.5.1. Fieldwork objective

The objective of the fieldwork was to assess and understand the contribution from the agricultural sector and in particular, crop residue burning, to air pollution through integrated field and remote sensing analysis based on:

(1) Focus group discussions with government officials

(2) Household survey at the village level

(3) Field visits to targeted locations to check fire activity, supported with farmer and government official interviews; and

### 4.5.2. Area of interest

The areas of interest (AOIs) are delineated by the administrative areas of two districts in each of the selected provinces: Luangprabang and Savannakhet. These provinces were selected as they presented the highest fire frequencies out of the 18 provinces in the Lao People's Democratic Republic during 2015–2021 based on the fire activity analysis using the VIIRS fire product.

Luangprabang is geographically located in the north zone of the country. The province is known for upland rice and maize production and is dominated by forest land (96 percent), while cropland covers only 2 percent, and rice paddy fields represent 1 percent of total provincial area.

Savannakhet is located in the south of the Lao People's Democratic Republic and famous for rice paddy production. According to the 2018 land cover map, 17 percent of the province is covered by rice fields, whereas other cropland areas cover 11 percent of the total provincial area.

### 4.5.3. Sampling strategy

The sampling strategy was based on the following:

- AOI: Two districts in each province
- Grid: A ~10 $km^2$ hexagonal grid at the national scale, L14 (Sahr, White and Kimerling, 2003).
- Sample selection: 4 clusters (Hexagon) × 5 samples = 20 in each province (40 in total).
- Sample location: Random selection within selected hexagons (or cluster) of five field sample locations and one focus group discussion per cluster. Whereas villages for household survey were selected randomly, based on accessibility and availability of the farmers for survey.

The field data collection is broadly categorized into three sections, namely.

1. Focus group discussion
2. Household survey at village level
3. Sample location visits within cluster

The focus group discussion targeted local governmental agency staff from the district Agriculture and Forest Office, DAFO, the Lao People's Democratic Republic in order to understand the dynamics of air pollution and different drivers from their prospective at the district scale. Whereas household interviews were performed at the village scale within a cluster, the selection of villages was random. Following the focus group discussion, field visits were conducted at the targeted locations to validate the remote sensing results.

## 4.6. Ground-based remote sensing measurements

There was a lack of available ground-based observations of atmospheric gases and aerosols from monitoring stations across the Lao People's Democratic Republic during the study period. Due to the limited data availability, comparisons of the satellite-derived pollution indicators and ground-based measurements were made with just $PM_{2.5}$ measurements from monitoring stations located in Laungprabang and Vientiane Capital for 2020 and 2021. Comparisons were based by taking the monthly averages of the daily $PM_{2.5}$ readings and comparing them with the equivalent monthly averages of the pollution indicators at these provinces. Appendix 2 presents the results of the comparison.

The MODIS-derived AODs were compared with the AODs from the Aerosol Robotic Network (AERONET). This data is accurate, cloud free and with a 15 min temporal resolution when available. The AERONET AODs are derived from a global network of sun and sky scanning radiometers. Currently, there is data available from one AERONET station in the Lao People's Democratic Republic in Luangnamtha. The data is available from https://aeronet.gsfc.nasa.gov/. The monthly MODIS AODs for the Luangnamtha province were compared with the corresponding AERONET AODs over the study period. See Appendix 2 for the comparison between the two AOD datasets.

## 4.7. Software

QGIS (v. 3.24.0, QGIS.org), IDL (v. 6.3, RSI), HEG (HDF-EOS to GeoTIFF Converter (HEG-C), 2019), MeteoInfoLab (v. 3.2.1, Yaqiang, 2019) and Microsoft Excel (v. 2203, Microsoft Corporation) were used for the data analysis and visualization. The Kobo Toolbox (http://www.kobotoolbox.org) was adopted for the field work data collection.

# 5. Results

## 5.1. Spatio-temporal trends of atmospheric pollution indicators in the Lao People's Democratic Republic

Key Messages:

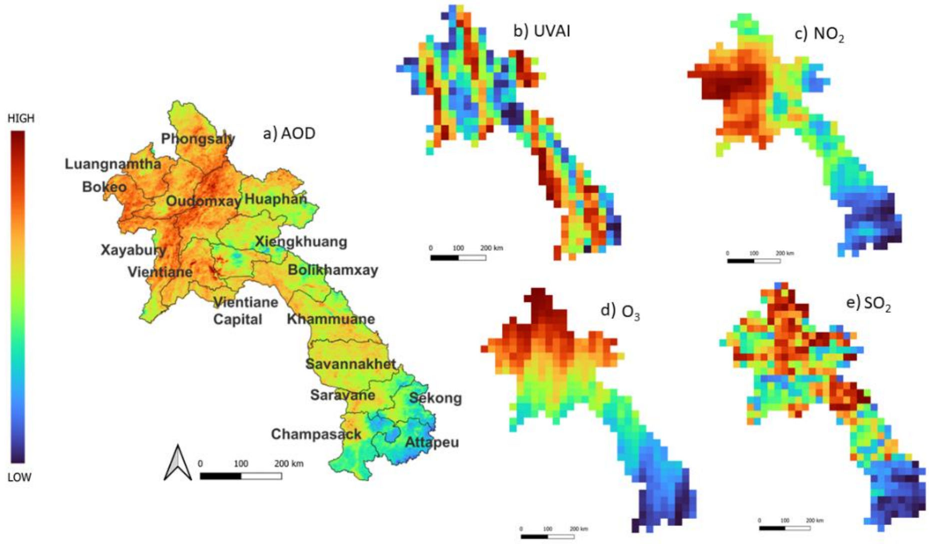
1. North and central regions typically exhibit higher levels of $NO_2$, $SO_2$, $O_3$ and AOD, while the southern region dominates elevated UVAI amounts.
2. $NO_2$, $SO_2$, UVAI and AOD monthly averages peak during the dry season.
3. Bokeo; Phongsaly; Oudomxay; Luangprabang; and Savannakhet are pollution hotspots.
4. Annual crops and grassland, paddy rice, steep slope agriculture and cassava are the key landcover classes mapped to regions with elevated pollution indicator amounts.

### 5.1.1. Summary over study period

Figure 5 presents the pollution indicator means for the period 2015–2021 across the Lao People's Democratic Republic. The higher amounts of AOD, $NO_2$, $O_3$ and $SO_2$ in the north of the country may be associated with the biomass burning that occurs in this region. UVAI values are higher in the southern zone compared to the rest of the country. This could be attributed to the higher sensitivity of the UVAI to smoke plumes above clouds, suggesting greater plume heights (Vadrevu *et al.*, 2015). Furthermore, $SO_2$ column amounts present elevated levels in the top central zone (Vientiane Capital and Bolikhamxay). Vientiane Capital is associated with high levels of transport and Bolikhamxay with high industrial activity (Appendix 1).

Figure 5 shows the mean of the pollution indicators for the rainy and dry seasons of the entire study period (2015–2021) averaged across the country. $NO_2$, $SO_2$ and AOD exhibit greater values during the dry season compared to the rainy season, which can be linked to the high frequency of fires during the latter season. The values for the northern zone of these pollution indicators are the highest, followed by those in the central zone. In contrast, $O_3$ (northern zone) and UVAI (particularly in the south) values exhibit higher amounts in the rainy season. The higher UVAI values in the south during the rainy season suggest that it is unlikely that the elevated UVAI values in this zone observed in Figure 6 are due to biomass burning as this trend is not observed in the fire activity analysis (Section 5.2.1). However, fires are still observed during the beginning of the rainy season, and thus they can possibly explain this trend in UVAI values. Note that the differences between seasons for $O_3$ column amounts are minimal. $NO_2$ column amounts exhibit the greatest differences between seasons.

**Figure 5:** Mean of the pollution indicators for the study period (2015–2021). Mean values of a) aerosol optical depth and b) ultraviolet aerosol index and average column amounts of c) nitrogen dioxide; d) ozone and; e) sulphur dioxide




*Source:* Authors' elaboration. Administrative boundaries obtained from National Geographic Department (NGD) of the Lao People's Democratic Republic.

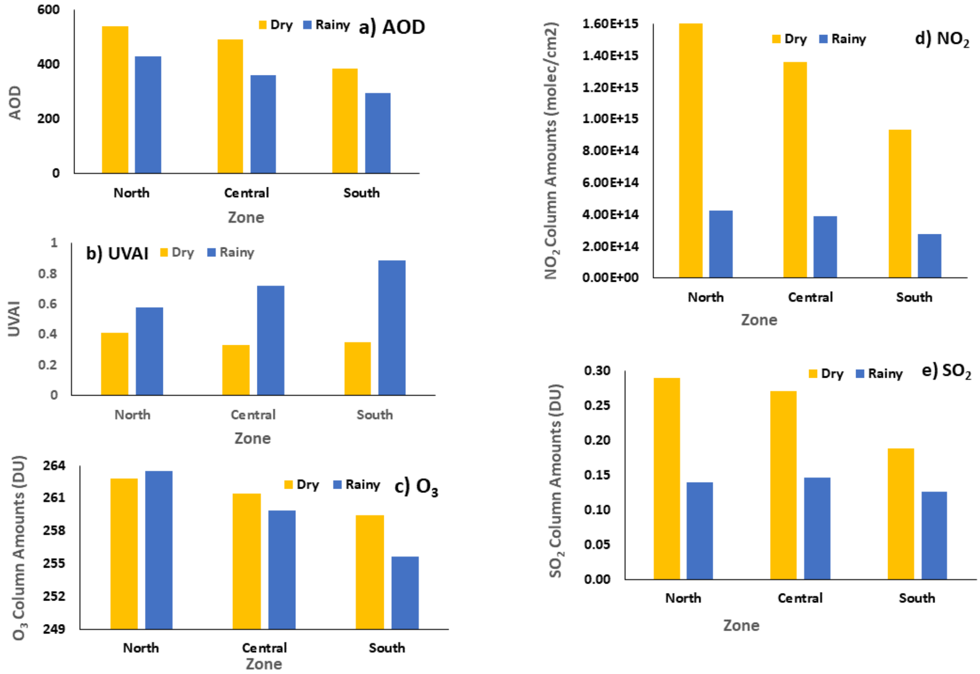
### 5.1.2. Annual variations

Figure 7 presents the yearly and seasonal yearly averages of the pollution indicators for each year of the study period. The UVAI exhibits an increase from 2018 onward. Furthermore, 2015 and 2016 UVAI values are higher in the dry season compared to the rainy season, and this relationship is reversed in 2017. This is also the case for the O3 column amounts, in addition to slightly higher dry season amounts in 2020.

Again, note that the relative differences in $O_3$ column amounts between years (and seasons) are low. The rainy season values for AOD, $NO_2$ and $SO_2$ generally do not show variation, while dry season values are higher at the beginning and end of the study period for AOD and $NO_2$. The possible drivers behind these trends will be discussed further on in this section. Based on the Kruskal-Wallis test, AOD, $SO_2$ and $NO_2$ exhibit significant differences in seasonal yearly values ($p < 0.05$, $p < 0.01$ and $p < 0.01$, respectively). This indicates the variation between seasons of these pollution indicators based on the yearly averages during the study period. Figure 8 presents the averages of the pollution indicators for each zone and year of the study period. $NO_2$ column amounts are consistently the highest (lowest) in the northern (southern) region for all years. $NO_2$ also exhibits the greatest differences between zones, and $O_3$ the least.

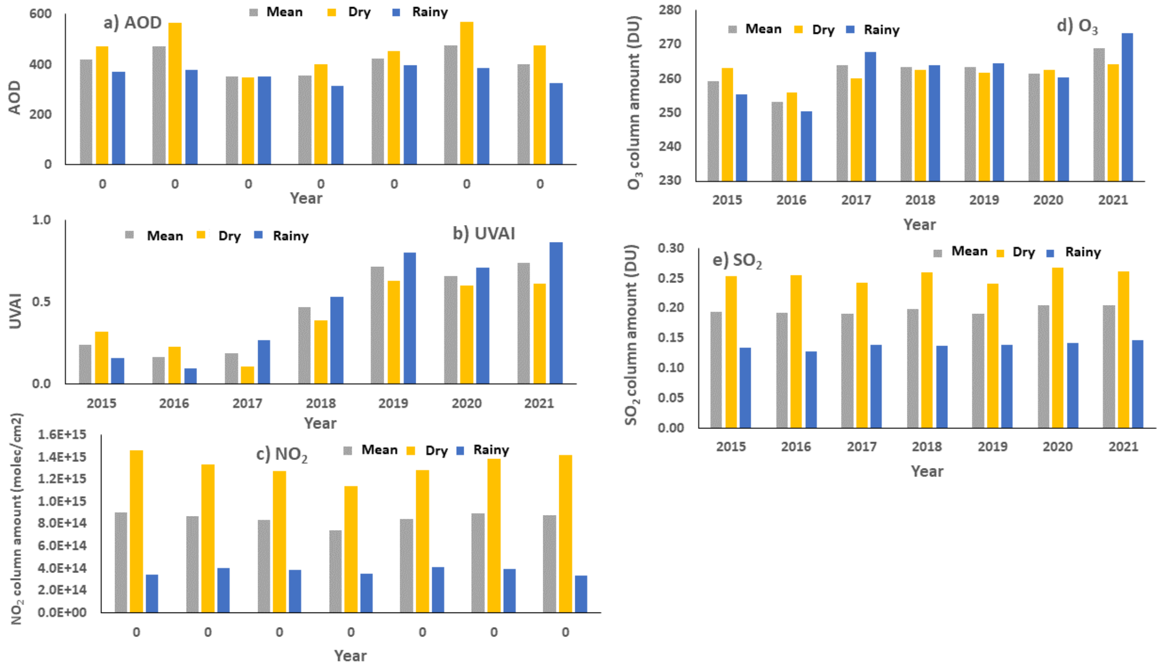
The southern zone consistently exhibits the lowest values for AOD and $SO_2$, and the highest values are almost always in the north. No consistent trend is observed for the zonal values of UVAI across each year.

**Figure 6:** Mean pollution indicators by zone (north, central, south) for the study period (2015–2021). Mean values of a) aerosol optical depth and b) ultraviolet aerosol index and average column amounts of c) ozone; d) nitrogen dioxide and; e) sulphur dioxide




*Source:* Authors' elaboration.

**Figure 7:** Yearly (mean) and seasonal yearly (dry, rainy) averages of pollution indicators for the study period (2015–2021). Mean values of a) aerosol optical depth and b) ultraviolet aerosol index and average column amounts of c) nitrogen dioxide; d) ozone; and e) sulphur dioxide



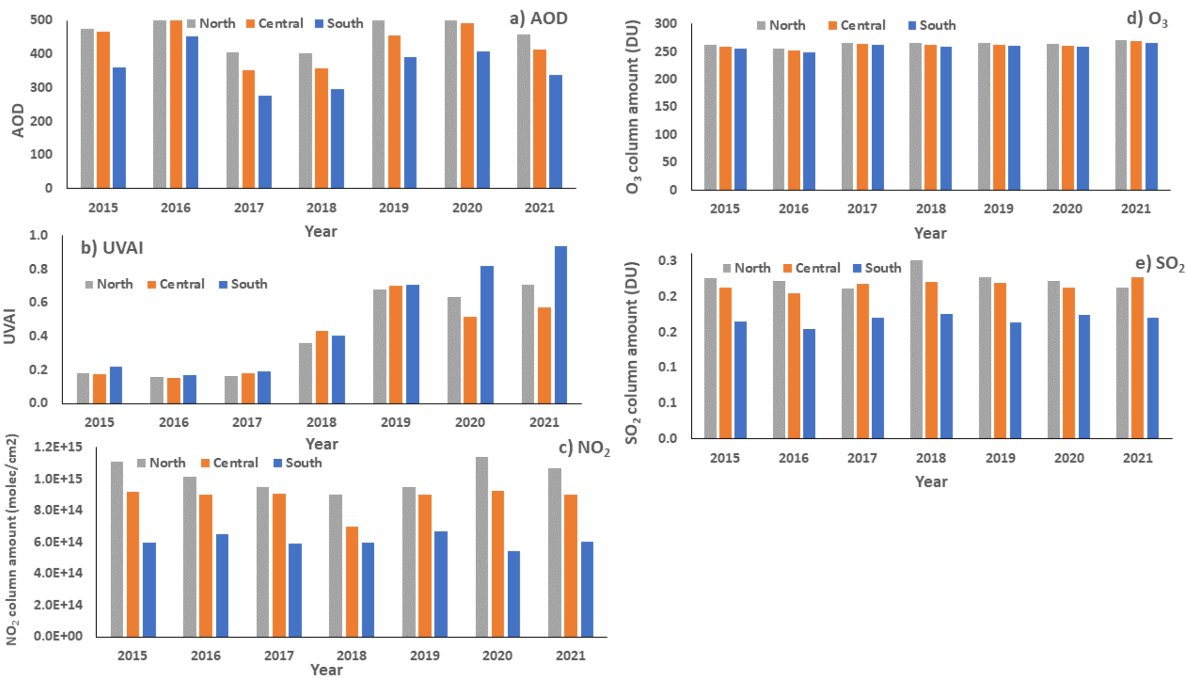

*Source:* Authors’ elaboration.

Based on the Kruskal-Wallis test, $SO_2$, $NO_2$ and AOD exhibit significant differences in zonal values ($p < 0.001$, $p < 0.001$, and $p < 0.05$, respectively). This highlights the variation between the northern, central and southern zones for these pollution indicators based on the yearly averaged values during the study period.

### 5.1.3. Monthly variations

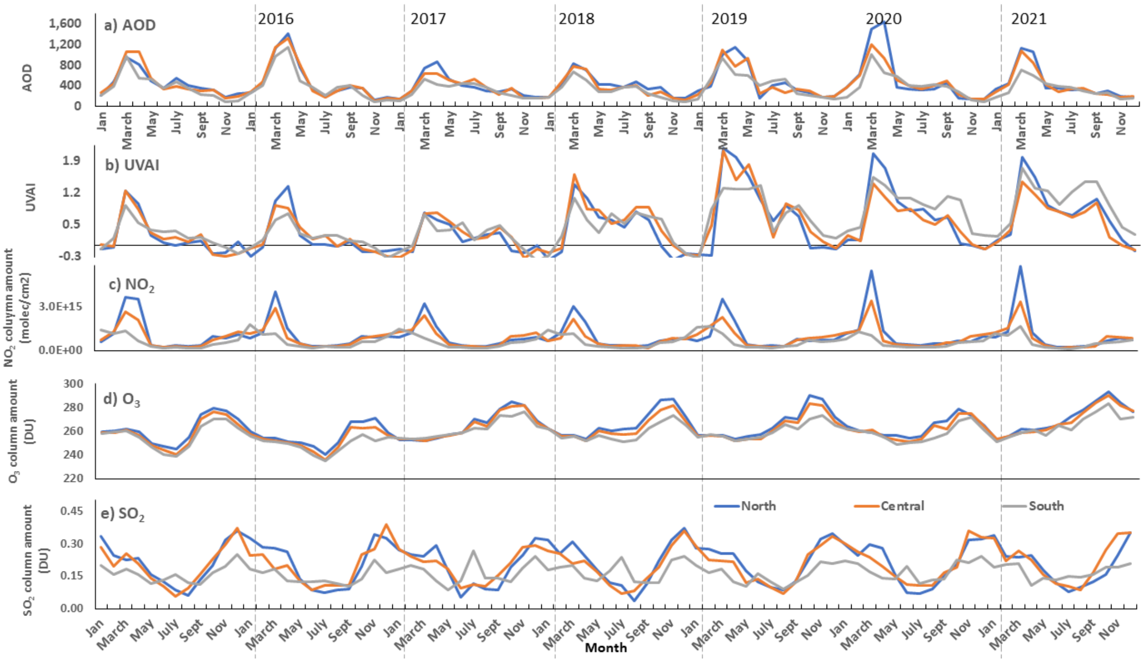
Figure 9 presents the monthly means of the pollution indicators throughout the study period (2015–2021) for each zone (north, central and south). Based on the Kruskal-Wallis test, there are significant differences between monthly values for each of the pollution indicators ($p<0.001$), indicating the monthly variations. Peaks can be observed in March and April for AOD, $NO_2$ and UVAI in all zones (less so in the south for $NO_2$). However, elevated amounts of UVAI continue during the rainy season, particularly for the later years of the study period. A secondary peak in the UVAI emerges as the study period progresses, with especially higher values in the south for 2020–2021. In comparison, $SO_2$ column amounts for the northern and central zones begin to increase at the end of the rainy season/beginning of the dry season (October/November), peaking around December/January and falling at the beginning of the rainy season. This is not true for the $SO_2$ column amounts in the south, which do not exhibit a particular trend. The trend in the north and south may be attributed to emissions from household heating due to colder temperatures (Lin *et al.*, 2019) (the south is generally warmer). The $O_3$ column amounts can be seen to peak around September to November for all zones, and slowly decrease during the beginning of the dry season. Note that although the maximum $O_3$ column amounts are observed for the rainy season in the north of the country (Figure 6), the country-averaged peaks occur at the end of the rainy season and at the beginning of the dry season. It can be observed that there exists a somewhat inverted relationship between the $O_3$ temporal trend and that of AOD, UVAI and $NO_2$, namely the peaks in $O_3$ approximately correspond to the troughs of the latter three pollution indicators and vice versa. In contrast, $SO_2$ and $O_3$ are observed to generally follow the same temporal trend.

**Figure 8:** Yearly averages of pollution indicators for the study period (2015–2021). Mean values of a) aerosol optical depth and b) ultraviolet aerosol index and average column amounts of c) nitrogen dioxide; d) ozone and; e) sulphur dioxide




*Source:* Authors' elaboration.

**Figure 9:** Monthly means of a) aerosol optical depth and b) ultraviolet aerosol index and column amounts of c) nitrogen dioxide; d) ozone and; e) sulphur dioxide for each year of the study period for each zone

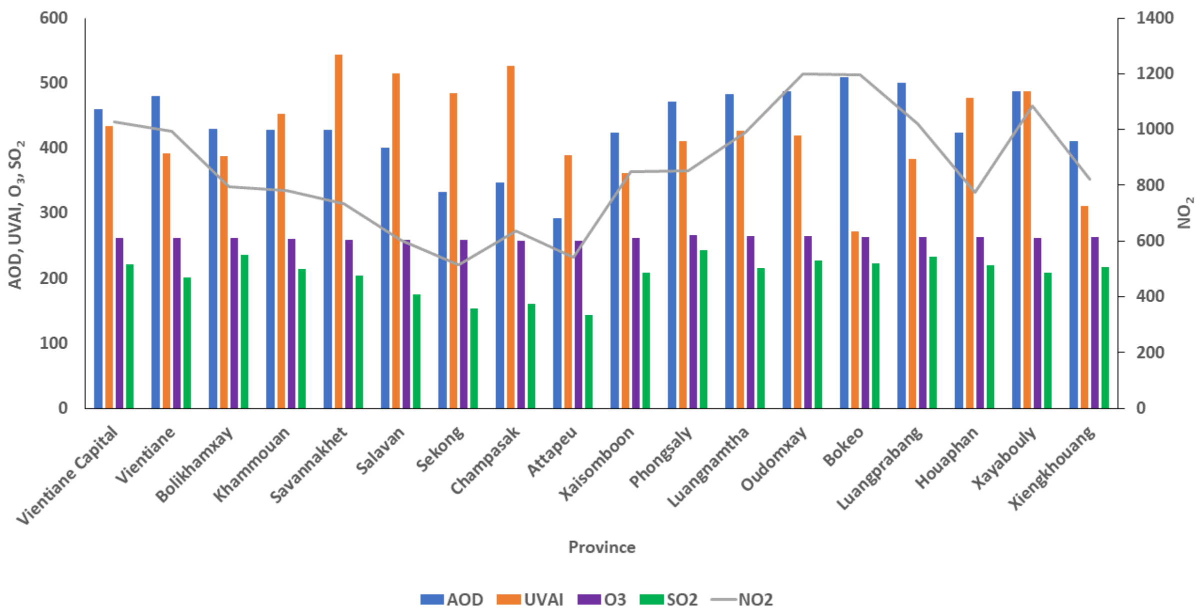



*Source:* Authors' elaboration

## 5.1.4. Provincial variations

Figure 10 presents the yearly means for the study period, respectively, for each province. The relative pollution levels per province varies with the pollution indicator. High values are observed for all pollution indicators for Vientiane Capital in the centre. Other provinces in the centre with relatively higher pollution levels include Vientiane (AOD and $NO_2$), Bolikhamxay ($SO_2$), Xiengkhouang ($SO_2$) and Xaisomboon ($SO_2$ and AOD); and northern provinces include Phongasly ($SO_2$, $O_3$ and AOD), Luangprabang ($SO_2$, AOD, $NO_2$), Bokeo (AOD, $NO_2$ and $SO_2$-some years), and Luangnamtha (AOD, $NO_2$ and UVAI-some years). The southern provinces of Sekong, Saravane, and Savannaket exhibit relatively high values of UVAI (not for all years). In general, as seen in the previous figures, the northern provinces present the highest values of $NO_2$ and AOD, the central (and some northern) provinces dominate for higher $SO_2$ values, and southern and (some northern provinces) exhibit higher UVAI values. Note that all pollution indicators exhibit troughs for the southern province of Attapeu. All pollution indicators demonstrate significant differences in values between provinces (Kruskal-Wallis test: $NO_2$, UVAI, $SO_2$ and AOD $p < 0.001$; $O_3$ $p < 0.05$).

**Figure 10:** Study period means of each province for aerosol optical depth and the ultraviolet aerosol index; and column amounts of ozone, nitrogen dioxide and sulphur dioxide. Note that the pollution indicator values were normalised to fit onto the same graph

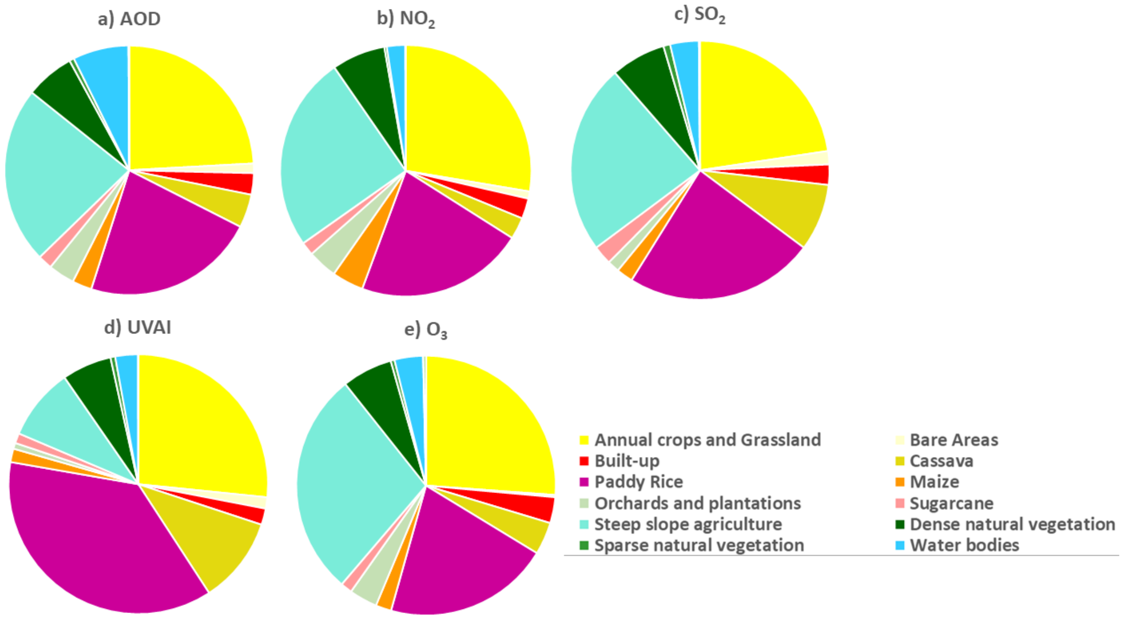



*Source:* Authors' elaboration.

## 5.1.5. Pollution indicators and land cover

In order to gain more insight on the areas that exhibit elevated values of the pollution indicators determined for 2015–2021, the land cover types were mapped for the pixels that exhibited values in the 90th percentile for each pollution indicator (Figure 11). This was performed using the averaged values for the entire study period and the 2018 land cover map from DALaM. Annual crops and grassland are consistently mapped to approximately 25 percent of the areas with elevated pollution indicators. Paddy rice also makes up a consistent percentage (approximately 22 percent), with the exception of UVAI, where the proportion is greater (39 percent). This reflects the positive significant correlation between rice production and the majority of the pollution indicators. Steep slope agriculture also plays a consistent role in the land cover mapped to elevated values of AOD, $NO_2$, $SO_2$ and $O_3$ (approximately 25 percent).

**Figure 11:** Land cover types associated with the values of each pollution indicator in the 90th percentile. a) AOD; b) UVAI; c) $NO_2$; d) $O_3$; and e) $SO_2$



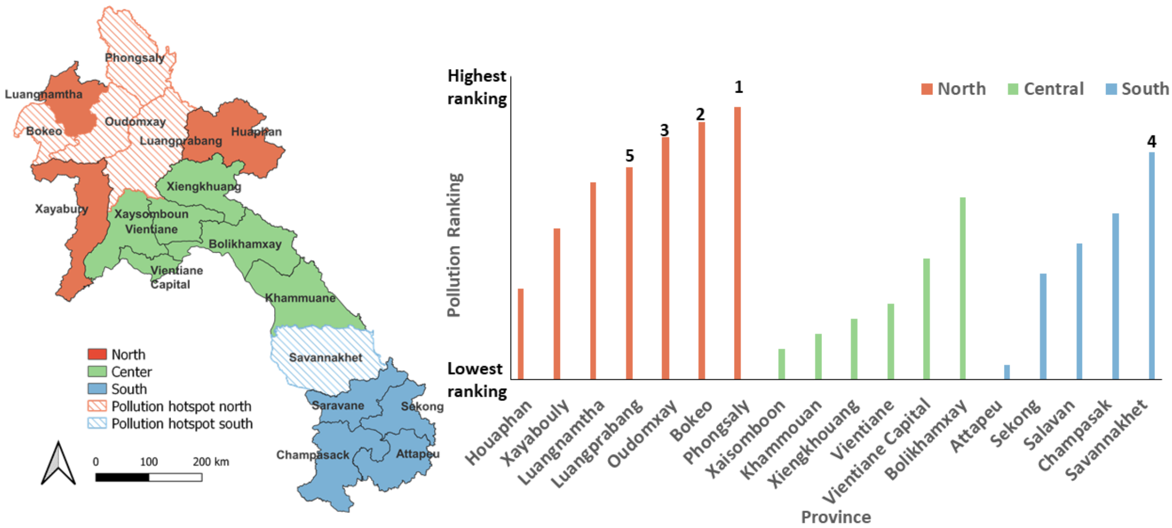

*Source:* Authors' elaboration.

In contrast, the UVAI mapping presents a greater percentage of cassava compared to the other pollution indicators, and a smaller percentage for steep slope agriculture. This agrees with the positive significant correlation between UVAI and starchy root production at the provincial level. Moreover, built-up areas make up approximately 3 percent of the areas mapped to the elevated amounts for all pollution indicators, suggesting urban sources of pollution. Note that water bodies were present in the mapped areas, implying the presence of plumes traversing above water bodies. The trend in land cover types associated with pollution hotspots agrees with the fire presence across cropland classes, namely, annual crops and grassland (31 percent); steep slope agriculture (28 percent); paddy rice (20 percent); cassava (15 percent); and maize (4 percent).

### 5.1.6. Pollution indicator hotspots

The provincial means of all the pollution indicators averaged over the study period were used to select the following five provinces as pollution hotspots: Bokeo; Phongsaly; Oudomxay; Luangprabang; and Savannakhet (Figure 12). This was based on the provinces with the highest values for each pollution indicator. The majority are located in the north, as this zone generally exhibited the highest pollution indicator values, while the selection of Savannakhet in the south is attributed to the elevated UVAI values for this province.

**Figure 12:** Left - the five provinces selected as pollution hotspots, namely Bokeo, Phongsaly, Oudomxay, Luangprabang and Savannakhet, based on the provincial means of each pollution indicator averaged over the study period; right – the provinces ranked in terms of their pollution score




*Source:* Authors' elaboration. Administrative boundaries obtained from National Geographic Department (NGD) of the Lao People's Democratic Republic.

When looking at the individual pollution species, the following pollution hotspots are obtained based on the corresponding provincial means averaged over the study period:

- $NO_2$: Oudomxay, Bokeo, Xayabouly, Vientiane Capital and Luangprabang.
- $SO_2$: Phongsaly, Bolikhamxay, Luangprabang, Oudomxay, and Bokeo.
- $O_3$: Phongsaly, Luangnamtha, Oudomxay, Bokeo, and Luangprabang.
- AOD: Bokeo, Luangprabang, Xayabouly, Oudomxay, and Luangnamtha.
- UVAI: Savannakhet, Champasak, Salavan, Xayabouly, and Sekong.

$NO_2$, $SO_2$, $O_3$ and AOD share common hotspots, however the provinces selected as the pollution hotspots for UVAI are distinct to those of the other pollution indicators, with the exception of Xayabouly (which was selected for $NO_2$, AOD and UVAI).

## 5.2. Exploring the potential drivers of the pollution indicators

Key Messages:

1. Climate, agriculture production and fire activity are the key drivers of the pollution indicators.
2. The northern zone of the Lao People's Democratic Republic consistently presents the most fire activity across the study period.
3. Luangprabang, Oudomxay, Huaphan, Xayabury, and Phongsaly are forest fire hotspots; and Luangprabang, Xayabury, Vientiane, Savannakhet, and Oudomxay are crop fire hotspots.
4. Trajectory modelling reveals the potential of transboundary pollution to the Lao People's Democratic Republic from neighbouring countries.

### 5.2.1. Relationship between pollution indicators and potential drivers

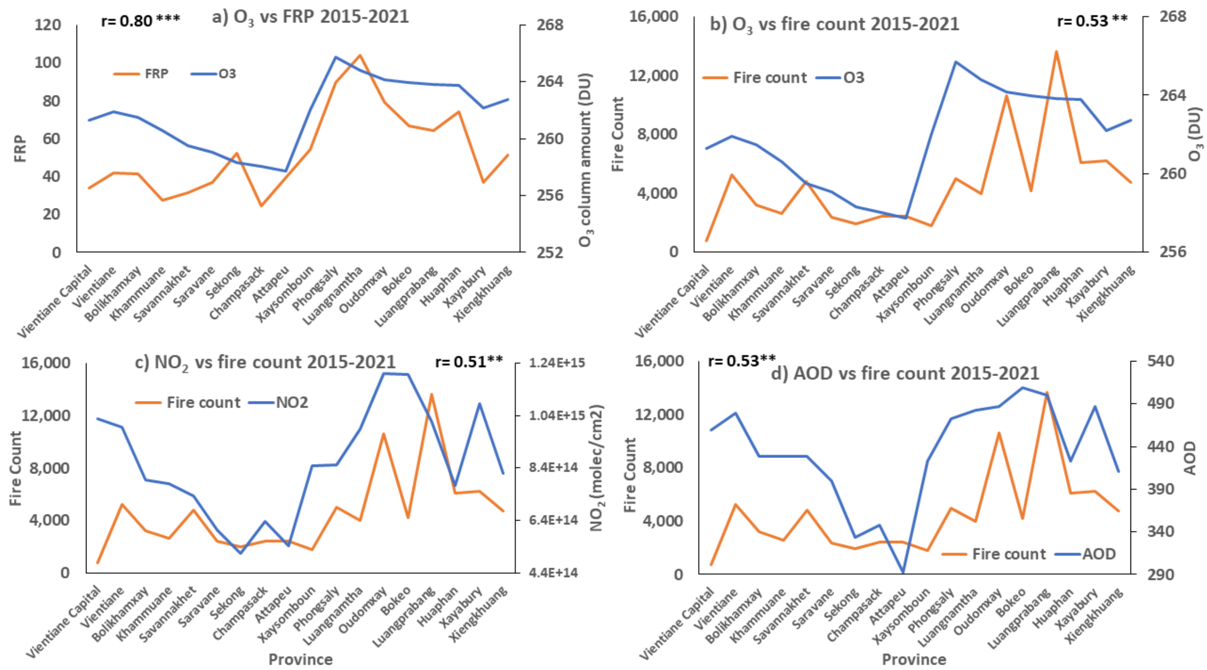
To identify the potential sources and underlying mechanisms of the pollution indicators in this work, the provincial means of the pollution indicator levels and the potential drivers across the study period were compared (see Appendix 1 for corresponding maps). The Pearson correlation coefficient was used to determine the statistical significance of the relationships identified amongst variables (Table 1 in Appendix 1).

$NO_2$, AOD and $O_3$ present significant positive correlations with both FRP and fire count (Figure 13). The highest provincial means of FRP and fire count are concentrated in the north of the Lao People's Democratic Republic, as is the case for the aforementioned pollution indicators. Numerous studies report $NO_2$ to be released from biomass burning (e.g. Schreier *et al.*, 2014), while AOD is also frequently associated with vegetation fires (e.g. Butt *et al.*, 2018; Vadrevu *et al.*, 2015). Vadrevu *et al.* (2015) also reported AOD-fire count correlations to be stronger for forest, plantation and peat fires compared to agricultural systems. Although $O_3$ is not directly emitted from biomass burning, its precursors are (e.g. $NO_2$, $CH_4$, and VOCs), and their presence in the atmosphere can consequently enhance tropospheric ozone levels (Wang *et al.*, 2018a). Note that $SO_2$ and UVAI are not significantly correlated with FRP or fire count, as the relatively higher provincial means are distributed more in the central and southern zones, respectively. Previous studies report elevated $SO_2$ levels over industrial regions (e.g. Lin *et al.*, 2019). Here, although $SO_2$ provincial means are not significantly correlated with industrial activity, the province of Bolikhamxay presents peak values of both $SO_2$ and industrial activity. Vadrevu *et al.* (2015) determined a significant positive correlation between FC and UVAI in the Lao People's Democratic Republic, and suggested UVAI to be a better indicator of forest, plantation and peatland fires in Asia compared to agricultural fires. It is also important to note the lack of up-to-date and complete information on industrial, mining and energy activity used in this analysis.

$O_3$ provincial mean column amounts are observed to have a strong relationship with climate, with significant correlations with sunshine duration, temperature and maximum relative humidity. $O_3$ is formed when sunlight is present via reactions between $NO_X$ and VOCs (McClure and Jaffe, 2018). In addition, $O_3$ concentrations are typically reported to be higher with higher temperatures and lower relative humidity. However, the opposite is true here, whereby higher $O_3$ column amounts are observed in the north of the Lao People's Democratic Republic, where temperatures and sunshine duration are relatively lower and relative humidity is higher. This may suggest the strong impact of the fire emissions in the north on $O_3$ column amounts. The enhancement of tropospheric $O_3$ has been linked to the release of $O_3$ precursors (e.g. $NO_X$, VOCs, NMHCs) (Jin and Holloway, 2015; Wei *et al.*, 2019b; Ziemke *et al.*, 2006), which are released by biomass burning. $SO_2$ is also negatively correlated with sunshine duration and temperature. Temperatures can vary on sunny days, resulting in a strong vertical convection, which can subsequently enhance the diffusion of atmospheric pollutants (Wu *et al.*, 2022). AOD and $NO_2$ are positively correlated with accumulated rainfall, which is likely to be linked to the lack of fires occurring during the rainy season, as well as the removal of these pollutants by the rain. UVAI exhibits a significant positive correlation with temperature (maximum and minimum), corresponding to the elevated values of this pollution indicator in the warmer regions of the country.

The significant positive correlation between UVAI and population may indicate non-biomass burning sources of atmospheric aerosols. Moreover, UVAI presents the strongest relationship with agricultural production, with significant correlations with lowland rice, dry season rice and starchy roots production, linked to the higher cultivation of these crops in the centre and south of the country relative to the north. Similarly, $SO_2$, AOD and $O_3$ are positively correlated with upland rainfed paddy, while $NO_2$ presents a positive relationship with maize. These crops are mainly produced in the northern region of the Lao People's Democratic Republic. Both $NO_2$ and $O_3$ are negatively correlated with dry season paddy production, and the same is also true for $O_3$ and lowland rice production. This is associated with the relatively lower production of these crops in the northern region of the Lao People's Democratic Republic.

**Figure 13:** Relationship between trends in provincial means (2015–2021) of a) FRP and $O_3$; b) fire count and $O_3$; c) fire count and $NO_2$; and d) fire count and AOD




*Source:* Authors' elaboration.

The relationships between pollution indicators and potential drivers varies when each zone (northern, central, southern) are considered separately (Table 1 in Appendix 1). For example, significant relationships with fire activity are observed just for $O_3$ in the north and centre (with FRP), and $NO_2$ and $SO_2$ with fire count in the south. The influence of climate on the pollution indicators is maintained in all zones. Moreover, both $SO_2$ and $NO_2$ exhibit a positive significant correlation with population and transport in the south of the Lao People's Democratic Republic. The southern region also exhibits the strongest relation between pollution indicators and agricultural activity, particularly for lowland rice and dry season paddy production.

In order to investigate the influence of the potential drivers on the pollution indicators across time, Table 4 presents the correlation between the two variable types based on their yearly means. Note that the industry, energy and mining activities were excluded from this analysis as the datasets were not available on a yearly basis. AOD and $NO_2$ present a significant relationship with fire count. Previous research has reported stronger AOD correlations with fire count compared to FRP (Vadrevu *et al.*, 2015). The influence of climate on the pollution indicators is present, but not as strong compared to the trends at the provincial level. $NO_2$ yearly column amounts are significantly (positively) associated with the production of lowland rice, dry season paddy, upland rainfed paddy and sugarcane. UVAI exhibits a positive significant correlation with starchy root production, transport and population.

**Table 4:** Pearson correlation between pollution indicators and potential drivers based on annual means for whole study area, considering available data (climate and fire datasets 2015–2021; agriculture datasets 2015–2019; transport dataset 2016–2020; population dataset 2015–2020). ***, ** and * denote significance levels of $p < 0.01$, 0.05 and 0.1, respectively. n=7

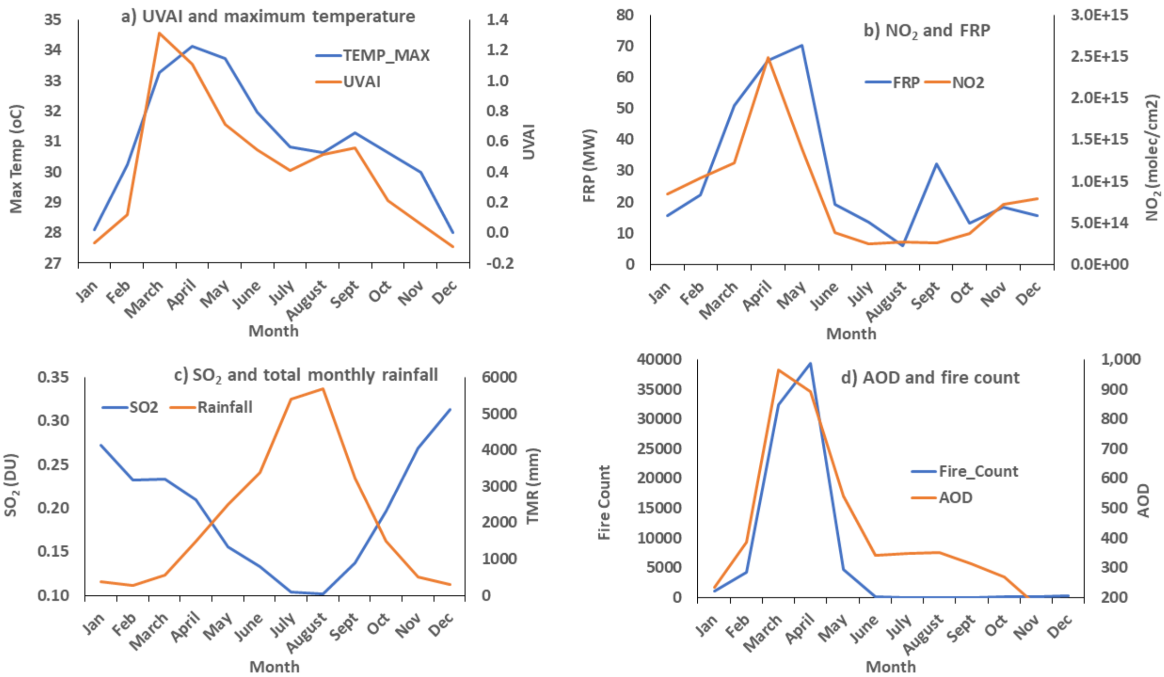
| | UVAI | AOD | $NO_2$ | $O_3$ | $SO_2$ |
|---|---|---|---|---|---|
| Temperature minimum | -0.46 | 0.71 | 0.63 | -0.77** | 0.10 |
| Temperature maximum | 0.04 | 0.74 | 0.80** | -0.39 | -0.28 |
| Relative humidity minimum | -0.67* | -0.60 | -0.39 | 0.02 | -0.10 |
| Relative humidity maximum | -0.78** | -0.62 | -0.35 | -0.03 | -0.37 |
| Accumulative rainfall | -0.24 | -0.59 | -0.71* | 0.14 | 0.27 |
| Sunshine duration | 0.58 | 0.54 | 0.67* | 0.14 | 0.08 |
| Fire count | 0.24 | 0.70* | 0.79** | -0.24 | -0.10 |
| FRP | -0.14 | 0.24 | 0.30 | -0.13 | -0.29 |
| Lowland rice | -0.83** | 0.42 | 0.78** | -0.57 | -0.60 |
| Dry season paddy | -0.63 | 0.61 | 0.94*** | -0.60 | -0.61 |
| Upland rainfed paddy | -0.55 | -0.78** | -0.41 | 0.31 | 0.32 |
| Maize | -0.76** | 0.58 | 0.86** | -0.69* | -0.53 |
| Starchy roots | 0.90*** | 0.36 | -0.08 | 0.12 | -0.01 |
| Sugarcane | -0.69* | 0.60 | 0.91*** | -0.63 | -0.63 |
| Transport | 0.93*** | 0.24 | 0.23 | 0.38 | 0.63 |
| Population | 0.79** | 0.09 | -0.28 | 0.32 | 0.49 |

The temporal influence of the potential drivers were further investigated by determining their correlation with pollution indicators based on the corresponding monthly means (Table 5 and Figure 14). Note that just the fire activity and climate variables were included for this analysis, as monthly datasets were not available for the remaining pollution indicators. The $NO_2$, UVAI and AOD monthly means are significantly positively correlated with FRP and fire count. This is not the case for $SO_2$ and $O_3$, however these two gases are strongly negatively correlated with accumulated rainfall. This is consistent with the literature, whereby rain can clear the atmosphere from pollutants, but also cause acid rain in the presence of $SO_2$ (e.g. Ranaarif and Yuwono, 2021). AOD, $NO_2$ and UVAI are strongly correlated with wind speed, which may indicate the transport of these pollutants from other areas. Sunshine duration exhibits a significant (positive) relationship with $SO_2$, $NO_2$ and $O_3$ monthly averaged column amounts.

**Table 5:** Pearson correlation between pollution indicators and potential drivers. Based on monthly averages for the whole study period (2015–2021). ***, ** and * denote significance levels of $p < 0.01$, 0.05 and 0.1, respectively. n=12

| | UVAI | AOD | $SO_2$ | $NO_2$ | $O_3$ |
|---|---|---|---|---|---|
| FRP | 0.73*** | 0.78*** | 0.00 | 0.80*** | -0.12 |
| Fire count | 0.79*** | 0.93*** | 0.17 | 0.82*** | 0.02 |
| Accumulative rainfall | 0.20 | -0.08 | -0.92*** | -0.46 | -0.80*** |
| Temperature minimum | 0.91*** | 0.82*** | -0.45 | 0.53 | -0.43 |
| Temperature maximum | 0.53* | 0.21 | -0.88*** | -0.17 | -0.69** |
| Windspeed | 0.59** | 0.66** | -0.11 | 0.66** | -0.17 |
| Relative humidity minimum | -0.16 | -0.49 | -0.73*** | -0.74*** | -0.53* |
| Relative humidity maximum | -0.46 | -0.73*** | -0.51* | -0.89*** | -0.33 |
| Sunshine duration | -0.15 | 0.16 | 0.82*** | 0.61** | 0.68** |

**Figure 14:** Relationship between trends in monthly means (2015–2021) of a) UVAI and maximum temperature; b) $NO_2$ and FRP; c) $SO_2$ and total monthly rainfall; and d) AOD and fire count




*Source:* Authors' elaboration.

This agrees with the favourable role of sunshine hours in the formation of ozone. Furthermore, temperature and relative humidity are implied to play a significant role in the monthly trends of the pollution indicators. Higher temperatures are associated with lower $SO_2$ and $O_3$ column amounts and vice versa for AOD and UVAI. Higher temperatures and relative humidity facilitate the conversion of $SO_2$ into sulphate (Lin *et al.*, 2019). Also, higher amounts of $SO_2$ during cooler temperatures may be linked to household heating. Moreover, higher temperatures facilitate photochemical reactions that are linked to AOD (Heng *et al.*, 2021). The $O_3$ depletion cycle (the conversion of ozone into atomic and molecular oxygen) is linked to seasonal transportation, photochemical reactions and ozone depletion, where the latter encapsulates multiple processes that involve climatic variables and gases in the atmosphere.

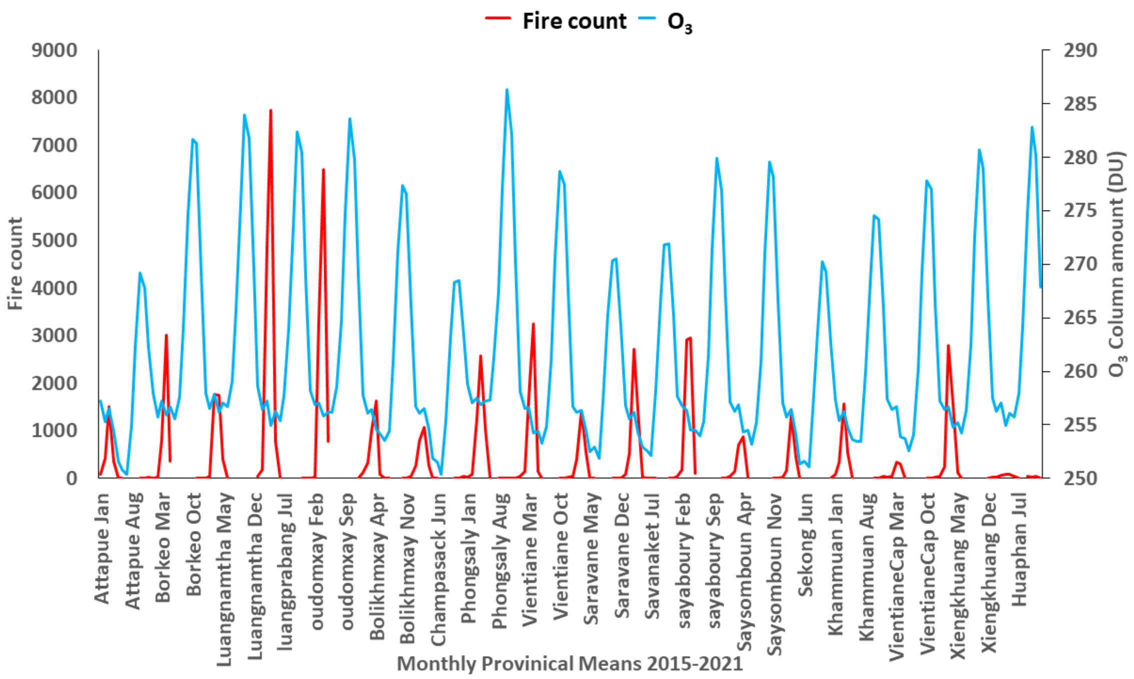
Further analysis was performed to investigate the relationship between the pollution indicators and potential drivers based on the provincial monthly means (Table 6). This analysis was only performed on the pollution indicator, climate and fire data as the temporal resolution of the remaining datasets was too coarse (1 year or more). All pollution indicators exhibit strong correlations with the climatic variables. In particular, the gaseous species are negatively correlated with temperature, while the opposite is true for the aerosol species. This could be attributed to the chemical reactions occurring in the atmosphere at higher temperatures, reducing the amount of $NO_2$, $O_3$ and $SO_2$ in the atmospheric columns. With the exception of $O_3$, relative humidity is negatively correlated with the pollution indicators, which agrees with previous research. Che *et al.* (2019) reported a negative relationship between aerosols and relative humidity in areas where biomass burning occurs frequently. Lin *et al.* (2019) linked higher temperatures and relative humidity to the conversion of $SO_2$ and $NO_2$ to sulphur and nitrate, respectively. The positive significant relationship between relative humidity and $O_3$ column amounts requires further investigation. The negative relationship typically observed between these two variables is linked to the lower amount of solar radiation and more wet deposition at a high relative humidity, both of which inhibit $O_3$ production, particularly at cooler temperatures (Shi *et al.*, 2022).

Apart from $SO_2$, all other pollution indicators exhibit a significant correlation with fire count and FRP. Note that $O_3$ is negatively correlated with the fire variables. $O_3$ is not directly emitted from biomass fires, however its precursors are, thus there is a time lag between the fire activity and the formation of $O_3$, which can be observed in Figure 15, revealing the offset between the fire activity and $O_3$ peaks.

**Table 6:** Pearson correlation between pollution indicators and potential drivers. Based on provincial monthly means for the whole study period (2015–2021). ***, ** and * denote significance levels of $p < 0.01$, 0.05 and 0.1, respectively. n = 216

| | UVAI | AOD | $NO_2$ | $O_3$ | $SO_2$ |
|---|---|---|---|---|---|
| Temperature minimum | 0.40*** | 0.09 | -0.41*** | -0.19*** | -0.65*** |
| Temperature Maximum | 0.51*** | 0.40*** | 0.07 | -0.32*** | -0.36*** |
| Relative humidity minimum | -0.10 | -0.38*** | -0.65*** | 0.20*** | -0.52*** |
| Relative humidity maximum | -0.18*** | -0.23*** | -0.18*** | 0.25*** | -0.13* |
| Accumulative rainfall | 0.22*** | -0.04 | -0.45*** | -0.20*** | -0.61*** |
| Sunshine duration | -0.12* | 0.07 | 0.37*** | -0.03 | 0.47*** |
| Wind speed | 0.12* | 0.15** | 0.09 | -0.11 | -0.05 |
| Fire count | 0.61*** | 0.72*** | 0.58*** | -0.24*** | 0.10 |
| FRP | 0.60*** | 0.66*** | 0.39*** | -0.33*** | -0.07 |

**Figure 15:** Monthly provincial means of fire count and $O_3$ column amounts (DU) across the study period (2015–2021)




*Source:* Authors' elaboration

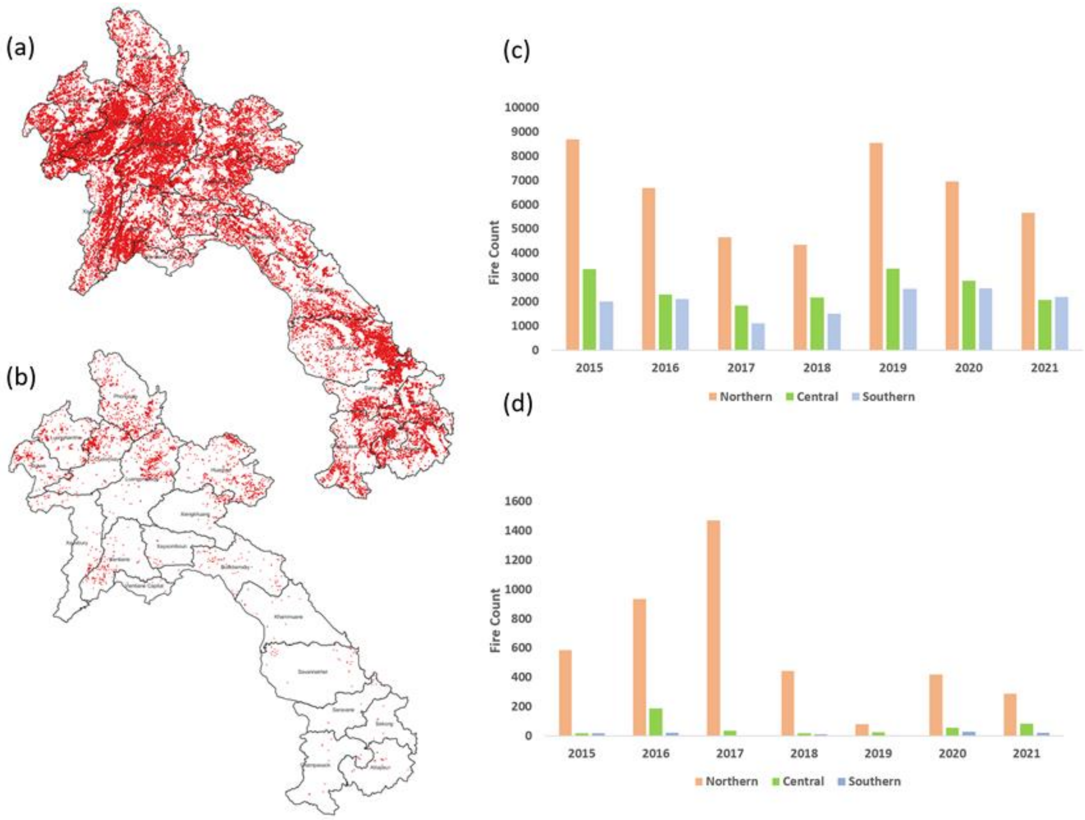
### 5.2.2. Monitoring fires

Fire archive data was analysed at the national and provincial scale for the study period to understand the spatial and temporal trends in the Lao People's Democratic Republic. Moreover, the detected fires were used as a proxy to understand the pollution dynamics in the country and their contribution to local air quality.

#### 5.2.2.1. Trend analysis

The spatial distribution of fires was studied separately for the dry and v seasons in the country to better estimate the trends at the national scale. Figure 16 presents two maps displaying the fire locations in the Lao People's Democratic Republic over the study period, as well as the trends at the regional scales by seasons. The highest number of fires are observed in the north of the country, which agrees with the zonal analysis of this project. The northern zone of the country is always dominated in terms of fire presence over the study period, followed by the central and southern zone. The fires detected in the rainy season are attributed to the prolonged fire season in the northern zone, which ends in May.

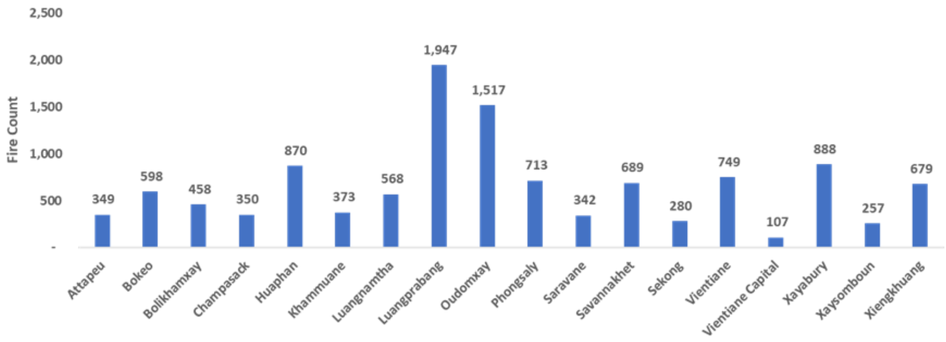
**Figure 16:** Spatial and temporal distribution of fires. (a) Dry season (November–April) fire distribution over study period, (b) rainy season (May–October) fire distribution over study period, (c) annual trend of dry season fires by regions, and (d) annual trend of rainy season fires by regions




*Source:* Authors' elaboration. Administrative boundaries obtained from National Geographic Department (NGD) of the Lao People's Democratic Republic.

Figure 17 presents the average number of fire events observed in the Lao People's Democratic Republic at the provincial scale. The northern province of Luangprabang has the highest number of fires (1,947 averaged over the study period), while the lowest number of fires (107 averaged over the study period) were detected in Vientiane Capital.

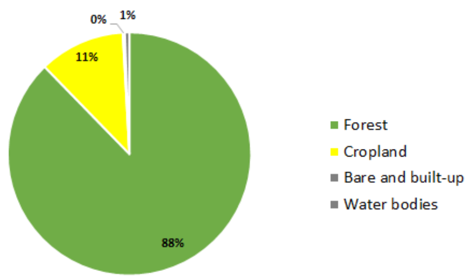
**Figure 17:** Average fire events observed over study period of 2015–2021 for each province

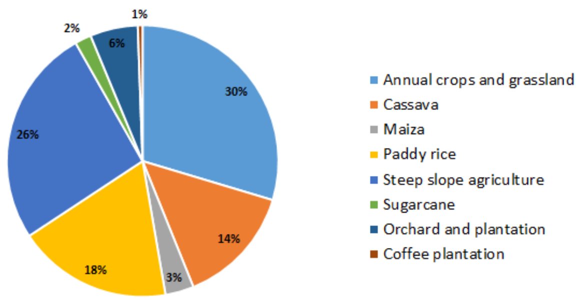



*Source:* Authors' elaboration.

The numerous fires observed in the rainy season are attributed to the seasonal definition used in the project context. Almost all of the rainy season fires occur in the month of May in the northern region of the country. The fire season in the north starts in late February and lasts until the end of May (Figure 19), whereas in the south and central of the Lao People's Democratic Republic, the fire season begins in January and ends in April. However, the peak fire activity months are March and April in the country. Fires are part of the cropping cycle in the Lao People's Democratic Republic  and are widely practised by the farmers, typically once a year. Farmers ignite fires for different reasons, but most common are to prepare the land for cultivation and to burn the crop residue.

**Figure 18:** Presence of fires by land cover classes, mainly forest land cropland categories




*Source:* Authors' elaboration.

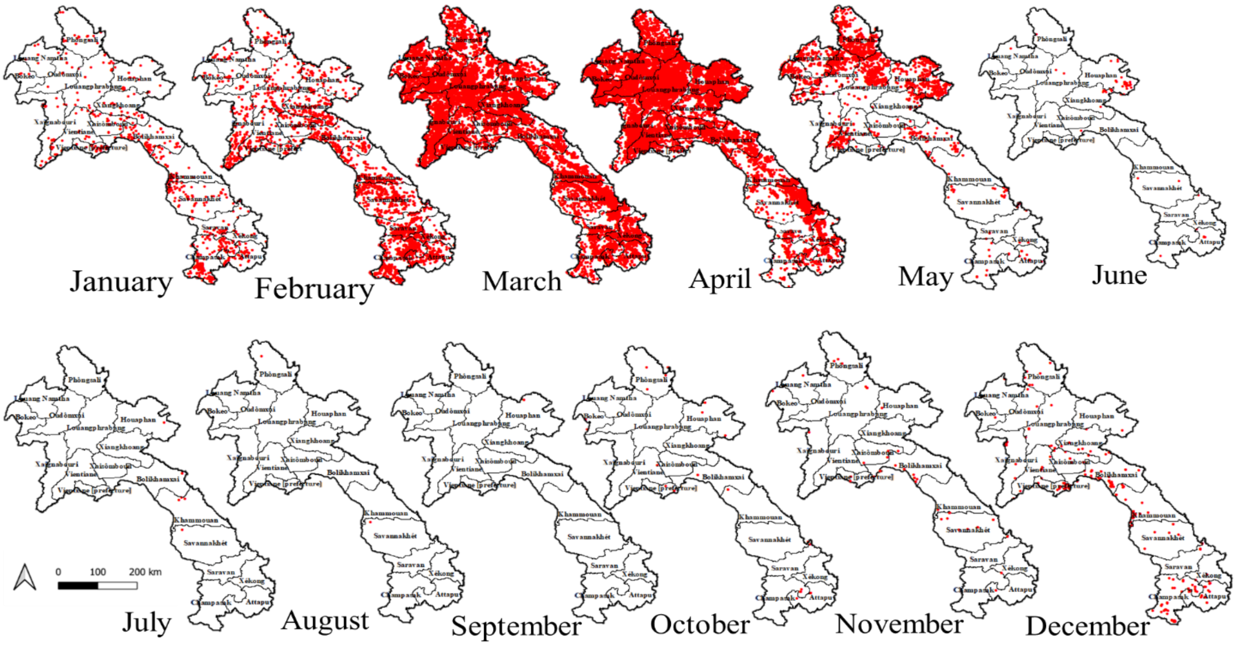
Figure 18 shows the presence of fires by land cover classes in the Lao People's Democratic Republic. Most of the fires are detected in the forest class, whereas only 10 percent of fires are linked to the agricultural sector. The distribution of fires by cropland categories reveals fires to be distributed across the country and occurring on all cropland types. Moreover, 88 percent of forest fires were further studied using the 2015 forest cover map from the Lao People's Democratic Republic Forestry Department. The results reveal that almost half of these fires come from the regenerated class (forest regrowth). The regenerated class includes all the regrowth activities in the country including those from fallow land. Therefore, it is hard to exactly quantify the contribution of cropland in this scenario. Clearly defining the classes will be useful to precisely calculate emissions from cropland.

Annual analysis over the provinces by land cover classes was performed using the land cover maps from different sources, namely, the 2015 forest cover map and the 2018 land cover map. The results exhibit a homogeneous pattern in forest land, whereas cropland trends are also almost identical, with a few exceptions. In 2015, the low land area exhibited an elevated number of fires when compared to other years. The same trend is observed for 2017 for the upper land area. The highest number of fires are observed in the forest land class, which could indicate the ongoing disturbance in the forest land, as in most cases, it is very hard to differentiate forest and fellow land, especially for short temporal periods.

#### 5.2.2.2. Fire season in the Lao People's Democratic Republic

According to different studies (London, 2003), March and April are the peak fire months in the country, although an in-depth analysis in this work discovered that it slightly varies in the north and south areas of the country, extending from February to May. However, March and April remain the key fire season months in the Lao People's Democratic Republic. Over the past five years, the fire alert analysis discloses that the fire season is slightly shifting backwards, with a decline in fire events in May in the upper land area, while in the central and lower land areas, there is a marginally increasing trend in February (Table 7). In the months of June–December, no significant fire events were recorded in the country.

**Figure 19:** Monthly fire events at the national scale




*Source:* Authors' elaboration. Administrative boundaries obtained from National Geographic Department (NGD) of Lao People's Democratic Republic.

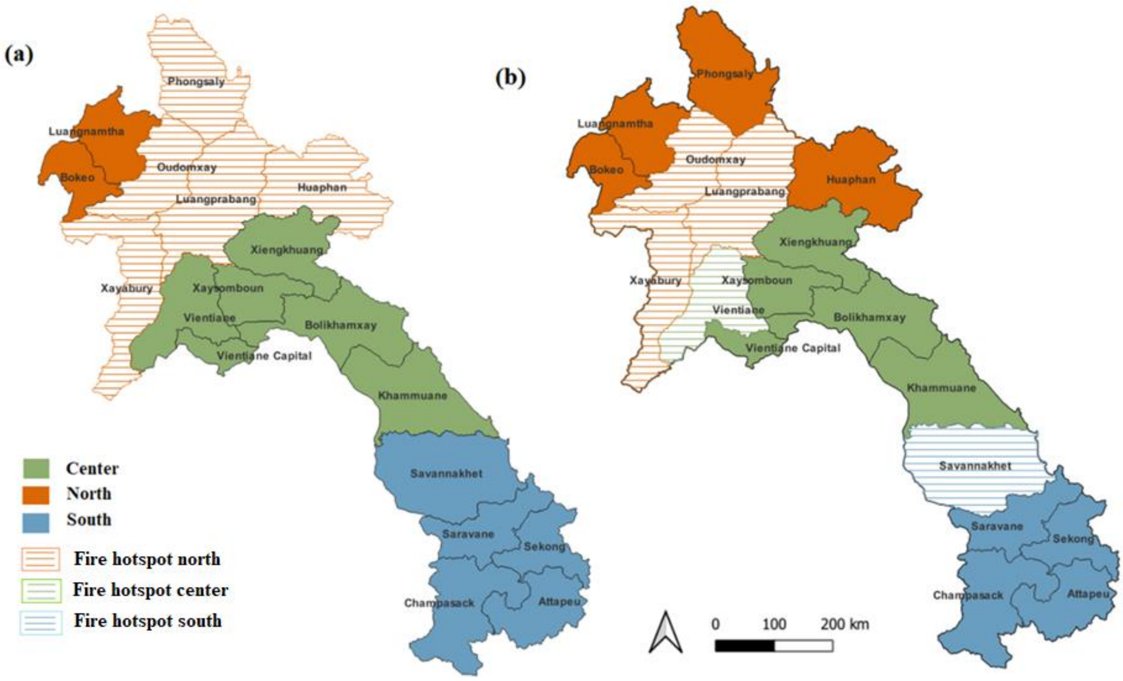
## 5.2.2.3. Fire hotspots

The latest available land cover map from DALaM was used to study the presence of fires by land cover classes, particularly in cropland areas. The map has 14 classes in total, with seven different cropland classes. The limitation of the map was it doesn't distinguish annual crops from grassland. Whereas regrowth on fallow land was also clearly defined here. Yet, this was the latest land cover data available from the country. Therefore, it was used in combination with fire information to identify the fire hotspots in two major classes namely, forest and cropland (including grassland). Fire presence was analysed by provinces and land cover classes, and the top five provinces with the highest number of fires were selected as fire hotspots in both the agriculture and forest classes. Although most fires (89 percent) were observed in the forest class. The 2015 forest cover map from forest department combines fallow land with potential regrowth project areas. The forest department is also working on the 2019 map; however, this was not available at the time of analysis. Therefore the 2018 land cover map was used.

**Table 7:** Seasonal variation of fires over study period (2015–2021)

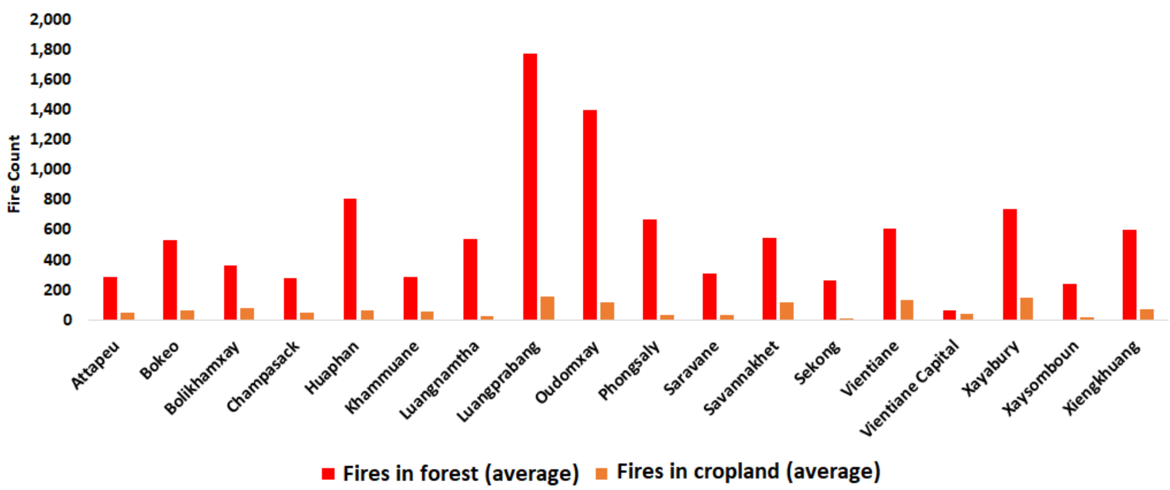
| Month | 2015 | 2016 | 2017 | 2018 | 2019 | 2020 | 2021 | Average |
|---|---|---|---|---|---|---|---|---|
| Jan | 191 | 51 | 62 | 85 | 231 | 256 | 171 | 150 |
| Feb | 339 | 370 | 253 | 446 | 1,120 | 1,134 | 607 | 610 |
| Mar | 4470 | 3060 | 2469 | 2115 | 7695 | 7780 | 4821 | 4630 |
| Apr | 8980 | 7567 | 4762 | 5333 | 5273 | 3161 | 4271 | 5621 |
| May | 594 | 1084 | 1508 | 461 | 92 | 490 | 385 | 659 |
| Jun | 3 | 57 | 2 | 1 | 8 | 12 | 6 | 13 |
| Jul | 4 | | | 1 | | 2 | | 2 |
| Aug | 1 | 1 | | | | | | 1 |
| Sep | | | | | 2 | | 2 | 2 |
| Oct | 13 | 1 | | 7 | 9 | | | 8 |
| Nov | 1 | 1 | 3 | 9 | 23 | 5 | 6 | 7 |
| Dec | 32 | 23 | 38 | 25 | 81 | 30 | 46 | 39 |

**Figure 20:** Distribution of fire hotspots at provincial scale in Lao People's Democratic Republic by land cover classes namely (a) forest and (b) cropland




*Source:* Authors' elaboration. Administrative boundaries obtained from National Geographic Department (NGD) of Lao People's Democratic Republic.

**Figure 21:** Graphical distribution of the fires by the forest and cropland classes at provincial scale based on land cover 2018 map




*Source:* Authors' elaboration.

The fire data was further grouped by agriculture classes including maize, corn, cassava, steep slope, rice paddy and all other crops and forest categories (dense and sparse vegetation and plantation classes) from the 2018 map. Based on provincial statistical analysis by land cover classes, hotspots in both forest and cropland are identified separately. The provinces Luangprabang, Oudomxay, Huaphan, Xayabury, and Phongsaly are identified as forest fire hotspots in respective order. The highest number of fires are observed in Luangprabang, Xayabury, Vientiane, Savannakhet, and Oudomxay in the cropland class. The provinces Luangprabnag, Oudomxay and Xayabury are identified in both categories, but in a different order (Figure 20). These hotspots are identified based on fire presence in different land cover classes and are also observed with the highest number of fires over the study period. Thus, it is difficult to quantify the total contribution of fires emissions from cropland and forest classes using these datasets.

### 5.2.2.4. Time series analysis

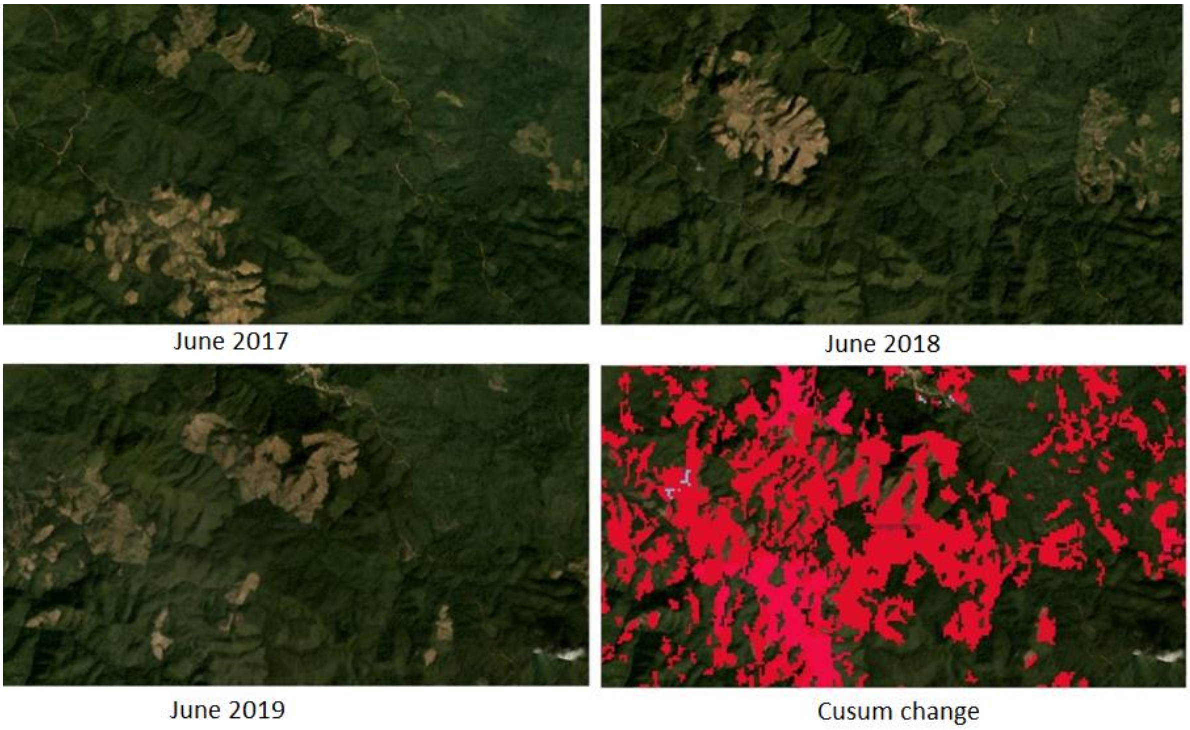
Time series analysis was performed on selected hotspots to map the fire events and changes related to cropland. Sentinel-1 data from 2015 to 2021 was downloaded using the time series download application in SEPAL (https://sepal.io/) and processed using the CUSUM (time series analysis application). The application uses the first available image as the historic period and subsequently monitors changes in the given data. The output comes in the form of a three-band image, where band one records the date of change, band two shows the confidence and third band stores the change value magnitude.

It is well understood by the scientific community that all changes from the time series analysis are not true changes. Therefore, the output was visually interpreted using planet high resolution imagery, revealing that all pixels with a confidence interval range greater than or equal to 0.72 show true changes and fire events. Consequently, all remaining pixels were removed to reduce the over estimations and false events.

### 5.2.2.5. Deforestation

Deforestation in this context is defined as any removal of forest vegetation with land use change. A forest mask from the 2015 land cover map was used as a base layer. All changes mapped over the forest layer were marked as deforested pixels.

**Figure 22:** Example of forest changes over different time periods and land use changes




*Source:* Authors' elaboration. Planet NICFI satellite imagery from https://www.planet.com/nicfi/

Figure 22 shows an example of slash and burn activity over time, detected as a change pixel in CUSUM. The majority of the deforestation captured in this context is the conversion of forest to cropland. Fires are used by farmers as a normal practice to clear land before sowing. Although traces of fires cannot be observed due to limitations in the remote sensing data, they are still activity happening.

### 5.2.3. Pollution hotspots and potential drivers

Section 5.1.6. identifies Bokeo, Phongsaly, Oudomxay, Luangprabang and Savannakhet as the pollution hotspots based on the provincial means of all pollution indicators across the entire study period. Luangprabang and Oudomxay are both identified as general fire hotspots in the Lao People's Democratic Republic; Luangprabang, Oudomxay and Phongsaly are determined as hotspots for fire events on forest land and Luangprabang, Oudomxay, and Savannakhet are identified as hotspots for fire events on crop land. Thus, all pollution hotspots have also been determined as fire hotspots, with the exception of Bokeo. In addition, the national dataset on mining indicates that several mines (gold, gypsum, limestone and barite) are located in Savannakhet, although it is not the province with the most mines (Vientiane is ranked first, followed by Khammuane). Savannakhet is also the province with the highest population and is ranked number two in terms of transportation (Vientiane Capital is number one). When considering the hotspots for the individual pollution indicators, $NO_2$, $SO_2$, $O_3$ and AOD share common provinces, while the UVAI hotspots are generally distinct. Champasak, the second ranked UVAI hotspot, has relatively high population and transport levels, as well as temperature, sunshine duration and wind speed averaged across the study period.

### 5.2.4. Trajectory modelling

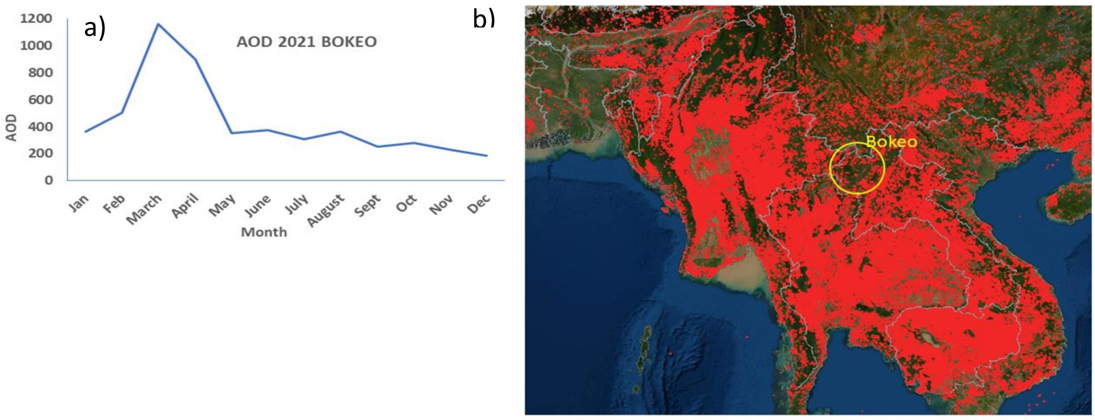
Transboundary pollution is a recognized problem in Southeast Asia, with pollution sources including rapid economic growth, industrialization, an increase in the global demand of natural resources, and biomass burning (Chen and Taylor, 2018). Numerous studies have demonstrated the occurrence of transboundary pollution in Southeast Asia (Hansen *et al.*, 2019; Kim Oanh *et al.*, 2018; Liang *et al.*, 2019; Pentamwa and Oanh, 2008; Sirimongkonlertkun, 2018; Yin, 2020). Thus, the possibility of transboundary pollution was investigated for the Lao People’s Democratic Republic, the only landlocked country in Southeast Asia. In particular, HYSPLIT was employed to model the 5-day air mass back trajectories originating from locations in Bokeo in the north of the Lao People’s Democratic Republic and Saravane in the south at altitudes of 500, 1500 and 2000 m ABL. Each back trajectory lasted 48 hours and was calculated every 24 hours.

Bokeo was selected as it exhibits the highest averaged study period AOD level at the provincial level, however it corresponds just to the 5th and 9th highest FRP and fire count, respectively. Thus, back trajectories of air parcels were modelled from this province during the fire season of 2021, corresponding to the peak in AOD in 2021 (Figure 23a). Appendix 3 presents example air-mass back trajectories determined from HYSPLIT. Air mass trajectories travel from Thailand, Myanmar, and even Bangladesh within 48 hrs to Bokeo during the fire season of 2021. Biomass burning frequency is high in these countries around March, as can be seen from Figure 23b. Sirimongkonlertkun (2018) identified March as the peak month for fire hotspots in Thailand, the Lao People’s Democratic Republic and Myanmar between 2014–2016, with the latter exhibiting the highest number of hotspots. These fires were linked to the post-harvest burning of crop residues to prepare the land.

Oanh *et al.* (2018) determined Indonesia as the top contributor to crop residue open biomass in Southeast Asia during 2010–2015, followed by Viet Nam, Myanmar, Thailand, and the Philippines. The air masses determined in this work are observed to vary with altitude and time. For example, in February, backward air masses from Myanmar and Thailand reached 2500 km, and lower altitudes for air masses originated from locations closer in Thailand. In March, air mass trajectories were traced back to Bangladesh and Thailand, with altitudes exceeding 2500 km. Air masses at lower altitudes generally originate from Thailand and the Lao People's Democratic Republic.

The second province selected for the trajectory modelling was Saravane, as it exhibits the highest study-period averaged UVAI values during the rainy season (a). The UVAI is more sensitive to the detection of plumes at high altitudes compared to the AOD. Back-trajectories of air parcels were modelled from this province during the 2021 rainy season, examples of which are shown in Appendix 3. Air mass trajectories are observed to travel from Cambodia, Myanmar, Thailand, Viet Nam, and even China within 48 hr to Saravane during the rainy season. The air parcel trajectories travelling at the highest altitude (2000 km) are from China and the Gulf of Thailand, passing over Cambodia. Between June and August, the backward air parcels at lower altitudes generally come from the southwest of the Lao People's Democratic Republic (e.g. Andaman Sea, Cambodia, Gulf of Thailand, Malaysia), while in September–October, the lower altitude trajectories change, originating from the Lao People's Democratic Republic, Viet Nam and across eastern China.

**Figure 23:** a) Monthly AOD for the northern province of Bokeo during 2021. b) Map of fires/hotspots (VIIRS and MODIS) from NASA FIRMS (Fire Information for Resource Management System) for March 2021 for Lao People's Democratic Republic and neighbouring countries

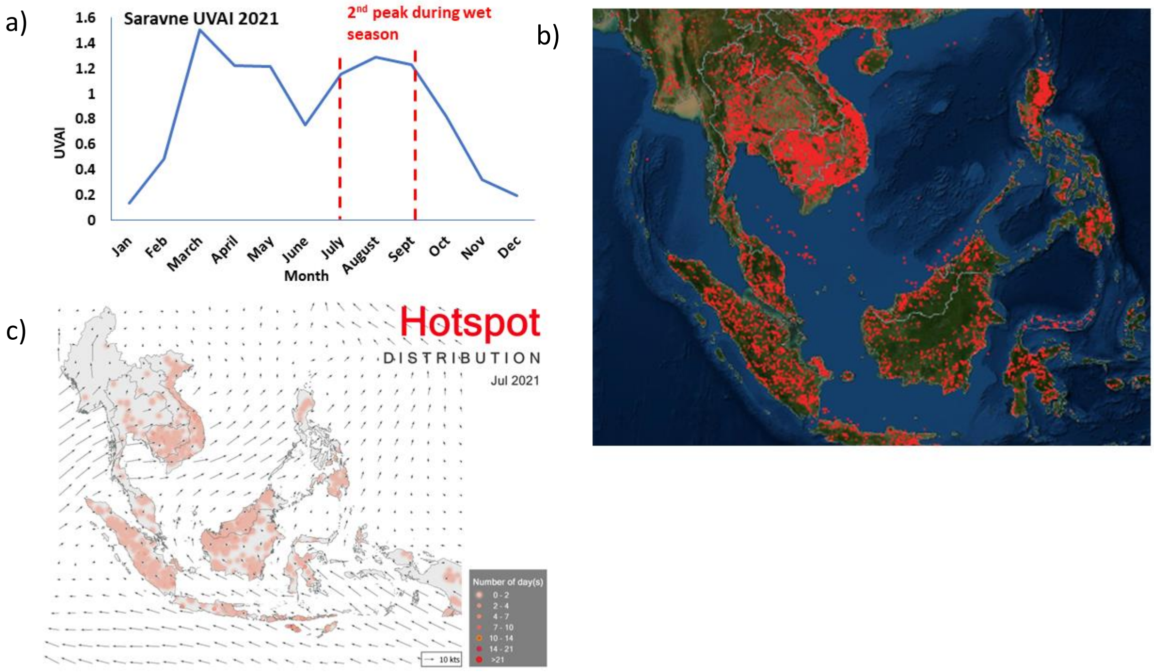



*Source:* a) This analysis; b) Fire Information for Resource Management System. 2022a. *Active fires/thermal anomalies for Southeast Asia*, March 2021. NASA. https://firms.modaps.eosdis.nasa.gov/map/#d:24hrs;@0.0,0.0,3z

Southeast Asia is reported to experience haze episodes during June–August attributed to forest fires in the region (e.g. Pentamwa and Oanh, 2008). In order to highlight this, b and c present fire hotspots detected in the countries surrounding the Lao People's Democratic Republic, corresponding to the countries mapped with the back-trajectories in Appendix 3. Liang *et al.* (2019) determined the peak fire activity of the Indochinese Peninsula (Cambodia, the Lao People's Democratic Republic, Myanmar, Thailand and Viet Nam) to be between March and May, and that of the Malay Archipelago (Brunei Darussalam, Timor-Leste, Indonesia, Malaysia, Papua New Guinea, the Philippines and Singapore) between August and October. This difference is attributed to the variations in latitude and crop harvest seasons. Yin (2020) also determined the main fire season of equatorial Southeast Asia to occur between August to October.

The results suggest the possibility of the transportation of atmospheric pollutants from neighbouring countries to the Lao People's Democratic Republic, although it is not possible to determine the actual sources. Also note that from Table 6, UVAI and AOD are both positively significantly correlated with wind speed, again suggesting the transport of these pollutants by the wind.

**Figure 24:** a) Monthly UVAI for the southern province of Saravane during 2021. b) Map of fires/hotspots (VIIRS and MODIS) from NASA FIRMS (Fire Information for Resource Management System) for July 2021 for Lao People's Democratic Republic and neighbouring countries). c) Distribution of hotspots detected in July 2021 based on NOAA-20 satellite surveillance for ASEAN region




*Source:* a) This analysis; b) Fire Information for Resource Management System. 2022b. *Active fires/thermal anomalies for Southeast Asia*, June 2021. NASA. https://firms.modaps.eosdis.nasa.gov/map/#d:24hrs;@0.0,0.0,3z; c) ASEAN Specialised Meteorological Centre. 2021. *Review of regional haze situation for July 2021*. http://asmc.asean.org/haze-review-of-regional-haze-situation-for-july-2021/.

## 5.3. Understanding the dynamics of air pollution in Luangrabang and Savanakhet provinces

Key Messages:

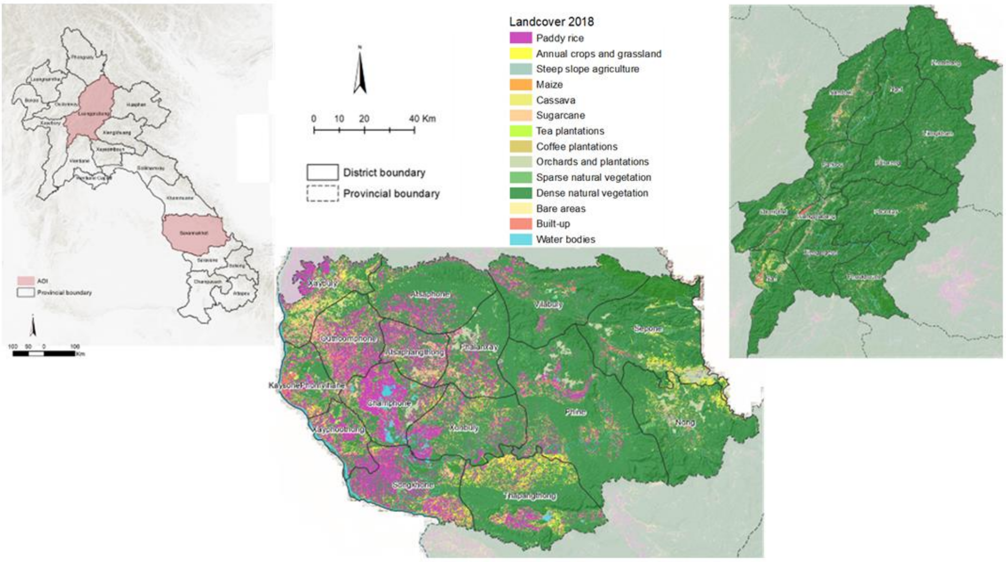
1) Based on the observations from all datasets, fires make less of a contribution to air pollution in Savanakhet compared to Luangrabang.
2) Burning to clear (fallow) land is the most common (42.1 percent) cause of fires in Luangrabang, while for Savanakhet it is the burning of post-harvest crop residue (25.90 percent). In terms of deforestation, agricultural expansion (22.8 percent) followed by timber production (5.26 percent) are the main drivers in Luangrabang, while for Savanakhet its fuel wood extraction (24.7 percent) followed by agricultural expansion (3.7 percent).

Field work was piloted in two provinces, namely Luangrabang and Savanakhet in the Lao People's Democratic Republic. The selection of the provinces was made based on the geospatial analysis and the distinct properties of the two areas. In particular, Luangrabang is a highly forest area and known for upland rice production, whereas Savanakhet is more of an agricultural province and is known for rice and cassava production. Both provinces exhibit the highest number of average fires in their respective zones.

Luangrabang province is located in the northern zone of the country and is known for its upland rice production. The province covers a total area of 1 994 900 ha, with 92 percent comprising forest land (1 844 925 ha) and only five percent as cropland (98 760 ha). The population density in the north is relatively low, with a population of 2 141 000 in 2020. Luangrabang is the highest populated province in the north, with a total population of 467 000 in 2020. The average temperature of the province is 25.12 $^{o}$C and 28.03 $^{o}$C in the dry and rainy seasons, respectively. Based on the Lao People's Democratic Republic 2018 land cover map from DALaM. (Figure 25) steep slope agriculture and rice paddy are the main crops in Luangrabang.

Savanakhet province, which is located in the southern zone of the country, has a total area of 2 129 000 ha, 68 percent of which is forest (1 441 801 ha) and 27 percent is cropland (572 644 ha). The province receives an annual rainfall of 4.3 mm, while the highest recorded temperature in the province is 29.5 $^{o}$C in 2020. The province is known for its low land rice production (FAO, 2020a), which is the most cultivated crop in the country, followed by annual crops. The south is the highest populated zone in the Lao People's Democratic Republic, with a total population of 2 554 000 in 2020, and Savanakhet exhibits the highest population of all provinces, at 1 070 000 in 2020.

**Figure 25:** Land cover distribution based on 2018 Lao People's Democratic Republic land cover map



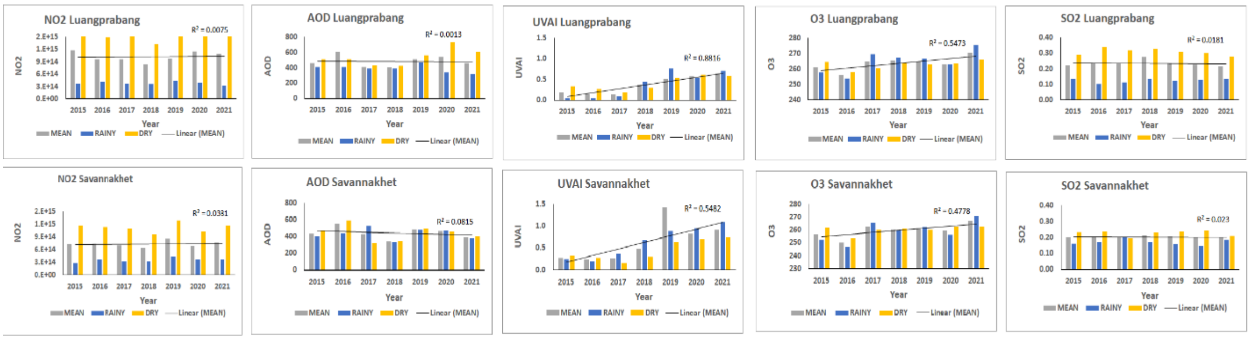

*Source:* FAO. 2021. State of the art agricultural land cover maps for the Lao People's Democratic Republic: part of the Land Resources Information Management System (LRIMS). Vientiane, Laos, FAO. https://www.fao.org/publications/card/en/c/CB3699EN/. Administrative boundaries obtained from National Geographic Department (NGD) of Lao People's Democratic Republic.

## 5.3.1. Air pollution dynamics

The air pollution dynamics of the two provinces were investigated at the provincial scale to better understand the local climatic and air pollution variations over the study period. Figure 26 presents the temporal variation of each pollution indicator for Luangprabang and Savannakhet. Seasonal (rainy and dry) and yearly variations are studied based on the average values. An increasing trend in both UVAI and $O_3$ is observed for both provinces, while the remaining pollution indicators (AOD, $NO_2$ and $SO_2$) remain constant on average. In general, peak $NO_2$, $SO_2$ and AOD emissions are observed during the dry season, which is related to the fire activity during this part of the year in the Lao People's Democratic Republic. Note that with the exception of UVAI, Luangprabang generally exhibits higher values of the pollution indicators compared to Savannakhet. This may be attributed to the greater amount of fire activity for the former, while the greater values of UVAI may be linked to the relatively high population and transport activity in Savannakhet.

Moreover, there is a greater difference between the UVAI seasonal levels for Savannakhet, with higher values during the rainy season. This could be attributed to transboundary pollution.

**Figure 26:** Average yearly and seasonal (rainy and dry) air pollution indicators over the study period for the two provinces

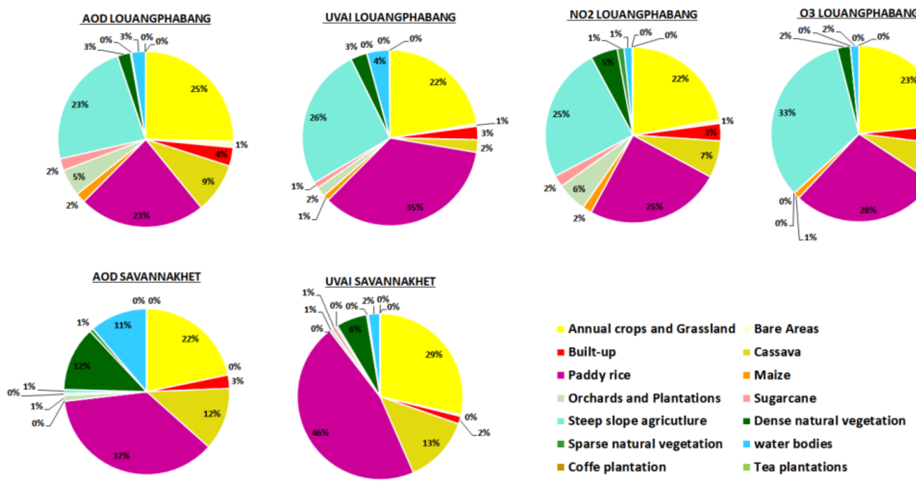



*Source:* Authors' elaboration.

The air pollution indicators were linked to the land cover map from 2018 to understand the potential sources of the pollutants (Figure 27) based on the pixels with the highest indicator values in both provinces. In Luangphabang, the majority of elevated pollution values are observed under steep slope agriculture class, followed by rice paddy and annual cropland. In contrast, rice paddy is the class associated with the greatest amount of elevated pollution values, followed by annual cropland for Savannakhet.

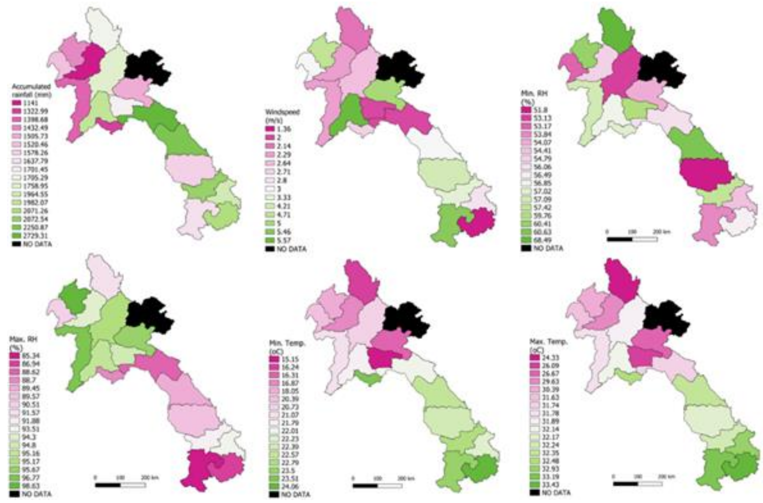
Figure 28 reveals the differences in climatic variables between the two provinces. For example, Luangphabang generally exhibits a greater amount of rainfall, has a lower wind speed, higher relative humidity and lower temperature compared to Savannakhet. These differences can also explain the variations in air pollution dynamics between the two provinces, which is described in detail in the main document.

**Figure 27:** Air pollution variables by land cover classes, based on 2018 Lao People's Democratic Republic land cover map




*Source:* Authors' elaboration

**Figure 28:** Provincial means of climatic variables averaged over the study period



*Source:* Lao People's Democratic Republic Department of Meteorology and Hydrology, Ministry of Natural Resources and Environment. Administrative boundaries obtained from National Geographic Department (NGD) of Lao People's Democratic Republic.

The field survey data ranked air pollution as "low" in both provinces for the period 1990 until present, with the exception of 2010–2015, which was described to have medium levels of air pollution.

Forest fires (and other factors including dust storms) were observed to make the greatest contribution to air pollution ("high severity"); followed by agricultural burning, domestic burning, waste burning, industrial activity, and mining activity ("medium severity"); and slash-and-burn cultivation, power plants and transportation ("low severity"). Based on the field data, most of the pollution indicators (waste burning, domestic burning, power plants, mining activity and transportation) increased over the past five years, while slash-and-burning cultivation and industrial activity remained stable, and agricultural burning declined.

Integrating the observations from all datasets implies that fires make less of a contribution to air pollution in Savanakhet compared to Luangrabang, with other sources being more dominant. This is because of the different farming system practices between the two provinces. The impacts of pollution also seem to be lower in Savanakhet compared to Luangrabang. This coincides with the remote sensing analysis, whereby all pollution indicators were observed to be high in Luangrabang, except for UVAI.

### 5.3.2. Characterization of fires

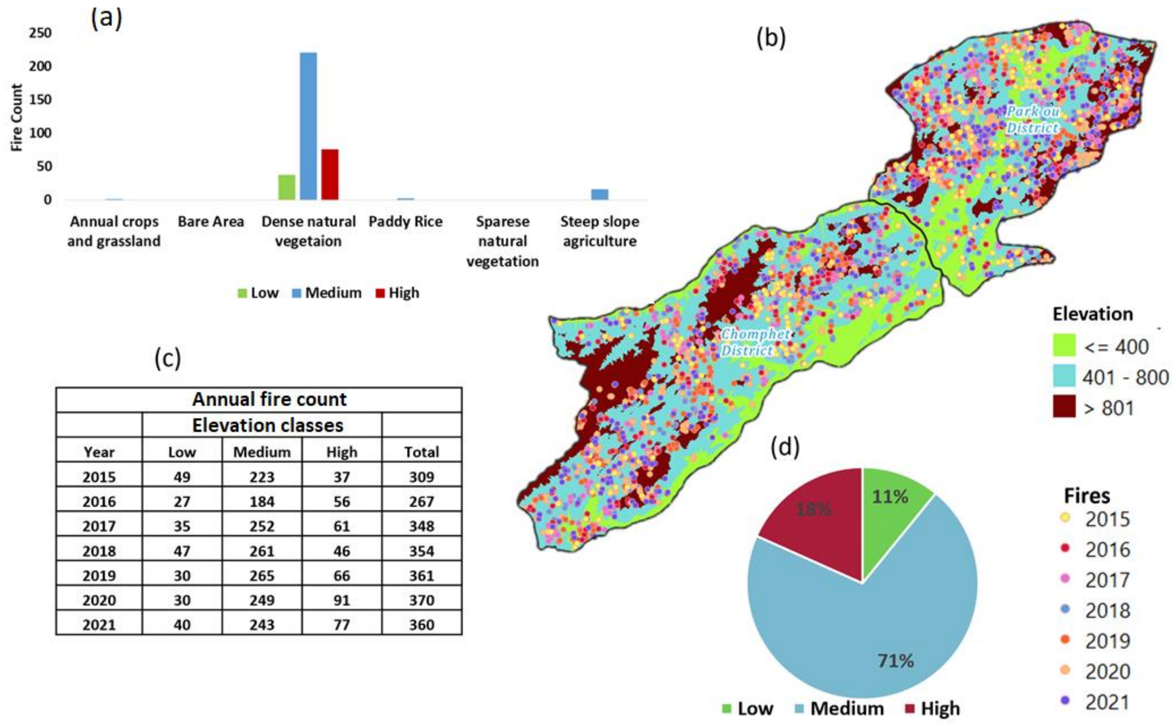
Luangrabang is the province identified with the highest number of fire events over the study period in the current analysis, with an average fire count of 1947. The northern zone generally dominates the fire count across the country. A pilot field exercise was conducted in two districts, namely, the Chompet and Park Ou districts, in Luangrabang province to understand the local dynamics. Most fires are anthropogenic in nature and mostly used to prepare the land for crops. Therefore, the presence of fires is observed over all cropland categories, which means almost all agricultural activities use fires in the cropping cycle.

The highest number of fires are observed at the medium elevation level (71 percent), which is attributed to the dense natural forest category (Figure 29). According to Van Gansberghe (2005), the pioneering shifting cultivation (PSC) system, namely, the clearing of a new piece of land for each rotation, is commonly practised in mountainous areas. The current 2018 land cover map does not distinguish between shifting cultivation and regrowth; therefore, it is not possible to confirm whether all fires observed in the forest class are indeed forest fires. The spatial analysis results are also aligned with farmer interviews, whereby agricultural expansion is identified as a major driver of deforestation in the north (61.9 percent).

The frequency of fires is relatively low in the southern part (Savanakhet) of the country compared to the north. The burning of post-harvest crop residue is the dominant region for burning, followed by clearing land. The distribution of fires by elevation is dominated in the medium elevation range (52 percent), while a large chunk of fires (42 percent) is also observed in lowland areas.

As with the northern region, most fires are observed in the dense natural vegetation class, followed by cropland. A significant number of fires are observed in the cassava, and annual cropland classes (Figure 30). This is because annual cropland is the most adopted system in the southern region, and typically involves the rotation between existing plots only, which is also defined as rotational shifting cultivation (RSC). Based on the household survey data from the two districts of Xayabury and Outhoomphone in Savanakhet, the main driver of deforestation in the south is fuelwood extraction (76 percent).

**Figure 29:** (a) Fire presence by elevation and land cover classes, 2021; (b) spatial distribution of annual fires over elevation map; (c) total annual fire events by elevation classes; and (d) average fire count by elevation, in Luangrabang province

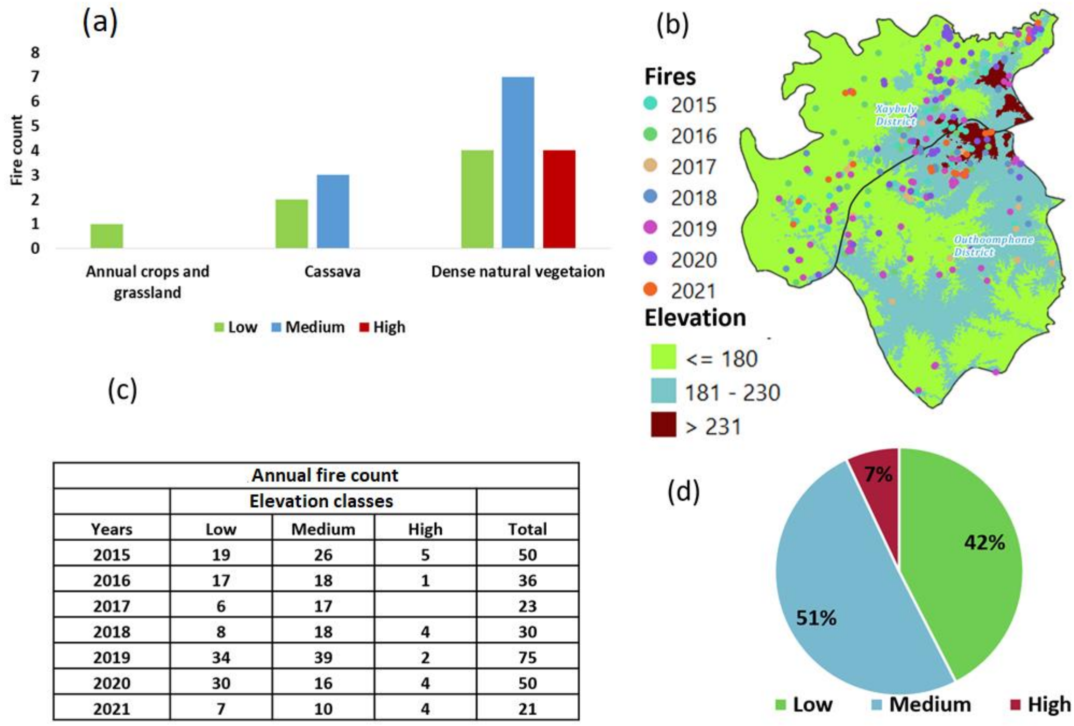



| Annual fire count | | | | |
|---|---|---|---|---|
| | Elevation classes | | | |
| Year | Low | Medium | High | Total |
| 2015 | 49 | 223 | 37 | 309 |
| 2016 | 27 | 184 | 56 | 267 |
| 2017 | 35 | 252 | 61 | 348 |
| 2018 | 47 | 261 | 46 | 354 |
| 2019 | 30 | 265 | 66 | 361 |
| 2020 | 30 | 249 | 91 | 370 |
| 2021 | 40 | 243 | 77 | 360 |

*Source:* Farr, T.G., Rosen, P.A., Caro, E., Crippen, R., Duren, R., Hensley, S., *et al.* 2007, The shuttle radar topography mission: Reviews of Geophysics, v. 45, no. 2, RG2004. https://doi.org/10.1029/2005RG000183. Administrative boundaries obtained from National Geographic Department (NGD) of Lao People’s Democratic Republic.

In terms of burning-related agricultural activities, burning to clear (fallow) land is the most common (42.1 percent) cause of fires in Luangrabang, followed by the burning of crop residue after harvesting (~22.8 percent), and the burning of new growth for pasture grazing (19.3 percent) (Figure 31). The main land use types on which fires occur are fallow land (54.39 percent) and agricultural land (36.84 percent), with fires occurring once per year and typically in April. The length of the fallow land is mainly 1–2 years in both provinces. In Luangrabang, a total of 22/66 households (36.4 percent) indicated that deforestation is still happening in the province and the main driver is agricultural expansion (22.8 percent), followed by timber production (5.26 percent), and fuel wood (5.3 percent) in the north. Whereas in Savannakhet, the main driver of deforestation is fuel wood extraction (24.7 percent), followed by agricultural expansion (3.7 percent).

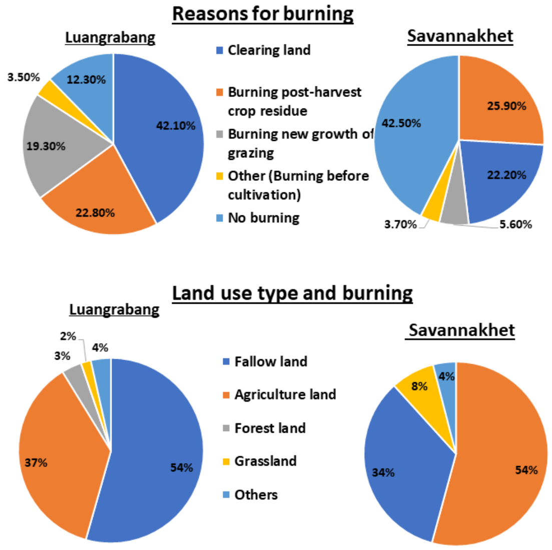
**Figure 30:** (a) Fire presence by elevation and land cover classes, 2021; (b) spatial distribution of annual fires over elevation classes; (c) total annual fire events by elevation classes; (d) average fire count by elevation in Savanakhet province




| Annual fire count | | | | |
|---|---|---|---|---|
| | Elevation classes | | | |
| Years | Low | Medium | High | Total |
| 2015 | 19 | 26 | 5 | 50 |
| 2016 | 17 | 18 | 1 | 36 |
| 2017 | 6 | 17 | | 23 |
| 2018 | 8 | 18 | 4 | 30 |
| 2019 | 34 | 39 | 2 | 75 |
| 2020 | 30 | 16 | 4 | 50 |
| 2021 | 7 | 10 | 4 | 21 |

*Source:* Farr, T.G., Rosen, P.A., Caro, E., Crippen, R., Duren, R., Hensley, S., *et al.* 2007, The shuttle radar topography mission: Reviews of Geophysics, v. 45, no. 2, RG2004. https://doi.org/10.1029/2005RG000183. Authors' elaboration. Administrative boundaries obtained from National Geographic Department (NGD) of Lao People’s Democratic Republic.

**Figure 31:** a) Reasons for agricultural burning according to farmers in Luangrabang and Savannehket; b) land use type on which agricultural burning occurs according to farmers in Luangrabang and Savannehket




*Source:* Authors' elaboration.

Unfortunately, the sample based field data collection exercise was conducted outside of the fire seasons, therefore the team was not able to collect enough information related to fire activity. Consequently, just a single sample in each province was identified with fire activity out of the total 20 samples. All questionnaires are provided in detail in Appendix 4.

### 5.3.3. Farming practices

The agriculture sector plays an important role in the domestic economy, accounting for 16.51 per cent of national GDP in 2020 (Lao Statistics Bureau, 2021), and employing 70 per cent of the active population. The agri-food sector is becoming more commercialized in the Lao People's Democratic Republic, and currently approximately a third of farmers' products are for sale, although still around 80 percent of the rural population are subsistence farmers. Agriculture and food consumption are both rice-based, and several additional crops are also cultivated. Livestock is growing in importance, as the regional demand for protein drives farmers to commercialize their capacity (Association of Southeast Asian Nations, 2021). The farming systems in the Lao People's Democratic Republic are divided into the following two categories.

1) Lowland rainfed and/or irrigated farming systems of the Mekong River flood plains and tributaries have large contiguous cropped land in central and southern riverine plains.

Rice paddy production is the main cereal crop produced by the country, which accounts for 75 percent of lowland regions, mainly in Xayaboury, Khammouane, Savannakhet, and Champasak provinces. Furthermore, perennial crops are produced for both subsistence and commercial purposes.

2) The upland agriculture system is generally practised in the northern mountains. The crops are categorized as annual crops, including upland rice, cash crops (e.g. maize, cassava) and perennial crops such as leguminous and agroindustry tree plantations (e.g. rubber, banana, agroforestry trees) with almost equal proportion (FAO, 2020).

In Luangprabang province, the main farming activities are upland rice, maize (as the main crop cultivation), livestock and agricultural practices, while off-farming activities include handicrafts, small scale businesses and trading. The average household size in the province is 6 pp, with a mean farm size of 3.2 ha. This was calculated based on the field data from two sample districts (with populations of 21 818 and 28 327 for Park Ou and Chomphet, respectively). Upland rice is grown in the northern region using shifting cultivation, which begins with land preparation between January and April, sowing the plants between mid-April and May, weeding between June and August, and harvesting in September or October (Epprecht *et al.*, 2018).

The average household livelihood is not dependent on a single activity, with key activities compromising rice farming (95 percent of all family farms), livestock raising (68 percent), commercial annual farming (14 percent), tree crop farming (47 percent), and horticulture (41 percent) (FAO and NAFRI, 2022).

Savannakhet province is the main paddy grower in the country, with key farming activities including lowland rice production, followed by sugarcane and cassava cultivation. Almost 90 percent of the population is actively engaged in rice cultivation, and the majority of rural farmers in Savannakhet have small landholdings, between 2 to 3 hectares of paddy land (Baird, Piyadeth and Ninchaluene, 2021).

# 6. Conclusions

## 6.1. Understanding the atmospheric pollution and determining adequate action plans

The current work analyses the spatio-temporal trends of atmospheric $NO_2$, $SO_2$, $O_3$, AOD and UVAI in the Lao People's Democratic Republic for the period 2015–2021 by integrating Earth observation and national datasets with GIS and statistical methods. The fire activity within the country was also determined for the study period and the underlying fire dynamics were explored in terms of the spatial and temporal patterns, as well as land cover types. The relationships between the pollution indicators and potential drivers (fire activity, climate, energy, industry, mining, population, transport, and agricultural activity) were analysed across the different spatial and temporal scales. The following key observations were made.

Higher amounts of $NO_2$, $SO_2$, $O_3$ and AOD were observed in the north of the Lao People's Democratic Republic. This coincides with the fire activity distribution determined for the study period. Elevated UVAI levels were mainly observed in the southern region. Bokeo, Phongsaly, Oudomxay, Luangprabang and Savannakhet were identified as pollution hotspots. $NO_2$, $SO_2$ and AOD levels in the dry season (November–April) exceeded those of the rainy season (May–October). This can be linked to the occurrence of fires at this time. In particular, the fire activity analysis indicated the main fire season of the Lao People's Democratic Republic to occur between February to May, with peaks in March and April. This coincides with the peaks of $NO_2$, AOD and UVAI, however the latter exhibited elevated values during the rainy season, with a second peak around August.

Backward air-mass trajectories were modelled from Saravane (UVAI hotspot) using HYPLIT to explore the possibility of transboundary pollution as one of the underlying reasons for the high UVAI values during the rainy season. Results revealed air-mass trajectories to have travelled as far as from Cambodia, Myanmar, Viet Nam, and even China. Southeast Asia is known to experience haze from large forest fires in this region during June–October (Liang *et al.*, 2019; Pentamwa and Oanh, 2008; Yin, 2020). $O_3$ levels were also greater in the rainy season, which can be attributed to the transport of $O_3$ and its precursors and meteorological dynamics. However, the seasonal differences for $O_3$ column amounts were minimal. In addition, $SO_2$ levels exhibited a peak in December and January for the northern and central zones, which may be associated with emissions from household heating using wood and coal during colder temperatures. Back-trajectory modelling from Bokeo also demonstrated the possibility of transboundary pollution during the fire season in 2021.

Provinces with high values of pollution indicators include Bokeo, Luangnamtha, Luangrabang, Oudomxay, Vientiane Capital and Xayabuly. The southern provinces of Sekong, Saravane and Savannaket were associated with high levels of UVAI, with the latter also having the highest population and transport (no. of vehicles), as well as the highest sugarcane, lowland rainfed paddy and dry season paddy production. Relatively low values for all pollution indicators were determined for Attapeu in the south. In terms of fire activity, Luangprabang demonstrated the maximum number of fire events, and Vientiane Capital the lowest, suggesting non-biomass burning pollution sources in Vientiane Capital, or plumes travelling from neighbouring regions. When considering just agricultural land, Savarnakhet, Xayabury, Huaphan, Saravane and Vientiane are identified as potential agricultural fire hotspots. Furthermore, analysis revealed the potential presence of deforestation following slash-and-burn activities.

At the provincial level, $NO_2$, AOD and $O_3$ were observed to be significantly positively correlated with FRP and fire count. All pollution indicators exhibited a significant relationship with differing climate indicators, revealing the impact of weather conditions on atmospheric pollutants. In addition, UVAI was positively correlated with population, and presented the strongest relationship with agricultural activity (lowland rice, dry season rice, starchy root production). Upland rice (maize) was significantly correlated with $SO_2$, AOD, and $O_3$ ($NO_2$). The highest values of AOD, $NO_2$, $SO_2$ and $O_3$ were generally mapped to annual crops and grassland, steep slope agricultural and paddy rice, while for UVAI, paddy rice, annual crops, grassland, and cassava formed the largest proportion. This agrees with the observed relationships between UVAI and agricultural activity. In addition, the mapped land cover classes agree with the fire presence across cropland classes determined in the fire analysis; annual crops and grassland (31 percent); steep slope agriculture (28 percent); paddy rice (20 percent); cassava (15 percent) and maize (4 percent).

Due to lack of time and resources, qualitative data collection in the field was limited to just two provinces in the north and south of the Lao People's Democratic Republic. The feedback from the fieldwork agrees with the relationships determined between the pollution indicators and agricultural activity and fires. In particular, fires have a greater contribution to air pollution in the northern province of Luangrabang compared to the southern province Savanakhet, the majority of which are forest fires. It also confirms the main fire activity period (March–April) determined in this work. The incomplete national datasets on industry, energy and mining activity prevent a full comparison between the field work and remote sensing results, and highlight the need for up-to-date national datasets on such activities. The data from the fieldwork also indicates the role of domestic and waste burning as pollution sources, however no data was available for these activities for the remote sensing analysis. The responses from government officials identify the impact of pollution to be greater in the north compared to the south, in line with pollution indicator levels.

The current study developed a geospatial methodology to monitor atmospheric pollution, and when integrated with both national and field data, it is possible to investigate the corresponding pollution sources, however such data must be up-to-date and cover the entire country. The results aim to aid the Lao People's Democratic Republic Government in understanding the atmospheric pollution and fire activity dynamics across the country, and to help identify potential sources of pollution to determine adequate action plans to reduce pollution and its impact. In particular, this assessment will contribute to national action plans for the reduction of air pollution emissions, including the Strategy on Climate Change of the Lao People's Democratic Republic; the Intended Nationally Determined Contributions (NDC) under UNFCCC; the Lao Agriculture Development Strategy to 2025 and Vision to 2030; and the National Socioeconomic Development Plan 2021–2025 Outcome 3, Output 1: Environmental Protection and Sustainable Natural Resources Management.

## 6.2. Challenges for the monitoring of air pollution in the Lao People's Democratic Republic

The atmospheric pollution levels in certain regions of the Lao People's Democratic Republic are observed to be high in numerous months throughout the year. As detailed in Section 1, atmospheric pollution can have an impact on the health of the population, and this was also mentioned in the feedback from the fieldwork in this study. Elevated amounts of atmospheric pollutants also influence climate at the local level (smog and haze), as well at the larger scale (climate change). In addition, agricultural inputs are also affected by atmospheric pollution due to indirect effects via changes in local weather patterns, such as rainfall and temperature.

Thus, based on the conclusions, it is suggested that the Lao People's Democratic Republic take actions to reduce atmospheric pollution. However, the country faces several challenges in reducing emissions, which are described in the following.

Absence of a regular monitoring system: There is a current lack of national methodological approaches endorsed by national partners. This results in limited consistency and stability in the monitoring of air pollution in the Lao People's Democratic Republic.

Data gaps/incomplete database: At present, there is no comprehensive emissions database that is up-to-date and includes data from all sectors across the country. The limited research typically includes gaps (species emissions, industry information etc.) due to the lack of data. This prevents the accurate analysis of the current levels of pollution and there is no information indicating the current key pollution sources. Thus, there is a requirement to generate an accurate emission database for the Lao People's Democratic Republic that provides current and historical emission data of the key species at the national, regional and sector levels.

Ground station data: Satellite data can be complemented with data collected at the ground. However, there is limited data availability, and the monitoring of pollutant species (e.g. $SO_2$, $NO_2$, PM etc.) is not consistent in the Lao People's Democratic Republic. For example, monitoring stations for key pollutant species are sparsely distributed and present large gaps across time. This makes it difficult to validate top-down emission estimates from satellite imagery.

Lack of technical capacities: There are limited technical capacities in data management and archiving, modelling, information technology, the application of geospatial and remote sensing techniques etc. This subsequently restricts the applicability of the latest atmospheric pollution techniques and the corresponding data collection.

Data management: The Lao People's Democratic Republic has a noted lack of a comprehensive information and data sharing system (information technology, legal, etc.). This prevents the country from working together to make the most of the available data and inhibits the development of an inclusive air pollution monitoring network.

Accessibility of data: In terms of bottom-up emission estimates, there is a lack of country specific EFs and challenges in obtaining activity data across the relevant sectors. This subsequently complicates sectoral emission estimates. Accurate estimates of sector emissions require an extensive amount of up-to-date activity data from each sector. Such data (amount of fuel consumed, livestock populations, manure management system data, fertilizer applications, waste composition, population burning waste etc.) is often unavailable. Data that is available requires a large amount of liaising with the relevant parties and is often highly time consuming. It is suggested that this lack of data and time delay in acquiring the necessary data is accounted for when planning the emission estimates.

## 6.3. Recommendations for the future monitoring of air pollution in the Lao People's Democratic Republic

Given the aforementioned challenges, there is an urgent demand to routinely obtain the required data in order to accurately investigate emissions and facilitate emission estimates, aiding in the decisions of policy makers. In order to improve the national information system by increasing its capacity to support actions for pollution reduction, the following strategies are proposed to reduce the air pollution in the Lao People's Democratic Republic.

A key strategy is the enhancement of technical capacities in the application and analysis of the latest technologies and approaches for the measurement and monitoring of air pollution in the Lao People's Democratic Republic. These include geospatial and remote sensing techniques based on Earth observation methods, the application of machine learning and Big Data, the Internet of Things, crowdsourcing approaches, statistical analysis, etc. This can be initiated through training, workshops and hand-on sessions on the current methods used to monitor air pollution.

In terms of specific technical approaches, instruments such as OMI, MODIS, and CALIOP offer data over the past two decades, allowing for comprehensive time series analysis, however their relatively course spatial resolution does not facilitate investigations at the finer scale, which may limit the identification of hotspots. More recently launched Earth observation instruments (e.g. TROPOMI) offer data at a higher spatial resolution, yet long-term data is not available. Thus it is recommended that monitoring techniques integrate both high spatial resolution for potential hotspot identification with coarser spatial data for temporal analysis to take advantage of both datasets.

The monitoring of fires can be tricky, and they can only be traced within a short period of time after the incident. Slash and burn activities generally do not cover a larger scale, especially when shifting cultivation is commonly practised. Therefore, high resolution imagery is crucial to accurately quantify the fire information. Sentinel-2 is a good option due to its higher spatial and temporal resolution compared to Landsat, making it a strong candidate for burned area mapping.

Further technical recommendations include the monitoring of additional atmospheric gas species, which will help aid in understanding the atmospheric pollution dynamics of the country. For example, $CO_2$ observations can be derived from NASA's OCO-3 instrument, yet the temporal resolution is 16 days (2.25 km × 1.29 km). GOSAT and GOSAT-2 also offer atmospheric $CO_2$ data at a higher temporal resolution (3 and 6 days, respectively), but with a coarser spatial resolution (approximately 10.5 km). Additional atmospheric pollutants include $CH_4$, a greenhouse gas that plays a key role in the formation of ozone, and CO, emitted from fossil fuel combustion, both of which can be monitored using TROPOMI. Furthermore, future work will benefit from the investigation of atmospheric aerosol properties, for example aerosol type and aerosol height, offering an insight into the possible sources. For example, aerosols detected at a high altitude may suggest plumes resulting from high-biomass fires. Such information can be obtained from satellite products, such as those from CALIPSO, MODIS and TROPOMI.

Regular monitoring is crucial to take timely actions and monitor the progress of implemented activities. Therefore, it is suggested that the Lao People's Democratic Republic considers developing or adopting from an existing platform a routine to monitor air pollution indicators on a regular basis. It would be beneficial to have updated monthly information available on the key climatic variables (e.g. wind speed, temperature, relative humidity, sunshine hours, rainfall) as well as the key atmospheric pollutants ($PM_{2.5}$, $SO_2$, $NO_2$, $CO_2$ etc.). This data could be available in locations across the country, allowing for the comprehensive temporal and spatial monitoring of air pollution. Thus, it is proposed that monitoring are set up in all provinces in the country and regular maintenance is be performed to ensure the operability of all sensors.

A centralised platform could be set up with cross-sectorial data sharing protocols and field collection campaign and supported with innovative techniques (e.g. eddy covariance systems). This can provide an easy flow of information from the respective sections to fill in the gaps of the current data analysis, for example the integration of national datasets (e.g. industrial activity) when determining the potential sources of atmospheric pollution, or the use of activity data (e.g. industrial power consumption) to quantify the emissions from different sectors. This requires the compilation of up-to-date national databases on industrial, energy and mining activity, as highlighted in this work. It will be beneficial for the platform to maintain consistency in definitions, methods, analysis etc. throughout departments. For example, a clear definition or understanding on how fallow land is used in the context of land cover maps will be useful to quantify the fires in relevant categories, and to determine information related to forest and cropland fires.

Furthermore, the results from the fieldwork identified waste burning and domestic burning as key contributors to pollution, thus detailed information could be compiled on these activities. Additional information, for example on crop management can prove to be useful in the monitoring of air pollution dynamics (e.g. pesticide and fertilizer applications). For example, the use of pesticides in the Lao People's Democratic Republic has increased over the past few years to clear land, replacing the burning of crop residue due to restrictions in burning implemented by the country. Furthermore, national scale burned areas maps can be helpful for fire emission estimates. Field data can be collected during the fire/dry season for the validation of fire and fire presence by land cover. Qualitative data collection in the field is also useful for the calibration of remote sensing generated results. Global datasets may be employed to provide insight on the underlying dynamics of atmospheric pollution and the corresponding drivers, for example deforestation estimates (e.g. https://data.globalforestwatch.org/documents/gfw::agriculture-linked-deforestation/about), particularly when data in the Lao People's Democratic Republic is not available.

It is recommended that support is given to national pro-poor intervention plans to ensure that the most vulnerable people are not negatively impacted by emission reduction policies. Such plans include supporting farmers in replacing fires with alternative approaches that have less of an impact on the environment, providing subsidies to farmers to implement the new methodologies, and giving incentives to zero fire commodities to encourage farmers. Capacity development is crucial to increase the awareness about the impacts of air pollution and open burning for local communities, as well as local and national staff. This includes the raising awareness of alternative approaches to reduce and over time replace open biomass burning. Moreover, supporting the adoption of sustainable and resilient land management technologies and approaches by farmers, for example to implement low emission alternative approaches (e.g. low-level agricultural burning, chipping, and mulching) have the potential to contribute reducing emissions.

Finally, this work demonstrated that the Lao People's Democratic Republic is likely to be experiencing transboundary pollution from its neighbouring countries, particularly during the corresponding burning seasons. The Lao People's Democratic Republic is a member of the Association of Southeast Asian Nations (ASEAN), along with Brunei Darussalam, Cambodia, Indonesia, the Lao People's Democratic Republic, Malaysia, Myanmar, Philippines, Singapore, Thailand and Viet Nam, with the aim of controlling transboundary pollution. In December 2020, government officials in Thailand held a meeting with Cambodia, Myanmar and the Lao People's Democratic Republic to discuss how the transboundary pollution that was predicted to occur in the following year within the Mekong Subregion could be reduced. Strategies included the implementation of technology to forecast air quality in advance, the use of satellite imagery to monitor air pollution, and the development of a system to detect forest fires. It was also encouraged to replace burning with fuel reduction and utilization prior to the potential haze episode. The governments in the region are encouraged to continue working collaboratively for the monitoring and reduction of emissions.

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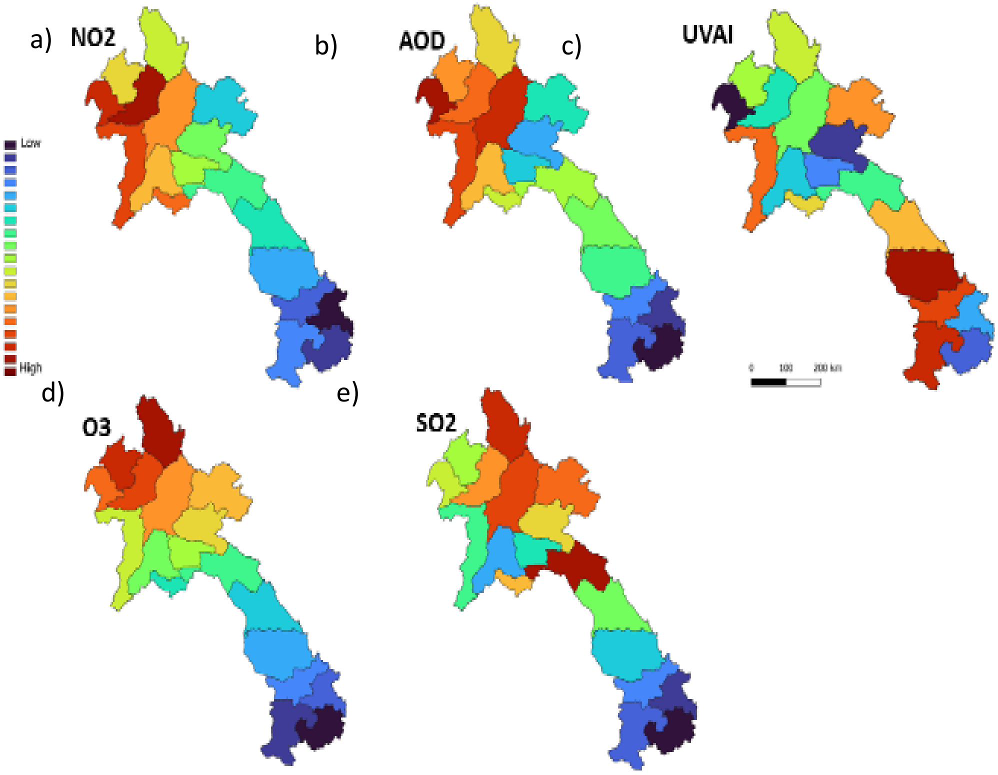
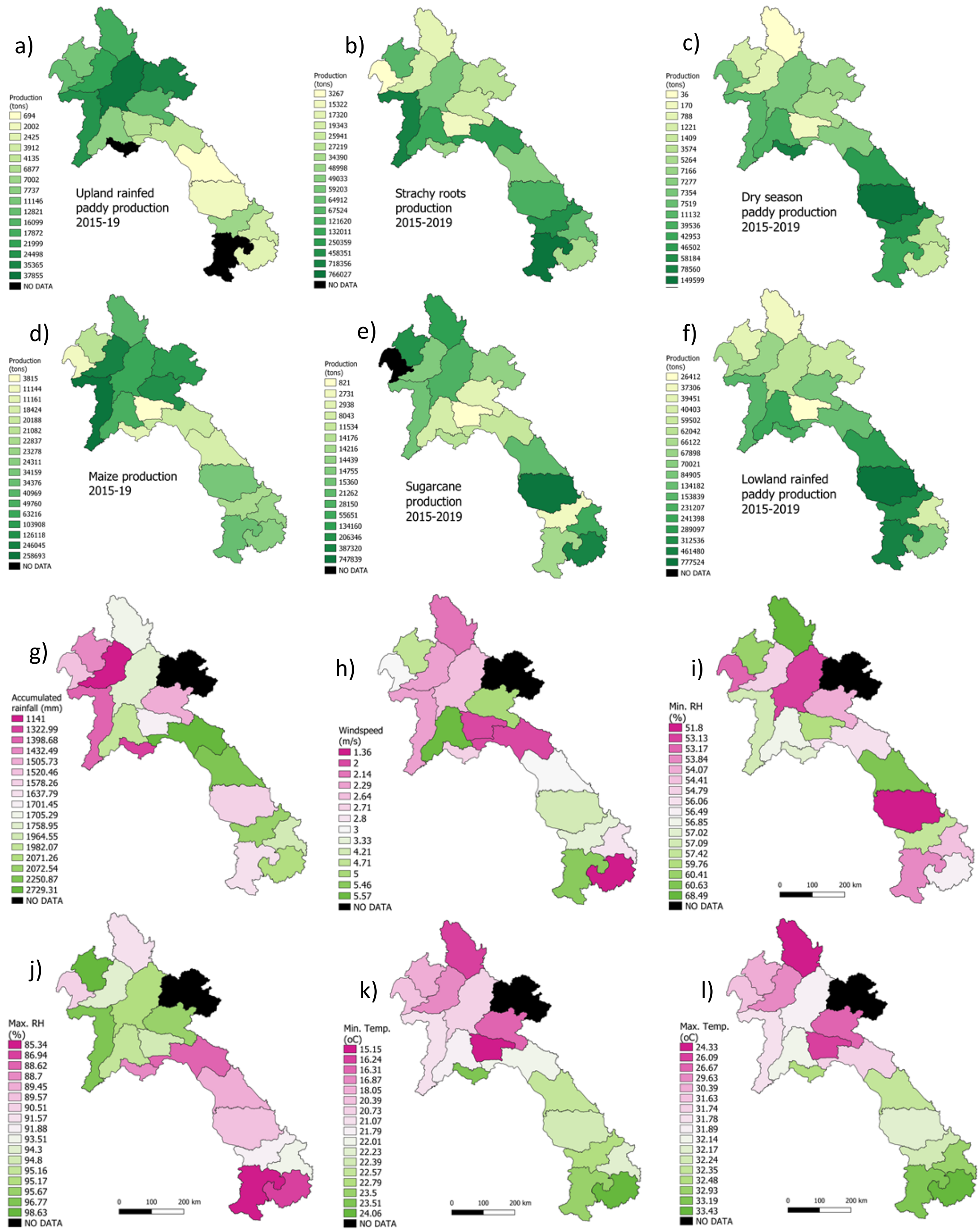
# Appendix 1 Zonal means of pollution indicators and potential drivers and their correlations

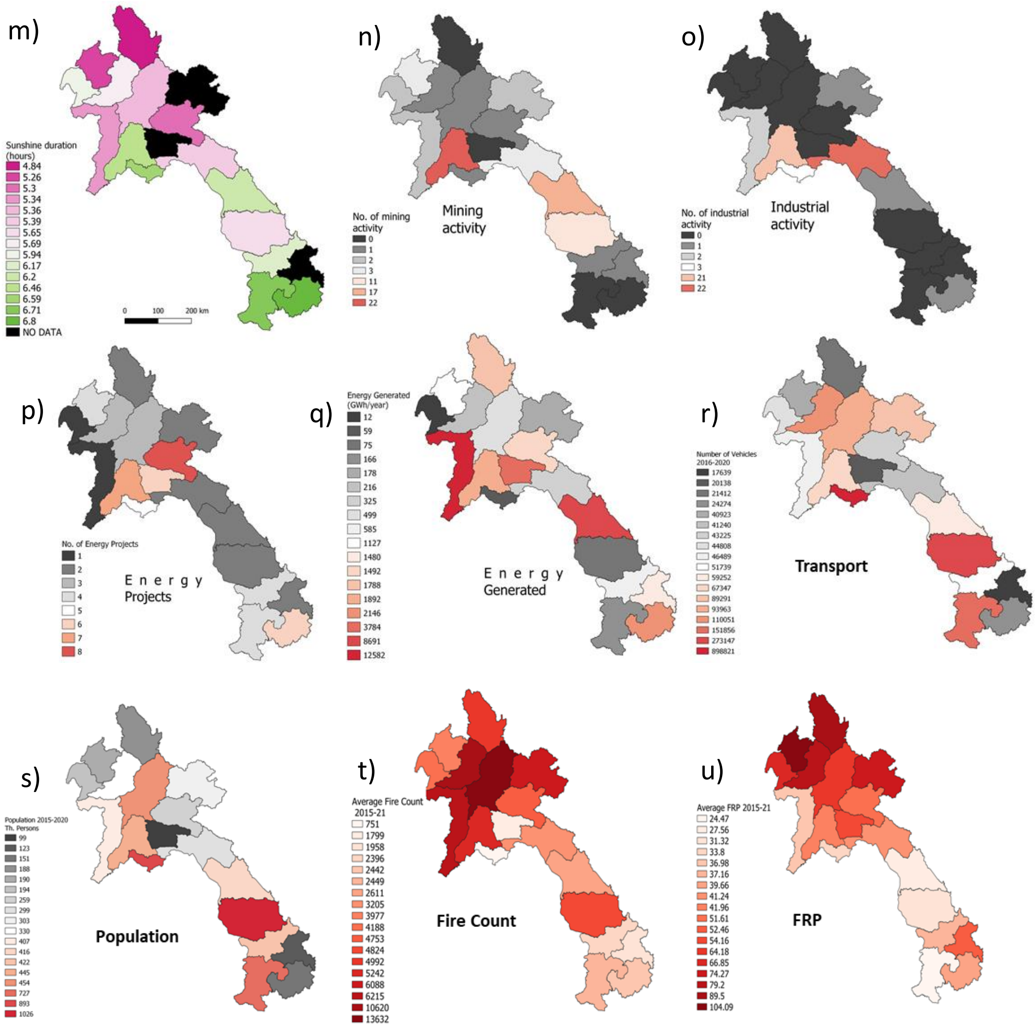
**Figure A1. 1:** Provincial means of pollution indicators for the study period (2015–2021). Mean values of a) aerosol optical depth and b) ultraviolet aerosol index and average column amounts of c) ozone; d) nitrogen dioxide and; e) sulphur dioxide




*Source:* Authors' elaboration. Administrative boundaries obtained from National Geographic Department (NGD) of Lao People's Democratic Republic.

**Figure A1. 2:** Provinical means of potential drivers for the entire study period. a) Upland rainfed paddy production; b) startchy roots production; c) dry season paddy production; d) maize production; e) sugarcane production; f) lowland rainfed paddy production; g) accumulated rainfall; h) windspeed; i) minimum relative humidity; j) maximum relative humidty; k) minimum temperature; l) maximum temperature; m) sunshine duration; n) mining activity; o) industrial activity; p) number of energy projects; q) energy generated; r) transport; s) population; t) fire count; and u) FRP






*Source:* Authors' elaboration. Administrative boundaries obtained from National Geographic Department (NGD) of Lao People's Democratic Republic.

**Table A1. 1:** Pearson correlation between pollution indicators and potential drivers for the whole country and grouped into zones (north, centre, south). Based on provincial means for whole study period (2015–2021). ***, ** and * denote significance levels of $p < 0.01$, 0.05 and 0.1, respectively. n=18

| | **$NO_2$** | **$O_3$** | **$SO_2$** | **AOD** | **UVAI** |
|---|---|---|---|---|---|
| $NO_2$ | 1.00 | | | | |
| $O_3$ | 0.75*** | 1.00 | | | |
| $SO_2$ | 0.71*** | 0.86*** | 1.00 | | |
| AOD | 0.90*** | 0.82*** | 0.84*** | 1.00 | |
| UVAI | -0.46* | -0.49** | -0.39 | -0.32 | 1.00 |
| FRP | 0.40* | 0.80*** | 0.46 | 0.44* | -0.34 |
| Fire count | 0.51** | 0.53** | 0.46 | 0.53** | -0.14 |
| Sunshine duration | -0.34 | -0.74*** | -0.73*** | -0.55** | 0.19 |
| Temperature minimum | -0.40 | -0.73*** | -0.54** | -0.41* | 0.48* |
| Temperature maximum | -0.21 | -0.63*** | -0.51** | -0.28 | 0.41* |
| Relative humidity minimum | -0.01 | 0.39 | 0.28 | 0.15 | -0.03 |
| Relative humidity maximum | 0.45* | 0.58** | 0.33 | 0.52** | -0.22 |
| Wind | -0.03 | -0.07 | -0.13 | 0.04 | 0.16 |
| Accumulated rainfall | -0.56** | -0.40 | -0.19 | -0.40* | 0.02 |
| Industry | 0.05 | -0.10 | 0.24 | 0.02 | -0.04 |
| Mines | 0.11 | -0.14 | 0.20 | 0.13 | 0.21 |
| Energy | -0.32 | -0.30 | -0.34 | -0.49** | -0.18 |
| Energy generated | 0.17 | -0.01 | 0.06 | 0.15 | 0.12 |
| Transport | 0.19 | -0.11 | 0.13 | 0.12 | 0.18 |
| Population | 0.02 | -0.31 | 0.00 | 0.07 | 0.54** |
| Lowland rice | -0.40 | -0.60*** | -0.32 | -0.29 | 0.70*** |
| Dry Season paddy | -0.44* | -0.58** | -0.34 | -0.30 | 0.66*** |
| Upland Rainfed paddy | 0.38 | 0.62*** | 0.44* | 0.42* | -0.03 |
| Maize | 0.47** | 0.31 | 0.26 | 0.32 | 0.09 |
| Starchy roots | -0.15 | -0.40 | -0.32 | -0.16 | 0.55** |
| Sugar cane | -0.23 | -0.24 | -0.18 | -0.17 | 0.29 |
| | | | | | *NORTH* |
| | *$NO_2$* | *$O_3$* | *$SO_2$* | *AOD* | *UVAI* |
| $NO_2$ | 1.00 | | | | |
| $O_3$ | -0.33 | 1.00 | | | |
| $SO_2$ | -0.21 | 0.72* | 1.00 | | |
| AOD | 0.82** | -0.08 | 0.08 | 1.00 | |
| UVAI | -0.50 | -0.29 | -0.34 | -0.64 | 1.00 |
| FRP | -0.31 | 0.88*** | 0.37 | -0.20 | -0.11 |
| Fire count | 0.21 | -0.20 | 0.34 | 0.21 | 0.05 |
| Sunshine duration | 0.96*** | -0.43 | -0.37 | 0.82** | -0.57 |

| | **$NO_2$** | **$O_3$** | **$SO_2$** | **AOD** | **UVAI** |
|---|---|---|---|---|---|
| Temperature minimum | 0.36 | -0.80** | -0.52 | 0.73* | -0.16 |
| Temperature maximum | 0.67* | -0.77** | -0.68* | 0.77** | -0.14 |
| Relative humidity minimum | -0.84** | 0.64 | 0.38 | -0.87** | 0.35 |
| Relative humidity maximum | -0.11 | -0.32 | -0.60 | -0.26 | 0.71* |
| Wind | -0.07 | 0.22 | -0.41 | 0.05 | -0.10 |
| Accumulated rainfall | -0.66 | 0.30 | 0.52 | 0.08 | -0.28 |
| Industry | -0.14 | -0.80** | -0.67* | -0.32 | 0.65 |
| Mines | 0.12 | -0.38 | -0.87** | -0.05 | 0.09 |
| Energy | -0.11 | 0.46 | 0.16 | -0.02 | 0.16 |
| Energy generated | 0.12 | -0.68* | -0.55 | 0.11 | 0.50 |
| Transport | 0.16 | -0.29 | 0.02 | -0.17 | 0.16 |
| Population | 0.14 | -0.70* | -0.15 | 0.08 | 0.37 |
| Lowland rice | 0.35 | -0.90*** | -0.62 | 0.17 | 0.36 |
| Dry Season paddy | 0.12 | -0.87** | -0.55 | 0.06 | 0.06 |
| Upland Rainfed paddy | -0.37 | -0.39 | 0.11 | -0.40 | 0.39 |
| Maize | 0.32 | -0.63 | -0.37 | -0.06 | 0.58 |
| Starchy roots | 0.17 | -0.77* | -0.62 | 0.12 | 0.50 |
| Sugar cane | -0.23 | 0.69* | 0.11 | 0.13 | -0.30 |
| | | | | | *Central* |
| | *$NO_2$* | *$O_3$* | *$SO_2$* | *AOD* | *UVAI* |
| $NO_2$ | 1.00 | | | | |
| $O_3$ | 0.05 | 1.00 | | | |
| $SO_2$ | -0.36 | -0.18 | 1.00 | | |
| AOD | 0.86** | -0.22 | -0.39 | 1.00 | |
| UVAI | 0.23 | -0.96*** | 0.04 | 0.46 | 1.00 |
| FRP | -0.13 | 0.90** | -0.16 | -0.37 | -0.91** |
| Fire count | -0.13 | 0.52 | -0.30 | 0.07 | -0.52 |
| Sunshine duration | 0.75* | -0.51 | -0.56 | 0.82** | 0.73* |
| Temperature minimum | 0.35 | -0.74* | 0.26 | 0.61 | 0.82** |
| Temperature maximum | 0.35 | -0.74* | 0.18 | 0.65 | 0.82 |
| Relative humidity minimum | -0.15 | -0.68 | -0.34 | 0.02 | 0.63 |
| Relative humidity maximum | 0.06 | 0.81* | -0.69 | -0.06 | -0.75* |
| Wind | 0.32 | 0.48 | -0.56 | 0.35 | -0.35 |
| Accumulated rainfall | -0.55 | -0.41 | 0.39 | -0.09 | 0.24 |
| Industry | 0.20 | -0.33 | 0.82** | 0.16 | 0.34 |
| Mines | 0.29 | -0.75* | 0.19 | 0.23 | 0.80 |
| Energy | 0.19 | 0.56 | 0.01 | -0.33 | -0.51 |
| Energy generated | -0.37 | -0.63 | -0.32 | -0.22 | 0.53 |
| Transport | 0.70 | -0.28 | 0.20 | 0.43 | 0.45 |
| Population | 0.72 | -0.44 | 0.12 | 0.62 | 0.62 |
| Lowland rice | -0.07 | -0.82** | 0.36 | -0.01 | 0.77* |

| | $NO_2$ | $O_3$ | $SO_2$ | AOD | UVAI |
|---|---|---|---|---|---|
| Dry Season paddy | 0.09 | -0.81* | 0.14 | 0.12 | 0.82** |
| Upland Rainfed paddy | 0.03 | 0.82** | 0.07 | -0.40 | -0.80* |
| Maize | -0.02 | 0.60 | 0.13 | -0.33 | -0.59 |
| Starchy roots | -0.01 | -0.31 | 0.82** | 0.14 | 0.27 |
| Sugar cane | 0.41 | -0.15 | -0.54 | 0.78* | 0.29 |
| | | | | | *South* |
| | *$NO_2$* | *$O_3$* | *$SO_2$* | *AOD* | *UVAI* |
| $NO_2$ | 1.00 | | | | |
| $O_3$ | 0.71 | 1.00 | | | |
| $SO_2$ | 0.89** | 0.95** | 1.00 | | |
| AOD | 0.80 | 0.97*** | 0.96*** | 1.00 | |
| UVAI | 0.71 | 0.72 | 0.77 | 0.85* | 1.00 |
| FRP | -0.75 | -0.16 | -0.40 | -0.36 | -0.44 |
| Fire count | 0.88** | 0.72 | 0.87* | 0.70 | 0.46 |
| Sunshine duration | -0.82* | -0.98*** | -0.98*** | -0.93 | -0.66 |
| Temperature minimum | -0.23 | -0.72 | -0.58 | -0.64 | -0.65 |
| Temperature maximum | -0.61 | -0.98*** | -0.89** | -0.95** | -0.71 |
| Relative humidity minimum | -0.64 | -0.35 | -0.56 | -0.40 | -0.55 |
| Relative humidity maximum | -0.28 | 0.46 | 0.18 | 0.30 | 0.18 |
| Wind | 0.67 | 0.33 | 0.50 | 0.55 | 0.87* |
| Accumulated rainfall | -0.81* | -0.34 | -0.60 | -0.48 | -0.68 |
| Industry | -0.75 | -0.38 | -0.53 | -0.53 | -0.40 |
| Mines | 0.80 | 0.80 | 0.89** | 0.74 | 0.51 |
| Energy | -0.93** | -0.86* | -0.97*** | -0.93** | -0.87* |
| Energy generated | -0.43 | -0.54 | -0.55 | -0.63 | -0.90** |
| Transport | 0.96*** | 0.61 | 0.83* | 0.70 | 0.68 |
| Population | 0.98*** | 0.63 | 0.84* | 0.76 | 0.76 |
| Lowland rice | 0.94** | 0.75 | 0.91** | 0.83* | 0.84* |
| Dry Season paddy | 0.69 | 0.85* | 0.88** | 0.82* | 0.74 |
| Upland Rainfed paddy | -0.28 | 0.20 | -0.04 | 0.25 | 0.26 |
| Maize | 0.84* | 0.24 | 0.51 | 0.40 | 0.40 |
| Starchy roots | 0.28 | -0.06 | 0.05 | 0.19 | 0.51 |
| Sugar cane | 0.61 | 0.43 | 0.57 | 0.34 | 0.00 |

# Appendix 2 Comparison of pollution indicators derived from satellite imagery with ground-based measurements

Due to the lack of data, the space-borne pollution indicators derived in this work were compared with just ground-based $PM_{2.5}$ ($\mu g/m^3$) air quality measurements collected during 2020 and 2021 from one monitoring station in Laungprabang and four monitoring stations in Vientiane Capital (Table A2. 1). No ground-based gas species datasets were available to perform a comprehensive comparison with the equivalent pollution indicators. The ground-based measurements were of a daily temporal resolution, and thus the monthly averages were considered for the comparison with the satellite derived data. Note that the ground-based measurements are point measurements, while the satellite-derived datasets are averages of large spatial areas. The strongest agreement between the satellite and ground-based measurements was observed with AOD and $NO_2$ for both provinces, and the weakest for $O_3$.

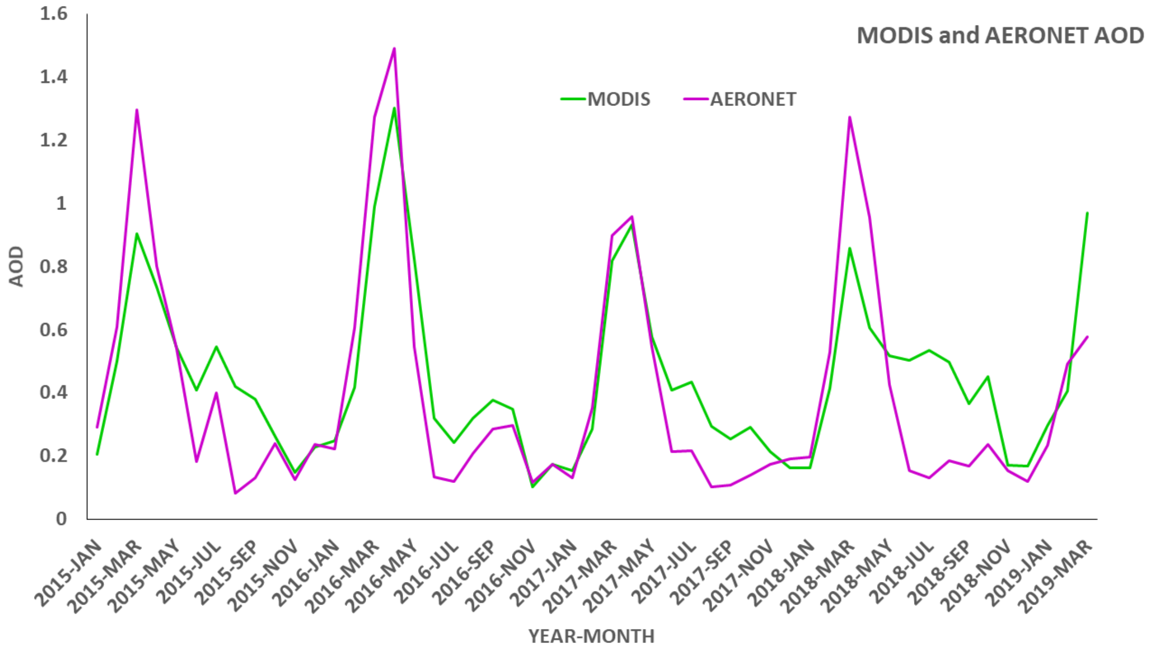
**Table A2. 1:** Pearson correlation between ground-based $PM_{2.5}$ ground-based measurements and the satellite-derived pollution indicators for the provinces Laungprabang and Vientiane Capital. Based on monthly averages for 2020–2021. ***, ** and * denote significance levels of $p < 0.01$, 0.05 and 0.1, respectively

| | Laungprabang $PM_{2.5}$ ground-based | Vientiane Capital $PM_{2.5}$ ground-based |
|---|---|---|
| Laungprabang AOD | 0.60*** | 0.59*** |
| Vientiane Capital AOD | 0.62*** | 0.60*** |
| Laungprabang UVAI | 0.34 | 0.34 |
| Vientiane Capital UVAI | 0.36* | 0.41** |
| Laungprabang $SO_2$ | 0.56*** | 0.57*** |
| Vientiane Capital $SO_2$ | 0.27 | 0.21 |
| Laungprabang $NO_2$ | 0.78*** | 0.72*** |
| Vientiane Capital $NO_2$ | 0.84*** | 0.82*** |
| Laungprabang $O_3$ | -0.23 | -0.32 |
| Vientiane Capital $O_3$ | -0.14 | -0.23 |

**Figure A2. 1:** Monthly trends in AOD determined from MODIS and AERONET sunphotometers for the province of Luangnamtha

Figure A2. 1 compares the AOD derived from MODIS and AERONET for the province of Luangnamtha for the study period. There is a strong agreement in the temporal trends between the two datasets, particularly between January and May. The MODIS AOD exceeds the AERONET AOD during the rainy season. This may be attributed to the differences in datasets; the MODIS AOD is an average of the whole province, while the AERONET AOD is determined from sun photometers with a 1.2° full field of view (FOV).

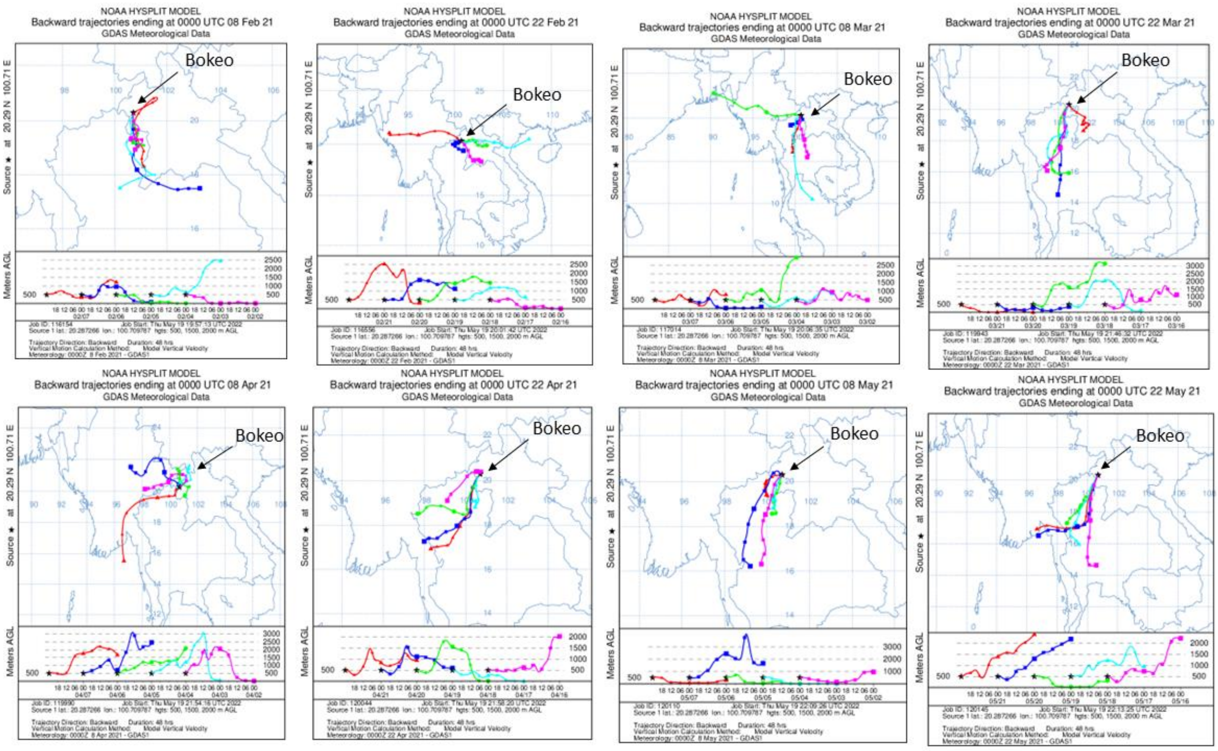
**Figure A2. 1:** Monthly trends in AOD determined from MODIS and AERONET sunphotometers for the province of Luangnamtha




*Source:* Authors' elaboration.

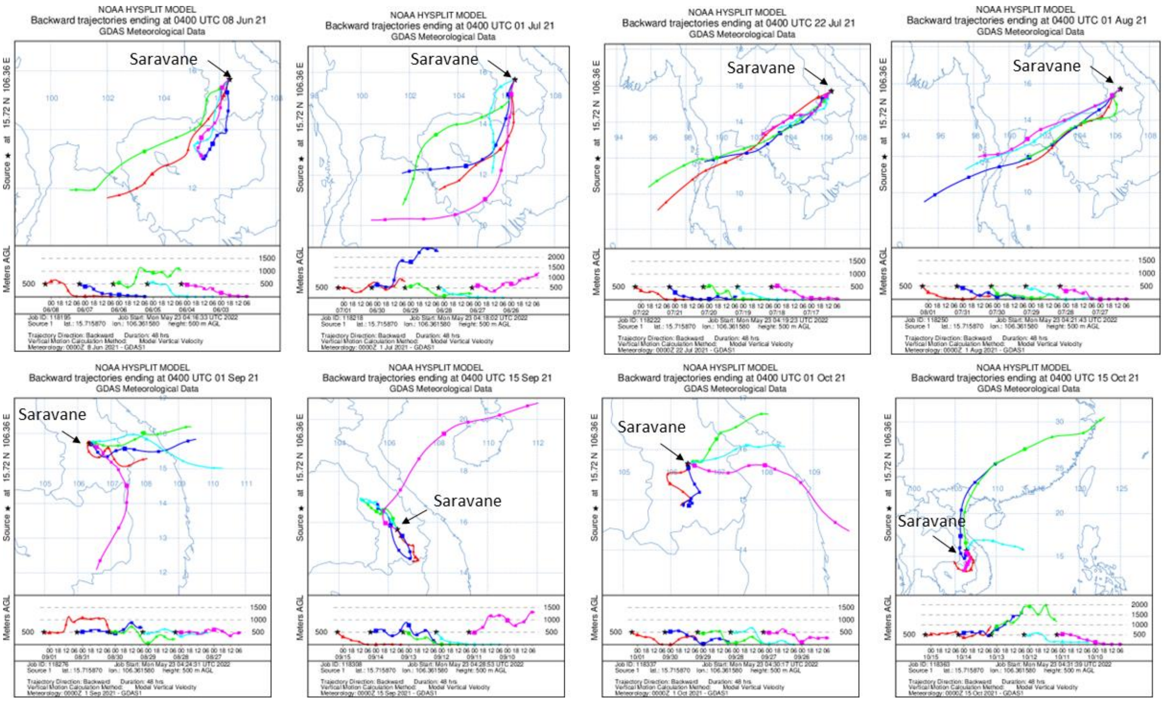
# Appendix 3 Air parcel back-trajectory modelling

**Figure A3. 1:** Air-mass back trajectories during the 2021 fire season in Bokeo




*Source:* HYSPLIT trajectory model.

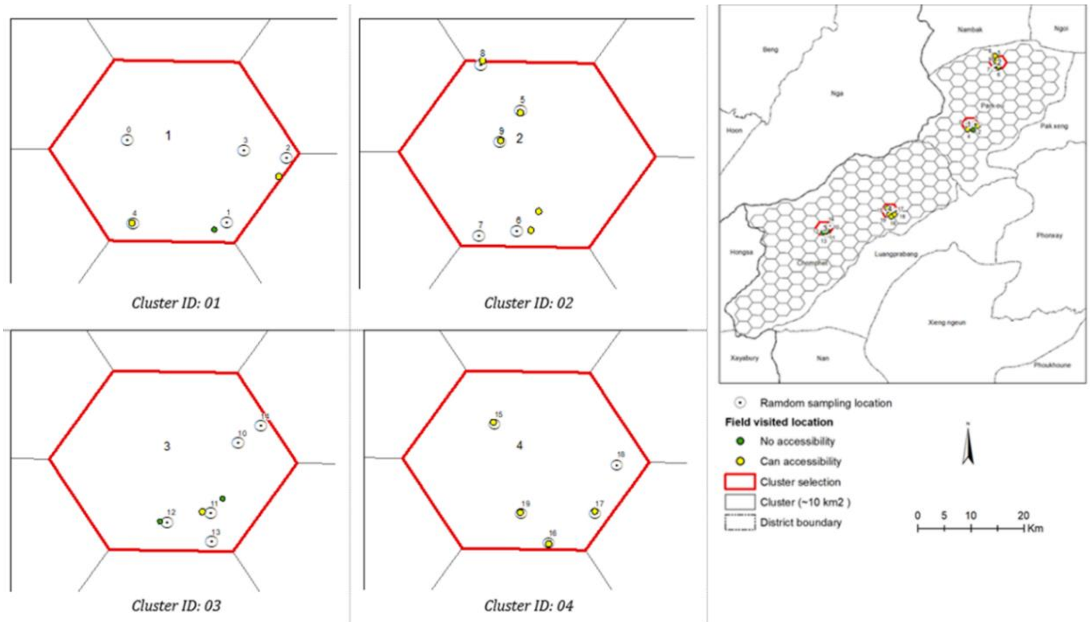
**Figure A3. 2:** Air-mass back trajectories during the 2021 rainy season in Saravane




*Source:* HYSPLIT trajectory model.

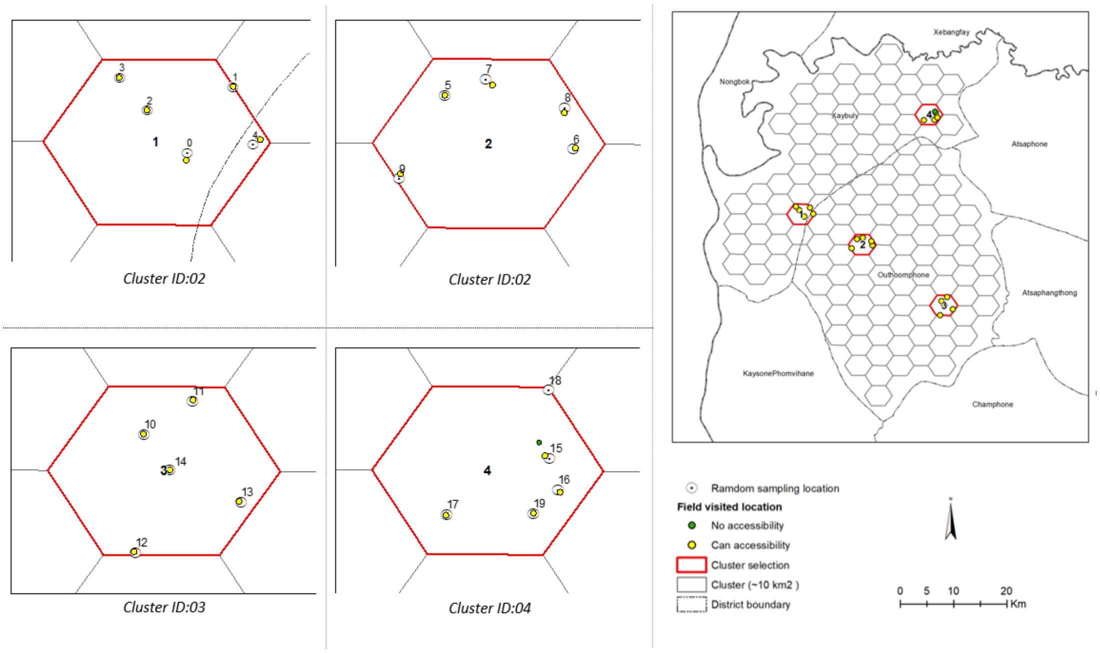
# Appendix 4 Summary of field survey in Luangprabang and Savanakhet Provinces

**Figure A4. 1:** Map with results of fields visited with/without accessibly in two districts in Luangprabang Province




*Source:* Authors' elaboration. Administrative boundaries obtained from National Geographic Department (NGD) of Lao People's Democratic Republic.

**Figure A4. 2:** Map with results of fields visited with/without accessibly in two districts in Savannakhet Province




*Source:* Authors' elaboration. Administrative boundaries obtained from National Geographic Department (NGD) of Lao People's Democratic Republic.

**Table A4. 1:** Notes of the fields visited in the two districts of Luangprabang province

| Cluster ID | Sample ID | Ref-Long | Ref-Lat | District | Accessibility | Current land cover type | Fire events | Deforestation | URL- take a photo * | Notes |
|---|---|---|---|---|---|---|---|---|---|---|
| **1** | 0 | 102.26 | 20.13 | Park Ou | No | NA | NA | NA | NA | NA |
| | 1 | 102.28 | 20.11 | Park Ou | Estimate (bearing: 45°, distance: 250 m) | Pastureland | No | No | 1653980425192.jpg | No burns were found on this location, this area was cleared from fallow land to grow pasture for livestock. It may have been cleared about 3 years ago. |
| | 2 | 102.29 | 20.12 | Park Ou | Estimate (bearing: 25°, distance: 320 m) | Maize | No | No | 1653979667067.jpg | Cropland area (about 2 ha) with a slope. |
| | 3 | 102.28 | 20.12 | Park Ou | No | NA | NA | NA | NA | NA |
| | 4 | 102.26 | 20.11 | Park Ou | Yes | Pastureland | No | No | 1653901627206.jpg | Pastureland (about 6 ha) with steep slope. |
| **2** | 5 | 102.33 | 20.279 | Park Ou | Yes | Rice paddy | No | No | 1653970232721.jpg | Rice paddy surrounded with rubber and teak plantations. |
| | 6 | 102.33 | 20.26 | Park Ou | Estimate (bearing: 220°, distance: 520 m) | Pastureland | No | No | 1653969511471.jpg | Pastureland, about 6 ha. |
| | 7 | 102.33 | 20.26 | Park Ou | Estimate (bearing: 250°, distant: 900 m) | Upland rice | No | No | 1653970939042.jpg | Upland rice area, size about 3 ha. |
| | 8 | 102.33 | 20.28 | Park Ou | Yes | Teak | No | No | 1653967174383.jpg | Teak plantation area (about 20 years), surround by fallow (3–4 years) and upland rice fields. |
| | 9 | 102.33 | 20.27 | Park Ou | Yes | Old fallow > 5 yrs | No | No | 1653971492394.jpg | Old fallow land with bamboo (about 6 years). |
| **3** | 10 | 101.93 | 19.88 | Chomphet | Estimate (bearing: 12°, distance 1200 m) | Young fallow < 5 yrs | No | No | 1654066795807.jpg | The hilly with steep slope is inaccessible. This area is used for crop cultivation and pasture for livestock. |
| | 11 | 101.92 | 19.87 | Chomphet | Yes | Rubber | No | No | 1654063566466.jpg | Open land area and planted rubber trees, about 2 ha. |
| | 12 | 101.92 | 19.87 | Chomphet | Yes | Teak | No | No | 1654063574073.jpg | Hilly area with teak plantation (about 20 years), near the road and has surrounding rubber plantations.. |
| | 13 | 101.92 | 19.87 | Chomphet | No | NA | NA | NA | NA | NA |
| | 14 | 101.93 | 19.88 | Chomphet | No | NA | NA | NA | NA | NA |
| **4** | 15 | 102.07 | 19.93 | Chomphet | Yes | Cleared fallow land | Yes | No | 1654054010353.jpg | Fallow land (about 5 years) was burned approximately one week ago. Size of about 1 ha and surrounded by old fallow forest. |
| | 16 | 102.08 | 19.91 | Chomphet | Yes | Teak | No | No | 1654048619448.jpg | Mixed fallow land and teak plantations (about 2 ha). |
| | 17 | 102.09 | 19.91 | Chomphet | Yes | Open forest | No | Yes | 1654054116123.jpg | Open forest area, about 5 ha. |
| | 18 | 102.09 | 19.92 | Chomphet | No | NA | NA | NA | NA | NA |
| | 19 | 102.08 | 19.91 | Chomphet | Yes | Settlement | No | No | 1654050856146.jpg | Settlement area surrounded by teak plantations and pasture land. |

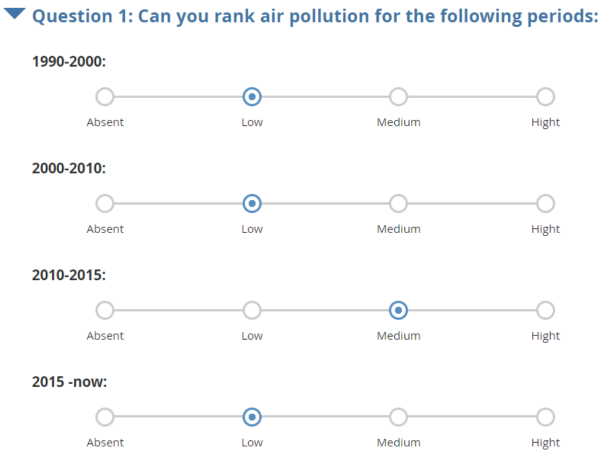
**Table A4. 2:** Notes of the fields visited in the two districts of Savanakhet province

| Cluster ID | Sample ID | Ref-Long | Ref-Lat | District | Accessibility | Current land cover type | Fire events | Deforestation | URL- take a photo * | Note |
|---|---|---|---|---|---|---|---|---|---|---|
| **1** | 0 | 104.89 | 16.85 | Xaybuly | Yes | Sugarcane | No | No | 1654568354458.jpg | Agriculture land used for sugarcane with an area of about 20 ha. |
| | 1 | 104.9 | 16.86 | Xaybuly | Yes | Sugarcane | No | No | 1654573495184.jpg | Sugarcane surround by dry open shrub. |
| | 2 | 104.88 | 16.85 | Xaybuly | Yes | Rice paddy | No | No | 1654568813281.jpg | Paddy field surround a sugarcane and rubber plantation, about 10 years old. |
| | 3 | 104.88 | 16.86 | Xaybuly | Yes | Rubber | No | No | 1654570427241.jpg | Ten year old rubber plantation. |
| | 4 | 104.9 | 16.85 | Xaybuly | Yes | Sugarcane | No | No | 1654572867726.jpg | Sugarcane (about 10 ha) with dry open forest to the north and south. |
| **2** | 5 | 104.97 | 16.81 | Outhoum-phone | Yes | Livestock area | No | No | 1654505139218.jpg | Dry open shrub/forest used for livestock. |
| | 6 | 104.99 | 16.80 | Outhoum-phone | Yes | Rice paddy | No | No | 1654503839161.jpg | Paddy field with an area of about 5 ha. |
| | 7 | 104.97 | 16.81 | Outhoum-phone | Yes | Rice paddy | No | No | 1654506283979.jpg | Paddy field and with a stream and forest along stream. |
| | 8 | 104.99 | 16.81 | Outhoum-phone | Yes | Rice paddy | No | No | 1654505958889.jpg | Paddy field (about 2 ha) surrounded by bamboo and young fallow. |
| | 9 | 104.96 | 16.80 | Outhoum-phone | Yes | Cassava | No | No | 1654504221898.jpg | Cassava area and surrounding sugarcane. |
| **3** | 10 | 105.09 | 16.72 | Outhoum-phone | Yes | Mixed forest | No | No | 1654495953079.jpg | Forests area with villager's gardens close by. |
| | 11 | 105.1 | 16.73 | Outhoum-phone | Yes | Rice paddy | No | No | 1654492383921.jpg | Paddy field surround by cassava and forest. |
| | 12 | 105.09 | 16.70 | Outhoum-phone | Yes | Rice paddy | No | No | 1654499942369.jpg | Paddy field and surrounding forest. |
| | 13 | 105.11 | 16.71 | Outhoum-phone | Yes | Rice paddy | No | No | 1654492067564.jpg | Paddy field, about 20 ha. |
| | 14 | 105.1 | 16.72 | Outhoum-phone | Yes | Old fallow > 5 yrs | No | No | 1654494291250.jpg | Old fallow area, about 3 ha. |
| **4** | 15 | 105.09 | 16.99 | Xaybuly | Yes | Dry open forest | No | No | 1654586293381.jpg | Dry open forest with grasslands (about 20 ha). |
| | 16 | 105.09 | 16.99 | Xaybuly | Yes | Dry open forest | No | No | 1654585763737.jpg | Dry open forest. |
| | 17 | 105.07 | 16.98 | Xaybuly | Yes | Dry open forest | No | No | 1654589581240.jpg | Dry open forest surround by cassava. |
| | 18 | 105.09 | 17.00 | Xaybuly | Estimate (bearing: 20°, distance 950 m) | Grassland | Yes | No | 1654586921953.jpg | Grassland used for sugarcane for 2 years. Burned after harvest. |
| | 19 | 105.08 | 16.98 | Xaybuly | Yes | Dry open forest | No | No | 1654584363006.jpg | Dry open forest surround by paddy fields. |

**Results of questionnaire A in Luangrabang province**

**For group discussion with PORNE/PAFO Government offices in the province to assess the contribution of anthropogenic activity to air pollution.**

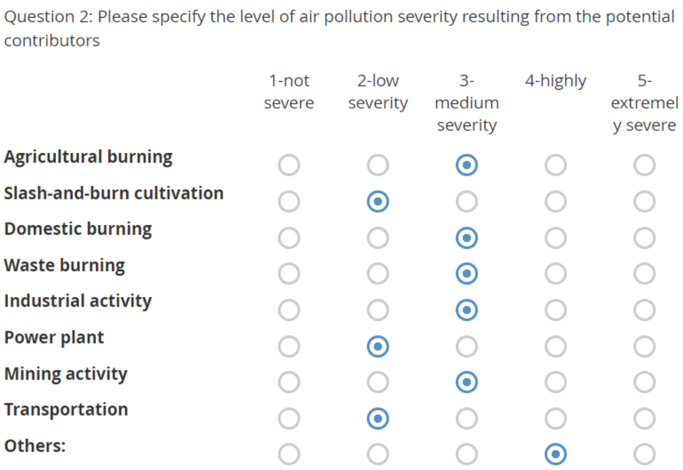
## Rank air pollution for the following periods:



Question 1: Can you rank air pollution for the following periods:

| Period | Absent | Low | Medium | Hight |
|---|---|---|---|---|
| 1990-2000: | ○ | ● | ○ | ○ |
| 2000-2010: | ○ | ● | ○ | ○ |
| 2010-2015: | ○ | ○ | ● | ○ |
| 2015 -now: | ○ | ● | ○ | ○ |

## Level of air pollution severity resulting from the potential contributors



Question 2: Please specify the level of air pollution severity resulting from the potential contributors

| | 1-not severe | 2-low severity | 3-medium severity | 4-highly | 5-extremely severe |
|---|---|---|---|---|---|
| Agricultural burning | ○ | ○ | ● | ○ | ○ |
| Slash-and-burn cultivation | ○ | ● | ○ | ○ | ○ |
| Domestic burning | ○ | ○ | ● | ○ | ○ |
| Waste burning | ○ | ○ | ● | ○ | ○ |
| Industrial activity | ○ | ○ | ● | ○ | ○ |
| Power plant | ○ | ● | ○ | ○ | ○ |
| Mining activity | ○ | ○ | ● | ○ | ○ |
| Transportation | ○ | ● | ○ | ○ | ○ |
| Others: | ○ | ○ | ○ | ● | ○ |

## Contribution period of potential air pollution drivers

| Contributors | Throughout the year | Part of the year: Approx. start | Part of the year: Approx. end |
|---|---|---|---|
| Agricultural burning | | April | May |
| Slash-and-burn cultivation | | December | May |
| Domestic burning (fuelwood for cooking) | X | | |
| Waste burning | X | | |
| Industrial activity | X | | |
| Power plant | X | | |
| Mining activity | X | | |

| | |
|---|---|
| Transportation | X |
| Others: (e.g. forest fires and dust storms) | X |

## Effect of each contributor

**Question 4: What are the specific effects of each contributor?**

| Effects | Smog/haze | Changes in breathing | Difficulty in vision | Changes in weather | Other... |
|---|---|---|---|---|---|
| Agricultural burning | ☑ | ☑ | ☑ | ☑ | ☐ |
| Slash-and-burn cultivation | ☑ | ☑ | ☑ | ☑ | ☐ |
| Domestic burning | ☐ | ☑ | ☐ | ☐ | ☐ |
| Waste burning | ☑ | ☑ | ☑ | ☑ | ☐ |
| Industrial activity | ☑ | ☑ | ☑ | ☑ | ☐ |
| Power plant | ☐ | ☐ | ☐ | ☐ | ☐ |
| Mining activity | ☐ | ☐ | ☐ | ☑ | ☐ |
| Transportation | ☑ | ☑ | ☐ | ☑ | ☐ |
| Others: | ☐ | ☐ | ☐ | ☐ | ☐ |

## Evolution of each contributor over the past five years

Question 5: Indicate the evolution of each contributor over the past five years

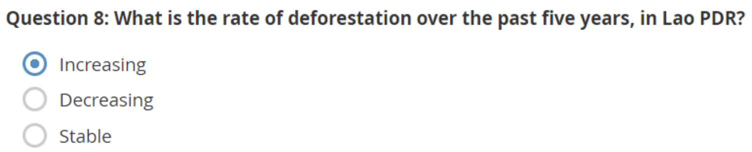
| | Greatly reduced | Reduced | Stable | Increased | greatly increased] |
|---|---|---|---|---|---|
| Agricultural burning | ◉ | ○ | ○ | ○ | ○ |
| Slash-and-burn cultivation | ○ | ○ | ◉ | ○ | ○ |
| Domestic burning | ○ | ○ | ○ | ◉ | ○ |
| Waste burning | ○ | ○ | ○ | ◉ | ○ |
| Industrial activity | ○ | ○ | ◉ | ○ | ○ |
| Power plant | ○ | ○ | ○ | ◉ | ○ |
| Mining activity | ○ | ○ | ○ | ◉ | ○ |
| Transportation | ○ | ○ | ○ | ◉ | ○ |
| Others: | ○ | ○ | ○ | ○ | ○ |

## Solutions to the air pollution caused by the contributors

| Contributors | Solution 1 | Solution 2 | Solution 3 |
|---|---|---|---|
| **Agricultural burning** | Raising awareness on environmental protection every year | There are rules/regulations | Law/regulation enforcement |
| **Slash-and-burn cultivation** | Raising awareness on environmental protection every year | There are rules/regulations | Law/regulation enforcement |
| **Waste burning** | Raising awareness on waste management every year | | |
| **Industrial activity** | Monitoring | There are rules/regulations | |

| | | |
|---|---|---|
| **Power plant** | Monitoring | There are rules/regulations |
| **Mining activity** | Monitoring | There are rules/regulations |
| **Transportation** | Follow the management regulations | There are rules/regulations |

**Deforestation**


Question 8: What is the rate of deforestation over the past five years, in Lao PDR?

Increasing

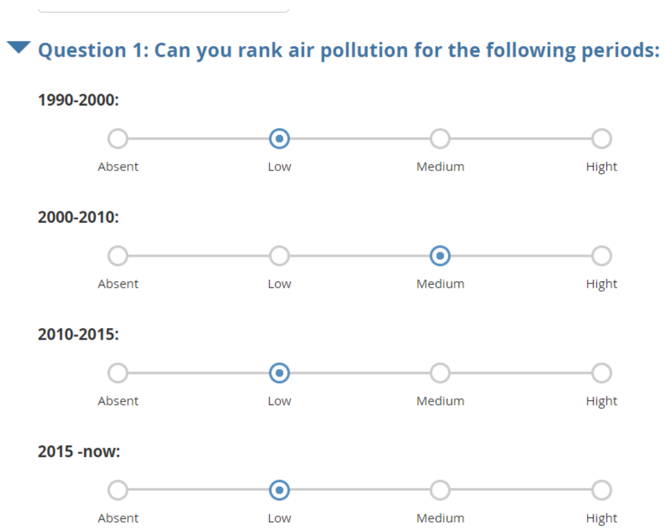
Decreasing

Stable

**Results of questionnaire A in Savanakhet province**

**For group discussion with PORNE/PAFO Government offices in the province to assess the contribution of anthropogenic activity to air pollution.**

**Rank air pollution for the following periods:**


Question 1: Can you rank air pollution for the following periods:

1990-2000:

Absent Low Medium Hight

2000-2010:

Absent Low Medium Hight

2010-2015:

Absent Low Medium Hight

2015 -now:

Absent Low Medium Hight

## Level of air pollution severity resulting from the potential contributors

Question 2: Please specify the level of air pollution severity resulting from the potential contributors

| | 1-not severe | 2-low severity | 3-medium severity | 4-highly | 5-extremely severe |
|---|---|---|---|---|---|
| **Agricultural burning** | ○ | ◉ | ○ | ○ | ○ |
| **Slash-and-burn cultivation** | ○ | ○ | ◉ | ○ | ○ |
| **Domestic burning** | ◉ | ○ | ○ | ○ | ○ |
| **Waste burning** | ○ | ○ | ◉ | ○ | ○ |
| **Industrial activity** | ○ | ○ | ○ | ◉ | ○ |
| **Power plant** | ◉ | ○ | ○ | ○ | ○ |
| **Mining activity** | ○ | ◉ | ○ | ○ | ○ |
| **Transportation** | ○ | ○ | ○ | ◉ | ○ |
| **Others:** | ○ | ○ | ○ | ○ | ○ |

## Contribution period of potential air pollution drivers

| Contributors | Throughout the year | Part of the year: Approx. start | Part of the year: Approx. end |
|---|---|---|---|
| Agricultural burning | | April | May |
| Slash-and-burn cultivation | | December | May |
| Domestic burning (fuelwood for cooking) | X | | |
| Waste burning | | November | February |
| Industrial activity | | November | February |
| Power plant | X | | |
| Mining activity | | November | June |
| Transportation | X | | |
| Others: (e.g. forest fires and dust storms) | X | | |

## Effect of each contributor

**Question 4: What are the specific effects of each contributor?**

| **Effects** | Smog/haze | Changes in breathing | Difficulty in vision | Changes in weather | Other... |
|---|---|---|---|---|---|
| **Agricultural burning** | ☑ | ☐ | ☐ | ☐ | ☐ |
| **Slash-and-burn cultivation** | ☑ | ☐ | ☐ | ☐ | ☐ |
| **Domestic burning** | ☑ | ☑ | ☐ | ☐ | ☐ |
| **Waste burning** | ☑ | ☑ | ☑ | ☐ | ☐ |
| **Industrial activity** | ☐ | ☑ | ☐ | ☐ | ☐ |
| **Power plant** | ☑ | ☐ | ☐ | ☐ | ☐ |
| **Mining activity** | ☑ | ☑ | ☐ | ☐ | ☐ |
| **Transportation** | ☑ | ☑ | ☐ | ☐ | ☐ |
| **Others:** | ☐ | ☐ | ☐ | ☐ | ☐ |

## Indicate the evolution of each contributor over the past five years

Question 5: Indicate the evolution of each contributor over the past five years

| | Greatly reduced | Reduced | Stable | Increased | greatly increased] |
|---|---|---|---|---|---|
| **Agricultural burning** | ○ | ◉ | ○ | ○ | ○ |
| **Slash-and-burn cultivation** | ○ | ◉ | ○ | ○ | ○ |
| **Domestic burning** | ○ | ○ | ◉ | ○ | ○ |
| **Waste burning** | ○ | ◉ | ○ | ○ | ○ |
| **Industrial activity** | ○ | ○ | ◉ | ○ | ○ |
| **Power plant** | ○ | ○ | ◉ | ○ | ○ |
| **Mining activity** | ○ | ◉ | ○ | ○ | ○ |
| **Transportation** | ○ | ○ | ○ | ◉ | ○ |
| **Others:** | ○ | ○ | ○ | ○ | ○ |

## Solutions to the air pollution caused by the contributors

| Contributors | Solution 1 | Other |
|---|---|---|
| **Agricultural burning** | There are rules/regulations on fire burning, but action is limited | |
| **Slash-and-burn cultivation** | There are rules/regulations on fire burning, but action is limited | |
| **Domestic burning** | There are rules/regulations on fire burning, but action is limited | |
| **Waste burning** | Avoid burning waste | |
| **Industrial activity** | Apply measures and follow the environmental management plan | Some factories do not follow the regulations |
| **Power plant** | There are measures for mitigation | |
| **Mining activity** | There are measures for mitigation | |
| **Transportation** | In general, no measures for mitigation | |

## Deforestation

**Question 8: What is the rate of deforestation over the past five years, in Lao PDR?**

○ Increasing
◉ Decreasing
○ Stable

**Results of questionnaire B in Luangprabang province**

**For focus group discussion at the village level within four clusters to assess the contribution of farming to air pollution through crop residue burning**.

There are 55 household (HH) representatives from 10 villages and two district (Park Ou and Chomphet district) in Luangprabang province that participated in the interview and discussion.

| Cluster ID | Number of villagers that participated in interview and discussion |
|---|---|
| Cluster 01 | 8 HH (Huaykor village: 3 hh, Hatkor village : 5 hh ), Pak Ou district |
| Cluster 02 | 22 HH (Nonsavan village: 5 hh, Huaylae village: 9 hh, Huaymark village: 8 hh), Pak Ou district |
| Cluster 03 | 6 HH ( Na Arang village: 4 hh, Huaythak village: 2 hh), Chomphet district |
| Cluster 04 | 21 HH (Bouamxieng village: 5 hh, Buamlao village: 11 hh, Huayon village: 5 hh), Chomphet district |

**Key findings from discussion.**

- Average household size in two districts : 6 pp
- Average farm size per HH in two districts: 3.2 ha
- Farming activities:
  - Growing pasture/livestock
  - Crop cultivation (rice paddy, upland rice, maize, industrial trees)
- Off- farming activities:
  - Female/merchant
  - Handicrafts
  - Worker
  - Small businesses

| Cluster ID | Average household size (people) | Average farm size per household (ha) |
|---|---|---|
| Cluster 01 | 4.6 | 2.7 |
| Cluster 02 | 6.4 | 2.4 |
| Cluster 03 | 6.0 | 4.0 |
| Cluster 04 | 6.0 | 3.7 |

**i) Key findings for agriculture practices:**

Based on the interview, 55 hh (96 %) have cultivated crops this year, and 87% (50 HHs) use burning in the field to prepare the land for crop cultivation.

**Type of land used for crop cultivation: Fallow land is the most common land-type used for annual crop cultivation, followed by permanent agriculture land (paddy field and pastureland)**

| | *Frequency (Freq)* | *(%)* | *Ranking* |
|---|---|---|---|
| *Fallow land* | *28* | *49.12* | *1* |
| *Permanent agriculture land* | *26* | *45.61* | *2* |
| *Newly cleared land (convert of forest)* | *6* | *10.53* | *3* |
| *Other (land are borrowed, lent to cultivate)* | *1* | *1.75* | *4* |

**Number of plots/parcels per household is mostly 2–3 plots**

| | *Freq* | *(%)* | *Ranking* |
|---|---|---|---|
| *2–3 plots* | *37* | *64.91* | *1* |
| *1 plot* | *12* | *21.05* | *2* |
| *4–5 plots* | *6* | *10.53* | *3* |
| *>5 plot* | *2* | *3.51* | *4* |

**Average size of a plot is 1 ha and > 1 ha**

| | *Freq* | *(%)* | *Ranking* |
|---|---|---|---|
| *1 ha* | *24* | *42.11* | *1* |
| *> 1 ha* | *22* | *38.6* | *2* |
| *0.5 ha* | *7* | *12.28* | *3* |
| *Other* | *3* | *5.26* | *4* |

**Main agricultural activities in villages are crop cultivation and livestock (one household can perform multiple crop cultivation such as rice paddy, perennial crop and livestock)**

| | *Freq* | *(%)* | *Ranking* |
|---|---|---|---|
| *Crop cultivation* | *35* | *80.7* | *1* |
| *Livestock* | *33* | *57.89* | *2* |
| *NTPFs collection* | *12* | *21.05* | *3* |

**Main types of crop cultivation in the village are rice paddy, upland rice and pastureland**

| | Freq | (%) | Ranking |
|---|---|---|---|
| *Rice paddy* | *31* | *54.4* | *1* |
| *Upland rice* | *11* | *19.3* | *2* |
| *Growing pasture* | *7* | *12.3* | *3* |
| *Orchard tree* | *7* | *12.3* | *3* |
| *Maize* | *3* | *5.3* | *4* |
| *Other (Rubber tree, vegetable)* | *3* | *5.3* | *5* |

**ii) Key findings for fire occurrence:**

***87% or participants responded that the main nature of fires is anthropogonic***

**Main propose of fire burning-related agricultural activities**

| | Freq | (%) | Ranking |
|---|---|---|---|
| *Burning to clear land (fallow land)* | *24* | *42.1%* | *1* |
| *Burning of crop residue after harvesting* | *13* | *22.8%* | *2* |
| *Burning new growth of pasture grazing* | *11* | *19.3%* | *3* |
| *Other (Burning before cultivation)* | *2* | *3.5%* | *4* |
| *None burning* | *7* | *12.3%* | |

**Main land use types on which fires occur is mostly fallow land and agriculture land, and fires occur one time per year mostly in April.**

| | Freq | (%) | Ranking |
|---|---|---|---|
| *Fallow land* | *31* | *54.39* | *1* |
| *Agriculture land* | *21* | *36.84* | *2* |
| *Forest land* | *2* | *3.51* | *3* |
| *Grassland* | *1* | *1.75* | *4* |
| *Others* | *3* | *3.51* | *5* |

**Length (years) of fallow land is mostly 1–2 years.**

| | Freq | (%) | Ranking |
|---|---|---|---|
| *1–2 yrs* | *38* | *66.67* | *1* |
| *3–4 yrs* | *14* | *24.56* | *2* |
| *> 5 yrs* | *1* | *1.75* | *3* |

**iii) Key findings for deforestation (forest land converted to agriculture land)**

*From interview, 21 HH (36.4%) respondents states that deforestation still happening, the main cause of deforestation is agriculture expansion (22.8%), followed by timber production and fuel wood (5.3% each).*

| | *Freq* | *(%)* | | *Ranking* | |
|---|---|---|---|---|---|
| *Agriculture expansion* | *13* | *22.81* | | *1* | |
| *Timer production* | | *3* | *5.26* | | *2* |
| *Fuel wood* | *3* | *5.26* | | *3* | |
| *Other* | *2* | *3.51* | | *4* | |

**Rate of deforestation in recent years (last 5 year)**

| | *Freq* | *(%)* |
|---|---|---|
| *Decrease* | *52* | *91.23* |
| *Stable (no change)* | *5* | *8.77* |

**Percentage of villagers would like to change existing crop cultivation practices**

*From the interview with 57 HHs, 34 HH (58.6 %) would like to change the existing crop cultivation practices, and 23 HH (39.6%) do not expected a change.*

***Reason of wanting to change existing crop cultivation practices (58.6%)***

| | *Freq* | *(%)* | |
|---|---|---|---|
| *Low production* | | *12* | *21.1* |
| *High labour intensive* | *10* | *18.5* | |
| *Reduce air pollution* | *5* | *9.3* | |
| *soil is degradation* | *4* | *7.4* | |
| *Other (Hight capital, increasing income)* | | *3* | *5.6* |

***Reason of not wanting to change existing crop cultivation practices (49.6%)***

| | *Freq* | *(%)* | |
|---|---|---|---|
| *High production* | | *11* | *19.3* |
| *Low labour intensive* | *6* | *10.5* | |
| *Other (good income, no land, less weeding)* | | *5* | *8.8* |
| *Satisfied/happiness* | *1* | *1.8* | |

**Result of questionnaire B in Savannakhet Province:**

**Focus group discussion at the village level within cluster selection to assess the contribution of farming to air pollution through crop residue burning**.

54 household (HH) representing six villages and two district in Savannakhet province participated in the interview and discussion.

| Cluster ID | Number of villagers participating in the interview and discussion |
|---|---|
| Cluster 01 | 10 hh (Khamnonsoung village ), Xaybourу district |
| Cluster 02 | 8 hh( Somsa art village is 7 hh, and Nakou village is 1 hh), Outhouphone district |
| Cluster 03 | 15 hh ( Laoyai village: 15 hh), Outhouphone district |
| Cluster 04 | 21 hh (Nogkhietlueang village is 12 hh, Nahueang village is 9 hh), Xaybourу district |

**Key findings from discussion.**

- Average household size in the two districts: 6.9 people
- Average farm size per household in the two districts: 8.1 ha
- Farming activities:
    - *Crop cultivation (rice paddy, sugarcane and cassava)*
    - *Rubber plantation*
    - *Livestock*
- Off-farming activities:
    - Female/merchant
    - Skilled worker

| Cluster ID | Average household size (people) | Average farm size per household (ha) |
|---|---|---|
| Cluster 01 | 6.90 | 9.00 |
| Cluster 02 | 8.50 | 8.88 |
| Cluster 03 | 6.53 | 4.67 |
| Cluster 04 | 6.62 | 10.00 |

**i) Key findings for agriculture practices:**

54 HHs (100 %) have cultivated crops (paddy field, sugarcane, cassava) this year, and 39 HH (72%) use of fire burning on the field to prepare the land for cultivation

**Land type used for crop cultivation:**

| | *Freq* | *(%)* | |
|---|---|---|---|
| *Permanent agriculture land (paddy field)* | | *37* | *68.2* |
| *Fallow land* | *18* | *33.61* | |
| *Other (dry open shrub/forest)* | *6* | *11.75* | |
| *Newly cleared land (convert of forest)* | | *4* | *7.41* |

**Number of plot/parcel per household**

| | *Freq* | *(%)* | |
|---|---|---|---|
| *2–3 plots* | | *37* | *66.67* |
| *1 plot* | *11* | *20.37* | |
| *4–5 plots* | | *6* | *11.53* |
| *>5 plot* | *1* | *1.8* | |

**Average size (ha) of a plot**

| | *Freq* | *(%)* |
|---|---|---|
| *> 1 ha* | *46* | *85.19* |
| *1 ha* | *24* | *11.11* |
| *0.5 ha* | *2* | *3.7* |

**Main agricultural activities in villages are rice paddy, following sugarcane cultivation and cassava** (one household can perform many crop cultivations such as rice paddy, sugarcane and cassava cultivate and livestock)

| | Freq | % |
|---|---|---|
| o *Rice paddy* | *52* | *98.1* |
| o *Sugarcane* | *12* | *22.2* |
| o *Cassava* | *8* | *14.8* |
| o *Rubber Plantation* | *3* | *5.6* |
| o *Livestock* | *3* | *5.6* |

**Dominant farming systems in the village**

| | *Freq* | *(%)* | | *Ranking* | |
|---|---|---|---|---|---|
| *Cash crop* | *40* | *74.07* | | *1* | |
| *Subsistence crop* | | *33* | *61.11* | | *2* |
| *Other* | *2* | *3.7* | | *3* | |

### ii) Key findings for fire occurrence:

***49 HH (90%) state that the nature of fires is mostly anthropogonic***

**Main propose of fire burning-related agricultural activities**

| | *Freq* | *(%)* | *Ranking* |
|---|---|---|---|
| *Burning of crop residue after harvesting* | *14* | *25.9%* | *1* |
| *Burning to clear land* | *12* | *22.2%* | *2* |
| *Burning new growth of pasture grazing* | *3* | *5.6%* | *3* |
| *Other (Burn for facilitate hunting and mushroom)* | *2* | *3.7%* | *4* |
| *None burning* | *23* | *42.5%* | |

**Main land use types on which fires occur. Fires occur once per year** (farmers generally burn crop residue [sugarcane] after harvesting once a week during November and December).

| | *Freq* | *(%)* |
|---|---|---|
| *Agriculture land* | *27* | *50* |
| *Fallow land* | *17* | *31.4* |
| *Grassland* | *4* | *7.1* |
| *Others (dry open shrub/forest)* | *2* | *3.7* |

**Length (years) of fallow land**

| | *Freq* | *(%)* |
|---|---|---|
| *1–2 yrs* | *52* | *96.3* |

**iii) Deforestation (forest land converted to agriculture land)**

*17 HH (31.4%) stated that deforestation is still happening, and the main cause of deforestation is fuel wood (24.7%), followed by agricultural expansion (3.7%).*

| | *Freq* | *(%)* |
|---|---|---|
| *Fuel wood* | *13* | *24.7* |
| *Agriculture expansion* | *2* | *3.7* |
| *Other (fuel for charcoal)* | *2* | *3.7* |

**Rate of deforestation in recent years (last 5 year)**

| | *Freq* | *(%)* |
|---|---|---|
| *Decrease* | *25* | *46.29* |
| *Stable (no change)* | *25* | *46.29* |
| *Increase (who have owner land )* | *4* | *7.4* |

**Average frequency used to clear a new land for cultivation**

| | *Freq* | *(%)* |
|---|---|---|
| *Clearing a new parcel every year* | *11* | *20.4* |
| *Clearing a new parcel every 2–3 years* | *5* | *9.3* |

**Number of villagers that would like to change existing crop cultivation practices**

*From the 54 HHs, 38 HH (70.4%) do not expected to change existing crop cultivation practices, and 16 HH (26.9%) would like to change existing crop cultivation practices.*

***Reasons for not wanting to change* existing crop cultivation practices *(70.4%)***

| | *Freq* | *(%)* |
|---|---|---|
| *High production* | *20* | *37.0* |
| *Low labour intensive* | *7* | *12.96* |
| *Traditional practice* | *4* | *7.41* |
| *Satisfied/happiness* | *3* | *5.56* |
| *limited capital* | *2* | *3.70* |
| *limited land for cultivation* | *2* | *3.70* |

***Reasons for wanting to change* existing crop cultivation practices *(26.9%)***

| | *Freq* | *(%)* |
|---|---|---|
| *Low production* | *6* | *11.1* |
| *High labour intensive* | *3* | *5.6* |
| *Increase income* | *4* | *7.4* |
| *Other* | *3* | *5.6* |

**Main obstacles for the implementation of new practices**

| | *Freq* | *(%)* | |
|---|---|---|---|
| *Lack of budget* | *32* | *59.26%* | |
| *Lack of knowledge* | *2* | *3.70%* | |
| *Lack of labour* | *8* | *14.81%* | |
| *Lack of support* | | *2* | *3.70%* |
| *Others (soil degradation,* | | *4* | *7.41%* |
| *Area is dry open shrub* | | *2* | *3.70%* |
| *land of land* | *3* | *5.56%* | |

# Appendix 5

# Questionnaires A, B and C for the interviews/discussions at the provincial level, for local farmers and the field data collection, respectively

**Questionnaire A for group discussion with the Provincial Natural Resource and Environment Office (PORNE), Provincial Agriculture and Forestry Office (PAFO) at the province level to assess the contribution of anthropogenic activity to air pollution**

**Target respondent:** Provincial officers
**Objective:** Gain insight into pollution drivers and guidance on reducing air pollution

Date:…………………
District: ……………
Province: …………
**Question 1: Can you rank air pollution for the following periods:**

- 1990–2000: absent low medium high
- 2000–2010: absent low medium high
- 2010–2015: absent low medium high
- 2015–now: absent low medium high

**Question 2: Please specify the level of air pollution severity resulting from the potential contributors [fill in table 1- not severe; 2- low severity, 3- medium severity, 4-highly severe, 5-extremely severe].**

| Contributors | 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|---|
| Agricultural burning | | | | | |
| Slash-and-burn cultivation | | | | | |
| Domestic burning (e.g. fuelwood for cooking) | | | | | |
| Waste burning | | | | | |
| Industrial activity | | | | | |
| Power plant | | | | | |
| Mining activity | | | | | |

| | | | | | |
|---|---|---|---|---|---|
| Transportation (e.g. cars, buses and other vehicles) | | | | | |
| Others: (e.g. forest fires and dust storms) | | | | | |

**Question 3: Please specify when drivers potentially contribute to air pollution [fill in table].**

| Contributors | Throughout the year | Part of the year | |
|---|---|---|---|
| | | Approx. start | Approx. end |
| Agricultural burning | | | |
| Slash-and-burn cultivation | | | |
| Domestic burning (e.g. fuelwood for cooking) | | | |
| Waste burning | | | |
| Industrial activity | | | |
| Power plant | | | |
| Mining activity | | | |
| Transportation (e.g. cars, buses and other vehicles) | | | |
| Others: (e.g. forest fires and dust storms) | | | |

**Question 4: What are the specific effects of each contributor?**

| Contributors | Smog/haze | Changes in breathing | Difficulty in vision | Changes in weather | Other … |
|---|---|---|---|---|---|
| Agricultural burning | | | | | |
| Slash-and-burn cultivation | | | | | |
| Domestic burning (e.g. fuelwood for cooking) | | | | | |

| | | | | | |
|---|---|---|---|---|---|
| Waste burning | | | | | |
| Industrial activity | | | | | |
| Power plant | | | | | |
| Mining activity | | | | | |
| Transportation (e.g. cars, buses and other vehicles) | | | | | |
| Others: (e.g. forest fires and dust storms) | | | | | |

**Question 5: Indicate the evolution of each contributor over the past five years [1- greatly reduced; 2-reduced; 3- stable; 4-increased; 5- greatly increased].**

| Contributors | 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|---|
| Agricultural burning | | | | | |
| Slash-and-burn cultivation | | | | | |
| Domestic burning (e.g. fuelwood for cooking) | | | | | |
| Waste burning | | | | | |
| Industrial activity | | | | | |
| Power plant | | | | | |
| Mining activity | | | | | |
| Transportation (e.g. cars, buses and other vehicles) | | | | | |
| Others: (e.g. forest fires and dust storms) | | | | | |

**Question 6: Please provide any solutions to the air pollution caused by the contributors (e.g. alternative practices, the regulation of fire burning, reducing transportation, avoid burning waste, recycling).**

| Contributors | Solution 1 | Solution 2 | Solution 3 | Etc. |
|---|---|---|---|---|
| Agricultural burning | | | | |
| Slash-and-burn cultivation | | | | |
| Domestic burning (e.g. fuelwood for cooking) | | | | |
| Waste burning | | | | |
| Industrial activity | | | | |
| Power plant | | | | |
| Mining activity | | | | |
| Transportation (e.g. cars, buses and other vehicles) | | | | |
| Others: (e.g. forest fires and dust storms) | | | | |

**Question 7: What is the rate of deforestation over the past five years in the Lao People's Democratic Republic?**

- Increasing
- Decreasing
- Stable

**Questionnaire B for focus group discussion at the village level within cluster selection to assess the contribution of farming to air pollution through crop residue burning**

Target respondent: Villager

Objective: Gain insight into pollution drivers from a local perspective and obtain information to fill in gaps from the national datasets.

Cluster ID Selection: ……… Date: ……….

Villages: …………. Interviewer: …………

District: …………… No participants to focus group: ……

Province: …………

**Section 1. Respondent information**

- Respondent name
- Profession
- Household size
- Population
- Farm size
- Lat
- Long
- Farming activities
- Off-farm activities
- Others

**Question 1: Did you cultivated crops this year?**

- Yes
- No

**Question 2: Did you burn crop residuals/fields to prepare the land for crop cultivation?**

- Yes
- No

**Question 3: What type of land is used for crop cultivation?**

- Permanente agricultural land
- Fellow Land
- Newly cleared plots
- Other…

**Question 4: How many field parcel belong to/are owned by your family?**

- One
- Two –three
- Four – five
- More than five

| **Section 2. Agriculture practices** |
|---|

Question 5: What are the main agricultural related activities in the villages? [Can select more than one choice]

- Crop cultivation
- Livestock
- Non-timber forest products (NTFPs)
- Other:…

Question 6: What are the dominant farming systems in the village?

- Cash crops
- Subsistence crops
- Other

Question 7: What is the type of crop cultivation in the village?

- Agroforestry
- Upland rice
- Rice paddy
- Other:

## Section 3. Fire occurrences in agriculture

Question 8: What is the nature of fires in the Lao People's Democratic Republic?

- Natural
- Anthropogenic

Question 9: Which fire-related agricultural activities contribute to air pollution in the Lao People's Democratic Republic? (Can select more than one choice)

- Burning of crop residue after harvesting
- Burning before sowing
- Burning to clear land
- Burning new growth of grass for cattle grazing
- other: ……….

Question 10: What are the main land use types on which fires occur?

- Agricultural land
    - Rice paddy
    - Cassava
    - Maize
    - Commercial crops
    - Bamboo
- Forest land
- Grassland
- Bare land
- Settlements

Question 11: What is the fire occurrence per year on average for individual parcels?

a. One time
b. Two time
c. More than two times

Question 12: What is the length of the fallow period (years)?

- 1–2 years
- 3–4 years
- 5 years
- > 5 years

## Section 4. Deforestation

Question 13: Is deforestation happening in the village?

- **Yes**
- **No**

Question 13a. If yes, what is the main cause of deforestation?

- Agriculture expansion
- Industrial activities
- Fuel wood
- Timber production
- Mining
- Energy production (e.g. dams)
- Urbanization
- Village expansion
- Infrastructure building (e.g. roads)
- Other…

Question 14: What is the rate of deforestation in recent years [last 5 years]?

- Increasing
- Decreasing
- Stable

Question 15: What is the deforestation frequency in context of agriculture expansion? (What is the average frequency used to clear the land for shifting cultivation purposes?)

- Clearing a new parcel every year
- Clearing a new parcel every 2–3 years
- Clearing a new parcel every 4–5 years
- Clearing a new parcel every 6 or more

Question 16: What is the average size of a parcel in the Lao People's Democratic Republic?

- 0.5 hector
- 1 hector
- >1 hector

Question 17: How many parcels can be cleared by a single farmer? (Are there any restrictions or guidelines implemented to reduce further deforestation?)

- 1–3 parcels
- 4–5 parcels
- 6 or more parcels

Question 18: Would you like to make changes to existing crop cultivation practices?

- Yes
- No

Question 18a If YES, what are the main reasons? (Can select more than one option.)

- High production
- Not labour intensive
- Other…..

Question 18b If NO, what are the main reasons? (Can select more than one option.**)**

- Low production
- High labour intensive
- Other…..

Question 19: What are the main obstacles for the implementation of new practices?

- Lack of information
- Lack of resources
- Lack of support
- Other …

**Questionaries C for the field data collection at the village level to validate the remote sensing results and check the fire burning contribution to air pollution in the Lao People's Democratic Republic**

**Objective:** To collect field data to compliment the results from the geospatial analysis

Kobo Collection (https://www.kobotoolbox.org/) was used for the field data collection. The collection method was designed on the web application and subsequently uploaded onto the mobile application.

Information about sample collector:
Name:
Institute:
Email id:

Name of province:……..
Cluster ID selection: ………
Sampling location ID: ………..

1. **GPS coordinates**

   Latitude/ longitude: --------------------------

   Date/time: --------------------------

   Waypoint ID: --------------------------

   Take a photo

2. **Can the sample location be accessed?**
   - Yes it can be accessed
   - No accessibility

   If, no [provide more information]

   - Bearing from viewpoint to sample location: ----------------------
   - Distance from viewpoint to sample location: ----------------- metres
   - Photo

3. **What are current land cover types in the location?**
    - Agricultural land
        - Annual crop
            - Maize
            - Cassava
            - Sugarcane
            - Sweet corn
            - Vegetables
            - Bean
            - Tobacco
            - others
        - Perennial Crops
            - Rubber
            - Coffee
            - Banana
            - Teak
            - Other
    - Forest land
        - Dry dipterocarp forest
        - Evergreen Forest
        - Mixed forest
    - Grassland
    - Bare land
    - Settlements
4. **Are there any traces of deforestation in the location?**
    - Yes (answer Question 5)
    - No
5. **Provide an estimation of the deforestation area (ha)?**
6. **Are there any fire events in the location?**
    - Yes- fires have occurred in this year (answer Questions 7 & 8)
    - Yes- fires are occurring now (answer Questions 7 & 8)
    - No
7. **What is the land cover type of the fire?**
    - Crop residual burning
    - Slash and burn
    - Fire in forest land
    - Fire in other
8. **Area burnt by fires (estimate field size - ha)**
9. **Take photos in north, south, west and east directions**
10. **Notes/comments**

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